

Karlsruhe Institute of Technology (KIT)
Institute of Applied Geosciences

Salinization of Groundwater and Surface Water Resources in the Context of Natural and Anthropogenic Changes in the Southern Mekong Delta, Vietnam

Zur Erlangung des akademischen Grades eines

DOKTORS DER NATURWISSENSCHAFTEN

(Dr. rer. nat.)

von der KIT-Fakultät für

Bauingenieur-, Geo- und Umweltwissenschaften

des Karlsruher Instituts für Technologie (KIT)

genehmigte

DISSERTATION

von

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Tag der mündlichen Prüfung: 23.01.2026

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Erklärung

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbstständig verfasst und die Grundsätze des Karlsruher Instituts für Technologie (KIT) zur Sicherung guter wissenschaftlicher Praxis in ihrer aktuell gültigen Fassung beachtet habe. Alle benutzten Hilfsmittel wurden vollständig und genau angegeben.

Bei der Erstellung dieser Arbeit wurde ChatGPT ausschließlich zur sprachlichen Überarbeitung und Verbesserung der Lesbarkeit eingesetzt. Die Verantwortung für den gesamten Inhalt der Veröffentlichung liegt vollständig bei mir.

Ort, Datum

Unterschrift

Acknowledgements

This work was carried out at the Institute of Applied Geosciences at the Karlsruhe Institute of Technology as part of the ViWaT-Engineering project, a joint German–Vietnamese cooperation initiative funded by the German Federal Ministry of Research, Technology and Space (funding reference: 02WCL1474A). The publication of scientific studies was supported by the KIT-Publication Fund of the Karlsruhe Institute of Technology.

I would like to express my sincere gratitude to my supervisor, Prof. Dr. Stefan Norra, for the opportunity and trust to work in the ViWaT project, which ultimately led to this dissertation. I truly appreciated the positive and motivating working atmosphere I experienced under Prof. Norra’s leadership since my Bachelor thesis eleven years ago and his full scientific and personal support to develop my career.

In this context, I would also like to sincerely thank PD Dr. Elisabeth Eiche for always having an open door for me and supporting me in every possible way, whether with laboratory work, discussing scientific ideas, or institute matters.

A special thanks goes to Dr. Nicolas Börsig, who guided me through the first years of my PhD, joined several field trips, and intensely discussed research ideas and methods with me. His valuable contribution to my work cannot be understated.

Likewise, Van Cam Pham greatly supported me during our joint trips to Vietnam and became a good friend over the years. Thank you for introducing me to Vietnamese culture and for our countless conversations.

I am really glad that Felix Dörr joined ViWaT halfway through the project. Not only did he bring new perspectives and knowledge into our group, but we quickly discovered many shared personal and work-related interests, which is why we so closely work and publish our research together.

I also thank Hoan Viet Tran for his continuous support. Not only do we both work in the same hydrogeological context, but Hoan Viet Tran was also responsible for the communication between German and Vietnamese partners, providing important insights, data, and invaluable support for this work.

Acknowledgements

I want to thank all project partners of the ViWaT-Engineering project. I really appreciate that I could work in this multidisciplinary group of friendly and encouraging people. A special thanks goes to Dr. Andreas Schenk for his encouraging attitude and interest in my research. I also want to thank Dr. Vu Hoang Thai Duong for his continuous support and for always being available to discuss my work and future research directions, as well as to connect me with researchers from Vietnam. Likewise, I also want to thank Dr. Roderick van der Linden for his valuable insights into meteorology. I want to thank Dr. Johannes Ho for his support during our joint field campaigns.

I want to thank all members of my PhD committee, especially Prof. Franz Nestmann, for initiating the ViWaT project, for his motivational speeches, and for his drive to make a difference by linking scientific research with practical application.

I thank Prof. Andreas Fink and Prof. Stefan Hinz for expanding the interdisciplinary scope of my work and demonstrating the importance of working in a friendly atmosphere. Lastly, I would like to sincerely thank Prof. Ulf Mohrlök for joining my committee and for his interest to evaluate my work.

Beyond the people directly engaged in my research, I want to thank my dear colleagues at the Institute of Applied Geosciences at KIT.

First, I would like to sincerely thank Prof. Jochen Kolb, who, as head of the department, supported both me and the working group in every possible way and created a supportive and low-stress working environment.

I am especially thankful to Andre Wilhelms, with whom I have shared so many good and fun experiences over the years as a fellow PhD student. We had countless discussions about almost everything and memorable field trips. Thank you for your energetic and motivational attitude.

I would like to thank Dr. Flavia Digiacoio for always being there for me to discuss my work, institute life, and many other things. Likewise, I want to thank Dr. Teba Gil-Diaz for being such a supportive office neighbor and for reviewing this dissertation. I look forward to continuing our collaboration on current projects. Similarly, I want to thank Tino Wilhelm-Degenhardt, who also reviewed my work and is always available for an office chat. I am excited about our future research. I want to thank Dr. Simon Hector for his tips and for reviewing this work. I also want to thank former fellow PhD students

of our working group. Thank you, Dr. Jing Qian, Dr. Jingwei Yang and Dr. Hongyan Wang.

My gratitude extends to all current and former staff members, laboratory employees, and technicians from the Department of Geochemistry and Economic Geology for analyzing samples and supporting me in countless ways. Thank you, Maya Denker, Nadine Hüll, Chantalle Kotschenreuther, Claudia Mößner, Gesine Preuß, Maria Maravillas Prieto Sevilla, Ralf Wachter, Kristian Nikoloski.

I also thank our department's administration, especially Victoria Weist, for assisting me with countless applications, documents, contracts, and finances. Your help made my life much easier and allowed me to focus on my research. I also want to thank Andrea Friedrich and Laura Neira.

This dissertation is the right place to thank my good friends and fellow students Felix Haberland, Albert Riehm, and Dr. Lars Yström, who pushed me through the first years of my Bachelor's studies and have supported me since the very beginning of our journey in 2011. Together, Lars and I fought our way through the Master's program, sharing many challenging but ultimately very successful moments.

I also thank Fabian Simon, who helped me improve my work life balance throughout my PhD with countless rounds of our favorite games.

Even though words cannot express my gratitude, I would like to thank my family. Without them, this work would not have been possible. My parents, Regina and Peter Bauer, always supported me throughout school, even when it was not easy, and during my studies, always believing in me. I also want to thank my sister Esther and her family for being there for me.

Finally, and most importantly, I want to thank my wonderful wife, Ilka. I am incredibly grateful to her, for keeping me motivated and confident and for supporting me in every possible way. I also want to thank her whole family for their encouragement over the past years. Thank you!

Abstract

In the context of climate change impacts and anthropogenic pressures, available freshwater resources are steadily declining on a global scale, causing severe freshwater scarcity in many regions worldwide. This phenomenon is particularly pronounced in the highly populated mega-deltas of Southeast Asia. As a consequence of natural resource overexploitation and land subsidence, the sea is progressively reclaiming many of these low-lying coastal areas.

The Mekong Delta in Vietnam, renowned for its vast rice paddy fields and dense network of rivers and irrigation channels, is among the most seriously affected delta regions worldwide and is increasingly threatened in its future persistence by the progressive *loss of land and freshwater*. Seawater intrusion and salinization of valuable freshwater resources compromise drinking water supply, agricultural production, and ecosystem stability. Seawater intrusion is a challenge for water resources management in most coastal regions worldwide, yet substantial knowledge gaps concerning relevant cause–effect relationships persist.

To resolve this, the case of Mekong Delta was investigated in this dissertation, shedding light on the spatiotemporal distribution of saline and fresh water resources and to identify natural and anthropogenic drivers of progressive salinization. Therefore, field data from five sampling campaigns conducted between 2018 and 2022 in the southernmost province of the Mekong Delta, Ca Mau, and monitoring data from established stations were analyzed. In particular, geochemical and hydrometeorological data were evaluated using traditional and improved methods, and results on groundwater and surface water salinization in the southern Mekong Delta are presented in three scientific publications.

In the first study, a hydrogeochemical investigation across the most exploited aquifers in Ca Mau Province was conducted. Molar ion ratios and water-type analysis, which both are the result of water–rock interactions, and the development of a hydrogeological model, revealed that groundwater composition is shaped by past marine transgression and regression cycles and recent salinization. High salinity conditions are attributed to human activities, such as well construction and pumping, that promote vertical infiltration of saline water from the saline shallow aquifer or the surface.

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To assess riverine seawater intrusion dynamics, interannual salinity variations from 2000 to 2022 were analyzed in the second publication, using trend analysis and correlations between extreme salinity events and the timing and extent of hydrological drought conditions, defined by low-discharge periods of the Mekong River. It was shown that human modifications of the hydrological regime, primarily due to dam construction and upstream reservoir management, cause significant negative discharge anomalies, which substantially decrease the freshwater gradient and promote seawater intrusion. At the same time, land subsidence estimates derived from water-level records between 2000 and 2022, amounting to 1.5 to 2.5 cm/a, increase the delta's overall vulnerability to seawater intrusion. This high vulnerability of the Mekong Delta is reflected in pronounced salinity variations, with salinity gradually increasing by more than 10 g/L during the dry season and significant interannual differences in peak salinity levels of up to 15 g/L, regularly reaching and exceeding seawater salinity levels of 35 g/L.

Subsequently, in the third publication, harmonic analysis of hourly water-level and salinity records from the dry seasons of 2017 and 2018 demonstrates that sub-seasonal salinity dynamics are controlled by tide-driven water-level fluctuations. A Harmonic Least Squares approach was developed and applied to effectively capture the extent of tidal influence and the temporal variability of tidal control during the study period. Stationary and non-stationary behavior expected in estuarine systems was captured by a 45-day sliding windowed Harmonic Least Squares reconstruction, obtaining weighted R^2 values of 0.85 to 0.98 for water level and 0.53 to 0.73 for salinity.

In addition, this dissertation integrates insights from further co-authored studies, covering hydrogeological groundwater modeling, new findings on the drivers of land subsidence, groundwater quality and water use, as well as land use dynamics in the Mekong Delta. Together, the studies presented in this dissertation offer a holistic and multidisciplinary perspective on salinization and freshwater availability in the Mekong Delta by considering the complex interrelationships among its various system components. As a synoptic outcome, the continuous *loss of land and freshwater* that ultimately leads to progressive salinization is presented, revealing a cascading cycle in which rising salinity levels cause multiple negative effects and maladaptation, further reinforcing salinization of both groundwater and surface water.

This dissertation provides a comprehensive scientific foundation for the development of sustainable water-management strategies in the Mekong Delta. The methods and synoptic concept can be directly applied to other, equally vulnerable delta systems in Southeast Asia and beyond. Finally, this work highlights the need for close cooperation between interdisciplinary scientific communities and local decision-makers, outlining a path forward for the Mekong Delta and other similarly affected regions worldwide.

Zusammenfassung

Im Zusammenhang mit dem Klimawandel und verstärkten anthropogenen Einflüssen nehmen die weltweit verfügbaren Süßwasserressourcen kontinuierlich ab. In vielen Regionen der Erde führt dies bereits zu Wasserknappheit. Die großen Deltaregionen Südostasiens weisen aufgrund ihrer hohen Bevölkerungsdichte eine besonders große Vulnerabilität auf. Zu den weltweit am stärksten betroffenen Deltaregionen zählt das Mekong-Delta in Vietnam, das für seine ausgedehnten Reisfelder sowie sein dichtes Netz aus Fluss- und Bewässerungssystemen bekannt ist. Die zukünftige Existenz des Mekong-Deltas ist zunehmend gefährdet, da infolge der Übernutzung natürlicher Ressourcen sowie der fortschreitenden Landabsenkung Salzwasser immer weiter in die niedrig gelegenen Küstenregionen eindringt. Infolgedessen kommt es zu einer Versalzung wertvoller Süßwasserressourcen, was die Trinkwasserversorgung, die landwirtschaftliche Produktion und die Stabilität von Ökosystemen erheblich beeinträchtigt. Obwohl Salzwasserintrusion in Küstenregionen weltweit eine zentrale Herausforderung für das Wasserressourcenmanagement darstellt, bestehen weiterhin erhebliche Wissenslücken hinsichtlich der zugrunde liegenden Ursache–Wirkungs-Zusammenhänge.

Vor diesem Hintergrund wurde in der vorliegenden Dissertation das Mekong-Delta untersucht, um die räumlich-zeitliche Verteilung von Süß- und Salzwasserressourcen zu erfassen und die natürlichen sowie anthropogenen Einflussfaktoren der fortschreitenden Versalzung zu identifizieren. Hierzu wurden Felddaten aus fünf Probenahmekampagnen zwischen 2018 und 2022 in der südlichsten Provinz des Mekong-Deltas, Ca Mau, sowie Monitoringdaten bestehender Messstationen ausgewertet. Es wurden insbesondere geochemische und hydrometeorologische Daten mithilfe etablierter und weiterentwickelter Methoden analysiert. Die Ergebnisse zur Grund- und Oberflächenwasserversalzung im südlichen Mekong-Delta sind in drei wissenschaftlichen Studien publiziert.

In der ersten Publikation wurde eine hydrogeochemische Untersuchung der am stärksten genutzten Aquifere in der Provinz Ca Mau durchgeführt. Molare Ionenverhältnisse und Wassertypanalysen, die das Resultat von Wasser-Gesteins-Wechselwirkungen

sind, sowie das entwickelte hydrogeologische Modell zeigten, dass die Grundwasserzusammensetzung sowohl durch frühere marine Transgressions- und Regressionsphasen als auch durch rezente Versalzungsprozesse geprägt ist. Erhöhte Salzgehalte sind dabei vor allem auf anthropogene Aktivitäten wie Brunnenbau und Grundwasserentnahme zurückzuführen. Diese Aktivitäten begünstigen eine vertikale Infiltration salzhaltigen Wassers aus oberflächennahen salinen Aquiferen oder aus Oberflächengewässern.

Im Zentrum der zweiten Publikation stand die Analyse der Salzwasserintrusionsdynamik in Oberflächengewässern. Hierbei wurden jährliche Schwankungen der Salinität im Zeitraum von 2000 bis 2022 untersucht. Mithilfe von Trend- und Korrelationsanalysen konnte ein signifikanter Zusammenhang zwischen extremen Versalzungsereignissen und hydrologischen Dürreperioden nachgewiesen werden. Es konnte gezeigt werden, dass menschliche Eingriffe in das hydrologische Regime, insbesondere durch den Bau von Staudämmen und das Reservoirs-Management im Oberlauf des Mekongs, signifikante negative Abflussanomalien verursachen. Diese verringern den hydraulischen Süßwassergradienten erheblich und fördern das Vordringen von Meerwasser. Gleichzeitig erhöhen Landabsenkungsraten von 1,5 bis 2,5 cm pro Jahr, welche aus Wasserstandsdaten zwischen 2000 und 2022 berechnet wurden, die generelle Anfälligkeit des Deltas gegenüber Salzwasserintrusion zusätzlich. Diese hohe Vulnerabilität spiegelt sich in ausgeprägten Salzgehaltsschwankungen wider. Während der Trockenzeit steigt der Salzgehalt graduell um mehr als 10 g/L an, und zwischen den Jahren treten Unterschiede in den maximalen Salzgehalten von bis zu 15 g/L auf. Dabei werden Meerwassersalzgehalte von 35 g/L regelmäßig erreicht oder überschritten.

Die dritte Publikation zeigt auf Basis einer Spektralanalyse von stündlichen Wasserstands- und Salzgehaltsdaten aus den Trockenzeiten 2017 und 2018, dass die intra-saisonale Dynamik der Salinität maßgeblich durch gezeitenbedingte Schwankungen des Wasserstands kontrolliert wird. Hierfür wurde ein Harmonic-Least-Squares-Ansatz entwickelt und angewendet, mit dem das Ausmaß des Gezeiteneinflusses und die zeitliche Variabilität der gezeitenkontrollierten Prozesse während des Untersuchungszeitraums zuverlässig erfasst werden konnten. Die sowohl stationären als auch nicht-stationären Muster wurden mithilfe eines 45-tägigen sliding windowed Harmonic-Least-

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Squares-Ansatzes rekonstruiert, wobei gewichtete R^2 -Werte von 0,85 bis 0,98 für den Wasserstand und 0,53 bis 0,73 für den Salzgehalt erzielt wurden.

Darüber hinaus integriert diese Dissertation Erkenntnisse aus weiteren Publikationen mit Ko-Autorenschaft, darunter hydrogeologische Grundwassermodellierungen, neue Ergebnisse zu den Ursachen der Landabsenkung, zur Grundwasserqualität und Wassernutzung sowie zur Dynamik der Landnutzung im Mekong-Delta. In ihrer Gesamtheit liefern die in dieser Arbeit präsentierten Studien eine ganzheitliche und interdisziplinäre Perspektive auf die Versalzung und die Süßwasserverfügbarkeit im Mekong-Delta, indem sie die komplexen Wechselwirkungen zwischen den verschiedenen Systemkomponenten berücksichtigen. Als übergeordnetes Ergebnis wird der kontinuierliche Verlust von Land und Süßwasser aufgezeigt, der letztlich zu einer fortschreitenden Versalzung führt und einen sich selbstverstärkenden Rückkopplungseffekt auslöst. Steigende Salzgehalte führen in diesem Prozess zu vielfältigen negativen Auswirkungen und kontraproduktiven Anpassungsreaktionen, die die Versalzung von Grund- und Oberflächenwasser weiter verstärken.

Diese Dissertation liefert eine umfassende wissenschaftliche Grundlage für die Entwicklung nachhaltiger Wasserbewirtschaftungsstrategien im Mekong-Delta. Die angewandten Methoden und das entwickelte synoptische Konzept sind direkt auf andere, ähnlich vulnerable Deltasysteme in Südostasien und darüber hinaus übertragbar. Abschließend unterstreicht diese Arbeit die Notwendigkeit einer engen Zusammenarbeit zwischen interdisziplinären Forschungsgemeinschaften und lokalen Entscheidungsträgern und zeigt Zukunftsperspektiven für das Mekong-Delta sowie für andere weltweit vergleichbar betroffene Regionen auf.

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Abbreviations

EC	Electrical conductivity
GIS	Geographic Information System
FFT	Fast Fourier Transform
HLS	Harmonic Least Squares
LDP	Low discharge period
LSO	Land subsidence observatory
RSLR	Relative sea level rise
SDG	Sustainable development goal
SLR	Sea level rise
SWI	Seawater intrusion
TDS	Total dissolved solids

1 Introduction

1.1 Background: Water resources in river delta systems

The availability and sustainable use of water resources is a matter of global significance. The quantity and quality of ground- and surface waters is not only crucial to provide sufficient drinking water, it also determines land use and agricultural production, facilitates industrial growth and finally enables healthy ecosystems (Scanlon et al., 2023). In the context of climate change and the extensive anthropogenic transformation of the natural environment, hydro-meteorological regimes worldwide are changing substantially, causing numerous water-related challenges for humans and the environment (Hein et al., 2021). As the demand for freshwater rises sharply (Yan et al., 2022), it increasingly exceeds the available supply (Huggins et al., 2022; Wang et al., 2022), leading to local and regional water crises and failure to meet the Social Development Goals (SDG) set by the United Nations (UN). In the 2024 SDG report, the UN states that “progress in water and sanitation remains insufficient” and that in 2030 two billion people will likely not have access to safe drinking water (UN DESA, 2024). Furthermore, severe water scarcity and freshwater stress affected almost half of the world population for at least part of the year in 2022 (UN DESA, 2024). While water quality continues to decline and water stress intensifies globally, accelerated by climate change, the proportion of transboundary water resources that are effectively and co-operatively managed remains low (UN DESA, 2024).

Coastal areas and particularly large estuary systems play a critical role in this context as they are highly vulnerable given their high population density, significant agricultural production and diverse ecosystems as well as rich biodiversity (Becker et al., 2024; Michael et al., 2017). An estuary is the transition zone between a river and a sea and combines many characteristics of both, such as tidal waves and saline to fresh water conditions (Savenije, 2012). Due to the abundance of natural resources, estuaries have always been a hotspot for human settlements and agriculture (Anthony et al., 2025; Day Jr. et al., 2007; Macklin and Lewin, 2015). River deltas are a specific type of estuary, often characterized by an almost prismatic shape, low slope, and are dominated by upstream river discharge rather than tidal waves (Savenije, 2012). Many of the world’s major deltas are geologically young, having formed during the Holocene,

within the past 12,000 years (Stanley and Warne, 1994; Woodroffe, 1993). Large rivers, such as the Amazon, Ganges, Mississippi, Yangtze, Nile and Mekong transport sediments from their catchment area towards the sea. If the accumulation and deposition of sediments exceed erosional forces, river delta systems develop and grow (McManus, 2002). However, this fragile balance makes river delta systems highly susceptible to natural and anthropogenic change (Savenije, 2012). The world's largest deltas are inhabited by around 400 million people and are crucial for food security and industry (Edmonds et al., 2020; Kuenzer and Renaud, 2012).

Modern river deltas are often highly modified environments with little remains of the natural environment. They are shaped by human interventions of the last centuries and sometimes millennia, by changes in the upstream basin as well as in the delta itself (Anthony et al., 2014; Woodroffe et al., 2007). These interventions are designed to serve numerous socio-economic needs, but they reached an unprecedented scale, especially in the last few decades, adversely affecting delta stability and sustainable development with a concerning outlook if current practices do not change (Kondolf et al., 2022). For example, upstream dams and reservoirs trap sediments, significantly reducing the sediment flux to the sea to a degree that deltas can no longer sustain their landmass (Syvitski et al., 2005). Other human activities causing negative effects on delta systems include sand mining (Koehnken et al., 2020; Rentier and Cammeraat, 2022), mangrove deforestation (Friess et al., 2019; Guannel et al., 2016), soil and water degradation due to intensive agriculture and aquaculture (Corbau et al., 2019) as well as the unsustainable exploitation of freshwater resources (Tockner, 2021).

River delta systems have a low-lying topography and are rapidly changing environments, threatened by relative sea level rise (RSLR) and hydro-meteorological extreme events (Bucx et al., 2014; Ghirardelli et al., 2025; Tessler et al., 2015). The threat of large-scale inundation persists in many low-lying estuaries, but recent studies highlight that the Asian mega deltas are exceptionally prone, mainly due to accelerating rates of land subsidence (Becker et al., 2024; Bucx et al., 2014; Erban et al., 2014).

Against this background, seawater intrusion (SWI) into groundwater and river systems has become a common threat in many estuaries worldwide, negatively affecting agriculture and freshwater ecosystems (Bucx et al., 2014; Ghirardelli et al., 2025; Kaushal et al., 2021; Lee et al., 2025). Rising sea levels due to a warming climate combined

with land subsidence intensify SWI (Huning et al., 2024; Zamrsky et al., 2024). In addition, reduced groundwater recharge and declining upstream river discharge, caused by both climate change and increasing human water demand, substantially amplify the extent of SWI in both groundwater and river systems in many regions worldwide (Adams et al., 2024; Lee et al., 2025).

1.2 Study area - The Mekong Delta in Vietnam

Vietnam in Southeast Asia has a shoreline of 3,260 km length, equaling the distance from Oslo in Norway to Sicily in the south of Italy. Historically, life and socio-economic activities in Vietnam have therefore been closely linked to the coastal areas and the sea, while being strongly affected by sea level rise (SLR) and hydro meteorological extreme events (Veetil et al., 2021). The Red River Delta in the north and the Mekong Delta in the south of Vietnam together are home to nearly half of the country's population of over 100 million people. Although the Red River and its delta are relatively small, they host Hanoi, the capital of Vietnam, making the region one of the most densely populated in the world. The Mekong River Delta, on the other hand, is one of the largest delta systems globally. The Mekong River is the world's 12th-longest river and holds a similar ranking in annual discharge and an even higher ranking in sediment load. (Mikhailova, 2014).

Like many of the large rivers in Asia, the Mekong River originates in the Tibetan Plateau and flows for approximately half of its 4,800 km length through China before forming the border between Myanmar and Laos, and later between Laos and Thailand. It then continues into Cambodia and finally Vietnam, forming one of the world's largest delta systems, before discharging into the East Sea (also known as South China Sea) through eight major branches. In total, the Mekong River Basin, including numerous secondary catchments along its course, covers nearly 800,000 km², more than twice the size of Germany and approximately 4.5 times the area of the Rhine River catchment (Frings et al., 2014; Renaud and Kuenzer, 2012).

Together with the adjacent metropolis of Ho-Chi-Minh-City, the Vietnamese Mekong Delta region is home to 27 million people (GSOV, 2024). The Mekong Delta is often referred to as Vietnam's "rice bowl," playing a crucial role in national food security and contributing significantly to the country's agriculture and aquaculture export capacity.

Vietnam ranks as the world's third-largest rice exporter, providing nearly 15 % of global exports, with the Mekong Delta contributing up to 90 % (Huong et al., 2022; Maitah et al., 2020).

The socio-economic success of Vietnam began in 1986 with economic reforms towards an open market economy, called *Đổi Mới*, which translates to "renovation" or "innovation". In the Mekong Delta, this success is closely tied to its abundant natural resources, primarily its nutrient-rich soils and freshwater availability provided by the Mekong River. However, this rapid development has come at an environmental cost that people are now forced to adapt to, including land subsidence (Dörr, 2024; Erban et al., 2014; Kondolf et al., 2022), ecosystem loss due to mangrove deforestation (Vo et al., 2013), SWI (Loc et al., 2021a; Park et al., 2022), soil salinization (Loc et al., 2021b), and erosion (Anthony et al., 2015; Liu et al., 2017).

The sustainable development of the Mekong River Basin is a prominent topic since the early 1990s, when transboundary challenges were identified, particularly competing water use interests, and the willingness for cooperation lead to the founding of the Mekong River Commission (Browder and Ortolano, 2000). However, in the face of climate change, rapid economic and population growth, geopolitical tensions, and the inconsistent implementation of policies, these challenges have persisted and negative consequences intensified in their impact (Park et al., 2025). Amidst the economic boom in Vietnam and climate change impacts, the overexploitation of freshwater and hydrological interventions adversely impacted freshwater resources in recent years (Binh et al., 2025; Huggins et al., 2022). Despite being located in the tropics (8.5°-11° N) with average yearly precipitation rates above 2000 mm (Pham-Thanh et al., 2021), the Mekong Delta basin *freshwater status* is classified as extremely severe (Huggins et al., 2022). In addition, due to its high population, food crop production, economic relevance and biodiversity, the region was ranked as a *very high vulnerability* hotspot region globally, and the most vulnerable in Southeast Asia (Huggins et al., 2022).

1.3 Salinization of water resources in the Vietnamese Mekong Delta - Environmental and Socioeconomic Concerns

In many coastal environments, SWI into the river network and groundwater system is the primary source of freshwater degradation (Cao et al., 2021; Kaushal et al., 2021). In general terms, salinity is defined as the total sum of total dissolved solids (TDS, in

mg/L or g/L) in water (Vengosh, 2013). In marine and coastal environments, salinization is often understood as an increase in sodium (Na^+) and chloride (Cl^-) concentrations, since these ions account for approximately 90 % of TDS in seawater, which contains 35 g/L TDS on average (Vengosh, 2013). Salinity levels have a significant impact on the utilization of water resources. TDS concentrations above 1 g/L are increasingly considered unsuitable for human consumption (WHO, 2017). In Vietnam, the national limit for TDS in drinking water is set at 1.5 g/L (National Technical Regulation on Domestic Water Quality QCVN 01- 1/2018 BYT). In addition, many crops and industrial applications are sensitive to high salinity levels (Rengasamy, 2010; Vengosh, 2013). As a consequence, on the global scale, salinization of water resources is one of the most severe phenomena causing degradation of freshwater resources, endangering drinking water supply and agricultural production (Custodio and Bruggeman, 1987; Jones et al., 1999; Vengosh, 2013). In addition, soil salinization and damage to infrastructure are the direct consequence of SWI (Kurylyk et al., 2025; Tarolli et al., 2024). While salinization is often associated with recent SWI in coastal areas, particularly due to rising sea levels (Costa et al., 2023), numerous additional natural and anthropogenic sources and processes can also contribute to an increase of TDS in ground- and surface waters, regardless of location and water compartment (Mirzavand et al., 2020a; Vengosh, 2013). However, in the context of climate change and anthropogenic interventions, coastal areas are particularly prone to salinization due to direct SWI (Ghirardelli et al., 2025).

In the Mekong Delta, environmental challenges and salinization of water resources are most concentrated in the southernmost province Ca Mau. With the sea on three sides and a distinctly low-lying topography below 0.8 m in 2018, located on the Ca Mau Peninsular, Ca Mau Province is strongly susceptible to SWI (Khang et al., 2008; Minderhoud et al., 2019a). Particularly during the dry season from December to April, when limit precipitation occurs, seawater extends far inland (Hoanh et al., 2009; Khang et al., 2008). This exposure places it at the frontline of both climate change impacts and human interventions, establishing it as an ideal study location for SWI research. A map of the Mekong Delta and Ca Mau Province is presented in Figure 1, including information on altitudes in the region and hydrology.

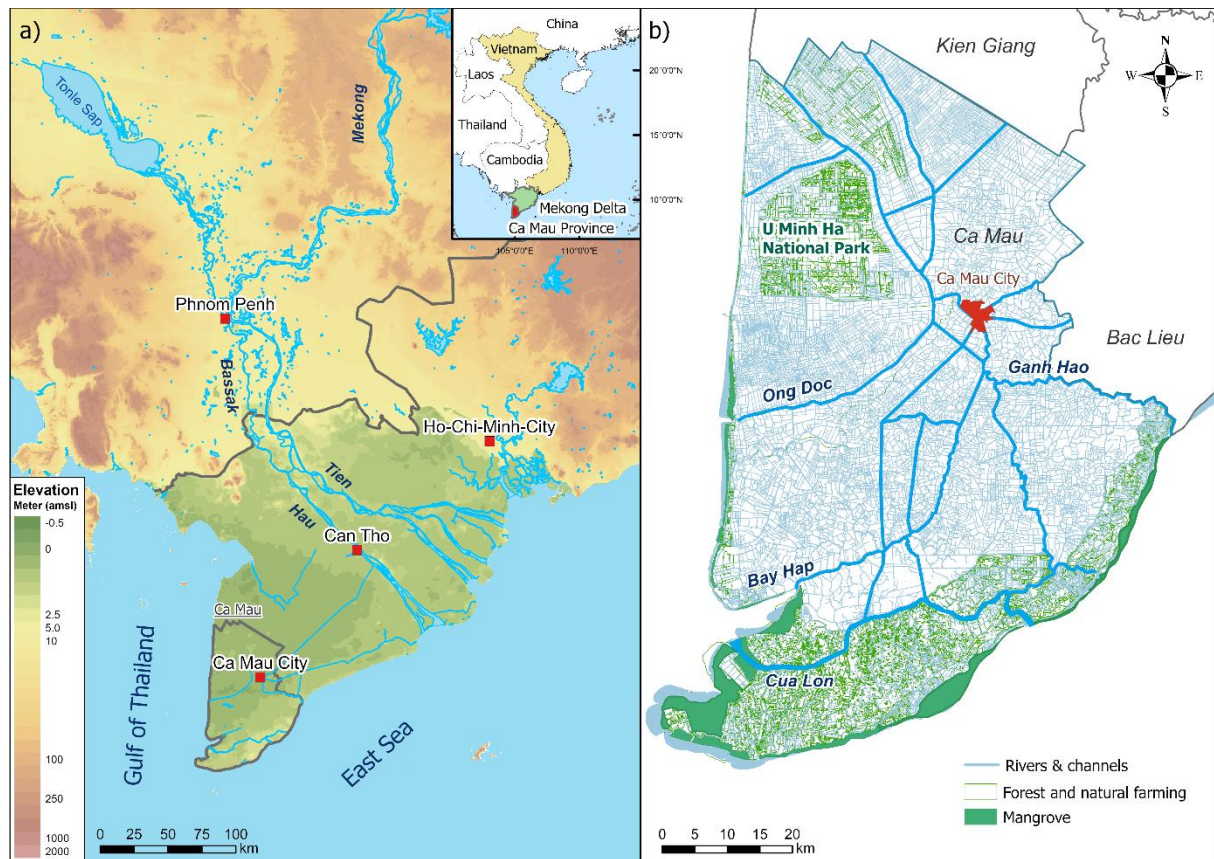


Figure 1 Overview of the Mekong Delta region in Southeast Asia. Surface elevation in 2018 (not linear) in the Mekong Delta by (Minderhoud et al., 2019b) and outside the Mekong Delta from the Global Topographic 30 Arc-Second Digital Elevation Model GTOPO30 (EROS, 2017). b) Ca Mau Province and its river network.

1.4 Environmental research in the Mekong Delta

In the face of the numerous water-related challenges in the Mekong Delta, the future success, and even the continued existence, of the region depends on its ability to translate its often-cited high adaptive capacity into effective mitigation measures (Huggins et al., 2022; Kondolf et al., 2022; Vu et al., 2022a; White and Kaplan, 2017). To realize this potential and enable evidence-based decision-making, comprehensive research efforts are essential (Huggins et al., 2022; Scown et al., 2023).

Figure 2 presents a Scopus-based analysis of published scientific documents on major river delta systems between 1980 and 2024, covering the fields of *Environmental Science*, *Agricultural and Biological Sciences*, and *Earth and Planetary Sciences*. The search terms included the commonly used names of the deltas, each combined with the word 'delta' (e.g., 'Ganges delta'), to ensure comprehensive coverage of publications referring to variants such as the Ganges-Brahmaputra or Ganges-Brahmaputra-

Meghna Delta. The graphs show that even though research on the Mekong Delta began relatively late, it now ranks as the most studied delta region outside of China (Figure 2), which can be largely attributed to advances in the Vietnamese research community and to various international research cooperation projects, including WISDOM (2007-2010), Rise and Fall (2014 – 2019) and ViWaT (2018-2022).

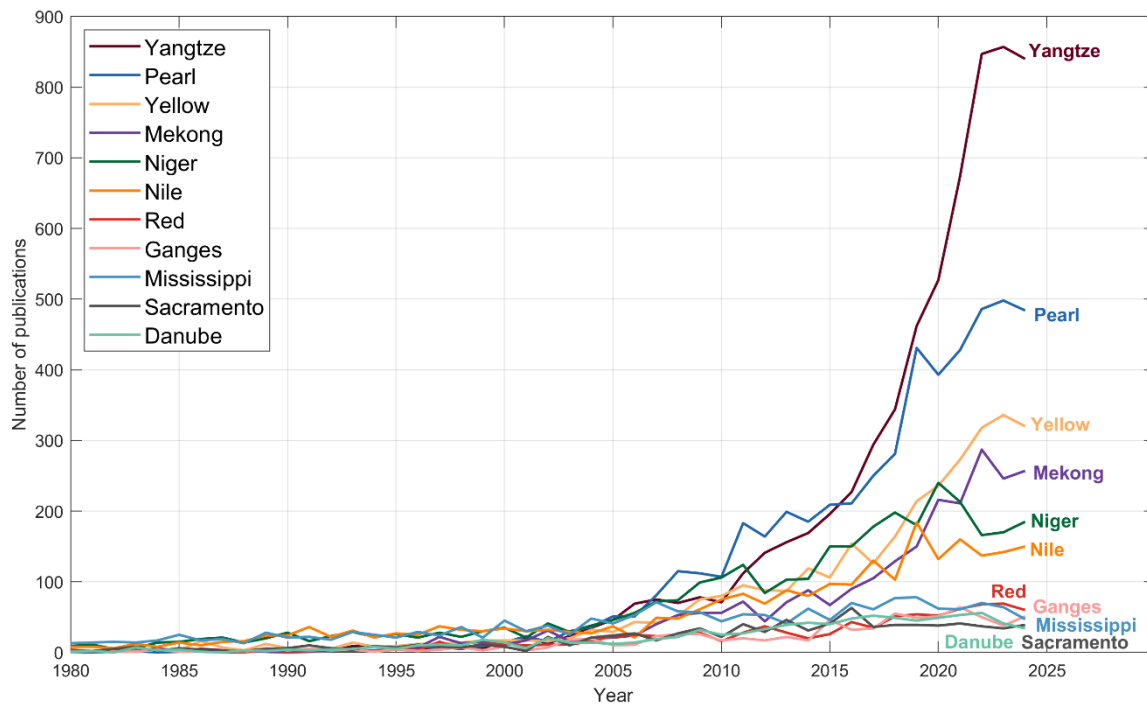


Figure 2 Number of publications per year for the most researched eleven river delta systems derived from a Scopus analysis for the period 1980-2024 among published scientific documents in the field of *Environmental Science, Agricultural and Biological Sciences* as well as *Earth and Planetary Sciences*.

A selection of studies published in the 2000s and early 2010s focusing on water resources and environmental issues in the Mekong Delta were compiled in a comprehensive book published in 2012, entitled “The Mekong Delta System”, which also emphasized the need for more in-depth research (Renaud and Kuenzer, 2012). Since then, the Mekong Delta gained significant more attention and international research projects evolved in the region, presenting a concerning outlook. In particular, Erban et al. (2014) demonstrated that the Mekong Delta faces significant threats from severe land subsidence, driven by subsurface sediment compaction resulting from declining groundwater levels due to overexploitation, and rising sea levels. Sand mining, numerous dykes and other protection infrastructures as well as changes in hydrology of the

Mekong River due to current and planned upstream dams were recognized to cause substantial morphological changes and erosion (Anthony et al., 2015; Brunier et al., 2014). SWI repeatedly caused severe agriculture yield losses in the coastal zones (Nguyen, 2017). Smajgl et al. (2015) stated that the Mekong Delta is not prepared for necessary adaptations to climate change. Shortly after, research concluded that these challenges represent an existential crisis for the Mekong Delta, as the overall vulnerability to natural events increase and large parts of the delta are threatened by permanent inundation due to RSLR (Minderhoud et al., 2017; Zoccarato et al., 2018). In 2022, scientists joint in a call for action to “save the Mekong Delta from drowning” (Kondolf et al., 2022).

The present dissertation was conducted within the framework of the ViWaT-Engineering project (Vietnam Water Technologies, BMFTR, grant No. 02WCL1474A), in which scientists from Vietnam and Germany aimed to develop integrated, science-based solutions to address the multifaceted environmental challenges of the Mekong Delta and to strengthen the region’s resilience to climate change and anthropogenic pressures. The project’s core objectives were to generate comprehensive datasets and establish a robust monitoring infrastructure, providing the foundation for developing mitigation strategies against coastal erosion and land loss, as well as for improving surface- and groundwater management (ViWaT, 2023).

The initiation of the first project phase ViWaT-Mekong-Go (01.11.2016 - 31.12.2018) and the main project ViWaT-Engineering (01.08.2018 - 31.12.2022) are based on the insights obtained by the studies in the mid-2010s, and both projects as well as this dissertation developed during a phase in which scientific knowledge in the Mekong Delta continuously and rapidly expanded (Figure 2). While this facilitated the integration of new insights and advanced both scientific understanding and project objectives, it also revealed substantial knowledge gaps. These gaps include the spatial and temporal distribution of fresh and saline water resources as well as the natural and anthropogenic factors that control this distribution in space and time.

1.5 Research focus and objectives

Given the profound socio-economic impacts of freshwater degradation in low-lying delta systems worldwide, and in the Mekong Delta in particular, this dissertation places strong emphasis on the processes and dynamics of water resource salinization. Although groundwater and surface water systems are often interconnected, the underlying processes, and particularly the rates of salinization, may differ due to varying exposure to salinization sources and spatiotemporal dynamics. This dissertation examines both water compartments individually, in the following framed as *Focus 1: Groundwater salinization processes*, and *Focus 2: Dynamics and factors controlling progressive riverine seawater intrusion*, and discusses their interactions in an integrated context. The following chapters introduce the research objectives associated with *Focus 1* and *Focus 2* and further summarize the objectives of complementary, co-authored environmental studies in the Mekong Delta. A summary of the research topics in the Mekong Delta and associated first- and co-authored publications are illustrated in Figure 3.

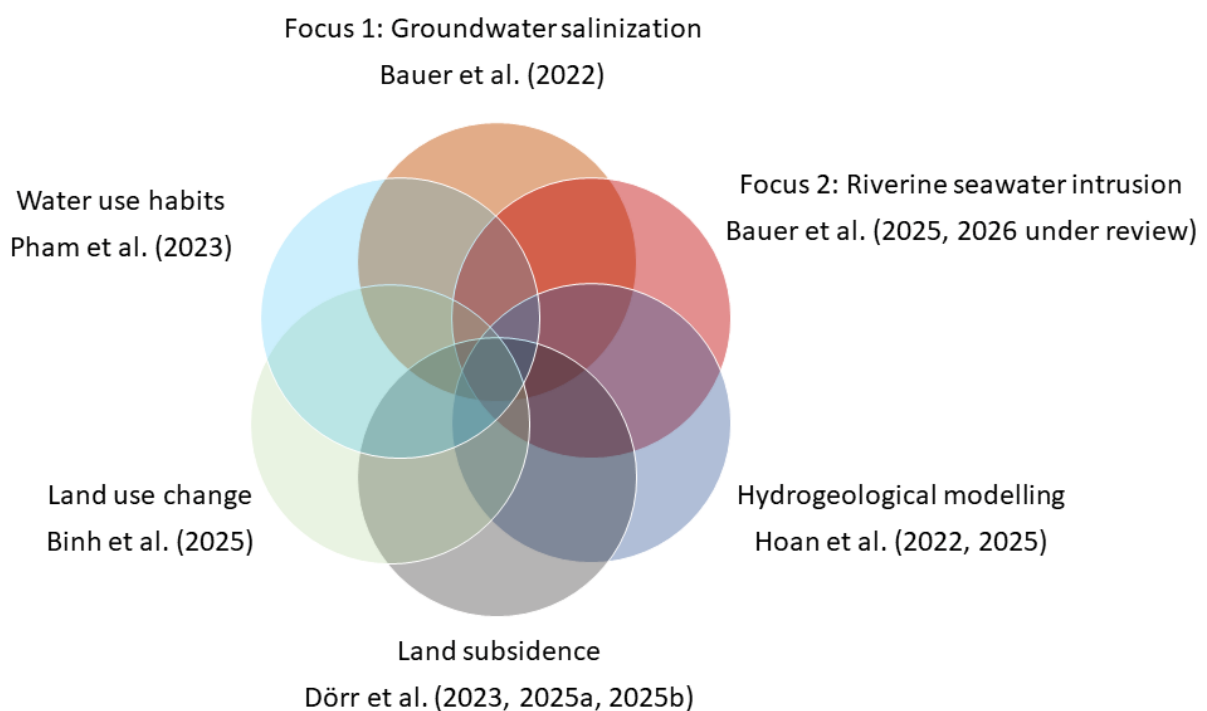


Figure 3 Overview of the research topics in the Mekong Delta and first- and co-authored publications.

1.5.1 Focus 1: Groundwater salinization processes in the Mekong Delta

Groundwater resources in coastal settings are particularly vulnerable to salinization due to overexploitation and sea level rise (Custodio and Bruggeman, 1987; Ferguson and Gleeson, 2012; Krishan et al., 2022). In the Mekong Delta, and especially in the rural areas, groundwater is the single most important and most reliable freshwater resource for the majority of people (Wagner et al., 2012). Due to the unreliability of public water suppliers and infrastructure, combined with advances in accessible drilling technology, the electrification of rural areas, and the affordability of pumps, groundwater is heavily overexploited (Wagner et al., 2012). Today, several hundred thousand unlicensed private groundwater wells exist in the Mekong Delta, vastly outnumbering the relatively small number of larger licensed wells used for drinking water production and industrial purposes (Tri, 2012; Wagner et al., 2012). The overexploitation of groundwater in the Mekong Delta, as well as in other delta systems, causes three major adverse effects:

- Deterioration of groundwater quality due to salinization by SWI and other hydro-geochemical processes (Ferguson and Gleeson, 2012; Xiao et al., 2021).
- Land subsidence due to a reduction of pore pressure and compaction of the unconsolidated sediment strata (Erban et al., 2014; Herrera-García et al., 2021; Minderhoud et al., 2017).
- Mobilization of contaminants, such as arsenic (e.g. Erban et al., 2013).

As a result of past cycles of marine transgression and regression, a vertically stacked sequence of seven confined aquifers separated by clay rich aquitards formed in the southern Mekong Delta, reaching a thickness of around 400 m (Nguyen et al., 2000; Pham et al., 2019). The most exploited aquifers in Ca Mau Province are the Pleistocene aquifer qp₂₋₃ (80-148 m) and the Pliocene aquifer n₂² (198-254 m) (Jenn et al., 2017). Previous studies suggested that fresh groundwater is unevenly distributed in the Mekong Delta, across and within the aquifers (Anderson, 1978; Pham et al., 2019; Wagner et al., 2012).

Different salinity sources exhibit distinct geochemical signatures, which can be used to identify them, trace mixing processes, and assess both their salinization potential and the rates at which salinization occurs (Appelo, 1994; Appelo and Postma, 2005; Jones

et al., 1999). Direct lateral salinization driven by SWI would substantially accelerate salinization rates, particularly closer to the coastline (Jones et al., 1999). Thus, the hypothesis that direct SWI is the primary driver of groundwater salinization requires confirmation or rejection.

Given the hydrogeological setting, as well as potential salinization pathways, the following research questions were outlined to address the hypothesis:

- What is the current geochemical composition of groundwater in Ca Mau Province and what are the influencing factors?
- What processes control the distribution of saline versus fresh groundwater in the deep Pleistocene to Miocene aquifers?
- How do natural and anthropogenic drivers affect progressive salinization?

To answer these research questions, a geochemical assessment utilizing 190 groundwater samples collected during field campaigns between 2017 and 2019 was conducted. The results are published in Bauer et al. (2022).

1.5.2 Focus 2: Dynamics and factors controlling progressive riverine seawater intrusion

In contrast to groundwater, rivers and lakes are more exposed to surface influences. In general, river water chemistry is naturally governed by the mixing of freshwater, reflecting the geological characteristics of the catchment, and seawater near the estuary. This natural composition can be significantly modified by anthropogenic inputs, such as agricultural drainage, mining activities, industrial or municipal wastewater as well as de-icing salts (Li et al., 2020; Pope et al., 2025; Vengosh, 2013).

Natural sources of river salinization are primarily linked to recent SWI in coastal areas or the dissolution of evaporites originating from ancient marine environments and concentration of solutes by evaporation in arid areas (Jalali et al., 2019; Tuttle and Grauch, 2009; Vengosh, 2013). Human alterations to hydrological regimes and the impacts of human induced climate change accelerate recent SWI in many coastal regions worldwide (Costa et al., 2023; Hendrickx et al., 2023; Mohammed and Scholz, 2017). For example, by changing discharge patterns of major rivers through extensive upstream

dam construction, river bed incision and human induces land subsidence, SWI is promoted in many coastal regions and delta systems worldwide, including the Mekong Delta (Eslami et al., 2021a; Matsoukis et al., 2023).

Riverine SWI is a natural recurring phenomenon in the Mekong Delta during the dry season, with brackish to saline conditions in the coastal zones, shaping land use and water management (Binh et al., 2025; Renaud et al., 2015). In recent years, extreme SWI events had a significant impact on agriculture and livelihoods in the region (Binh et al., 2025; Park et al., 2022). These insights lead to the hypothesis that riverine SWI varies markedly and is increasingly intensified by human activities, including extreme events.

Given the significance of riverine SWI in the Mekong Delta, particularly in Ca Mau Province, the following research questions were formulated:

- How does riverine SWI vary across interannual to sub-seasonal time scales and spatially?
- What are the contributing natural and anthropogenic factors and processes driving progressive riverine SWI?
- What are the trigger events for extreme SWI episodes?

To answer these research questions, time series of salinity data from 2000 to 2022 from three monitoring stations in Ca Mau Province, namely Song Doc located at the Gulf of Thailand, Ca Mau located inland south of the provincial capital and Ganh Hao located at the East Sea (Figure 1) were analyzed. By incorporating supporting data, including local precipitation, river water levels, and upstream discharge time series, interannual SWI dynamics were systematically characterized and major drivers of SWI fluctuations and their evolution in the southern Mekong Delta were identified. In addition, the causes of extreme SWI in the context of hydrological droughts, land subsidence, and upstream water management practices were investigated. The results are published in Bauer et al. (2025). To assess sub-seasonal salinity variations and tidal control on salinity dynamics, hourly salinity and water level data for the dry seasons of 2017 and 2018 were analyzed for the same three monitoring stations in Ca Mau Province. The study was submitted to Journal of Hydrology on 16.11.2025.

1.5.3 Complementary research topics in the Mekong Delta with my contribution

This chapter presents research objectives that were necessary to obtain a comprehensive picture of water-related challenges in the southern Mekong Delta, both within the context of salinization dynamics and beyond.

Hydrogeological models help verify whether all major processes at play have been identified and properly represented numerically. Therefore, the following research objectives were formulated and addressed under the lead of Hoan Viet Tran.

- What are the boundary conditions for hydrogeological processes on the Ca Mau Peninsular?
- How do high groundwater extraction rates influence total storage and freshwater reserves and what are possible salinization pathways?

These research questions are addressed in Hoan et al. (2025, 2022).

To investigate the relationship between groundwater extraction and land subsidence, an innovative depth-differentiated Land Subsidence Observatory (LSO) was constructed in Ca Mau Province as part of the ViWaT-Engineering project. The following research objectives were addressed:

- What are the driving forces of land subsidence in the Mekong Delta?
- What are the subsurface properties and can land subsidence be mitigated?

These research questions are answered in publications authored by Felix Dörr, in which I contributed as second author (Dörr et al. 2023, 2025a, 2025b).

Reducing groundwater overexploitation is the most immediate response to rising land-subsidence rates. However, before adapted strategies can be developed and alternative water resources introduced, it is essential to assess household and agricultural water-use practices. These points were investigated by Van Cam Pham, answering the following research questions:

- How important is groundwater for the people in Ca Mau Province, and how do they utilize this resource in their daily lives?

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- Does groundwater quality from private wells exceed Vietnamese limits for drinking and domestic use, and how is water quality related to people's perceptions of groundwater?

Finally, in the past, insufficient water quality and particularly high levels of salinity had a pronounced impact on land use transition and adaptation strategies in the Mekong Delta. The following research objective was outlined by Doan Van Binh:

- Assessing the relationship between SWI and drought conditions on rice yields and land use change in the Mekong Delta.

Taken together, the broad range of research objectives and studies presented here provides an integrated view of water related processes and challenges in the southern Mekong Delta and enables a holistic assessment of the cause–effect relationships driving progressive salinization.

2 Methods

This chapter presents an overview of the methods applied in the first-authored studies compiled in this dissertation. These methods were used to address the research questions and achieve the research objectives outlined in:

- Focus 1: Groundwater salinization processes in the Mekong Delta, and
- Focus 2: Dynamics and factors controlling progressive riverine seawater intrusion.

Full methodological details can be found in the respective publications included as appendices A.1 to A.3.

2.1 Field work and data acquisition

Ca Mau Province could be described as a “white spot” on the map, with limited publicly available information on the status of water resources, including the spatiotemporal distribution of groundwater and surface water quality and quantity as well as water related practices. Even though the study area was classified as a saline environment before, knowledge about salinization processes and dynamics were limited (Khang et al., 2008). Therefore, comprehensive sampling campaigns were conducted in Ca Mau Province, each lasting approximately two weeks, to collect water samples from a range of sources and to perform in-situ measurements. Figure 4 provides details about the sampling campaigns, gives an impression of the diverse water sources within the study area and illustrates the variety of environments investigated in the framework of this dissertation. The field campaigns included sampling of groundwater, river water, coastal seawater, rainwater, and water stored in containers, ponds, and agricultural fields.

During three field campaigns conducted in December 2018 and March, July and December 2019 in Ca Mau Province, a total of 170 groundwater samples were collected, primarily from private household wells, with the aim of covering the entire study area and all major aquifers. The dataset was complemented by 20 groundwater samples collected during earlier field campaigns in 2017 as part of the ViWaT-Mekong-Go project, in which I was not involved. In total, 190 groundwater samples were available for

analysis and evaluation. The sampling locations are shown in Figure 5a. In addition, 244 river, channel and offshore as well as 59 land use related samples and in-situ measurements were conducted (Figure 5b).

Details about the sampling procedure, sample preservation and laboratory analysis are provided in Bauer et al. (2022) and apply for both groundwater and surface water samples. Briefly, in-situ parameters, including temperature, electrical conductivity (EC) and pH were measured on site using a multi-parameter portable meter (WTW Multi 3630 IDS) and total alkalinity was measured with a titration test kit (MerckKGaA). All samples were filtered through a 0.45 μm cellulose-acetate filter (Satorius Stedim Biotech GmbH). Samples for cation analysis were treated with 50 μL of high-purity nitric acid to prevent cation precipitation, and 50 μL sodium azide was added to samples for anion analysis to inhibit microbiological processes. In the laboratories of the Institute of Applied Geosciences at the Karlsruhe Institute of Technology, Germany, samples were analyzed by the laboratory technicians using Inductively Coupled Plasma Mass Spectroscopy (ICP-MS, Thermo Fisher X-Series 2) for cations and Ion Chromatography (IC, Dionex ICS-1000) for anions.

In addition, data from river monitoring stations in Ca Mau Province (Figure 5b) and borehole stratigraphic data from 27 monitoring wells as well as GIS shapefiles for the river network and forest area were provided by National Center for Hydro-Meteorological Forecasting of Vietnam, Hanoi, the Southern Institute of Water Resources Research, and the National Center for Water Resources Planning and Investigation of Vietnam.

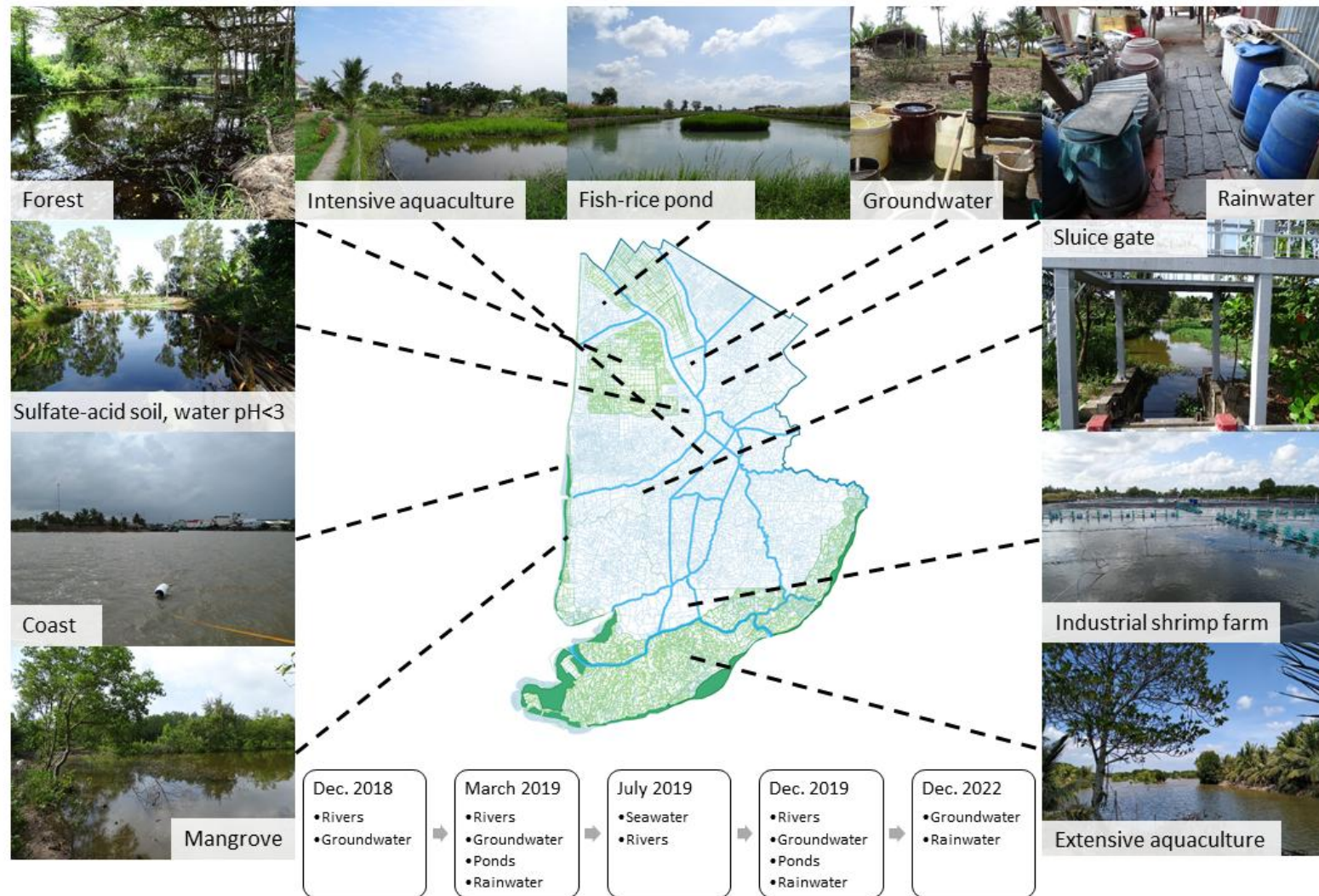


Figure 4 Overview of the variety of water bodies and settings sampled across five field campaigns between 2018 and 2022.

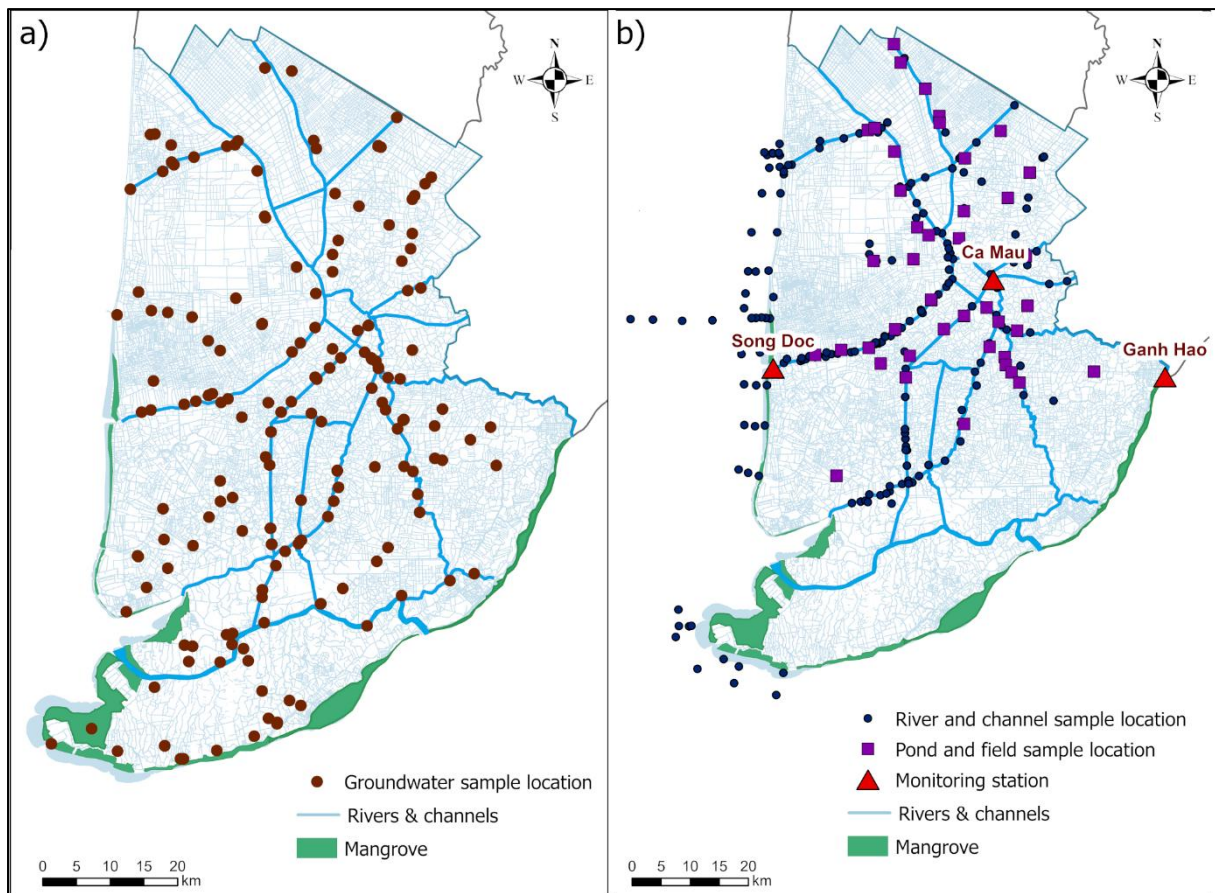


Figure 5 (a) Groundwater sample locations and (b) river, channel and coastal as well as land use related sample locations.

2.2 Groundwater geochemistry and salinization processes

Understanding the factors and processes that control the distribution of fresh and saline groundwater is key to evaluate the state and evolution of groundwater resources in the southern Mekong Delta. It is essential to distinguish direct SWI, which can lead to rapid salinization, from other processes, such as the release of connate water trapped during sediment deposition, vertical infiltration and percolation, mineral dissolution, and the upconing of deep fossil seawater (Jones et al., 1999). This chapter presents and summarizes the methods used to (i) characterize the distribution of fresh- and saline groundwater and (ii) to assess freshening and salinization processes with hydrogeochemical methods.

Groundwater composition in coastal areas is often governed by seawater and fresh-water mixing (Giménez-Forcada, 2010). Thereby, the resulting water is not a simple

mixture of the two endmembers, but is substantially modified by water-rock interactions, such as cation exchange processes (Appelo, 1994; Russak and Sivan, 2010). To assess mixing process and delineate the evolution of groundwater geochemistry in Ca Mau Province, well established methods were applied and improved.

2.2.1 Geochemical analysis - Molar ion ratios and water type

Calculating molar ion ratios of specific elements provides crucial insights into geochemical processes and represents a common fingerprinting method in geochemical assessments (Russak et al., 2016; Vengosh, 2013). Ratios of major and minor elements are particularly useful for source tracking of pollutants, including the identification of different salinization sources. For example, high concentrations of Cl^- might stem from irrigation return flows or SWI. These sources can be distinguished by B/Cl^- and I^-/Cl^- ratios, with high values indicating agricultural origin. The Cl^-/Br^- ratio can be used to assess the state of evaporation in seawater and evaporite dissolution (Jones et al., 1999), while further ratios, such as Br^-/Cl^- vs B/Cl^- , can indicate agricultural drainage, SWI, evaporite dissolution or hydrothermal origin (Vengosh, 2013). To assess water-rock interactions during salinization and freshening, numerous element ratios have been previously analyzed (e.g. Prusty and Farooq, 2021; Russak et al., 2021, 2016; Russak and Sivan, 2010)

In this work, Na^+/Cl^- , $\text{Ca}^{2+}/\text{Cl}^-$ and $\text{Mg}^{2+}/\text{Cl}^-$ molar ratios were calculated and compared to the conservative mixing line to assess the status of freshwater intrusion (freshening) or SWI (salinization) into the aquifers. In natural systems, Cl^- often acts conservatively and is commonly used as a reference ion. Seawater has a Na^+/Cl^- molar ratio of approximately 0.86 (Vengosh, 2013). Due to cation exchange, this ratio typically decreases below the conservative mixing line during salinization and increases during freshening (Jones et al., 1999). The decrease in Na^+/Cl^- occurs because during salinization the ion selectivity of mineral surfaces is masked by the proportional increase in the monovalent ion Na^+ (Sawhney, 1972). Na^+ replaces the divalent cations Ca^{2+} and Mg^{2+} on mineral surfaces. The divalent cations Ca^{2+} and Mg^{2+} are released into the water, leading to the formation of $\text{Ca}-\text{Cl}$ and $\text{Na}-\text{Mg}-\text{Cl}$ water types. Conversely, during freshening, when $\text{Ca}-\text{HCO}_3$ -type freshwater infiltrates a saline aquifer, the cation-exchange reaction is reversed (Appelo, 1994). Exchangeable Na^+ on mineral surfaces

is substituted by Ca^{2+} and Mg^{2+} due to their higher sorption selectivity (Carroll, 1959). This results in the characteristic Na-HCO_3 water type, an increase in the Na^+/Cl^- molar ratio above seawater levels, and a depletion of Ca^{2+} and Mg^{2+} (Appelo and Postma, 2004; Custodio and Bruggeman, 1987; Jones et al., 1999). Monitoring these molar ratios provides valuable insights into the current state of the aquifers and the role of water–rock interactions (Giménez-Forcada, 2010).

Since both freshwater intrusion and SWI modify groundwater composition in a predictable sequence through cation exchange, water type analysis provides a simple yet effective tool for assessing aquifer conditions. Traditionally, a Piper Diagram is drawn (Piper, 1944), while other visualizations, such as Stiff Diagrams, Schoeller Diagrams or Durov Diagrams are regularly published as well. More recently, the Hydrochemical Facies Evolution diagram was introduced, showing the main processes of SWI and freshening stages (Giménez-Forcada, 2010). However, because of the selectivity sequence of ions for mineral surfaces, particularly clays, classic water type analysis methods often fall short of capturing these processes in sufficient detail, as they tend to report mixed water types instead of more differentiated hydrochemical descriptions. To overcome this issue, a more detailed specification of water types was developed to gain deeper insights into mixed compositions. The conventional classification scheme was adapted to more accurately reflect different stages of salinization, with particular emphasis on cation-exchange processes. Proportions of major ions were calculated, and if only one cation or anion exceeded 33.3%, it was reported alone (e.g., Na-Cl water type). If two ions exceeded this threshold, the ion with the higher proportion is listed first, followed by the second in brackets (e.g., $\text{Na-Cl-(HCO}_3\text{)}$). A mixed water type is defined only when all three cations or anions contribute approximately equally (around 33.3 % each), in which case the type is classified as mixed (e.g., Na-Ca-Mg-Cl is denoted as Mix-Cl).

Figure 6 shows the evolution of $\text{Ca}^{2+}/\text{Cl}^-$ ratios and the corresponding water types defined during salinization and subsequent freshening, based on column experiments by Russak and Sivan (2010). Russak and Sivan (2010) used $\text{Ca}-(\text{Na})-\text{HCO}_3-(\text{Cl})$ water as the freshwater endmember and $\text{Na}-\text{Cl}$ water as the seawater endmember. During salinization, the pronounced increase in Ca^{2+} relative to the conservative mixing line is particularly evident, whereas during freshening the deviation is less pronounced. Figure 6b highlights the early stages of salinization and the late stages of freshening. In the early phase of salinization, Na^+ becomes dominant over Ca^{2+} , and after half of the pore volume has been exchanged, Cl^- surpasses HCO_3^- . At an exchanged volume of 0.65, the water type shifts to $\text{Na}-\text{Cl}$, which remains stable until the final stage of freshening, where more gradual geochemical changes become apparent. After HCO_3^- surpassed Cl^- as primary anion, Mg^{2+} becomes the second and then major cation. This occurs because Mg^{2+} is enriched in seawater relative to Ca^{2+} ($\text{Mg}^{2+}/\text{Ca}^{2+} \approx 5.2$), leading to preferential enrichment of Mg^{2+} during salinization on mineral surfaces and its release before Ca^{2+} during freshening. In the final stages of freshening, Ca^{2+} , which is relatively enriched in freshwater, becomes dominant, and additional Na^+ is released. As a result, Mg^{2+} gradually disappears from the water type, despite having been the initially dominant cation.

This adapted concept of cation exchange driven by water-rock interactions was applied by Bauer et al. (2022) to assess the state of salinization and freshening in the groundwater samples from Ca Mau Province.

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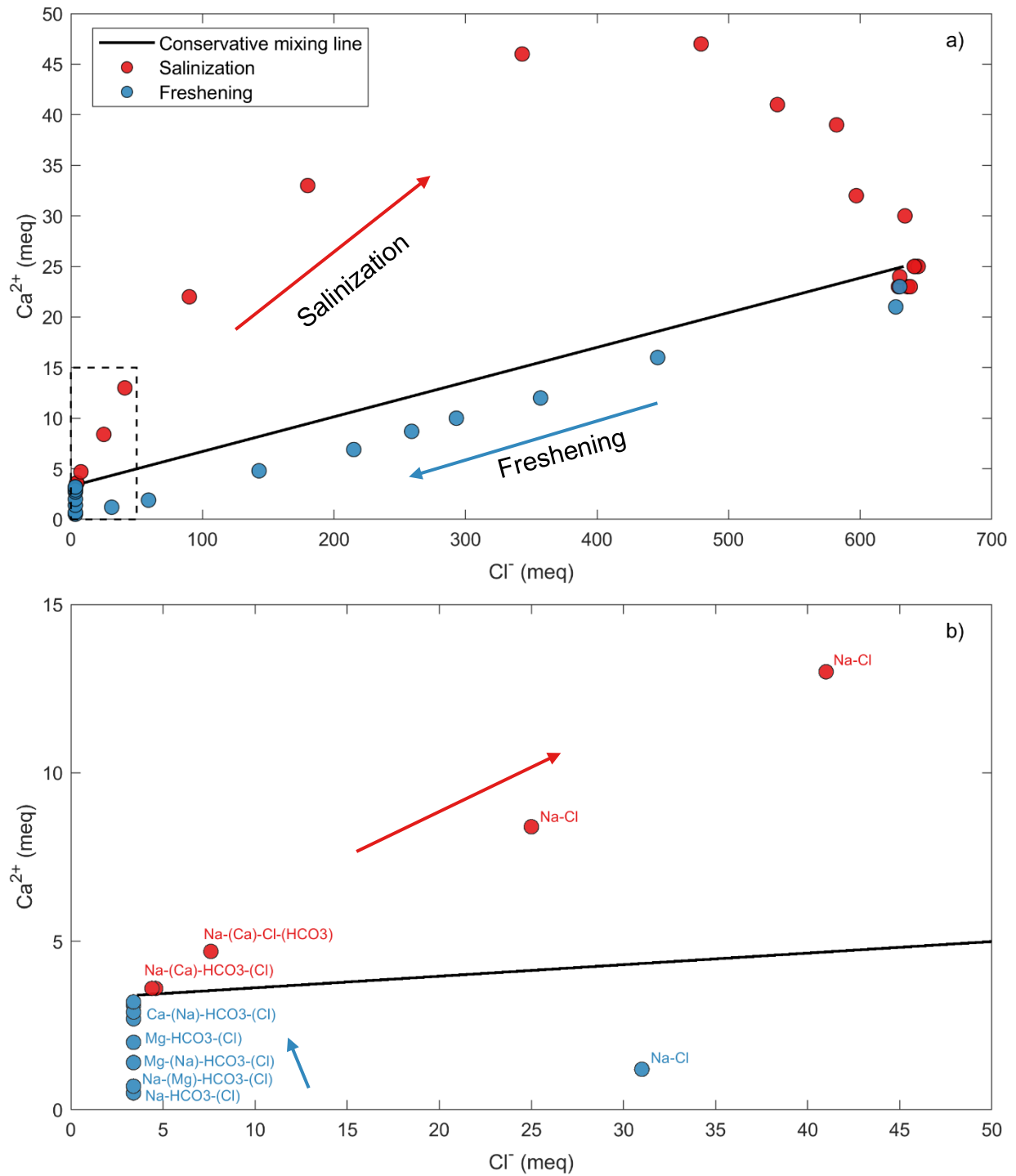


Figure 6 $\text{Ca}^{2+}/\text{Cl}^-$ molar ratio and geochemical evolution of detailed water types based on column experiments data by Russak and Sivan (2010).

2.2.2 Hydrogeological model – development of a MATLAB tool

Stratigraphic and hydrogeological modelling of subsurface strata based on borehole data enhances the understanding of the spatial distribution of key features, including the location of aquifers and aquitards as well as heterogeneities (Li et al., 2021). To accurately evaluate groundwater resources, particularly in a multilayered aquifer system such as the Mekong Delta, a reliable hydrogeological model is essential (Renard et al., 2010). To support the visualization and interpretation of subsurface structures, a MATLAB program was developed. This program was used to generate a subsurface model based on 27 borehole logs in Ca Mau Province, allowing for a comprehensive evaluation of the 3D distribution of fresh and saline groundwater samples and their assignment to the corresponding aquifers. The cross-section published in Bauer et al. (2022) was generated with this tool.

Because the boreholes differ in depth, all profiles were manually extended down to the deepest aquifer (n_1^3) using mean layer thicknesses derived from the available stratigraphic data. In the program, stratigraphic units are treated as vertically stacked (Turner, 2006). For each horizon, depth values from the boreholes are interpolated in map view using MATLAB's *griddata* with natural-neighbour interpolation based on a Delaunay triangulation, which yields smooth surfaces and is restricted to the convex hull of the input data (no extrapolation occurs beyond data support). Along the cross-section line, the gridded surfaces are sampled using MATLAB's *interp2*, which performs bilinear interpolation between neighbouring grid nodes.

The plotting functions include a 3D subsurface model and dynamically adjustable cross-sections defined by user-specified start and end points. The software also allows groundwater samples to be plotted based on their coordinates and depths, with scatter points grouped into five equal-width value bins and colored according to any selected measurement parameter, such as TDS. A simple graphical user interface makes the program accessible to various tasks, and it is not case-specific to this study. The graphical user interface is shown in Figure 7 with data from Bauer et al. (2022) as example. The required input consists of stratigraphic data, with aquifer, aquitard, or layer names in the first row and well or drill core IDs in the first column. Optionally, input boreholes can be displayed, and individual or multiple layers can be activated. By setting a distance threshold, only samples and wells within a given perpendicular distance from the

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cross-section are shown. Users can toggle between the 3D model and the cross-section being display in the larger axis using a separate button. Finally, figures can be exported in common image formats. The software and a hands-on instruction guide are available upon request. A future release on MATLAB File Exchange or GitHub is planned.

2 | Methods

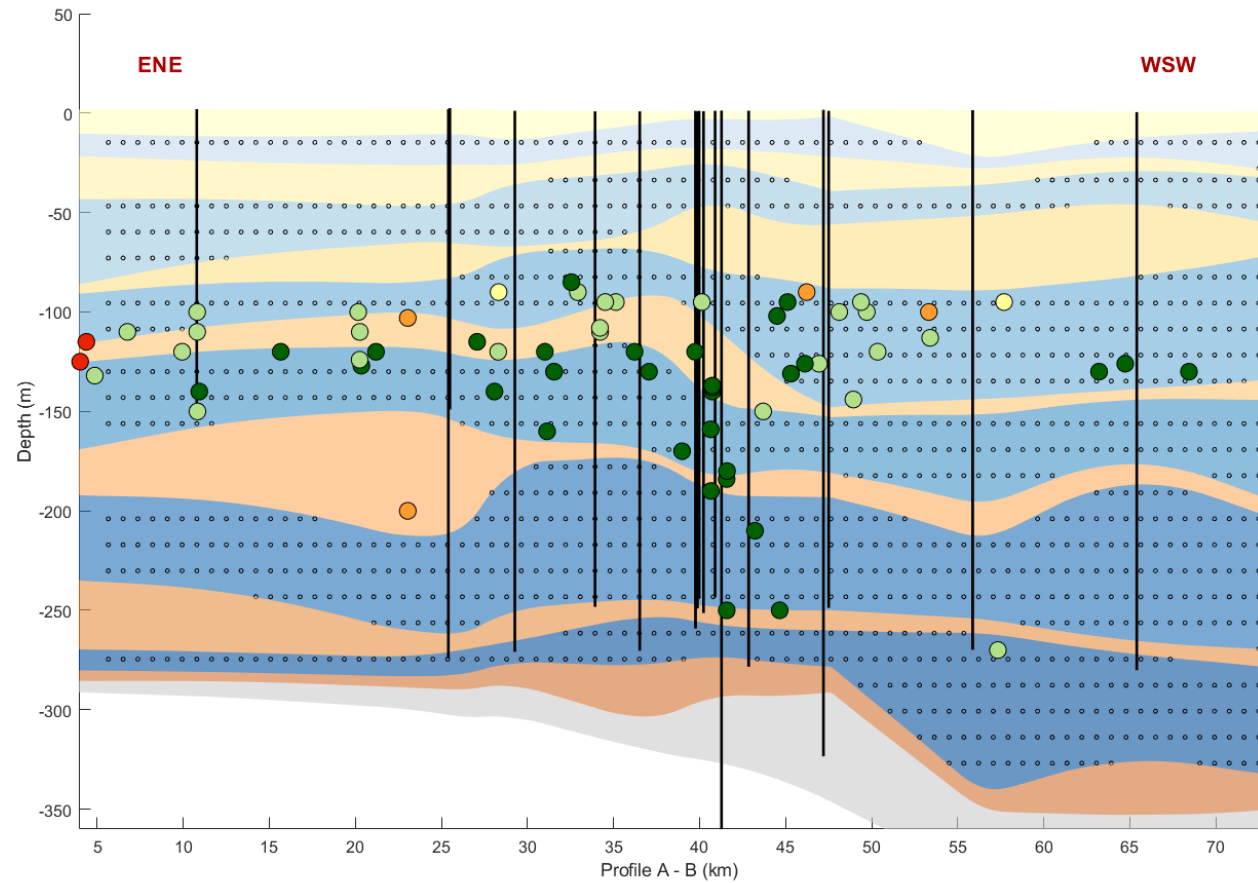
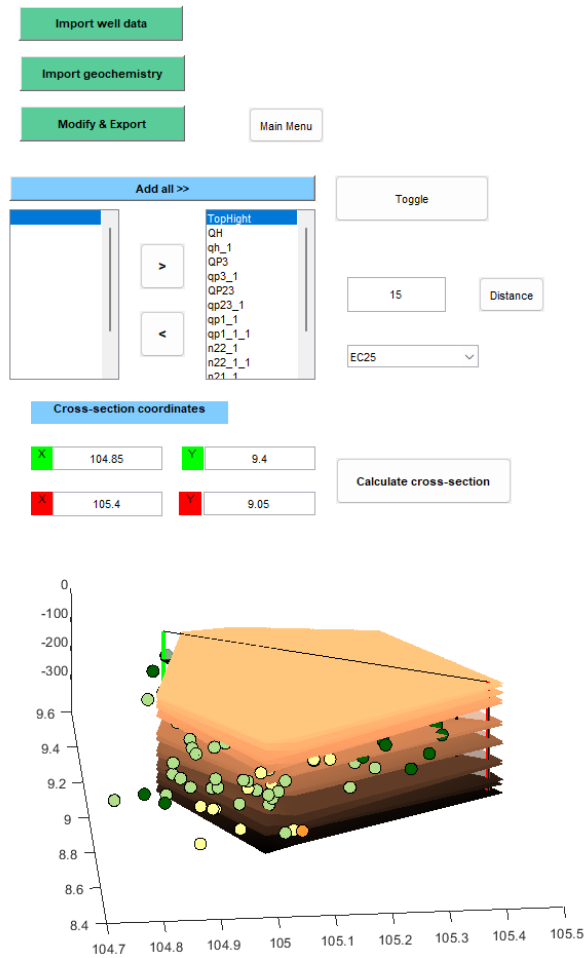


Figure 7 Interface of the subsurface model software developed in MATLAB to display stratigraphy, samples colored based on a selected parameter, and used boreholes for the calculation. In this example, the stratigraphic data from 27 boreholes in Ca Mau Province are used, and samples within a 15 km perpendicular distance to the cross-section are grouped into five categories reflecting electrical conductivity.

2.3 Riverine seawater intrusion

Riverine SWI is shaped by processes changing the pressure gradient between upstream freshwater discharge and sea-level. It is a dynamic balance continuously changing to reach equilibrium, which it will never achieve (MacCready, 2007; Savenije, 2012). In most natural settings, geochemical processes in coastal rivers exert only a limited influence on SWI conditions because the short residence times of surface water restrict salinity-related geochemical reactions relative to groundwater (Savenije, 2012). In this context it is more meaningful to identify and evaluate natural and anthropogenic processes controlling the pressure gradient (Nguyen and Savenije, 2006), and to assess them on all time scales.

The surface water salinity data collected during three field campaigns in 2018 and 2019 (Figure 5b) represent only snapshots within a highly dynamic estuarine system, where salinity levels and SWI can fluctuate markedly across diurnal, fortnightly, seasonal, and interannual timescales. Therefore, the focus of this work shifted from discrete monitoring campaigns to continuous monitoring data from the stations Song Doc, Ca Mau and Gan Hao (see chapter 2.1), which provide a more consistent basis for identifying causes and relationships driving parameter variability (Bieroza et al., 2023).

This chapter presents the methods used to analyze interannual salinity dynamics from 2000-2022 and sub-seasonal, tide-driven salinity fluctuations for the periods January to June in 2017 and in 2018.

Instead of relying on modelling approaches, which in previous studies were calibrated and validated using very short in-situ observation periods (Eslami et al., 2019; Khang et al., 2008; Lam, 2020; Tran et al., 2024), this work focused on direct data evaluation and time series analyses. The methods to assess both interannual and sub-seasonal salinity dynamics are outlined in the following chapters and are described in more detail in Bauer et al. (2025) and Bauer et al. (2026 - under review).

2.3.1 Interannual salinity dynamics

2.3.1.1 Freshwater proxy – Definition of the low discharge period

Salinity levels are highest during the dry season, when precipitation and river discharge are minimal, and lowest during the monsoon, when freshwater flow pushes seawater downstream. Overall water levels in most river deltas are primarily influenced by upstream discharge rather than tidal dynamics (Savenije, 2012). As upstream river discharge constitutes the largest freshwater influx into the delta, a Low Discharge Period (LDP) was defined as a proxy for the hydrological dry season instead of a rainfall-based definition. The LDP was characterized as the period when discharge at Tan Chau station, located near the Cambodian border on the Tien River, drops below a weekly average of 4,000 m³/s of daily maximum discharge and remains below this threshold until it rises above it for two consecutive weeks. The duration, start and end dates, and average discharge during each LDP were analyzed to explain salinity extreme events, and a Spearman correlation was conducted between LDP duration and mean and maximum April salinities, when the highest values typically occur. This approach to evaluate river discharge impacts on SWI was not used in the Mekong Delta before. In addition, the analysis also distinguished between the pre-dam and post-dam periods, as upstream dams and reservoir operations substantially alter river discharge patterns (Lu and Chua, 2021; Mohammed et al., 2018).

2.3.1.2 Trend analysis

Linear regression using MATLAB's *fitlm* function was applied to assess long-term trends in salinity and water level time series, ensuring comparability with previous studies in the Mekong Delta (Hak et al., 2016; MONRE, 2016; Nguyen et al., 2023). For water levels at Tan Chau and the coastal stations Song Doc and Gan Hao (2000–2022), monthly averages were calculated to reduce short-term fluctuations and data noise (Church and White, 2011). Following Nguyen et al. (2023), interannual variability was isolated by deseasonalizing the time series, which was achieved by subtracting the long-term monthly mean for each calendar month over the study period.

This approach enables the detection of long-term anomalies by removing predictable intraannual variability, such as seasons (Nguyen et al., 2023). Tidal influences were not explicitly considered here, as their short-term variability has little effect on interannual trends. For salinity, linear trends were derived from monthly averages of daily

maximum values, calculated separately for February, March, and April for the years 2000–2020. These months were chosen to ensure consistent data coverage and to capture peak dry-season conditions. Linear trends were estimated separately for each station and month. This monthly-resolution approach allows for a more detailed interpretation of salinity–water level relationships than previous studies.

2.3.1.3 Land subsidence calculation by water level trends

As RSLR triggers progressive SWI, land subsidence rates at the coastal monitoring stations Song Doc and Gan Hao (Figure 1b) were estimated based on the water level trends for the period 2000 to 2022. This concept is based on the assumption that tidal gauge stations are subject to subsidence as well, and thus they measure SLR and subsidence, potentially overestimating SLR (Liu et al., 2020). By subtracting SLR rates at the tectonically stable Vung Tau station, land subsidence rates and SLR can be distinguished. In the Mekong Delta, this concept was first applied by Nguyen et al. (2023) and was updated here for a more recent time frame, while also distinguishing the pre-dam and post-dam era of the Mekong River.

2.3.2 Sub-seasonal dynamics

While salinity is mainly regulated by upstream discharge in many estuaries worldwide, the tidal influence increases during periods of low flow conditions, for example in dry seasons (Gaiolini et al., 2023; Savenije, 2012). Understanding salinity dynamics on diurnal to fortnightly to sub-seasonal scale has many practical implications for local water management and SWI protection measures, such as adapted sluice gate operation.

2.3.2.1 Data preparation

In the Mekong Delta, most monitoring stations are not fully automated and therefore the salinity datasets for the years 2017 and 2018 have gaps up to a few days and at best only a 2-hourly resolution. In addition, data is only measured during the dry season months. To create a continuous 1-hour salinity dataset for the dry seasons of 2017 and 2018, the original 2-hour records with gaps were processed using a two-step linear interpolation with tidal phase alignment. First, measurements at the same local time

each day (e.g., 01:00) were extracted, and missing days were filled by linear interpolation between neighboring, valid observations. The data were then recombined into a continuous 2-hour series, and a second interpolation was applied to generate a continuous 1-hour dataset. The resulting 1-hour salinity dataset ensured compatibility with the 1-hour water level data and enabled the analysis of salinity variations in relation to water level fluctuations. In addition, 1-hourly timesteps are generally recommended for tidal analysis (e.g. Foreman, 2004).

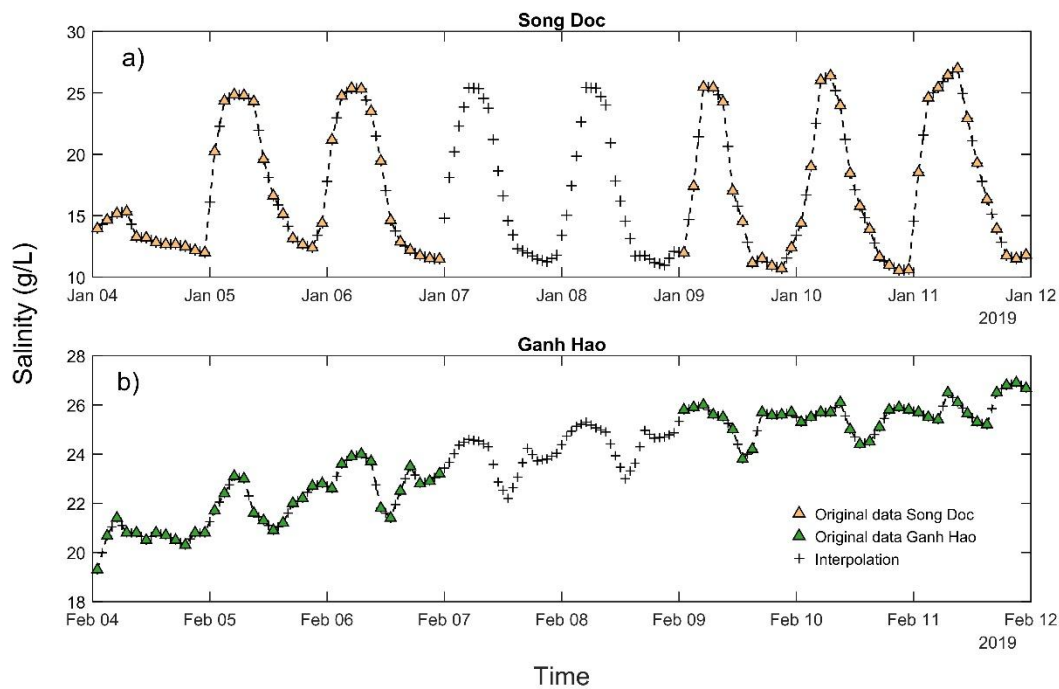


Figure 8 Interpolation of discontinuous salinity data at SD and GH to obtain a continuous 1-hourly dataset.

2.3.2.2 Harmonic analysis

Harmonic analysis of water level and dependent properties, such as sediment load or salinity, is a fundamental approach used in the study of estuarine, coastal and oceanic dynamics (Chen et al., 2012; Loc et al., 2021a). Water level fluctuations driven by tidal forces exhibit well-defined periodicities that can be analyzed using harmonic methods, providing both amplitudes and phase at dominant frequencies (Kvale, 2006; Kvale et al., 1995). Simplified, tide-driven water level fluctuations can be described as the sum of tidal constituents, each with a fixed frequency and amplitude. To demonstrate this, a synthetic water level time series was constructed as a simple sum of common tidal

constituents with fixed frequencies and realistic amplitudes (Figure 9a, b). For this synthetic example, the two major diurnal and two major semi-diurnal as well as the fortnightly spring-neap tidal constituents were used, which are shown in the time domain in Figure 9a. The resulting water level record (Figure 9b) shows typical semi-diurnal behavior, including two highs and lows per day, spring–neap tidal cycles, and tidal inequality (Figure 9b). MATLAB's Fast Fourier Transform (FFT) function (*fft*) was used to convert the time-domain data into the frequency domain, allowing the dominant periodic components to be identified. FFT analysis of this artificial time series reveals the expected tidal amplitude peaks (Figure 9c). However, some spectral leakage into neighboring frequencies is visible, illustrating a key limitation of FFT. FFT decomposes the signal into fixed, equally spaced frequency bins, which may not perfectly match theoretical tidal frequencies. The frequency resolution depends on the number of observations and is determined by the Rayleigh criterion, which requires that constituents be separated by at least $1/T$, where T is the time series length (Foreman et al., 2009; Pawlowicz et al., 2002). In this example, the time series spans 720 hours (30 days), resulting in a resolution of $1/30 \text{ d}^{-1}$ (0.0333 cpd). While this is sufficient to distinguish most tidal constituents, closely spaced pairs such as K_1 (1.0027 cpd) and P_1 (0.9973 cpd) or MSf and Mf (difference $\approx 0.0053 \text{ cpd}$) cannot be fully resolved. Consequently, the FFT-derived amplitudes differ slightly from the true amplitudes.

As an alternative, Harmonic Least Squares (HLS) estimation can be applied. This method fits sinusoidal functions with exact and predefined target frequencies to the time series, estimating their amplitudes and phases. Unlike FFT, HLS does not rely on fixed frequency bins and can separate target signals from noise and non-tidal variability more effectively, reducing amplitude loss. In this idealized example, HLS produced the exact input amplitudes, while FFT amplitudes were slightly lower but less than 1 % (Figure 9). In real-world timeseries the differences between FFT and HLS can be higher.

For the analyses published in Bauer et al. (2026 - under review), FFT was first applied to identify dominant tidal frequencies in the water level and salinity records. HLS was then used to estimate constituent amplitudes and phases for water level and salinity time series at Song Doc, Ca Mau and Ganh Hao in Ca Mau Province, covering January to June of 2017 and 2018. Tidal components were reconstructed from the HLS coefficients, and tidal control was quantified as the explained variance (R^2) relative to the

original time series. However, tides in natural estuaries are not purely harmonic signals. While astronomical forcing generates the primary tidal components, actual water level fluctuations are further influenced by morphology, residual currents, shallow-water effects and other non-stationary processes (Lobo et al., 2024; Matte et al., 2013). To account for these effects, a sliding-window HLS approach with a Hann taper was used. Window-specific R^2 values were weighted by their temporal coverage, enabling tidal control to be examined not only seasonally but also in its temporal evolution. Since water level fluctuations often drive salinity dynamics in estuarine environments (van Keulen et al., 2025; Wei et al., 2016), phase lag and magnitude response between water level (input) and salinity (output) were assessed. A transfer function was derived from the HLS coefficients, allowing to assess magnitude response and phase lag of salinity relative to tidal forcing at each frequency. More insights and results for Ca Mau Province are published in Bauer et al. (2026 - under review).

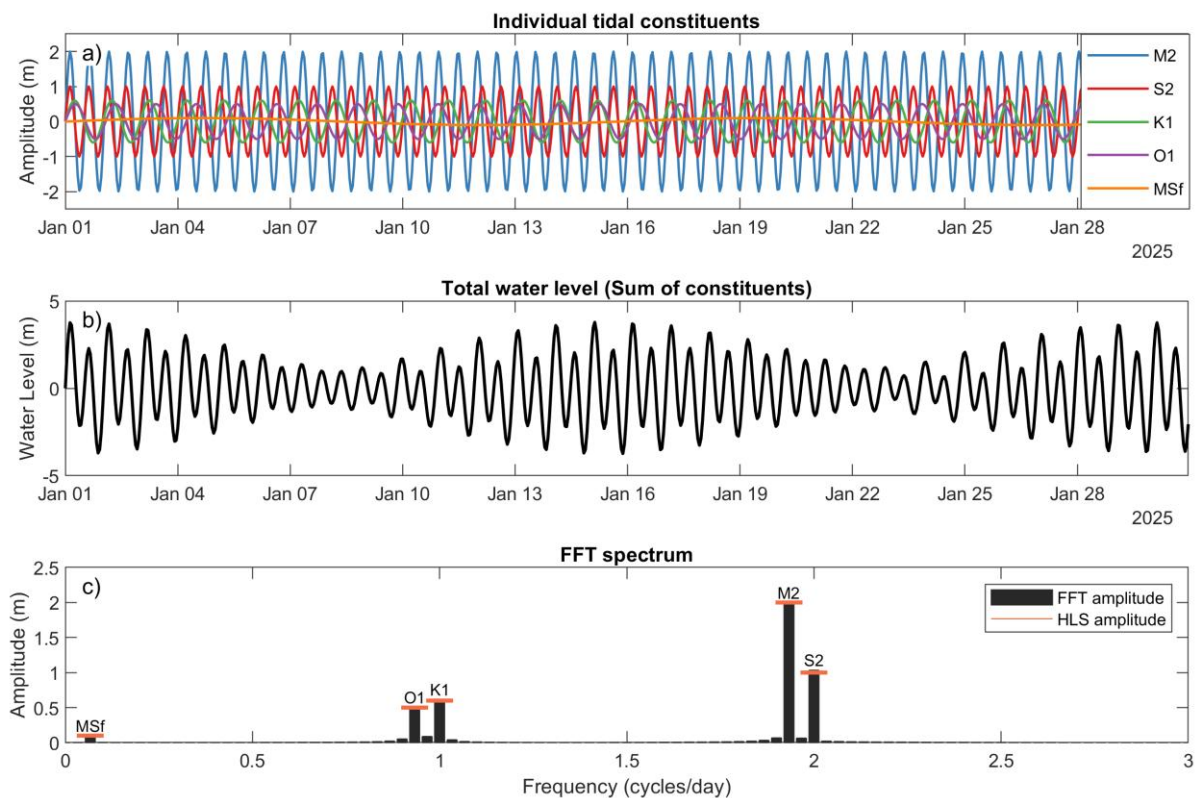


Figure 9 (a) Time series of tidal constituents M2, S2, K1, O1 and MSf, (b) total water level as the sum of tidal constituents and (c) FFT spectrum and Harmonic Least Squares amplitudes.

3 Scientific contributions

3.1 Summary

This dissertation provides novel insights in the fields of water resources, hydrology and SWI in the southern Mekong Delta. The work builds on three first-authored studies and seven co-authored studies that directly address the research objectives presented in Chapter 1.5 and Figure 3. In addition, two further studies to which I contributed examine water-related processes that can be applied to the Mekong Delta context. A comprehensive understanding of environmental and water related processes in the southern Mekong Delta, especially in Ca Mau Province, could only be achieved through an interdisciplinary and holistic approach. This is reflected in the range of first-authored and co-authored publications presented in this chapter, which combine geochemical analyses, hydrological observations, hydrogeological modeling, land subsidence monitoring and assessments of water use and land use. A list of all publications is provided in the appendix.

The following chapters summarize the scientific advancements in a thematic structure that follows the research objectives outlined in chapter 1.5. Subsequently, the studies I contributed to are presented in detail, highlighting both the contributions of others to my first-authored studies (chapter 3.2) and my role in the co-authored works (chapter 3.3).

All publications to which I contributed are highlighted in *italic* throughout Chapters 3 and 4. Lastly, four further co-authored studies in other areas of environmental research are listed in the end of this chapter.

3.1.1 Advances in groundwater salinization processes: Bauer et al. (2022)

Context: In *Bauer et al. (2022)*, I investigated the spatial distribution of fresh and saline groundwater resources in Ca Mau Province across multiple aquifers. I collected 190 groundwater samples and conducted a comprehensive geochemical assessment to delineate salinization sources and identify primary natural and anthropogenic processes governing observed signatures.

Key findings: As the first comprehensive groundwater investigation in Ca Mau Province, the study reveals that an originally saline aquifer, which had undergone natural

freshening during the last glacial maximum, is locally affected by recent salinization. Past freshening is reflected in samples with high Na^+/Cl^- molar ratios above that of seawater and a $\text{Na}-\text{HCO}_3$ water type. These fingerprints are the result of water–rock interactions, more specifically ion exchange processes. Further evaluation of ion ratios shows that samples with salinities between 2 and 4 g/L do not simply reflect less freshened groundwater, but are rather in the early stages of salinization. This recent salinization is attributed to anthropogenic activities, mainly well construction and pumping, which facilitate the downward migration of saline Holocene groundwater or saline surface water. It was also shown that EC, as a simple proxy for salinization in the sense of SWI associated with Cl^- and Na^+ ions, can be misleading. High concentrations of HCO_3^- originating from organic matter decomposition in marine sediments contribute substantially to observed EC values, which is why a full chemical analysis of groundwater samples is recommended. Finally, it was concluded that geochemical signatures are a local phenomenon, indicating that aquifers are at least partially connected.

3.1.2 New insights into groundwater quality and water use in Ca Mau: Bauer et al. (2022), Pham et al. (2023), Wang et al. (2019)

Context: Groundwater is the most important source of freshwater for domestic use and numerous socio-economic activities in the Mekong Delta (Wagner et al., 2012). *Bauer et al. (2022)* evaluated groundwater quality with respect to salinity levels, while *Pham et al. (2023)*, using partly the same set of samples, incorporated trace elements and evaluated water quality in relation to drinking water standards. We employed a holistic methodological design that combined 144 household surveys with groundwater analyses across all nine districts in Ca Mau Province. Thereby, water use habits, perceptions towards different water types, and the environmental awareness of people in Ca Mau Province were examined.

Key findings: In *Bauer et al. (2022)*, I showed that groundwater in most wells, though not all, exhibits salinity levels below the Vietnamese guideline threshold of 1.5 g/L for domestic use. However, many samples exceed limits for ammonium, boron, iron, barium, sodium, chloride, and sulfate (*Pham et al., 2023*). We provide the first province-wide evidence that residents mainly use groundwater for washing and cooking while relying on treated or alternative sources for drinking (*Pham et al., 2023*). People's perceptions towards groundwater could be directly linked to the water quality of their

household well. The study also revealed a pronounced dependence on groundwater use, coupled with limited awareness of overexploitation and its link to land subsidence. This is an important insight underscoring the need for targeted public education and sustainable water management strategies.

Context: Contamination of groundwater with geogenic arsenic is a major issue in many regions worldwide, particularly in the Asian deltas comprising of sediment strata from the Himalayas, including some areas in the Mekong Delta (Erban et al., 2013; Fendorf et al., 2010). Arsenic mobility can be influenced by SWI (Lian et al., 2024), which is why I considered arsenic as a potential contaminant in Ca Mau Province. To better understand arsenic mobility and its contamination potential in the study area, I contributed to *Wang et al. (2019)*, who investigated arsenic mobilization processes in the Hetao Basin, China, as a comparative study.

Key findings: This study provides novel evidence that weathering of evaporite (Ca- and Na-sulfate) minerals simultaneously drives groundwater salinization and controls arsenic mobility through coupled pH–Ca²⁺–sulfate processes. The work shows how these reactions can both inhibit arsenic release via lowered pH and promote mobilization through formation of stable thio-arsenic species under reducing conditions, revealing a previously underexplored link between evaporite weathering and arsenic contamination dynamics. In *Bauer et al. (2022)*, I reported negative saturation indices for major evaporites in all 190 groundwater samples, but as salinization is not governed by evaporite dissolution, which I tested using the Br⁻/Cl⁻ molar ratio (Vengosh, 2013) and because the occurrence of evaporites were not reported previously, I concluded that the mechanisms reported in *Wang et al. (2019)* do not apply to the Mekong Delta. In the project region Ca Mau Province, arsenic concentrations in groundwater samples were below 10 µg/L and therefore below any legal thresholds (*Pham et al., 2023*).

3.1.3 Improvements in groundwater modeling: Hoan et al. (2022), Hoan et al. (2025)

Context: By utilizing a newly developed groundwater model, we contributed to a better understanding of the complex subsurface system on the Ca Mau Peninsular and qualitatively assessed salinization pathways in the study area.

Key findings: Together, the two studies by *Hoan et al. (2022, 2025)* establish the first integrated hydrogeological and salinity-transport modeling framework for the Ca Mau Peninsula. In *Hoan et al. (2022)*, we introduce a high-resolution 3-D finite-element groundwater flow model that quantifies the full water balance across seven aquifers and extends the modeled domain 30 km offshore, revealing that nearly 40 % of groundwater inflow originates along the coast. Building on this, the follow-up study couples the flow model with a density-dependent transport simulation that derives spatially variable longitudinal dispersivity from sediment properties and integrates land-use-based TDS boundary conditions, enabling, for the first time, a process-based exploration of salinization pathways and land-use controls on shallow-aquifer salinity in a data-scarce delta environment.

3.1.4 Novel insights into causes and dynamics of land subsidence in the Mekong Delta: Dörr et al. (2023), Dörr et al. (2025a), Dörr et al. (2025b)

Context: As groundwater overexploitation substantially contributes to land subsidence (Erban et al., 2014; Minderhoud et al., 2017), a novel land subsidence observatory (LSO) was constructed within the ViWaT-Engineering project. In *Dörr et al. (2023)*, we utilize data from the LSO to evaluate the relationship between decreasing groundwater heads and land subsidence. Then, in *Dörr et al. (2025a)* we developed a novel approach to assess the potential for subsidence mitigation by utilizing passive subsurface characterization methods. Furthermore, hydraulic head dynamics in observation wells were analyzed and linked to land subsidence (*Dörr et al. 2025b*).

Key findings: *Dörr et al. (2023)* present the LSO as the first depth differentiated subsidence monitoring system in the region, confirming a direct correlation between declining groundwater heads and surface elevation loss. Subsequently, *Dörr et al. (2025a)* developed a passive subsurface characterization approach using tidal frequency analysis to derive elastic aquifer properties and rebound potential. In this study,

ocean tides were, for the first time, integrated into a passive subsurface characterization framework. By applying frequency analysis and disentangling overlapping signals, both the specific storage and elastic formation compressibility of the Pliocene aquifer n_2^2 were estimated as $5.9\text{--}7.8 \times 10^{-6} \text{ m}^{-1}$ and $6.4\text{--}7.5 \times 10^{-10} \text{ Pa}^{-1}$, respectively.

As these results indicate a low rebound potential, the study reveals that deep aquifers in the Mekong Delta have only a limited capacity for subsidence mitigation. In addition, it shows that mechanical loading exerts a significant influence on groundwater heads. Building on these findings, a follow up study used a multi-factor regression deconvolution analysis to remove surface loading signals from groundwater head time series. This analysis showed that rising groundwater heads during the rainy season do not reflect actual groundwater recharge but are instead caused by surface loading from aquaculture ponds (Dörr *et al.*, 2025a). In conclusion, groundwater levels decrease throughout the year and not only during the dry season, indicating the unsustainable exploitation of groundwater, which in the Mekong Delta results in pronounced land subsidence.

3.1.5 Revealing riverine seawater intrusion dynamics and controlling factors on multiple time scales: Bauer *et al.* (2025) and Bauer *et al.* (2026 - under review)

Context: In the Mekong Delta, rivers are increasingly affected by SWI, limiting their potential as reliable freshwater source for various socio-economic activities (Gugliotta *et al.*, 2017a; Khang *et al.*, 2008). To characterize river salinity conditions in the southern Mekong Delta and assess their variability across different time scales, time series data from three monitoring stations in Ca Mau Province were analyzed to evaluate interannual salinity variations from 2000 to 2022 in relation to hydrometeorological drivers (Bauer *et al.*, 2025) and to investigate sub-seasonal, tide-influenced dynamics during the dry seasons of 2017 and 2018 (Bauer *et al.*, 2026 - under review).

Key findings: In Bauer *et al.* (2025), I provide the first multi-decadal, observation-based assessment of salinity dynamics in the southern Mekong Delta covering the period 2000–2022. It is shown that salinity increases by more than 10 g/L during the dry season and that interannual differences in peak salinity levels reach up to 15 g/L. I developed the Low Discharge Period (LDP) concept to identify upstream discharge anoma-

lies and explain extreme SWI events. Early and prolonged LDPs and high salinity conditions are mainly caused by hydrological droughts in the Mekong River, which are substantially intensified by upstream reservoir management. In addition, land subsidence rates of up to 2.35 cm per year, derived from water level records, further increase the Mekong Delta's vulnerability to future SWI. Adapted upstream discharge management was identified as a key measure to mitigate SWI.

Subsequently, sub-seasonal salinity variations were examined in *Bauer et al. (2026 - under review)*. The study shows that salinity variations are controlled by tidal water level fluctuations in a complex setting shaped by co-oscillating tidal regimes from the East Sea and the Gulf of Thailand. Harmonic analysis identifies salinity variations at the major tidal frequencies, confirming a strong tidal influence. To quantify and demonstrate the temporal variability of tidal control during the study period from 2017 to 2018, a sliding-window Harmonic Least Squares approach was developed. This method captures the non-stationary behavior characteristic of estuarine systems and achieved weighted R^2 values of 0.85–0.98 for water level and 0.53–0.73 for salinity at the three monitoring stations.

For the first time, taken together, the two studies establish a process-based understanding of the spatiotemporal variability of salinity across multiple time scales in the southern Mekong Delta.

3.1.6 Identifying the causes for land use change and yield loss in the Mekong Delta: Binh et al. (2025)

Context: Land use in the Mekong Delta is primarily controlled by available water resources, which is why increasing salinity conditions led to significant land use transition in the past decades (Renaud et al., 2015). To explore this relationship in detail, I contributed to the study of *Binh et al. (2025)*, investigating how drought as well as SWI conditions have reshaped land use and rice yields across the Mekong Delta.

Key findings: By integrating long-term in situ hydrological monitoring, MODIS-based land use mapping, and rice yield data, we demonstrated clear links between extreme drought and SWI events, subsequent land use transitions from rice to aquaculture and drought-tolerant crops, and associated yield losses. In total, six major drought events were identified between 2000 and 2020, with the 2015–2016 drought having the

strongest socio-economic impact. Although the interval between drought events has decreased, it was also shown that the impacts of the extreme 2020 drought, which occurred during a strong El Niño phase, were partly mitigated due to lessons learned from previous events.

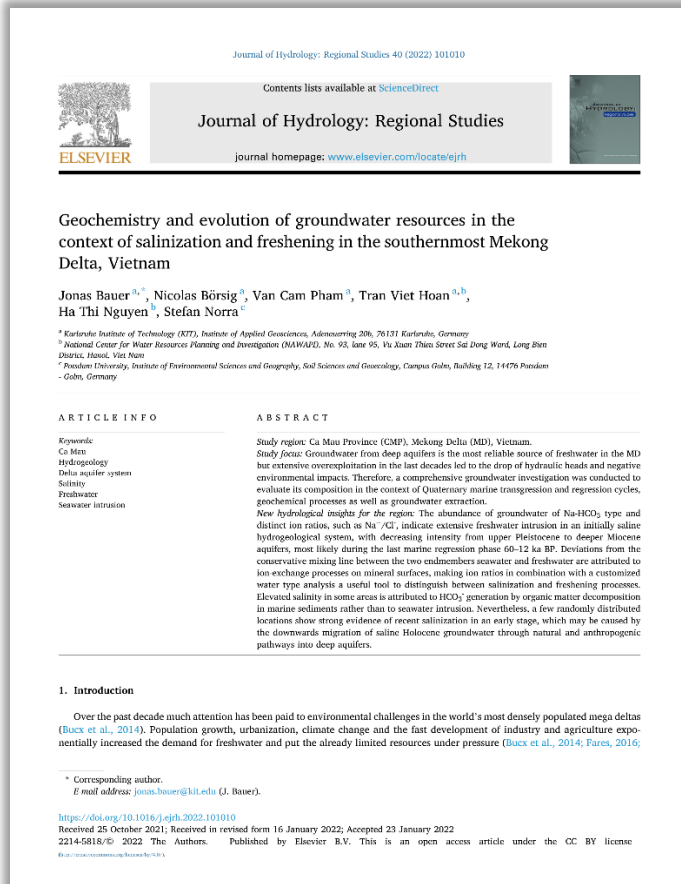
3.1.7 Developing novel machine learning methods to enhance water resources management: Qian et al. (2023)

Context: As in general water resources assessments and environmental studies substantially rely on monitoring and in-situ data, as highlighted in *Bauer et al. (2025, 2026 - under review)*, which in best case are continuous and of high reliability, new methods are continuously developed, particularly to enable machine learning approaches in the context of big data (Pan et al., 2025; Qian et al., 2023). One of these approaches involves cruise monitoring, where a boat is equipped with a multi-sensor probe to record water quality data alongside geographic coordinates (Holbach et al., 2014). This method enables the collection of high-resolution spatial data between fixed monitoring stations and could in the future be effectively applied in the Mekong Delta to enhance water quality assessments, particularly in secondary channels and along the coast. Therefore, I joined a cruise monitoring campaign in Qingcaosha Reservoir located at the Yangtze river mouth in Shanghai, China, obtaining data we used in our collaborative study (Qian et al., 2022).

Key findings: In *Qian et al. (2022)*, we introduce a novel, data-driven framework that combines in-situ cruise monitoring, remote sensing, and deep learning for near-real-time water quality assessment. The study's innovative use of deep embedded clustering enables the first automated delineation of water quality control regions and outperforms conventional models, marking a major step toward scalable, adaptive monitoring and management of dynamic aquatic environments.

3.2 First authorship scientific publications

3.2.1 Geochemistry and evolution of groundwater resources in the context of salinization and freshening in the southernmost Mekong Delta, Vietnam



Authors: Jonas Bauer, Nicolas Börsig, Van Cam Pham, Hoan Viet Tran, Ha Thi Nguyen, Stefan Norra

Year of publication: 2022

Authorship statement

This first-authored, peer-reviewed journal article answers the research questions outlined in *Focus 1: Groundwater salinization processes in the Mekong Delta*. The hypothesis was, that seawater is directly intruding freshwater aquifers due to intensive groundwater pumping. To reach the research objectives

Paper 1: Published in Journal of Hydrology: Regional Studies, 2022, 40. DOI: <https://doi.org/10.1016/j.ejrh.2022.101010>

and confirm or falsify the hypothesis, 190 groundwater samples were collected during four field campaigns in Ca Mau Province between 2017 and 2019 in the frame of the ViWaT-Engineering project. The geochemical composition was analyzed and the spatial and vertical distribution of fresh and saline groundwater resources was mapped. By applying established and improved methods, water-rock interactions were reconstructed and used to derive dominant natural and anthropogenic processes controlling the distribution of geochemical groundwater signatures and saline hotspots. The research objective was achieved, as this work substantially advances the state of knowledge on groundwater resources in the southern Mekong Delta. In addition, the results indicate that direct SWI is not the major cause for local salinization, but that

saline water from the surface and upper aquifer leak into underlying freshwater aquifers through boreholes and/or stratigraphic discontinuities. Thus, the initial hypothesis cannot be conclusively confirmed, yet direct SWI cannot be excluded for some locations or for future conditions.

The field campaigns were joined by the co-authors Nicolas Börsig and Van Cam Pham as well as other project partners. Hoan Viet Tran and Ha Thi Nguyen supported the field work with administrative tasks and supported me with scientific insights from the National Center for Water Resources Planning and Investigation of Vietnam. Samples were brought to the Karlsruhe Institute of Technology, Germany, and analyzed at the Institute of Applied Geosciences for cations and anions. I conducted the literature review and hence developed the research idea. I was then responsible for quality control, data organization and evaluation. These tasks included statistical analysis, creating maps in ArcGis and plots with MATLAB and ORIGIN, presenting the results in a meaningful way. In addition, a 3D hydrogeological model was constructed by a self-written MATLAB application able to create custom cross-sections and plot data points. This tool was mainly used for data visualization. The input data consisted of 27 borehole logs, which were pre-processed by Hoan Viet Tran. Throughout all these steps, Nicolas Börsig provided valuable guidance. The project and work were supervised by Stefan Norra, including reviewing and administrative tasks. The publication was critically reviewed by all co-authors.

Abstract

Study region: Ca Mau Province (CMP), Mekong Delta (MD), Vietnam.

Study focus: Groundwater from deep aquifers is the most reliable source of freshwater in the Mekong Delta but extensive overexploitation in the last decades led to the drop of hydraulic heads and negative environmental impacts. Therefore, a comprehensive groundwater investigation was conducted to evaluate its composition in the context of Quaternary marine transgression and regression cycles, geochemical processes as well as groundwater extraction.

New hydrological insights for the region: The abundance of groundwater of Na-HCO₃ type and distinct ion ratios, such as Na⁺/Cl⁻, indicate extensive freshwater intrusion in an initially saline hydrogeological system, with decreasing intensity from upper

Pleistocene to deeper Miocene aquifers, most likely during the last marine regression phase 60–12 ka BP. Deviations from the conservative mixing line between the two endmembers seawater and freshwater are attributed to ion-exchange processes on mineral surfaces, making ion ratios in combination with a customized water type analysis a useful tool to distinguish between salinization and freshening processes. Elevated salinity in some areas is attributed to HCO_3^- generation by organic matter decomposition in marine sediments rather than to seawater intrusion. Nevertheless, a few randomly distributed locations show strong evidence of recent salinization in an early stage, which may be caused by the downwards migration of saline Holocene groundwater through natural and anthropogenic pathways into deep aquifers.

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3.2.2 Seawater Intrusion in River Delta Systems. Inter-annual Dynamics and Drivers of Salinity Variations in the southern Mekong Delta, Vietnam



Authors: Jonas Bauer, Felix Dörr, Hoang Thai Duong Vu, Andreas Schenk, Hoan Viet Tran, Van Cam Pham, Nicolas Börsig, Roderick van der Linden, Ngoc Hoa Nguyen, Elisabeth Eiche, Stefan Norra

Year of publication: 2025

Authorship statement

This first-authored article, published in a peer-reviewed scientific journal, contributes to answer the research questions formulated in *Focus 2: Dynamics and factors controlling progressive riverine*

seawater intrusion. This study complements the previous groundwater investigation,

Paper 2 Published in Journal of Hydrology, 2025, 661.
DOI: <https://doi.org/10.1016/j.jhydrol.2025.133745>

as the overarching goal of this dissertation is to analyze the entire

water system with regard to salinization processes.

Preliminary insights from the 2018 and 2019 field campaigns, joined by co-authors Nicolas Börsig and Van Pham Cam, revealed high salinity levels in many areas of Ca Mau Province (Figure 11). However, in contrast to the previous study on groundwater salinization processes, these data provided only a snapshot of the conditions and were insufficient to capture the spatiotemporal dynamics. This is mainly because estuary systems are highly dynamic, and the confined aquifer system in the Mekong Delta reacts slower to change. Therefore, with the administrative support of Hoang Thai Duong Vu, Ngoc, Hoa Nguyen and Hoan Viet Tran, continuous data from various river monitoring stations was provided by Vietnamese institutions. After an initial inspection

of the data revealed substantial salinity variations, I developed the research concept and analyzed the data using time series and correlation methods. By analyzing hydro-meteorological time-series data for the period 2000-2022 from official monitoring stations in the Mekong Delta, interannual dynamics of SWI were presented for the first time and natural and anthropogenic cause-effect relationships successfully derived. The analysis focused especially on extreme events and the key processes that drive them, given their major implications for agriculture and water-resource management.

The study achieved the research objectives defined for the interannual timescale, underscoring the necessity of a follow-up investigation at the sub-seasonal scale. In addition, the research hypothesis, stating that SWI varies significantly and is controlled by human activities, can be clearly confirmed.

The analysis was particularly supported by Felix Dörr and Andreas Schenk through insightful discussions and support with data evaluation, and further supported by Hoang Thai Duong Vu, Van Cam Pham, Roderick van der Linden and Nicolas Börsig. This study was supervised by Elisabeth Eiche and Stefan Norra, who guided the research concept, project administration, and funding acquisition. All co-authors reviewed the scientific content and contributed to the editorial improvement of the manuscript.

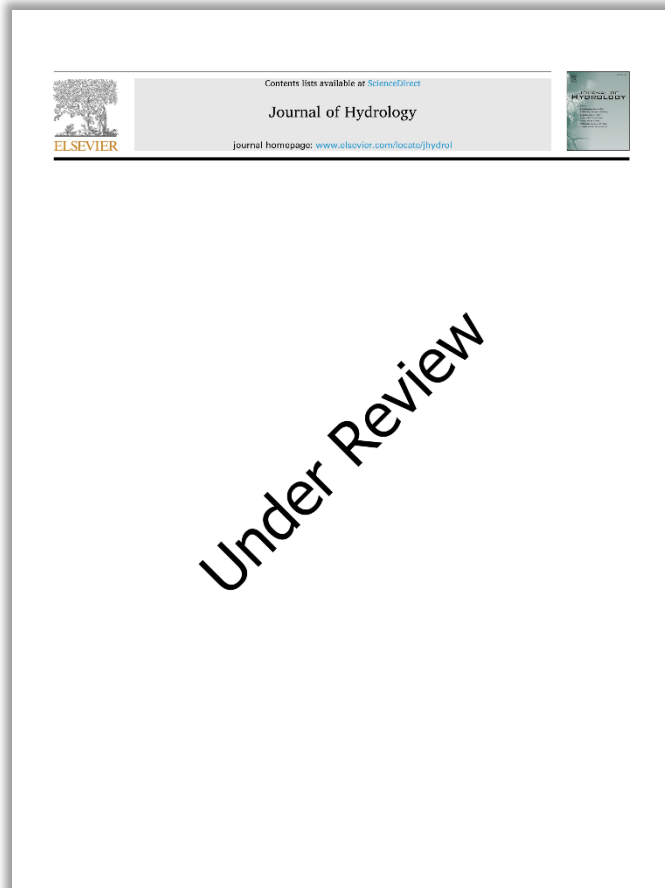
Abstract

Amidst intensifying impacts of climate change and anthropogenic pressure, seawater intrusion (SWI) emerges as a growing threat for delta systems worldwide, compromising freshwater resources and ecosystem stability. The Mekong Delta (MD) and its southernmost province Ca Mau are at the frontline of climate change impacts and anthropogenic modifications of the hydrological regime. To assess the inter-annual variability of river SWI, factors contributing to changes of the hydraulic pressure gradient between freshwater and seawater are analyzed. By utilizing long-term hydro-meteorological data from 2000 to 2022, the collective impact of catchment-scale and local-scale factors on salinity is evaluated. While salinity gradually increases by more than 10 g/L during the dry season, significant inter-annual differences of up to 15 g/L in peak salinity occur, regularly reaching and exceeding seawater salinity levels. Upstream

freshwater discharge patterns were identified as major control for coastal water levels and resulting salinity levels. While climate variability governs natural upstream discharge fluctuations, dam constructions and operational responses to low-rainfall years lead to unfavorable conditions along the Mekong River, shifting and prolonging the low discharge period in the delta. This intensifies hydro- logical drought conditions and triggers extreme SWI events. Land subsidence of up to 2.35 cm per year, derived from water level records, is driving relative sea level rise and increasing the Mekong Delta's vulnerability to future SWI. Mitigation strategies for SWI are examined from new perspectives, highlighting the benefits of increasing early dry- season discharge through rethought upstream reservoir operations and water storage concepts, as well as adapted local sluice gate management.

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3.2.3 Tidal Control of Salinity Dynamics and Seawater Intrusion in the Southern Mekong Delta, Vietnam



Paper 3 Submitted to Journal of Hydrology on 16.11.2025 and currently under review.

Authors: Jonas Bauer, Felix Dörr, Andreas Schenk, Vũ Hoàng Thái Dương, Hoan Viet Tran, Van Cam Pham, Nicolas Börsig, Roderick van der Linden, Ngoc Hoa Nguyen, Elisabeth Eiche, Stefan Norra

Submission date: 16.11.2025

Authorship statement

This scientific study was submitted to *Journal of Hydrology* on 16.11.2025 and is currently under review. This study was written by me and complements the previous study about interannual riverine salinity variations by shedding light on the

sub-seasonal, tide-driven salinity variations. Thus, the research objective of characterizing riverine salinity dynamics across different time scales was accomplished, and the supporting evidence for the previously established hypothesis was further strengthened.

The analysis draws on time series data from the same three monitoring stations in Ca Mau Province used in the preceding study, concentrating on the most recent data available for January to June in 2017 and in 2018. I developed the study idea in close cooperation with Felix Dörr. In this work I was responsible for data processing and evaluation, focusing on time series analysis, including harmonic analysis. The statistical and time series evaluation was supported by Felix Dörr and Andreas Schenk. Data acquisition was supported by Hoang Thai Duong Vu and Ngoc Hoa Nguyen. Hoan Viet Tran, Van Cam Pham, Nicolas Börsig, and Roderick van der Linden supported this

work through numerous discussions on the research direction, by sharing their expertise in their respective fields, contributing to the interpretation of the study's regional implications, and providing additional contextual insights. This study was supervised by Elisabeth Eiche and Stefan Norra, who provided guidance on the research concept, project administration, and funding acquisition.

Abstract

As sea levels rise and freshwater resources decline, seawater intrusion (SWI) poses an increasing threat to many delta systems worldwide. Effective mitigation strategies for SWI require a fundamental understanding of underlying processes, which classical numerical and machine learning models often struggle to provide yet. In the Mekong Delta, Vietnam, SWI recurs annually during the dry season, adversely affecting agriculture and ecosystems. Building on previous work that analyzed interannual salinity variations in Ca Mau Province from 2000 to 2022, this study examines the sub-seasonal interplay between tide-driven water level fluctuations and salinity. Time series analyses, including harmonic analysis, were applied to data from three monitoring stations in Ca Mau Province between January and June in 2017 and in 2018. Results show that co-oscillations of two different tidal regimes in the east and in the west influence water level patterns and ultimately salinity dynamics. Frequency analyses revealed salinity variations at major tidal frequencies. A sliding window Harmonic Least Squares approach captured the non-stationary behavior expected in estuarine systems at all three stations, with weighted R^2 values of 0.85 to 0.98 for water level and 0.53 to 0.73 for salinity. The findings of this study highlight the spatiotemporal complexity of salinity variations in the study region and underscore the importance of process-based understanding for developing reliable numeric models and effective SWI mitigation strategies.

© The full article was submitted to Journal of Hydrology and is currently under review. The manuscript is included in Appendix A.3. The final version will be reprinted here with kind permission from Elsevier under the Creative Commons Attribution License.

3.3 Co-authored related scientific publications

3.3.1 An Improved Groundwater Model Framework for Aquifer Structures of the Quaternary-Formed Sediment Body in the Southernmost Parts of the Mekong Delta, Vietnam



Paper 4 Published in *Hydrology*, 2022, 9. DOI: <https://doi.org/10.3390/hydrology9040061>

Authors: Tran Viet Hoan, Karl-Gerd Richter, Nicolas Börsig, **Jonas Bauer**, Nguyen Thi Ha, Stefan Norra

Year of publication: 2022

Authorship statement

This peer-reviewed scientific journal article was written by Hoan Viet Tran in the frame of the ViWaT-Engineering project. The research objective of this study was to extent the understanding of the subsurface and groundwater flow processes in the Ca Mau Peninsular. I supported Hoan Viet Tran by reviewing the work and participated in regular discussions about water quality, salinization, and

environmental challenges in the study area. Insights from my work and this study directly informed each other and mutually supported the development of the research direction. In total my contribution to this article amounts to 5 %.

Abstract

The Ca Mau peninsula (CMP) is a key economic region in southern Vietnam. In recent decades, the high demand for water has increased the exploitation of groundwater, thus lowering the groundwater level and leading to risks of degradation, depletion, and land subsidence, as well as salinity intrusion in the groundwater of the whole Mekong Delta region. By using a finite element groundwater model with boundary expansion to

the sea, we updated the latest data on hydrogeological profiles, groundwater levels, and exploitation. The basic model setup covers seven aquifers and seven aquitards. It is determined that the inflow along the coastline to the mainland is 39 % of the total inflow. The exploitation of the study area in 2019 was 567,364 m³/day. The most exploited aquifers are the upper-middle Pleistocene (qp2–3) and the middle Pliocene (n22), accounting for 63.7 % and 24.6 %, respectively; the least exploited aquifers are the upper Pleistocene and the upper Miocene, accounting for 0.35 % and 0.02 %, respectively. In the deeper aquifers, qp2–3 and n22, the change in storage is negative due to the high exploitation rate, leading to a decline in the reserves of these aquifers. These groundwater model results are the calculations of groundwater reserves from the coast to the mainland in the entire system of aquifers in the Ca Mau. This makes groundwater decision managers, stakeholders, and others more efficient in sustainable water resources planning in the Ca Mau and Mekong Delta (MKD).

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3.3.2 The Utilization of a 3D Groundwater Flow and Transport Model for a Qualitative Investigation of Groundwater Salinization in the Ca Mau Peninsula (Mekong Delta, Vietnam)



Authors: Tran Viet Hoan, Karl-Gerd Richter, Felix Dörr, **Jonas Bauer**, Nicolas Börsig, Anke Steinel, Van Thi Mai Le, Van Cam Pham, Don Van Than, Stefan Norra

Year: 2025

Authorship statement

This peer-reviewed scientific journal article was written by Hoan Viet Tran and builds upon the groundwater model developed in Hoan et al. (2022). The research objective addressed in this study evolves around exploring salinization pathways into the complex multi-aquifer system of the Ca Mau Peninsular using hydro-

geological modelling approaches. Building on the previous studies (Bauer et al., 2022; Hoan et al., 2022), this work expands our understanding of groundwater salinization and subsurface processes in the Mekong Delta. In this work, I supported Hoan Viet Tran throughout the revision process and participated in regular discussions on water quality, salinization pathways and processes, as well as broader environmental challenges in the study area. In total my contribution to this article amounts to 5 %.

Abstract

The Ca Mau Peninsula (CMP), the southernmost region of the Mekong Delta, is increasingly threatened by groundwater salinization, posing severe risks to both the fresh-water supply and land sustainability. This study develops a three-dimensional,

density- dependent groundwater flow and salinity transport model to investigate salinization dynamics across the Ca Mau's complex multi-aquifer system. Unlike previous studies that largely rely on model calibration, this research introduces a novel approach by systematically deriving the spatial distribution of longitudinal dispersivity based on sediment characteristics. Moreover, detailed land use mapping is integrated to assign spatially and temporally variable Total Dissolved Solids (TDS) values to the uppermost layers, thereby enhancing the model realism in areas where monitoring data are limited. The model was utilized not only to simulate the regional salinity evolution, but also to critically evaluate conceptual hypotheses related to the mechanisms driving groundwater salinization. Results reveal a strong influence of seasonal and land use factors on salinity variability in the upper aquifers, while deeper aquifers remain largely stable, affected primarily by paleosalinity and localized pumping. This integrated modeling approach contributes to a better understanding of regional-scale groundwater salinization and highlights both the potential and the limitations of numerical modeling under data-scarce conditions. The findings provide a valuable scientific basis for adaptive water resource management in vulnerable coastal zones.

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3.3.3 Vietnams Mekong-Delta - Landsenkung infolge von Grundwasserübernutzung



Authors: Felix Dörr, Jonas Bauer, Hoan Viet Tran, Stefan Norra und Franz Nestmann

Year of publication: 2023

Authorship statement

This article, published in a peer-reviewed scientific journal, was written in German by Felix Dörr. The objective of this study is to assess land subsidence resulting from groundwater extraction in the Mekong Delta. The analysis draws on depth-differentiated compaction data from the Land Subsidence Observatory constructed in 2022 within the ViWaT project, and re-

Paper 6 Published in Wasserwirtschaft, 2023, 11. DOI: <http://doi.org/10.1007/s35147-023-1922-3>

lates observed subsidence rates to declining hydraulic heads measured in groundwater wells installed as part of the same project. In this study, I contributed insights into the subsurface strata and groundwater-related issues in the study area. I supported the work by providing scientific context, participating in the planning of the monitoring equipment, and conducting regular revisions. Overall, my contribution to this article amounts to approximately 10 %.

Abstract

Das Mekong-Delta ist Lebensraum für ca. 21,5 Mio. Menschen und sieht sich seit einigen Jahren mit zunehmend existenzbedrohenden Landsenkungsprozessen (bis zu 3 cm/a) konfrontiert. Als einer der Hauptgründe dafür gilt die starke Grundwasserentnahme. Um die Prozessdynamik besser untersuchen zu können, wurde ein im Me-

3 | Scientific contributions

kong-Delta bislang einmaliges Messsystem zur tiefen- differenzierten Landsenkungsmessung an einem Pilot-Standort aufgebaut, dessen vorläufige Messdaten eine Korrelation zwischen Landsenkung und dem fallenden Grundwasserspiegel zeigen.

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3.3.4 Passive Subsurface Characterization in Subsiding Deltas: Assessing Land Subsidence Mitigation Potential with Frequency Analyses of Groundwater Heads and Superposing Harmonic Drivers



Authors: Felix Dörr, Jonas

Bauer, Gabriel C. Rau, Remi Va-

lois, Hoan Viet Tran, Van Cam

Pham, Le Thi Mai Van, Anke Stei-

nel, Franz Nestmann, Stefan

Norra

Year of publication: 2025

Authorship statement

This peer-reviewed scientific journal article was written by Felix Dörr and addresses the use of passive subsurface characterization methods to better understand subsurface dynamics in the context of land subsidence in the southern Mekong Delta. This study closes

an important knowledge gap by showing that the potential to mitigate land subsidence is low and emphasizes the need to address its underlying causes, especially groundwater overexploitation. I supported this study through continuous review and discussion of the applied methods, results, visualizations, and their implications for the study region. The map presented in the paper was created by me. In total, my contribution to this article amounts to 10 %.

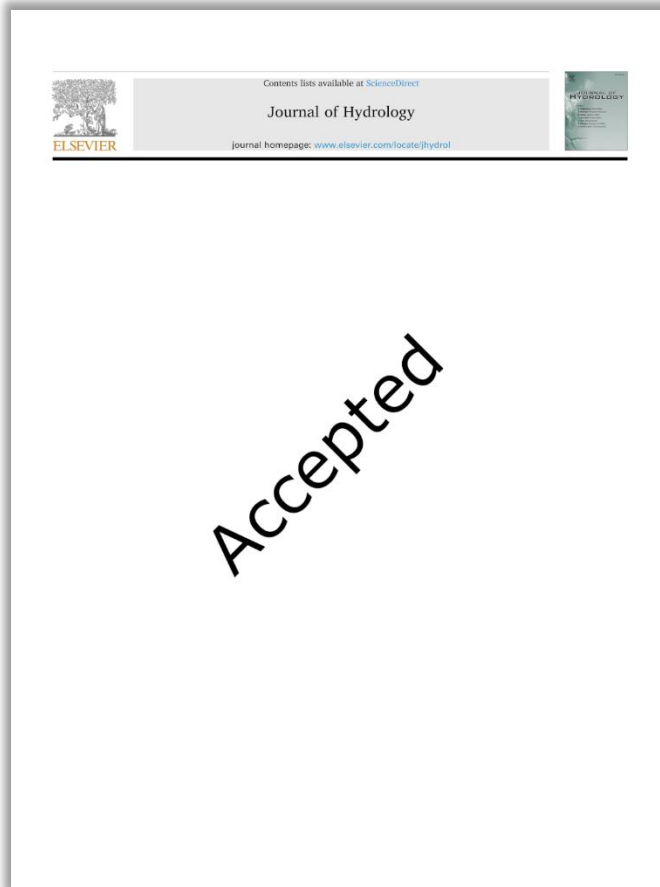
Abstract

Many of the world's low-lying river deltas are experiencing severe land subsidence, posing significant challenges to sustainable development. Effective mitigation strategies require a thorough understanding of subsurface processes and comprehensive

parameterization, which are often hindered by limited investigations and resources. In this context, passive subsurface characterization (PSC) methods are particularly advantageous, as they utilize existing datasets to estimate hydraulic and geomechanical properties of the subsurface. This study conducts a detailed frequency analysis of 43 groundwater head time series in the southern Vietnamese Mekong Delta, revealing harmonic signals and imprints of mechanical loading in groundwater heads. These signals are identified as a superposition of five key drivers: (i) Earth tides, (ii) atmospheric tides, (iii) ocean tides, (iv) river tides, and (v) anthropogenic groundwater extraction. By disentangling Earth and ocean tides from atmospheric tides at the semi-diurnal frequency S_2 , the specific storage and elastic formation compressibility of the intensely exploited middle Pliocene aquifer are estimated to $5.9\text{--}7.8 \cdot 10^{-6} \text{ m}^{-1}$ and $6.4\text{--}7.5 \cdot 10^{-10} \text{ Pa}^{-1}$, respectively. This indicates a low land rebound and water storage potential and therefore an insignificant subsidence mitigation potential of this confined aquifer. By revealing that groundwater pumping may leak into amplitude spectra and corrupt quantitative PSC, this study underscores that accurate parameter estimations require a careful disentanglement of various superposing drivers. While the complex interplay of multiple tidal forcing limited previous PSC-applications in subsiding deltas, the novel integration of ocean tide loading on the solid Earth enables PSC-parameter estimations in coastal groundwater systems.

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3.3.5 The recharge illusion: How seasonal surface loading can hide continuing groundwater re-source declines in confined deltaic aquifers



Paper 8 Accepted in Journal of Hydrology, 2025

Authors: Felix Dörr, **Jonas Bauer**, Gabriel C. Rau, Elias Lewi, Hoan Viet Tran, Le Thi Mai Van, Remi Valois, Anke Steinel, Franz Nestmann, Stefan Norra

Journal: Journal of Hydrology

Submission Date: 23.07.2025

Acceptance Date: 24.11.2025

Authorship statement

In this study led by Felix Dörr, we for the first time in the Mekong Delta use the concept of loading effects to show that apparent rising groundwater levels in the rainy season do not reflect recharge but are attributed to surface loading

from aquaculture ponds. Corrected head data show that groundwater levels are decreasing through-out the year, which before was often misinterpreted as actual recharge. These insights are essential for groundwater recharge assessments, which form the basis for sustainable water management planning. Together with the previous work by Felix Dörr, this study contributes to the overarching research objectives that seek to improve our understanding of land subsidence dynamics in the Mekong Delta. For the first time, a ground-based and physically informed evaluation of land subsidence that complements and extends existing remote sensing analyses is provided, strengthening the scientific foundation for future mitigation and adaptation strategies.

I supported this study through continuous review and discussions about the applied methods, results and implications. My contribution to this work amounts to 10 %.

Abstract

Reliable estimates of groundwater recharge are critical for managing water resources and preventing groundwater depletion. However, groundwater recharge estimates can be distorted when loading signals are mistakenly interpreted as signs of groundwater recharge. This study introduces a novel extension to existing frequency-domain methods to quantify loading imprints in groundwater measurements by disentangling superposing signals from Earth, atmospheric, ocean, and river tides, using the K_1 tidal constituent to remove the river tide influence. This approach enables the application of frequency-domain methods for calculating the loading efficiency in deltaic groundwater systems, where superposing multiple forcing govern tidal constituents in groundwater heads. Using multi-factor regression deconvolution analysis, surface loading signals are removed from groundwater head time series. Applying this method to groundwater head data from the southern Vietnamese Mekong Delta strongly suggests that the observed seasonal rise in groundwater heads does not reflect recharge. Instead, the apparent upward trend in uncorrected data is attributed to mechanical surface loading from seasonal surface water accumulation linked to expanding aquaculture. The loading-corrected time series show a consistent decline during both dry and rainy seasons, aligning with observed annual depletion rates. This indicates a deficiency of net effective groundwater recharge throughout the year, reflecting unsustainable groundwater exploitation practices. The methods and findings of this study offer a scientific framework for the analysis of multiple superimposed surface loading processes in deltaic aquifer systems, thereby enhancing groundwater recharge assessments in such hydrogeological environments.

© The full article was submitted to Journal of Hydrology and was accepted on 24.11.2025. The manuscript is included in Appendix A.3. The final version will be reprinted here with kind permission from Elsevier under the Creative Commons Attribution License.

3.3.6 Groundwater Use Habits and Environmental Awareness in Ca Mau Province, Vietnam: Implications for Sustainable Water Resource Management



Authors: Van Cam Pham, Jonas Bauer, Nicolas Börsig, Johannes Ho, Long Vu Huu, Hoan Tran, Felix Dörr, Stefan Norra

Year of publication: 2023

Authorship statement

This peer-reviewed scientific journal article, written by Van Cam Pham addresses the research objective concerning the importance of groundwater for local communities, their water-use practices, and their perceptions of different water resources. New insights are based on questionnaires and on groundwater samples collected during

joint field campaigns between 2018 and 2020. The questionnaires investigated local perceptions and behaviors related to different water types in Ca Mau Province, with a particular focus on groundwater. The groundwater quality results, largely based on the same samples used in my study on salinization in Ca Mau Province (Bauer et al., 2022), were analyzed in the context of the respondents' answers. For this study, I provided occasional input for the questionnaire design and mainly supported Van Cam Pham during the sampling campaign, as well as in creating the map and several statistical plots. During the writing phase, I contributed insights into water quality issues and carried out regular revisions. Overall, my contribution to this article amounts to approximately 15 %.

Abstract

The Vietnamese Mekong Delta including Ca Mau province (CMP) is seriously affected by land subsidence. Ground- water over-extraction is considered to be a major driver for this process. To address the reduction of groundwater (GW) extraction as a potential counter measure for further subsidence, this study focuses on understanding the importance of GW in people's life and water using habits as well as their awareness with current environmental problems in CMP. Therefore, GW sampling campaigns and surveys were conducted in all 9 districts of CMP in 2019 and 2020. The analyzed water samples showed a connection with information from questionnaires and created a general picture of water using habits. GW plays an important role in people's lives, it is used for washing, cooking, drinking and other activities. People use GW for different purposes depending on their perception of water quality. For important and direct health related purposes, such as cooking or drinking, people prepare to treat water more carefully or choose another alternative water resource. The analytical approach to evaluation results based on viewpoints from general to detail helped to dig deeper into people's stories to explain research results with their behavior in each situation. When people are dependent on GW and have no option to use alternative water resources, the importance level of GW in their life increases and their awareness of GW over-extraction becomes less. If people have another water source to use such as tap water (TW), habits of using GW change. This opens up the idea that a potential alternative water will reduce the dependence of people on GW and protect GW from over-exploitation. Besides, people in CMP do not have much awareness of land subsidence or the reason leading to environmental problems. Therefore, raising the awareness of people by well-design education campaigns should be strongly considered.

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3.3.7 Indications that weathering of evaporite minerals affects groundwater salinity and As mobilization in aquifers of the northwestern Hetao Basin, China



Authors: Hong-Yan Wang, Hua-Ming Guo, Wei Xiu, **Jonas Bauer**, Guo-Xin Sun, Xiao-Hui Tang, Stefan Norra

Year of publication: 2019

Authorship statement

This article, published in a peer-reviewed scientific journal, was written by Hong-Yan Wang. In this study, geochemical processes are evaluated to assess the salinization of groundwater and arsenic mobilization in the Hetao Basin, China. In this study, I contributed to the review of the original manuscript and subsequent revisions, as well as supported the GIS-based visualization of the results. The processes investigated in this work are also relevant to the Mekong Delta, making the study highly significant for my research. In particular, arsenic contamination remains an important issue in certain parts of the Mekong Delta (Erban et al., 2013). In total my contribution to this article amounts to less than 5 %.

Paper 10 Published in *Applied Geochemistry*, 2019, 109.
DOI: <https://doi.org/10.1016/j.apgeochem.2019.104416>

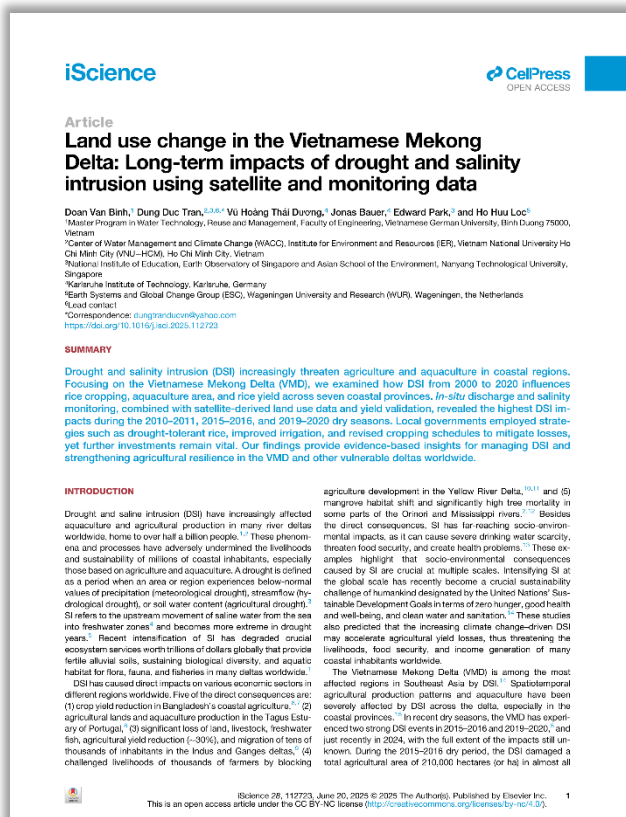
Abstract

Elevated arsenic (As) concentration and salinity (TDS > 1000 mg/L) seriously affect the groundwater quality in the Hetao Basin, China, however, the origin of groundwater salinity and its influence for As mobilization has not been widely studied. In this study,

the influence of evaporite minerals weathering on groundwater salinity and As mobilization were investigated by lithological and mineralogical analysis of sediments from two boreholes in combination with groundwater hydrogeochemical characteristics analysis in the northwestern Hetao Basin. Results from a water-leaching method suggest that Na and Ca related sulphates dominate the evaporite minerals in sediment samples. Groundwater salinization mainly results from evaporation and $\text{Na}^+/\text{Ca}^{2+}$ cation exchange followed by sulphate and silicate minerals weathering. Saturated indices for calcite, dolomite and unsaturated indices for gypsum as well as negative correlation between pH and SO_4^{2-} suggest that groundwater chemistry does not reach equilibrium with continual carbonates precipitation by an excessive Ca supply from Ca related sulphates weathering. The groundwater pH decreases and Ca^{2+} release during weathering of Ca related sulphates can retard As desorption from Fe (oxyhydr)oxides and clay minerals. Furthermore, pyrite minerals were also found in the sediments induced by high sulphide flux and it can cause As sequestration. However, modeling results suggest the occurrence of thio-As species in the study area, which can potentially enhance the As mobilization. This study contributes to the ongoing research into As mobilization in the groundwater of lacustrine basins.

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3.3.8 Land Use Change in the Vietnamese Mekong Delta: Long-term impacts of drought and salinity intrusion using satellite and monitoring data



Paper 11 Published in iScience, 2025, 28.
DOI: <https://doi.org/10.1016/j.isci.2025.112723>

Abstract

Drought and salinity intrusion (DSI) increasingly threaten agriculture and aquaculture in coastal regions. Focusing on the Vietnamese Mekong Delta (VMD) we examined how DSI from 2000 to 2020 influences rice cropping, aquaculture area, and rice yield across seven coastal provinces. In-situ discharge and salinity monitoring, combined with satellite-derived land use data and yield validation, revealed the highest DSI impacts during the 2010–2011, 2015–2016, and 2019–2020 dry seasons. Local governments employed strategies such as drought-tolerant rice, improved irrigation, and revised cropping schedules to mitigate losses, yet further investments remain vital. Our

Authors: Doan Van Binh, Dung Duc Tran, Hoang Thai Duong Vu, **Jonas Bauer**, Edward Park, Huu Loc Ho

Year of publication: 2025

Authorship statement

This article, published in a peer-reviewed scientific journal, was written by Doan Van Binh and explores the impact of drought and salinity on land use changes in the Mekong Delta.

Thematically, this study aligns well with my previous work, in which I investigated salinization dynamics on the interannual scale, with a particular emphasis on extreme events such as

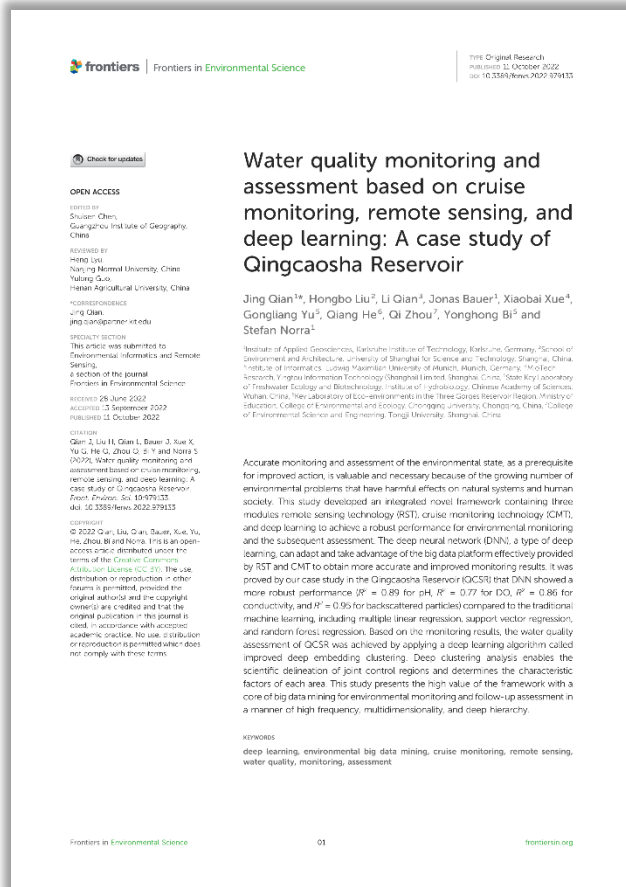
hydrological droughts (Bauer et al., 2025). Accordingly, in this work I contributed to the manuscript review and provided additional insights and context derived from my earlier research. In total my contribution to this article amounts to 5 %.

3 | Scientific contributions

findings provide evidence-based insights for managing DSI and strengthening agricultural resilience in the VMD and other vulnerable deltas worldwide.

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3.3.9 Water quality monitoring and assessment based on cruise monitoring, remote sensing, and deep learning: A case study of Qingcaosha Reservoir



Authors: Jing Qian, Hongbo Liu, Li Qian, Jonas Bauer, Xiaobai Xue, Gongliang Yu, Qiang He, Qi Zhou, Yonghong Bi, Stefan Norra

Year of publication: 2023

Authorship statement

In this peer-reviewed publication, authored by Jing Qian, water quality of the Qingcaosha Reservoir in Shanghai, China, is assessed by means of on-site data collection and correlation of parameters with satellite images via deep learning approaches. In this study I introduced the BIOFISH monitoring device to the team and provided guidance during field work. The

Paper 12 Published in Frontiers in Environmental Science, 2023, 10.
DOI: <https://doi.org/10.3389/fenvs.2022.979133>

BIOFISH is an innovative sensor system with integrated probes for water quality parameters and is dragged behind a boat to gather continuous data from a large area. I was partly involved in postprocessing the BIOFISH data and supported this work through continuous revision. In total my contribution to this article amounts to 5 %.

Abstract

Accurate monitoring and assessment of the environmental state, as a prerequisite for improved action, is valuable and necessary because of the growing number of environmental problems that have harmful effects on natural systems and human society. This study developed an integrated novel framework containing three modules remote sensing technology (RST), cruise monitoring technology (CMT), and deep learning to

achieve a robust performance for environmental monitoring and the subsequent assessment. The deep neural network (DNN), a type of deep learning, can adapt and take advantage of the big data platform effectively provided by RST and CMT to obtain more accurate and improved monitoring results. It was proved by our case study in the Qingcaosha Reservoir (QCSR) that DNN showed a more robust performance ($R^2=0.89$ for pH, $R^2=0.77$ for DO, $R^2=0.86$ for conductivity, and $R^2=0.95$ for backscattered particles) compared to the traditional machine learning, including multiple linear regression, support vector regression, and random forest regression. Based on the monitoring results, the water quality assessment of QCSR was achieved by applying a deep learning algorithm called improved deep embedding clustering. Deep clustering analysis enables the scientific delineation of joint control regions and determines the characteristic factors of each area. This study presents the high value of the framework with a core of big data mining for environmental monitoring and follow-up assessment in a manner of high frequency, multidimensionality, and deep hierarchy.

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3.4 Scientific contributions in other fields of environmental research

1. Title: Characterisation of temporal and regional differences in the elemental fractionation and mobility of urban particulate matter via online sequential extraction

Citation: Nischwitz et al. (2023)

Authors: Volker Nischwitz, **Jonas Bauer**, Stefan Norra

DOI: <https://doi.org/10.1080/03067319.2021.1977289>

2. Title: Variations of PM_{2.5} sources in the context of meteorology and seasonality at an urban street canyon in Southwest Germany

Citation: Song et al. (2022)

Authors: Junwei Song, Harald Saathoff, Linyu Gao, Reiner Gebhardt, Feng Jiang, Magdalena Vallon, **Jonas Bauer**, Stefan Norra, Thomas Leisner

DOI: <https://doi.org/10.1016/j.atmosenv.2022.119147>

3. Title: Chromophores and chemical composition of brown carbon characterized at an urban kerbside by excitation-emission spectroscopy and mass spectrometry

Citation: Jiang et al. (2022)

Authors: Feng Jiang, Junwei Song, **Jonas Bauer**, Linyu Gao, Magdalena Vallon, Reiner Gebhardt, Thomas Leisner, Stefan Norra, and Harald Saathoff

DOI: <https://doi.org/10.5194/acp-22-14971-2022>

4. Title: Spatio-temporal dynamics of aerosol distribution in an urban environment recorded in situ by means of a bike based monitoring system

Citation: Norra et al. (2023)

Authors: Stefan Norra, Junwei Song, Reiner Gebhardt, **Jonas Bauer**, Magdalena Broß, Marco Fuchs, Theresa Huber, Dennis Mack, Harald Saathoff

DOI: <https://doi.org/10.3389/fenvs.2023.749477>

4 Discussion: Integrated perspectives on salinization of water resources in the southern Mekong Delta

Given their high population density and critical role in agricultural production, the sustainable development of deltas worldwide will attract increasing attention from both the scientific community and the public throughout the twenty-first century. The Mekong Delta is among the world's most vulnerable delta systems (Eslami et al., 2021a; Huggins et al., 2022), and many of the challenges it faces, such as SWI and land subsidence (*Bauer et al., 2025, 2022; Dörr et al., 2023*), mirror processes observed in many other deltas globally (Bucx et al., 2015; Huning et al., 2024; van Engelen et al., 2022). This makes the Mekong Delta an important case study for understanding the mechanisms that drive progressive salinization in low-lying coastal regions in South-east Asia and beyond.

This dissertation addresses key research gaps concerning the processes that control salinization of groundwater and surface water resources in the southern Mekong Delta. By analyzing riverine salinity dynamics on multiple time scales and identifying the mechanisms behind groundwater salinization, it is revealed how environmental drivers and human interventions interact to influence freshwater availability. In the following, these findings are integrated into a common framework, showing how the natural and anthropogenic processes contribute to the progressive salinization of water resources in the study region, and how they reinforce each other in a causal loop.

4.1 The cascading effects leading to progressive salinization in the Mekong Delta

4.1.1 Freshwater scarcity in a system under pressure

In the Mekong Delta, SWI has become the dominant driver of freshwater degradation in both groundwater and surface water, adversely affecting millions of people in their daily lives (*Bauer et al., 2026 - under review, 2025, 2022; Park et al., 2022*). As seawater extends far inland and interannual salinity variability increases uncertainty for freshwater-reliant activities (*Bauer et al., 2025*), people have to search for opportunities to adapt to local environmental conditions and use water resources fit for their needs. For example, although brackish surface water conditions in Ca Mau Province have

historically been common during the dry season, the progressive extension and intensification of SWI eventually triggered substantial land-use reforms in the year 2000, leading to a system-wide shift from freshwater-based rice farming to brackish and saline aquaculture, demonstrating how salinity regimes directly control land-use dynamics (Binh et al., 2025; Thong et al., 2010). This phenomenon is widely recognized in the Mekong Delta but can also be observed in other coastal areas in Southeast Asia and worldwide (Ali, 2006; Luo et al., 2022). While brackish to saline aquaculture can better cope with SWI, and even relies on sufficiently high salinity levels (Gao et al., 2016; Li et al., 2017), domestic use will always depend on freshwater. As communities adapt to SWI by employing diverse water-use practices, often out of necessity and with the aim of maximizing yields (Nguyen et al., 2019), freshwater resources continue to decline, increasing reliance on groundwater abstraction, particularly during high salinity dry season periods (Bauer et al. 2025). At the same time, these issues are not being addressed with the necessary consistency and determination by local decision-makers due to a lack of awareness (Pham et al., 2023) as well as complex administrative structures and financial boundaries (Ha et al., 2018; Minkman et al., 2022; Quang et al., 2024).

Together with many of the world's largest low-lying river deltas, the Mekong Delta is undergoing a phase of accelerating and partly irreversible *loss of land and freshwater*, driven by cascading processes that destabilize the delta. While scientific discussions about the complete inundation of the delta and the *restore or retreat* debate are already ongoing (Kondolf et al., 2022; Minderhoud et al., 2020; Nguyen et al., 2024; White and Kaplan, 2017), the exploitation of natural resources within the Mekong River Basin continues largely unabated. Groundwater extraction continues (Hoan et al., 2025), new dams and canal infrastructure are constructed (Ang et al., 2024; Nghi and Ha, 2025; Normandin et al., 2024), coastal protection measures only have a pilot status (Vu et al., 2022b) and alternative freshwater concepts are underdeveloped (Pham et al., 2023; Vinh et al., 2024). It can be argued that processes leading to a sediment deficit, such as upstream dam construction that traps vital sediments, extensive sand mining, coastal erosion and land subsidence, already exceed natural sedimentation (Tamura et al., 2020; Binh et al., 2020). As a result, the coastline continues to retreat, riverbanks destabilize, and seawater advances further inland (Anthony et al., 2015; Gugliotta et al., 2017b; Marchesiello et al., 2019). The analyses in Bauer et al. (2025, 2026 - under

review) indicate an increase in both SWI magnitude and duration, especially during prolonged low-discharge periods and strong tidal conditions. In addition, recent salinization of groundwater resources has been observed (Bauer *et al.*, 2022).

The multifaceted processes leading to this situation are inseparable, as they mutually reinforce one another. Identifying which process initiated the progressive *loss of land and freshwater* in the Mekong Delta is difficult. However, what these processes have in common is that, amid rising water demand in recent decades, natural resources have not been managed sustainably. This is highlighted in Bauer *et al.* (2022, 2025, 2026), showing that mismanagement of upstream reservoirs and pumping activities promote salinization as well as land subsidence (Dörr *et al.*, 2025b).

SWI is both a consequence of the processes driving the *loss of land and freshwater*, and simultaneously a reinforcing factor that further accelerates them. This synthesis builds directly on the combined insights of the individual studies presented in chapter 3 and is illustrated in Figure 10. The figure outlines the cascading chain of processes that begins with increasing water demand and groundwater overexploitation, followed by land subsidence, changes in hydraulic gradients and subsequent SWI, land use transitions and salinization of groundwater, which eventually forces people to tap deeper aquifers and thereby reinforces and perpetuates the cycle of progressive salinization. As this chain of processes continues to repeat, it may ultimately lead to the complete depletion of freshwater resources in the study area. Building on Figure 10, the following chapters outline the cascading processes and illustrate the studies conducted within this dissertation contribute to identifying the underlying cause–effect relationships for progressive salinization of ground- and surface water resources in the southern Mekong Delta. This synthesis can be directly transferred and applied to other vulnerable delta systems in Southeast Asia and beyond.

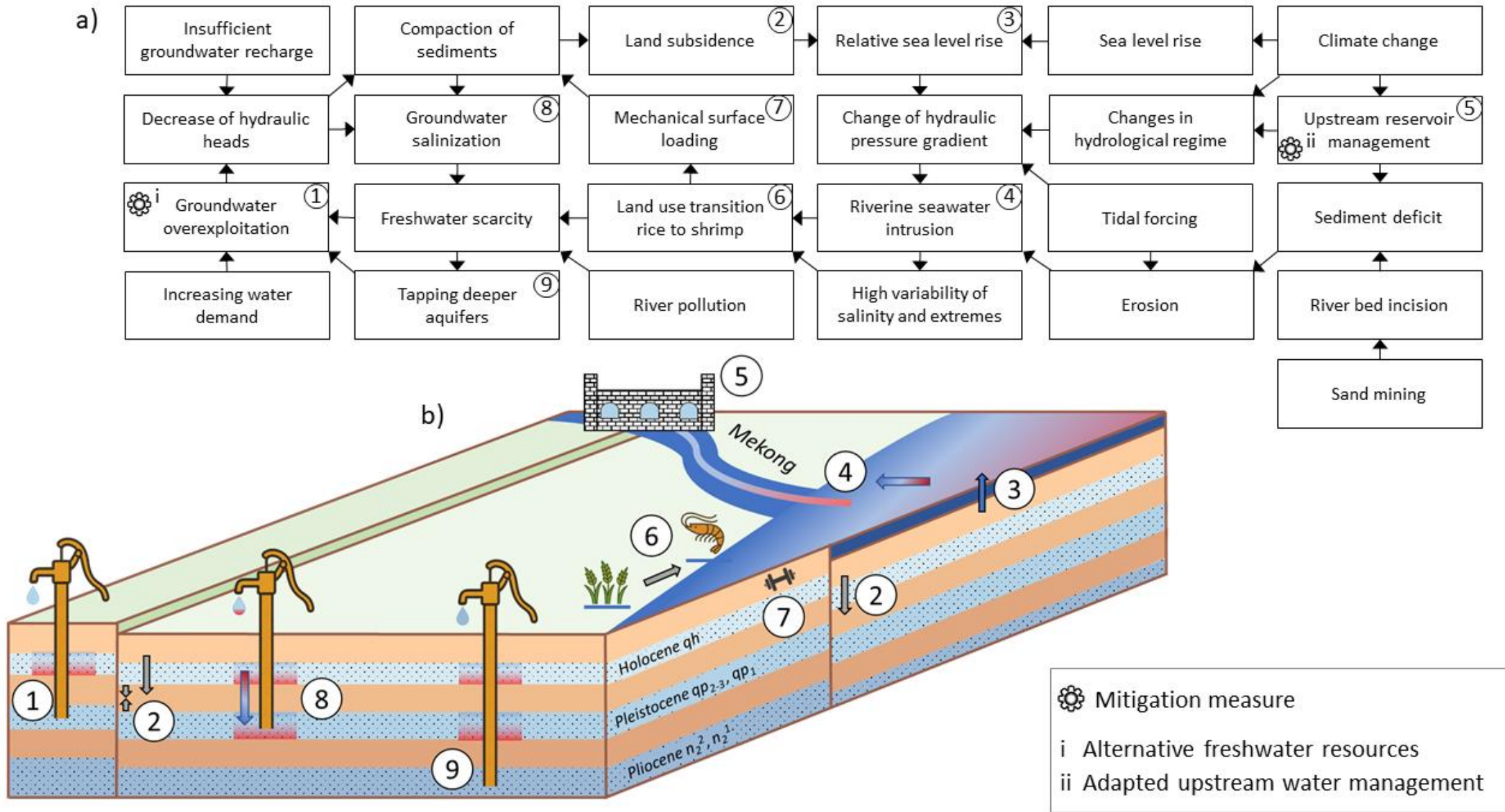


Figure 10 (a) Process-based causal loop diagram and (b) conceptual illustration of progressive salinization in the southern Mekong Delta.

4.1.2 Groundwater overexploitation causes land subsidence – The deltas vulnerability to riverine seawater intrusion increases

The Mekong River once supplied freshwater in sufficient quantity and quality for all socio-economic activities, but its capacity to do so has diminished due to growing demand, climate change, upstream reservoirs, pollution and advancing SWI (*Bauer et al., 2025; Binh et al., 2020; Lu and Chua, 2021; Muoi et al., 2022*). As surface water becomes increasingly saline and polluted, deep groundwater has become the most reliable freshwater source (*Pham et al., 2023*). This growing dependence marks the starting point of the reinforcing cycle presented in Figure 10. As a direct consequence of groundwater overexploitation (Figure 10-①), hydraulic heads in the confined aquifers are rapidly depleting (*Dörr et al., 2025b; Hoan et al., 2025*), reducing pore pressure and increasing the effective stresses on the fine-grained, clay-rich sediments (*Dörr et al., 2023; Erban et al., 2014*). This leads to compaction of compressible strata, resulting in land subsidence (Figure 10-②) that can locally reach rates of several centimeters per year (*Dörr, 2024; Dörr et al., 2025c; Minderhoud et al., 2017*). In *Bauer et al. (2025)*, land subsidence rates were derived from water level records at two coastal monitoring stations in Ca Mau Province, amounting to 1.27 cm/a at Song Doc and 1.75 cm/a at Gan Hao between 2000 and 2019, with increasing rates of 1.98 cm/a and 2.35 cm/a, respectively, since 2010. Land subsidence constitutes the major component of RSLR (Figure 10-③) in many Asian delta systems (*Becker et al., 2024*). Lowered land elevation reduces the freshwater-driven hydraulic pressure gradient and increases the deltas vulnerability to SWI as illustrated in Figure 10-④ (*Bauer et al., 2025; Eslami et al., 2021b; Savenije, 2012*).

4.1.3 Riverine seawater intrusion and high variability of conditions as the driving forces of land use transition – Implications and challenges

Figure 11 shows surface water salinity levels in Ca Mau Province measured during field campaigns in December 2018 and 2019, together with coastal water salinity from July 2019. It also includes land-use-related salinity levels measured in fields and ponds. Offshore salinity levels reach typical seawater conditions of nearly 50 mS/cm (~32.5 g/L). Further inland, salinity in the southern part of Ca Mau Province remains high, ranging from 20 to 40 mS/cm (13 to 26 g/L). Land use in the south of Ca Mau

Province is dominated by shrimp farming, which depends on saline water drawn directly from adjacent channels. Further north, salinity decreases, and brackish to freshwater activities are dominant. Some fields and ponds with lower salinity levels in the central and northern areas are surrounded by brackish channels, suggesting that other water sources, particularly groundwater, may be used for dilution. These spatial patterns confirm that land use is tightly aligned with the prevailing salinity conditions, and that even small-scale variations in channel salinity exert strong control over where freshwater or brackish activities remain viable.

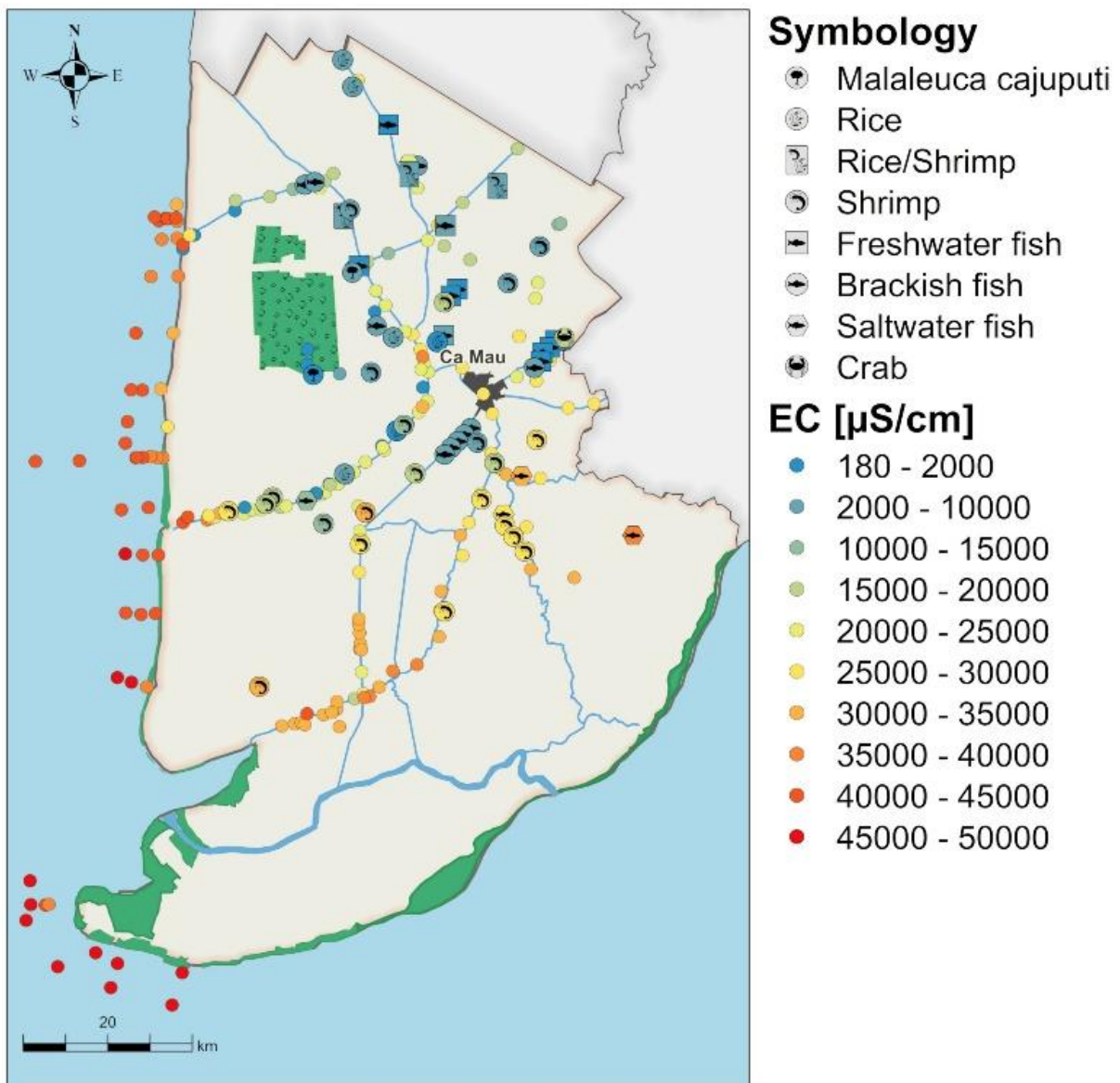


Figure 11 Distribution of salinity in rivers, channels and land use types measured in December 2018 and 2019 as well as coastal salinity levels in July 2019. TDS (g/L) can be estimated as $0.65 \times \text{EC (mS/cm)}$.

The data from these three field campaigns in Ca Mau Province, however, represent only a snapshot within a highly dynamic estuarine system, which is why the long-term salinity records evaluated in *Bauer et al. (2025, 2026 - under review)* are essential to assess SWI in its entirety.

Although SWI is largely accepted by shrimp farmers, the high variability in salinity conditions still poses considerable challenges for freshwater-dependent farmers and households. Between 2000 and 2022, peak dry season salinities varied by 5 g/L to 15 g/L, and seawater conditions of 35 g/L are regularly reached even in Ca Mau City located 40 km inland (*Bauer et al., 2025*). While climate-driven variability governs natural discharge fluctuations, dam construction and reservoir management (Figure 10-⑤) increasingly shape the duration and severity of low discharge periods and can intensify hydrological drought conditions, thereby triggering extreme SWI events (*Bauer et al., 2025*).

Superimposed on these interannual salinity variations, the pronounced sub seasonal salinity fluctuations and tidal patterns identified in *Bauer et al. (2026 - under review)* add further complexity to the system. Strong, short-term SWI can push the system over critical ecological or management thresholds. Daily salinity ranges reached up to 16 g/L at Song Doc and up to 5 g/L at Gan Hao and Ca Mau, driven by tidal water level fluctuations. Frequency analysis revealed that salinity variations occur at the dominant tidal frequencies, confirming a substantial tidal influence, but with strong local differences. By using harmonic analysis methods, the tidal control on sub-seasonal salinity fluctuations was shown and quantified (*Bauer et al. 2026 - under review*).

The tolerance threshold for traditional rice varieties is around 2 g/L (Korres et al., 2022; Zeng and Shannon, 2000), whereas shrimp thrive best in saline water with salinity levels between 20-30 g/L, depending on species and other environmental factors (Duy et al., 2012; Gao et al., 2016; Li et al., 2017). Therefore, areas regularly or even occasionally exposed to seawater are not suitable for rice farming, which is why SWI and the high variability of conditions caused substantial land use changes in the Mekong Delta (Figure 10-⑥). *Binh et al. (2025)* showed that SWI and drought conditions are the main driver for land use transition in the Mekong Delta, causing the substitution of freshwater rice farming with salinity-dependent shrimp farming. While increasing salinity initially promoted the shift toward shrimp farming, shrimp farmers now depend on

elevated salinity in adjacent channels, which creates conflicts with rice farmers who rely on freshwater conditions (Hoanh et al., 2009). At times, sluice gates are intentionally not operated to sustain shrimp farming, illustrating how local operational decisions can unintentionally intensify SWI and further reduce freshwater availability for other activities.

An often overlooked consequence of the expansion of aquaculture in the Mekong Delta is that the water stored in ponds increases the mechanical load on the subsurface (Figure 10-⑦), thereby raising effective stress in compressible sediments and potentially accelerating land subsidence (Dörr et al., 2025a). As a consequence, SWI is further accelerated.

When land use change is not enough to cope with significant salinity variations, and regular high salinity levels at or close to seawater conditions, farmers are forced to adapt by utilizing groundwater for irrigation and dilution of aquaculture ponds to maintain optimal conditions, particularly in the dry season, when rainwater is not available. Even though the use of groundwater for these activities is prohibited, previous studies show the high reliance of agriculture and shrimp farming on groundwater (Hamer et al., 2020; Tuan et al., 2024; Wilbers et al., 2025). Groundwater therefore serves as the critical buffer that enables farmers to cope with extreme or rapidly shifting salinity conditions and provides households with sufficient freshwater (Pham et al., 2023).

4.1.4 Pumping leads to salinization of groundwater resources

The overexploitation of groundwater to supply agriculture, aquaculture and households with sufficient freshwater not only accelerates land subsidence but also drives the salinization of aquifers (Figure 10-⑧). Across many deltas worldwide, the modern distribution of fresh and saline groundwater reflects past marine transgressions and regressions (van Engelen et al., 2021). Intensive pumping disrupts these natural patterns and often triggers local salinization (Hingst et al., 2024; Marie and Vengosh, 2001; Mirzavand et al., 2020b).

In Ca Mau Province, salinity hotspots occur at a local scale, and the few studies available agree that groundwater abstraction is the primary driver of salinization (Bauer et al., 2022; Hoan et al., 2025; Osenbrück et al., 2025). Bauer et al. (2022) identified the

processes that control the distribution of fresh and saline groundwater in the Pleistocene to Miocene aquifers, showing that freshwater infiltrated into a saline aquifer system, likely during the last glacial maximum, when the sea level was substantially lower and the upper sediments more permeable (Pham et al., 2019). This resulted in Na–HCO₃ water type as a result of characteristic water–rock ion exchange reactions, while the geochemical signatures of more saline groundwater samples with Na-Cl water type and low Na⁺/Cl⁻ ratios indicate early stages of salinization (Bauer et al., 2022).

Monitoring wells in the study area generally show stable salinity levels (Hoan et al., 2025; Pechstein et al., 2018). In contrast, abstraction wells frequently exhibit increasing salinity, which is consistent with the processes identified in Bauer et al. (2022) and can be attributed to recent saline infiltration from the surface, downward migration from overlying saline strata, or the release of connate water from compressible aquitards (Osenbrück et al., 2025). The interaction between surface water and the shallow aquifer qh (14–42 m) remains poorly constrained as they are separated by a thick clay layer (Figure 10). Nevertheless, several studies provide evidence of local hydraulic exchange and shallow subsurface SWI (Hoan et al., 2025; Nguyen et al., 2025; Xiao et al., 2024), suggesting that pumping may facilitate salinization from top to bottom in some areas. Upward migration of saline water from deeper units has not been confirmed. The aquifer most affected by salinization is qp₂₋₃ (80–148 m), which is also the most heavily exploited. In contrast, the deeper aquifer n₂² (198–254 m) still contains freshwater at most locations, indicating that salinization currently progresses from the top downward. Similar salinity levels at one location but in different aquifers was also demonstrated at two ViWaT pilot sites with closely spaced groundwater wells (ViWaT, 2023).

4.1.5 Tapping deeper aquifers as a response to salinization - the cycle repeats

When groundwater salinity reaches 2 to 4 g/L, it becomes unsuitable for drinking water production and agriculture, forcing farmers and households to drill new wells that tap deeper freshwater aquifers (Figure 10-⑨). In recent years, many businesses and households in Ca Mau Province have shifted from pumping the Pleistocene aquifers qp₂₋₃ and qp₁ to the deeper Pliocene aquifer n₂² for exactly this reason (Pham et al., 2023). While this response is understandable from a user perspective, it accelerates

the underlying problem. Continued abstraction from deeper aquifers further lowers hydraulic heads and increases land subsidence. Monitoring data from Ca Mau Province highlight how rapidly hydraulic heads have declined in the last decades. Prior to intensive abstraction, many wells exhibited artesian conditions, whereas current head levels have dropped to -15 m and below -20 m in densely populated areas such as Ca Mau City (Anderson, 1978; *Hoan et al.*, 2025; Jenn et al., 2017). Even a complete halt of pumping would not immediately stop land subsidence as the compaction of clay rich aquitards continues because pore pressures equilibrate only slowly with the lowering heads in adjacent aquifers (Hoffmann et al., 2003; Miller et al., 2020). This delayed response means that tapping deeper aquifers is only a temporary solution. Simultaneously, the cascading cycle of salinization of ground- and surface water is reinforced, threatening the overall freshwater security in the Mekong Delta.

4.2 Freshwater supply shortages – Scenarios and mitigation strategies

Because people rely heavily on groundwater as their primary freshwater source (*Pham et al.*, 2023), an abrupt ban with strict enforcement of pumping regulations is not a realistic option. This dependence creates a systemic constraint for water management in the study region. Aquifer n₂² likely constitutes the last practically accessible source of fresh groundwater for households. Below this depth, drilling becomes technically and economically challenging. Such a scenario would represent a critical turning point for the regional freshwater supply. Alternative water sources, such as rainwater harvesting and storage, are scarce and underdeveloped (*Pham et al.*, 2023; Thuy et al., 2019; Vinh et al., 2024) and the construction of pipeline infrastructure to divert freshwater from distant sources, for example from the Hau River to the southern delta plain, remains far from being realized.

A complete collapse of the freshwater supply, combined with the ongoing loss of land, would have dramatic and largely unforeseeable social, economic and ecological consequences. Already today, Ca Mau Province exhibits a pronounced out-migration rate, particularly due to drought and SWI (Duc et al., 2023; GSOV, 2024).

Immediate action is therefore required. The new evidence on cause-effect relationships driving progressive SWI and salinity dynamics presented in this dissertation provides the basis for developing effective countermeasures beyond the commonly proposed structural interventions and nature based solutions (e.g., Veetil et al., 2021; Vu

et al., 2022b). In particular, based on the analysis of interannual salinity variability in the southern Mekong Delta, and its correlation with changes in total upstream discharge and the timing of the low discharge period, it can be concluded that the most effective measure to directly mitigate riverine SWI is to increase upstream discharge of the Mekong River through adapted transboundary reservoir management during the dry season (❁-i), particularly in its early phase (Bauer et al. 2026 - under review). Previous studies have conceptually shown that enhancing upstream discharge in any setting can substantially counteract SWI (Cai et al., 2025; Sahwell and Solo-Gabriele, 2025). For the Mekong Delta, Binh et al. (2020) proposed emergency water releases during severe drought and SWI events. *Bauer et al. (2025)* showed that anthropogenically prolonged dry seasons with an early onset promote extreme SWI, which further highlights the need for adapted transboundary Mekong River discharge management. However, the observed decline in dry season discharge in recent years (*Bauer et al., 2025; Thu Minh et al., 2025*) and the continuation of large-scale infrastructure and upstream dam projects (Ang et al., 2024; Nghi and Ha, 2025) do not indicate that such discharge conditions will improve in the near future, presenting a concerning outlook.

In addition, effective long-term mitigation of SWI requires gradual phase out of practices that destabilize the delta and promote salinization. In particular, the highly unsustainable overexploitation of groundwater, which accelerates land subsidence and salinization (*Bauer et al., 2022; Dörr et al., 2025b; Hoan et al., 2025*), would represent an important first step toward slowing down the ongoing *loss of land and freshwater* in the Mekong Delta (❁-ii).

5 Conclusion

For the case of the Mekong Delta, this dissertation establishes a fundamental and holistic understanding of water resources salinization, which in the context of natural and anthropogenic change is a major constraint for freshwater availability in many coastal regions worldwide. The applied and advanced methods could successfully characterize and explain the spatiotemporal distribution and dynamics of fresh and saline ground- and surface water in Ca Mau Province by revealing primary cause-effect relationships.

Each first-authored study represents a distinct analytical component of this dissertation, addressing (i) salinization of the multi-aquifer groundwater system, (ii) the inter-annual dynamics of riverine SWI, and (iii) tidal-driven riverine salinity variability on sub-seasonal scales. In combination with the co-authored studies, this dissertation delivers a holistic, system wide perspective on the environmental processes governing salinization in the Mekong Delta. By revealing the cascading cycle of water demand and salinization that affects both groundwater and surface water resources, it is shown that the Mekong Delta is heading towards substantial freshwater supply shortages, with all its consequences. The growing number of publications on this topic, along with the various mitigation measures proposed, demonstrates an increasing awareness of this challenge. However, mitigation and adaptation strategies are still not implemented effectively. Given the multiple environmental and water-related pressures leading to the accelerating *loss of land and freshwater* in the Mekong Delta, the region may not have another decade in which difficult decisions can be postponed.

The studies presented here not only provide a comprehensive scientific basis for understanding the mechanisms driving progressive salinization, they also outline pathways toward more sustainable water management. In particular, adapted upstream reservoir management that targets more favorable discharge patterns for limiting riverine SWI, along with a substantial reduction in groundwater overexploitation through the introduction of alternative water resources, are among the most promising strategies for adaptation.

It is now essential for the scientific community to continue practice-oriented research and to communicate findings effectively to decision-makers and the public. While future work should continue to expand observational datasets, these data must increasingly serve to evaluate and refine mitigation strategies.

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Appendix

A First-authored publications

A.1

Bauer, J., Börsig, N., Pham, V.C., Hoan, T.V., Nguyen, H.T., Norra, S., 2022. Geochemistry and evolution of groundwater resources in the context of salinization and freshening in the southernmost Mekong Delta, Vietnam. J. Hydrol. Reg. Stud. 40. <https://doi.org/10.1016/j.ejrh.2022.101010>

A.2

Bauer, J., Dörr, F., Duong Vu, H.T., Schenk, A., Tran, H.V., Pham, V.C., Börsig, N., van der Linden, R., Nguyen, N.H., Eiche, E., Norra, S., 2025. Seawater intrusion in river delta systems. Inter-annual dynamics and drivers of salinity variations in the southern Mekong Delta, Vietnam. J. Hydrol. 661, 133745. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2025.133745>

A.3

Bauer, J., Dörr, F., Schenk, A., Dương, V.H.T., Tran, H.V., Pham, V.C., Börsig, N., Linden, R. van der, Nguyen, N.H., Eiche, E., Norra, S., 2026 (under review). Tidal Control of Salinity Dynamics and Seawater Intrusion in the South-ern Mekong Delta, Vietnam. J. Hydrol.

B Co-authored publications

B.1

Hoan, T.V., Richter, K.G., Börsig, N., Bauer, J., Ha, N.T., Norra, S., 2022. An Improved Groundwater Model Framework for Aquifer Structures of the Quaternary-Formed Sediment Body in the Southernmost Parts of the Mekong Delta, Vietnam. *Hydrology* 9. <https://doi.org/10.3390/hydrology9040061>

B.2

Hoan, T.V., Richter, K., Dörr, F., Bauer, J., Börsig, N., Steinel, A., Le, V.T.M., Pham, V.C., Than, D. Van, Norra, S., 2025. The Utilization of a 3D Groundwater Flow and Transport Model for a Qualitative Investigation of Groundwater Salinization in the Ca Mau Peninsula (Mekong Delta , Vietnam) 1–27.

B.3

Dörr, F., Bauer, J., Tran, H.V., Norra, S., 2023. Vietnams Mekong-Delta - Landsenkung infolge von Grundwasserübernutzung. *Forsch. | WASSERWIRTSCHAFT* 64–68.

B.4

Dörr, F., Bauer, J., Rau, G.C., Valois, R., Hoan, T.V., Pham, V.C., Van, L.T.M., Steinel, A., Nestmann, F., Norra, S., 2025. Passive subsurface characterization in subsiding deltas: assessing land subsidence mitigation potential with frequency analyses of groundwater heads and superposing harmonic drivers. *J. Hydrol.* 662.

B.5

Dörr, F., Bauer, J., Gabriel C, R., Lewi, E., Hoan Viet, T., Van, L.T.M., Valois, R., Steinel, A., Nestmann, F., Norra, S., 2025 (accepted). The recharge illusion: How seasonal surface loading can hide continuing groundwater re-source declines in confined deltaic aquifers. *J. Hydrol.*

B.6

Pham, V.C., Bauer, J., Börsig, N., Ho, J., Vu, L., Tran, H., Dörr, F., Norra, S., 2023. Groundwater Use Habits and Environmental Awareness in Ca Mau Province , Vietnam: Implications for Sustainable Water Resource Management. *Environ. Challenges* 13, 100742. <https://doi.org/10.1016/j.envc.2023.100742>

B.7

Wang, H.-Y., Guo, H.-M., Xiu, W., Bauer, J., Sun, G.-X., Tang, X.-H., Norra, S., 2019. Indications that weathering of evaporite minerals affects groundwater salinity and As mobilization in aquifers of the northwestern Hetao Basin, China. *Appl. Geochemistry* 109, 104416. <https://doi.org/https://doi.org/10.1016/j.apgeochem.2019.104416>

B.8

Binh, D. Van, Tran, D.D., Thái Dương, V.H., Bauer, J., Park, E., Loc, H.H., 2025. Land use change in the Vietnamese Mekong Delta: Long-term impacts of drought and salinity intrusion using satellite and monitoring data. *iScience* 28. <https://doi.org/10.1016/j.isci.2025.112723>

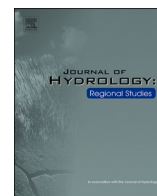
B.9

Qian, J., Liu, H., Qian, L., Bauer, J., Xue, X., Yu, G., He, Q., Zhou, Q., Bi, Y., Norra, S., 2022. Water quality monitoring and assessment based on cruise monitoring, remote sensing, and deep learning: A case study of Qingcaosha Reservoir. *Front. Environ. Sci.* 10, 1–13. <https://doi.org/10.3389/fenvs.2022.979133>



Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Geochemistry and evolution of groundwater resources in the context of salinization and freshening in the southernmost Mekong Delta, Vietnam

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ARTICLE INFO

Keywords:

Ca Mau
Hydrogeology
Delta aquifer system
Salinity
Freshwater
Seawater intrusion

ABSTRACT

Study region: Ca Mau Province (CMP), Mekong Delta (MD), Vietnam.

Study focus: Groundwater from deep aquifers is the most reliable source of freshwater in the MD but extensive overexploitation in the last decades led to the drop of hydraulic heads and negative environmental impacts. Therefore, a comprehensive groundwater investigation was conducted to evaluate its composition in the context of Quaternary marine transgression and regression cycles, geochemical processes as well as groundwater extraction.

New hydrological insights for the region: The abundance of groundwater of Na-HCO₃ type and distinct ion ratios, such as Na⁺/Cl⁻, indicate extensive freshwater intrusion in an initially saline hydrogeological system, with decreasing intensity from upper Pleistocene to deeper Miocene aquifers, most likely during the last marine regression phase 60–12 ka BP. Deviations from the conservative mixing line between the two endmembers seawater and freshwater are attributed to ion-exchange processes on mineral surfaces, making ion ratios in combination with a customized water type analysis a useful tool to distinguish between salinization and freshening processes. Elevated salinity in some areas is attributed to HCO₃⁻ generation by organic matter decomposition in marine sediments rather than to seawater intrusion. Nevertheless, a few randomly distributed locations show strong evidence of recent salinization in an early stage, which may be caused by the downwards migration of saline Holocene groundwater through natural and anthropogenic pathways into deep aquifers.

1. Introduction

Over the past decade much attention has been paid to environmental challenges in the world's most densely populated mega deltas (Bucx et al., 2014). Population growth, urbanization, climate change and the fast development of industry and agriculture exponentially increased the demand for freshwater and put the already limited resources under pressure (Bucx et al., 2014; Fares, 2016;

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<https://doi.org/10.1016/j.ejrh.2022.101010>

Received 25 October 2021; Received in revised form 16 January 2022; Accepted 23 January 2022

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Lam et al., 2018; Minderhoud et al., 2017). In many deltas, surface water is saline and polluted (Nguyen et al., 2019; Rahman et al., 2019), and rainwater is only available during the rainy season. Therefore, groundwater is the major and most reliable source of freshwater, which consequently leads to heavy overexploitation accompanied by various negative environmental impacts (Erban et al., 2014; Ferguson and Gleeson, 2012; Minderhoud et al., 2020, 2017; Werner et al., 2013). This also applies for the Vietnamese Mekong Delta (MD), the third largest delta on earth, which has around 17.3 million inhabitants (GSOV, 2019) and relies heavily on fresh groundwater (An et al., 2014; Gunnink et al., 2021; Ha et al., 2018). The most prominent negative environmental impact associated with groundwater overexploitation in the MD is the decrease of hydraulic heads and the potential of seawater intrusion, which would substantially degrade groundwater quality, limit its use and affect human health (Erban et al., 2014; Xiao et al., 2021; Rahman et al., 2019; Sohrabi et al., 2021). In addition, severe local land subsidence of several centimeters a year, which is induced by decreased pore pressure due to pumping, results in irreversible compaction of unconsolidated sandy aquifers and highly compressible clay layers (Erban et al., 2014, 2013; Karlsrud et al., 2020; Minderhoud et al., 2015; Parker, 2020; Thoang and Giao, 2015). In combination with additive processes, the low-lying MD is threatened in its very existence. Those include natural compaction of the upper Holocene sediment layers (Zoccarato et al., 2018), a decline of fluvial sediment supply transported by the Mekong River due to upstream dam constructions (Allison et al., 2017; Karlsrud et al., 2017; Kummur and Varis, 2007), salinization of surface water (Ferguson and Gleeson, 2012; Gugliotta et al., 2017) as well as sea-level rise due to global climate change (Smajgl et al., 2015; Woodroffe et al., 2007). Some parts of the MD are additionally facing heavy coastal and riverbank erosion (Anthony et al., 2015; Karlsrud et al., 2017; Liu et al., 2017; Luijendijk et al., 2018; Tamura et al., 2020). Weather extremes and natural hazards, including floods and prolonging dry seasons leading to severe droughts, like in early 2020, further threaten the area and potentially increase the demand for fresh groundwater (Moser et al., 2012; Phan et al., 2020). In coastal areas the consequences of groundwater extraction often surpass the impact of sea-level rise (Erban et al., 2014; Ferguson and Gleeson, 2012). Overall, the problems can be summarized as a progressive “loss of land and freshwater”, which will eventually lead to inundation of large parts of the delta (Minderhoud et al., 2020). As this was acknowledged in the last years by researchers and decision makers, initiatives like the Mekong Delta Plan and Basin Development Strategy Plan by the Mekong Delta Commission aim to solve abovementioned challenges, reduce groundwater overexploitation, and work towards a sustainable development of the MD (MDP, 2013; MRC, 2016).

In order to forecast the future development of groundwater resources in the MD, it is essential to understand the hydrogeological

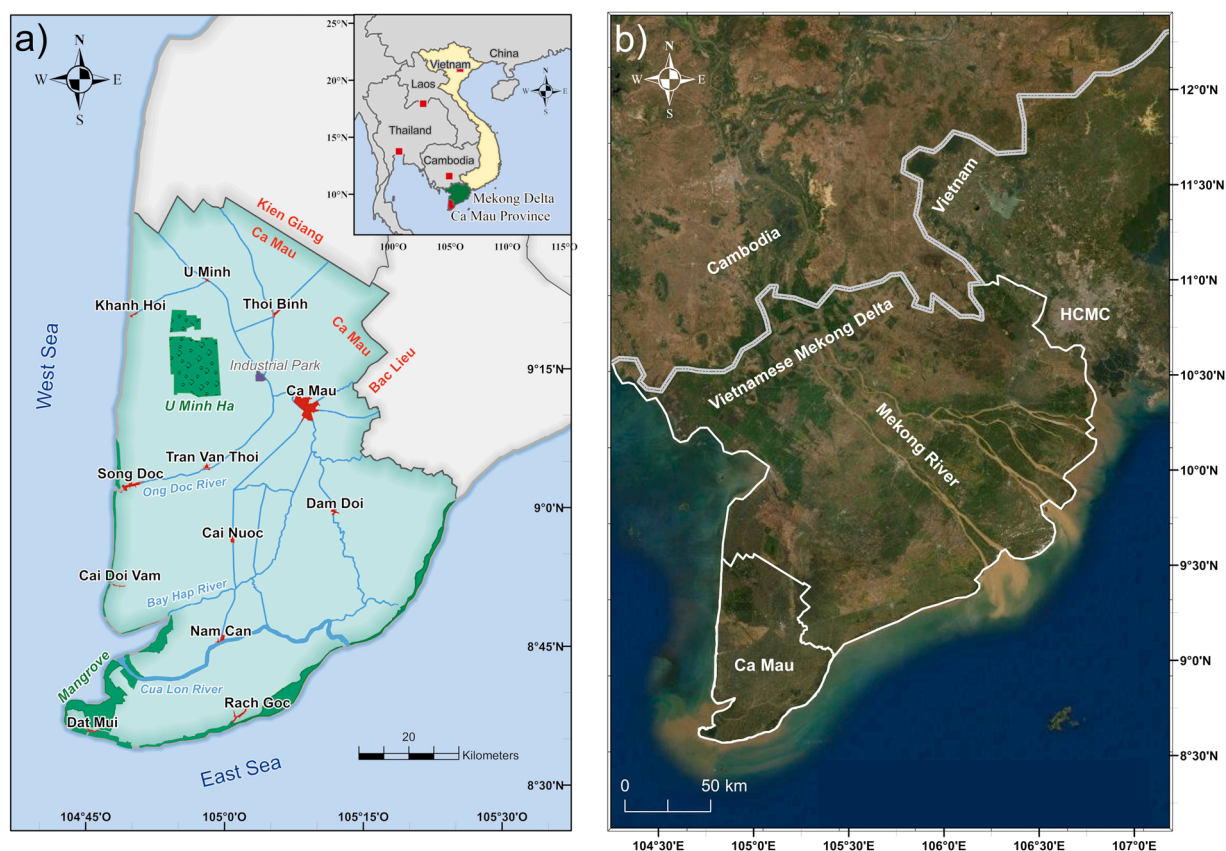


Fig. 1. (a) Schematic overview of CMP in Vietnam and (b) satellite overview of the Vietnamese Mekong Delta in South-East Asia. HCMC=Ho-Chi-Minh-City (Sources of satellite image: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community).

system and the main drivers leading to present groundwater geochemistry. Pham et al. (2019) showed in a regional fresh-saline groundwater distribution model over the whole MD that freshwater present in deep aquifers probably infiltrated during the marine regression phase during the last glacial maximum (LGM) 26–12 ka BP. However, in this previous approach, only total dissolved solids (TDS) and groundwater age were considered and no further insights on groundwater geochemistry were available. Detailed analysis, such as ion ratios and the assessment of water types provide the opportunity to describe the state of the aquifer and to distinguish between geochemical processes (Giménez-Forcada, 2010; Russak and Sivan, 2010; Amiri et al., 2016). Therefore, this study focuses on groundwater evolution and dynamics from a geochemical perspective. A comprehensive groundwater investigation was conducted in CMP, which was chosen as a representative study area for the southern MD to study salinity patterns in a spatial and temporal context. CMP is the southernmost province in Vietnam located on the Ca Mau Peninsula in the MD. It is surrounded by three sides to the sea and is therefore prone to seawater intrusion. It is important to identify the status of the aquifers and to delineate geochemical processes. For example, direct seawater intrusion would lead to accelerated salinization rates, while mixing of fresh and saline groundwater is much slower (Vengosh, 2013). Therefore, this study has direct implications for the whole MD region and contributes to a better understanding of the groundwater system and offers new insights to overcome groundwater related challenges in the region.

2. Materials and methods

2.1. Study area

2.1.1. Overview

CMP is the southernmost province in Vietnam and covers an area of 5221 km² (GSOV, 2019). It is part of the Ca Mau Peninsula in the MD, which includes neighboring provinces Kien Giang in the north and Bac Lieu in the northeast. Fig. 1 depicts the location of the study area in South-East-Asia and its main features. CMP is surrounded by the West Sea (Gulf of Thailand) to the west and by the East Sea to the south and east. While the delta has an extremely low average elevation level below 2.0 m above mean sea level (MSL), the average elevation level of CMP is estimated to be less than 1.0 m (Minderhoud et al., 2019; Zoccarato et al., 2018). In the tropical monsoon climate of the MD, the rain season in CMP lasts from May to November, which is followed by a pronounced dry season from December to April. CMP receives the highest precipitation in the MD due to the southwest monsoon, which can reach 2500 mm/year. The temperature ranges between 23 °C and 32 °C and relative humidity is constantly high at 76–86%. (Cosslett and Cosslett, 2014; GSOV, 2019).

The region inhabits around 1.2 million people, whereas around 300,000 live in the provincial capital Ca Mau City (CMC) (GSOV, 2019). A large proportion of the population lives in rural areas outside the smaller district capitals along the dense network of rivers and canals and are working in the agricultural sector. CMP has a special role in the agricultural sector of Vietnam, especially for shrimp farming (Cosslett and Cosslett, 2014; GSOV, 2019; Thong et al., 2010). Therefore, land use is dominated by brackish saltwater aquaculture and one-crop rice farming, sometimes alternating depending on the season and water availability, and rarely two-crop rice cultivation (Le et al., 2018; Nguyen et al., 2020).

2.1.2. Hydrogeology

In the late Neogene, comprising Miocene and Pliocene epochs, the former Mekong basin, a northwest-trending tectonic trough, started to subside due to the uplift of the Himalaya. High erosion rates resulted in a high sediment supply, which was deposited by fluvial transport and accumulated in the former Mekong basin (Nguyen et al., 2000). Within the Miocene to Holocene deposits

Table 1

Overview of aquifers in CMP. Depth and thickness of layers are derived from 27 borehole logs (Fig. 2) specifically for CMP. Average thickness calculated by interpolating down to the Miocene aquifer n_1^3 (chapter 2.2.4). Each aquifer is overlain by the corresponding aquitard (not included here). Ages after Cohen et al. (2013). The lower boundary from n_1^3 is estimated after Wagner et al. (2012).

Aquifer	qh	qp ₃	qp ₂₋₃	qp ₁	n ₂ ²	n ₂ ¹	n ₁ ³
Depth (m)	14-42	36-90	80-148	136-199	198-254	247-343	257- 364?
Thickness Ø (m)	14	23	41	35	52	32	-
Age	0 – 11.7 ka	11.7 ka – 2.58 Ma			2.58 – 5.33 Ma		5.33 – 23.0 Ma
Stage		upper	upper- middle	lower	middle	lower	upper
Epoch		Pleistocene			Pliocene		Miocene
Period	Quaternary				Neogene		

overlying the Mesozoic basement, a complex sequence of sedimentary layers of marine, alluvial and estuarial origin developed. Seven confined aquifers and aquitards were identified (Table 1), which differ in appearance and extend over the whole delta (Anderson, 1978; Nguyen et al., 2000; Wagner et al., 2012). The aquifer system in detail is described in Wagner et al. (2012). Briefly, aquifers consist of alluvial, marine-alluvial, and marine fine to coarse sands as well as gravel, aquitards of marine fine sands, silt and clay (Doan et al., 2018; Pechstein et al., 2018; Wagner et al., 2012). Saline and fresh groundwater is heterogeneously distributed across the aquifers (Anderson, 1978; Pham et al., 2019; Wagner et al., 2012). Intensive Quaternary marine transgression and regression phases had and have a significant influence on delta development worldwide as they define the depositional environment as well as intensive periods of erosion (Custodio and Bruggerman, 1987; Pham et al., 2019; Schimanski and Stattegger, 2005). During the last glacial maximum (LGM) 26–18 ka BP sea level was as low as – 130 m below present MSL, which correspond to around – 68 m below the paleo surface of the MD at that time, leading to erosion of sedimentary deposits of several tens of meters (Pham et al., 2019; Ta et al., 2002). Based on a fresh-saline groundwater model, Pham et al. (2019) assume, that freshwater primary infiltrated during this phase. While sedimentary top layers with a high permeability allowed extensive freshwater infiltration, rising sea levels after the LGM, which reached – 60 m at the end of the Pleistocene (12 ka BP) and 2–4 m above present MSL in the following Holocene (12–6.5–4.5 ka BP), promoted rapid sedimentation forming large-scale clayey mud facies sealing of underlying layers from saltwater intrusion (Pham et al., 2019). At that time, the entire MD up to the Cambodian border was inundated by the sea. Since then, while sea levels declined to present MSL, until recent sea level rise, deltaic sedimentation continued, and the MD propagated rapidly over 250 km southeastward of the Cambodian border to the East Sea (Nguyen et al., 2000; Ta et al., 2002). The dominant propagation characteristics changed from tidal to tidal-wave influenced, leading to a more southward-directed sediment transport and an open-bay system, which eventually created the Ca Mau Peninsula (Liu et al., 2017; Nguyen et al., 2010; Ta et al., 2002). It is estimated that the Ca Mau Peninsula was inundated until 2.0–1.0 ka BP (Liu et al., 2017).

Many households obtain their freshwater, mostly for daily needs and small businesses, from unlicensed private groundwater wells tapping the Pleistocene aquifers between 70 and 200 m. Over half a million extraction wells are estimated in the MD (Danh and Khai, 2015). Shallow groundwater is often brackish and potentially polluted (Anderson, 1978; Pechstein et al., 2018). Groundwater is furthermore utilized for commercial drinking water production, smaller businesses and aquaculture related industry. In the last few years, much effort was made to implement a tap water infrastructure, where groundwater from Pliocene wells deeper 170 m is subtracted, treated and further distributed. So far, however, tap water is only available in more urbanized areas.

Due to this development, hydraulic pressure heads in the main production aquifers qp₂₋₃, qp₁ and n₂² (Table 1) are now steadily declining, especially in populated areas like CMC, where hydraulic pressure heads dropped to – 25 m (Duy et al., 2021; Erban et al., 2014; Pechstein et al., 2018). Subsequently, a large drawdown cone around CMC developed (Erban et al., 2014), which disturbs the natural groundwater flow. A daily or seasonal fluctuation of groundwater levels is attributed to alternating extraction rates determined by water demand, rather than changes in natural recharge (Pechstein et al., 2018).

Natural groundwater recharge from outside the MD is highly limited, if there is any, as the low hydraulic gradient as well as artesian conditions before 1990 reduced groundwater velocity significantly, leading to high residence times in the order of several thousand or ten thousand years (Anderson, 1978; Benner et al., 2008; Pham et al., 1994). Therefore, groundwater might have even been stagnant before large-scale groundwater extraction began in recent decades or generally in case of pristine deeper aquifers. Since the early study of Anderson (1978), the lack of reliable well data to deduce the recharge area and hydraulic conditions remains. Only twelve observation wells exist in the Ca Mau Peninsula, whereas seven were constructed after 2017. Anderson (1978) postulated that groundwater might originate in Cambodia where surface water and shallow groundwater is fresh. Based on ¹⁴C and Deuterium/¹⁸O analysis, Ho et al. (1991) determined the recharge area in the northeast extension of the delta and formation outcrops in Cambodia at higher altitudes. Furthermore, the flow directions were determined by ¹⁴C isochrones. They consist of a northwest to southeast and a northeast to southwest component with transit times of 5.6 m/a for Pleistocene and around 2.5 m/a for Pliocene aquifers (Ho et al., 1991). Hydraulic conductivities in the aquifers are in the range of $1.0 \cdot 10^{-3}$ m/s and $3.0 \cdot 10^{-5}$ m/s and porosity is around 33% (Pechstein et al., 2018; Shrestha et al., 2016). Due to an impermeable Quaternary top layer a direct connection or recharge by surface water or precipitation in the study area is currently expected to be negligible (Anderson, 1978; Pham et al., 2019). Previously, it was assumed that the aquifers in the MD were not directly hydraulically connected, but Pham et al. (2019) assume that aquitards are heterogeneous and disconnected. This assumption is supported by the observation of similar geochemical and isotopic patterns as well as hydraulic pressure heads throughout the aquifers at some locations in the MD (Doan et al., 2018; Hanh and Roland, 2017; Pechstein et al., 2018). In addition, the moderate hydraulic conductivities of the aquitards do not necessarily preclude the interconnection of aquifers, especially since some aquitards comprise of considerable amounts of fine sand (Pechstein et al., 2018; Wagner et al., 2012). Furthermore, clear identification of aquifer and aquitard delineations in the area is difficult and not always possible. Drill logs conducted in the whole MD reveal that discontinuous clay lenses are heterogeneously embedded within aquifers (Erban et al., 2013). Age determination using ¹⁴C stable isotope techniques revealed, that the deep groundwater around U Minh (see Fig. 1) is older than 25 ka (Pechstein et al., 2018) and between 15 ka and > 40 ka in other parts of the delta, tending to increase from Pleistocene to Miocene (Doan et al., 2018; Ho et al., 1991; Hoang and Bäuml, 2019; Nguyen et al., 2004). Other studies showed inconclusive results with an apparent ¹⁴C age ranging from recent to older than 40 ka BP. However, data validity is sometimes not given because sampling- and measurement techniques are not available or insufficiently documented (Pechstein et al., 2018). Groundwater in the aquifer qp₂₋₃ and deeper is assumed to be at least semi-fossil (Pechstein et al., 2018). The present geochemical composition of groundwater is considered to be influenced by factors such as Tertiary geomorphology, Quaternary transgression and regression phases during the past 60 ka BP, and water-rock interactions, rather than by recent recharge or seawater intrusion (Doan et al., 2018; Pham et al., 1994, 2019). A baseline study was conducted in 2017 summarizing some hydrological information specifically for CMP but also pointing out that much more research is required in the region (Jenn et al., 2017).

2.2. Geochemical investigation

2.2.1. Sample locations and salinity analysis

The distribution of fresh ($\text{TDS} < 1 \text{ g/l}$) and saline groundwater (Rusydi, 2018) in the MD is highly heterogeneous and seems not to be correlated to depth or distance to the coast (Anderson, 1978; Pham et al., 2019). Saline groundwater prevails in the upper Holocene and late Pleistocene aquifer while fresh groundwater is unevenly distributed in Middle and Early Pleistocene, Pliocene, and Miocene aquifers (Wagner et al., 2012). In order to determine the salinity levels and distribution in CMP, a total of 190 groundwater samples were taken in five field campaigns between February 2017 and December 2019. As recent groundwater recharge in deep aquifers is negligible due to several less permeable aquitards and the low hydraulic gradient (Anderson, 1978; Pham et al., 2019) it was estimated that the time or season of sampling does not influence groundwater properties. The focus was on private household wells, but also samples from school wells, drinking water production companies, administrative buildings and smaller businesses were taken. Sample locations were randomly selected with the intention to cover the whole province. In addition, to cover the main production aquifers in CMP, wells of varying depth between 60 m and 310 m were chosen to represent the Middle Pleistocene qp₂₋₃, Lower Pleistocene qp₁, Middle Pliocene n₂² and Lower Pliocene n₂¹ aquifer (see Table 1). Since all wells are constructed in a closed system including a tap and a pump, construction details like well depth, diameter and year of construction rely on information given by the owner. Almost all private household wells are made of PVC with a diameter of 49 mm and are screened a few meters in the target aquifer.

Prior to sampling, standing water in the pipe was exchanged and the equipment was cleaned thoroughly with fresh groundwater at each location. Physiochemical parameters including temperature, pH and electrical conductivity (EC) were determined on site using a multi-parameter portable meter (WTW Multi 3630 IDS).

2.2.2. Groundwater composition

Groundwater in coastal aquifers is often the result of mixing between seawater, both recent and paleo, and freshwater (Giménez-Forcada, 2010; Jones et al., 1999). The deviation from the conservative mixing line between the two endmembers seawater and freshwater due to cation exchange reactions between groundwater and aquifer sediments is one of the most remarkable phenomena in coastal groundwater geochemistry (Jones et al., 1999; Russak and Sivan, 2010). In order to gain deeper insights on the geochemical composition and to derive these processes, a comprehensive analysis for cations and anions was conducted for each sample. For both analysis, 25 ml of sample groundwater was separately filtered through a 0.45 μm cellulose-acetate filter (Satorius Stedim Biotech GmbH). 50 μL of high-purity nitric acid was added to prevent cation precipitation (APHA, 2017) and microbiological processes were inhibited for accurate anion analysis by adding 50 μL sodium azide (Vanderford et al., 2011). The groundwater samples were transported to Germany and analyzed with ICP-MS (Thermo Fisher X-Series 2) for cations and Ion Chromatography (Dionex ICS-1000 with column IonPac As14 Suppressor ERS 500 and Methrom Compact IC 930 with column Metrosep A Supp 5–150. Eluent: $\text{NaHCO}_3/\text{Na}(\text{CO}_3)_2$) for anions in the laboratory of the Institute of Applied Geosciences at the Karlsruhe Institute of Technology, Germany.

Additionally, total alkalinity was determined by measuring the acid capacity to pH 8.2 and pH 4.3 with a titration test kit (Merck KGaA). Concentration of HCO_3^- and CO_3^{2-} were directly derived from the alkalinity results. However, especially in redox-sensitive marine and coastal settings, the difference between total alkalinity and carbonate alkalinity may not be neglected due to the impact of other buffering bases such as $\text{B}(\text{OH})_4^-$, NH_3 , $\text{Si}(\text{OH})_3\text{O}^-$, or F^- (Lukawska-Matuszewska, 2016).

The conversion factor for EC to TDS is highly depended on ionic water composition and may differ from the instrument value, which is typically calibrated by KCl solution (Vengosh, 2013). Therefore, TDS was calculated for each sample using the software Geochemist's Workbench (v. 12.0, Aqueous Solutions LLC) with the whole elemental composition as input data. Furthermore, the direct relationship between all parameters was calculated using pairwise Spearman correlation.

The calcium carbonate system in coastal groundwater settings is complex, and many processes actually lead to carbonate dissolution with subsequent increase in HCO_3^- and Ca^{2+} (Custodio and Bruggerman, 1987). In saline aquifers, mixing of calcium carbonate saturated fresh groundwater with seawater, which is typically oversaturated, produces brackish water which is undersaturated with regard to calcium carbonate due to the reduction in ionic strength, leading to calcite dissolution (Custodio and Bruggerman, 1987). The saturation indices for calcite ($\text{SI}_{\text{calcite}}$) were calculated using Geochemist's Workbench (v. 12.0, Aqueous Solutions LLC). Furthermore, SI of additional evaporites including aragonite, dolomite, gypsum, sylvite and halite were calculated.

The proportion of major cations $\text{Na}^+ + \text{K}^+$, Ca^{2+} and Mg^{2+} and anions HCO_3^- , Cl^- and SO_4^{2-} were calculated and displayed in a Piper Diagram (Piper, 1944). The water type can be derived from the upper diamond shape (Back and Hanshaw, 1965). Water type analysis can help to distinguish geochemical processes and to derive the origin of solutes. However, divisions and percentages used for classification should be selected as to best fit the characteristics of the investigated water (Freeze and Cherry, 1979). Therefore, to achieve a more detailed water type specification and to get more insights on mixed water types, the typical description was customized in order to more accurately display different states of salinization with an emphasis on cation-exchange processes. Proportions of major ions were calculated and if only one cation or anion was above 33.3%, it is written alone, like Na-Cl water type, while if two ions were above 33.3%, the ion with the higher proportion was written first, followed by the second ion in brackets, for example Na-Cl-(HCO_3). A mixed water type is thus only defined if all three anions or cations have an equal share of around 33.3%, e.g. Na-Ca-Mg-Cl is written as Mix-Cl.

2.2.3. Salinization and freshening

The evaluation of molar ion ratios is an appropriate tool to distinguish between seawater and freshwater intrusion in coastal aquifers (Appelo, 1994; Jones et al., 1999; Russak et al., 2016). Therefore, Na^+/Cl^- , $\text{Ca}^{2+}/\text{Cl}^-$ and $\text{Mg}^{2+}/\text{Cl}^-$ molar ratios were calculated and compared to the conservative mixing line. Generally, salinization of a freshwater aquifer by seawater intrusion proceeds

in the following steps (Appelo and Postma, 2004; Custodio and Bruggeman, 1987; Jones et al., 1999; Vengosh, 2013): In the early stages of salinization, fresh Ca^{2+} -dominated groundwater is enriched in Na^+ and Mg^{2+} . In general, divalent cations are exchanged on the mineral surface preferentially to monovalent cations (Carroll, 1959; Steudel and Emmerich, 2013). However, at a certain intensity of salinization ion selectivity is masked by the proportional increase in sorption with increasing concentration, especially of the monovalent ion Na^+ (Sawhney, 1972). In conclusion, during further salinization Na^+ exchanges divalent cations Ca^{2+} and Mg^{2+} from sedimentary rocks forming Ca-Cl and Na-Mg-Cl waters. Simultaneously, overall salinity increases, while also the proportion of divalent cations increases.

Conversely, freshwater inflow into saline coastal aquifers, also referred to as freshening, reverses the cation-exchange reaction contrary to the salinization process (Appelo, 1994). When freshwater of Ca-HCO_3 type intrudes the saline aquifer exchangeable Na^+ on mineral surfaces, especially clay minerals, is substituted by Ca^{2+} and Mg^{2+} , due to a higher sorption selectivity, and the water type changes to the characteristic Na- HCO_3 . The Na^+/Cl^- ratio increases above the level of seawater, while Ca^{2+} as well as Mg^{2+} become depleted (Appelo and Postma, 2004; Custodio and Bruggeman, 1987; Jones et al., 1999).

In the natural environment, Cl^- often acts as a conservative tracer and ion ratios are commonly calculated relative to Cl^- (Jones et al., 1999). Sea water has a Na^+/Cl^- molar ratio of around 0.86. Due to the above-mentioned cation exchange reactions, Na^+/Cl^- decreases below the conservative mixing line during salinization and increases during freshening.

2.2.4. Hydrogeological model

To fully evaluate the fresh-saline groundwater patterns in the context of stratigraphy and depth, samples were assigned to their respective aquifer based on available lithological information. As owners of private wells do not know their target aquifer and because no sufficient subsurface model was available for the region, a simplified hydrogeological model was constructed using lithological data from 27 borehole logs in CMP (Vuong, 2014), provided by the National Center for Water Resources Planning and Investigation Vietnam (NAWAPI), whereas six of them are part of the national monitoring network. The locations of the boreholes are shown in Fig. 2. The model serves two purposes: (i) assignment of samples to an aquifer and hence (ii) visualization of samples in depth to delineate aquifer dependent groundwater properties. A layer-based approach was chosen, where surfaces were created separately and

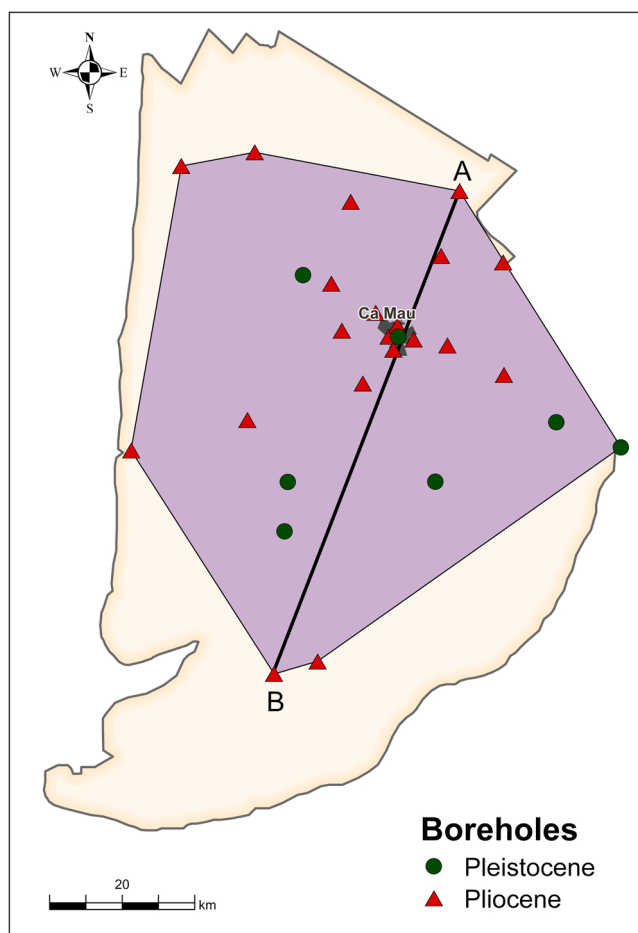


Fig. 2. Location of 27 boreholes (Vuong, 2014) and extent of the interpolation area (purple) used for the calculation of the hydrogeological model.

then stacked (Turner, 2006). This approach is common in sedimentary environments and is widely used for groundwater mapping (Natali et al., 2012). Subsurface modelling was conducted using MATLAB 2020b (MathWorks Inc.). Top and bottom boundaries from 14 layers recorded in 27 boreholes were used as 3-D scattered input data.

While almost all boreholes reach aquifer qp₁, except one, the number of boreholes reaching deeper layers are gradually decreasing with only seven reaching aquifer n₂¹ and only one the aquitard beneath. As this is a typical phenomenon in lithological data acquisition (Turner, 2006), all boreholes were vertically interpolated down to the Miocene aquifer n₁³ based on mean layer thickness from the available data. No information from outside the study area was used because depth and thickness of stratigraphic units significantly vary throughout the delta (Nguyen et al., 2000) and might have therefore distorted the calculation. For the model, a 2-D grid was created with a 100 m resolution in latitude and longitude direction using the *meshgrid* command, and for each layer a 3-D data interpolation was done using triangulation-based natural neighbor method with *griddata*, which was then visualized using the *mesh* command. It should be noted that the quality of the provided borehole logs could not be further evaluated here and thus no extensive model validation was conducted. Based on the straightforward model approach, the model does not consider discontinuous clay lenses within aquifers (Erban et al., 2013) and other potential small-scale characteristics, such as paleo channels as well as areas of non-deposition and areas of erosion (Turner, 2006).

Groundwater samples were plotted in this subsurface model to enable a sample to aquifer assignment. In order to account for a thin aquitard between aquifer qp₂₋₃ and qp₁ and to account for possible aforementioned uncertainties in the interpolation, it was only distinguished between Pleistocene and Pliocene samples. Samples outside of the convex hull were correlated with the nearest borehole and assigned to the respective aquifer. In addition, a 71.5 km long geological cross section was drawn through the model area. Samples, larger cities and monitoring wells within a 10 km perpendicular distance to the profile were included. Location of monitoring wells and the course of the cross section are displayed in Fig. 2. Most monitoring wells accumulate around CMC. Extrapolation outside the convex hull of the available borehole data was avoided intentionally to assure a more valid model within the verifiable boundaries. Therefore, the cross-section was not extrapolated to the sea.

3. Results

3.1. Water geochemistry

Major geochemical water parameters are listed in Table 2. EC values range between 571 $\mu\text{S}/\text{cm}$ and 5180 $\mu\text{S}/\text{cm}$. 21 samples have EC between 2500 and 3850 $\mu\text{S}/\text{cm}$ while two samples in the northwest have EC around 5000 $\mu\text{S}/\text{cm}$ (Fig. 5c). A mean conversion factor for EC to TDS of 0.81 was calculated. Note that this factor deviates from 0.67, which is commonly used by NAWAPI. As this conversion factor is highly depended on ionic water composition the conversion factor presented here is more accurate for the study area and should be considered for future water use guidelines.

Na⁺ is the dominant cation in the majority of samples in CMP. The Piper Diagram in Fig. 4 shows that Na-Cl, Na-HCO₃ and mixed water types occur in Pleistocene and Pliocene aquifers. Pliocene samples are depleted in Ca²⁺ + Mg²⁺ and contain over 70% Na⁺, while some Pleistocene samples contain more divalent cations, especially those with high EC and a higher proportion of Cl⁻. Sulfate only plays a minor role in the water composition, is mostly below 10% and never exceeds 25%. The spatial distribution of the detailed water type (see chapter 2.2.2) is presented in Fig. 3. In this classification the dominant water type is Na-HCO₃ and Na-HCO₃-(Cl). Only eleven samples are solely dominated by Cl⁻. It is striking that these samples of Na-Cl type, shown in red, are randomly distributed in CMP. Two samples in the north of CMP are of Ca-HCO₃ and Ca-(Na)-HCO₃ type, colored in blue.

The spatial distribution of EC in CMP (Fig. 5c) shows that EC is generally lower in the northeast and east. In the west and south, EC is mostly between 1000 $\mu\text{S}/\text{cm}$ and 2000 $\mu\text{S}/\text{cm}$ with some scattered hotspots of high EC above 2500 $\mu\text{S}/\text{cm}$. The concentration of HCO₃⁻ shows a rather sharp spatial pattern and is more than tripling from north to south from around 250 mg/L to 950 mg/L (Fig. 5a). By contrast, the concentration of Cl⁻ is more evenly distributed ranging mostly between 25.0 and 250 mg/L (n = 121) and 250–750 mg/L (n = 40). Only seven samples exceed 750 mg/L and 22 samples contain less than 25 mg/L Cl⁻, mainly accumulating northeast of CMC (Fig. 5b). Ca²⁺ and Mg²⁺ show a high correlation (p = 0.94) (Table A1 in appendix A) and high concentrations are linked to samples with highest Cl⁻ contents (Fig. A2 and A3 in appendix A). Furthermore, except a few samples, SO₄²⁻ concentrations are relatively low (Table 2) and are more evenly distributed (Fig. A4 in appendix A). Temperature ranges between 25.7 °C and 37.2 °C and generally increases with depth, following a normal geothermal gradient (Morgan, 1984). No significant correlation between depth

Table 2
Physio-chemical results of 190 groundwater samples from CMP (ion concentration in mg/L).

Parameter	Min	Max	Mean
EC ($\mu\text{S}/\text{cm}$)	571	5180	1560
pH	6.72	8.58	7.93
Na ⁺	55.1	745	273
Mg ²⁺	7.23	161	29.7
K ⁺	4.39	26.5	11.7
Ca ²⁺	6.82	168	31.1
Cl ⁻	1.35	1530	219
SO ₄ ²⁻	< 0.07	445	47.5
HCO ₃ ⁻	262	952	600

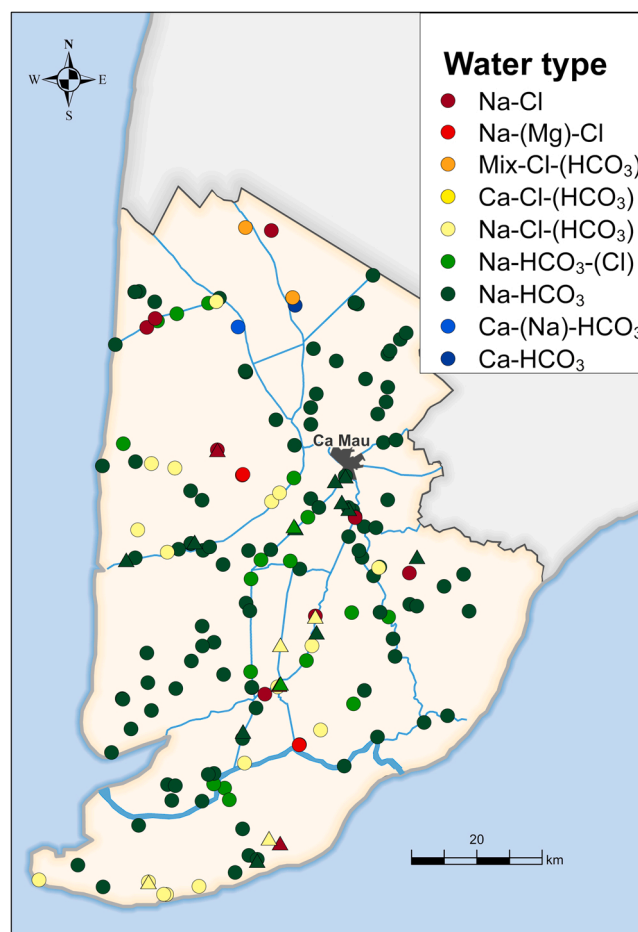


Fig. 3. Water type distribution in CMP. ● Pleistocene ▲ Pliocene.

and major ions was found (Table A1 in the appendix). 158 samples are oversaturated to calcite, mainly in the central and southern part of CMP (Fig. A5 in appendix A), with a maximum of 1.34, while only five samples are undersaturated to calcite with a minimum of -0.49 . Besides, 27 samples are in equilibrium with calcite ($-0.2 < SI < 0.2$). Like calcite, Aragonite is mostly oversaturated. While all samples are oversaturated in regard to dolomite, all samples are highly undersaturated in regard to gypsum, sylvite and halite. The results for all samples, including ion concentrations and SI, are provided in appendix B.

3.2. Hydrogeological model

The 71.5 km long hydrogeological cross section shown in Fig. 6 includes samples within a 10 km distance to the profile, which are colored according to their EC levels (compare Fig. 5c). Aquifers are labeled according to Table 1 and are illustrated in blue colors. Based on the 27 available borehole logs in the project region, the model approach and interpolation method could adequately construct the 14 distinct layers that overly each other smoothly without significant irregularities. Therefore, layered sequences seem to be dominant in the study area.

While Holocene layers are flat, deeper layers appear to dip down southwestward. 167 samples were assigned to the Pleistocene aquifers qp₂₋₃ and qp₁ and 22 samples to Pliocene aquifers n₂² and n₂¹. One sample might originate from the Miocene aquifer n₁³ from a depth of 310 m, but is added to the Pliocene samples for further interpretation for simplification. The profile illustrates that EC is generally below 1000 $\mu\text{S}/\text{cm}$ north of CMC and increases southwestward to 1000–2000 $\mu\text{S}/\text{cm}$. Along the cross section, groundwater samples with EC > 2000 $\mu\text{S}/\text{cm}$ are found solely and randomly distributed southwest of CMC, primarily in qp₂₋₃ but also in deeper aquifers towards Nam Can.

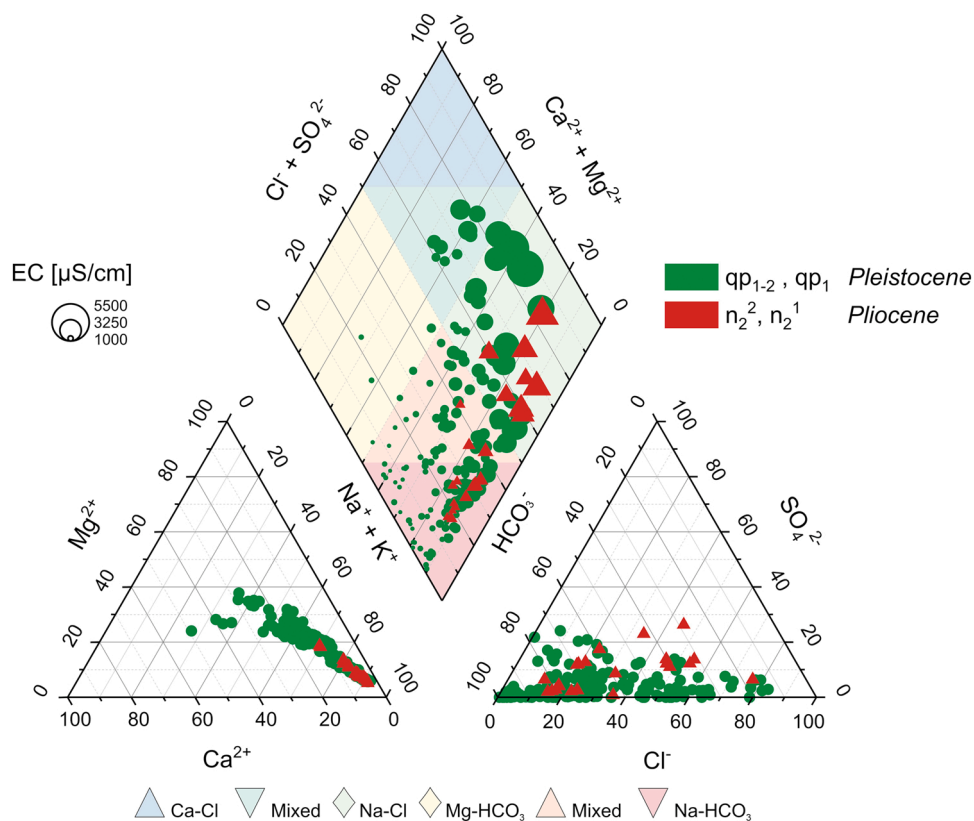
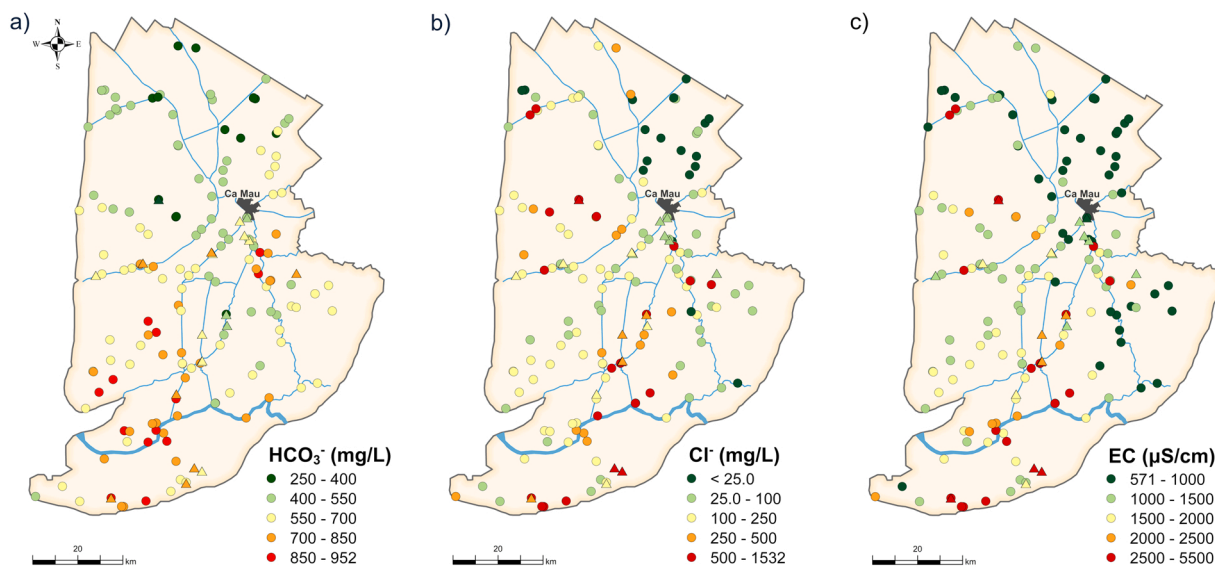


Fig. 4. Piper diagram. ● Pleistocene ▲ Pliocene.

Fig. 5. Spatial distribution map of (a) HCO_3^- , (b) Cl^- and (c) EC. ● Pleistocene ▲ Pliocene.

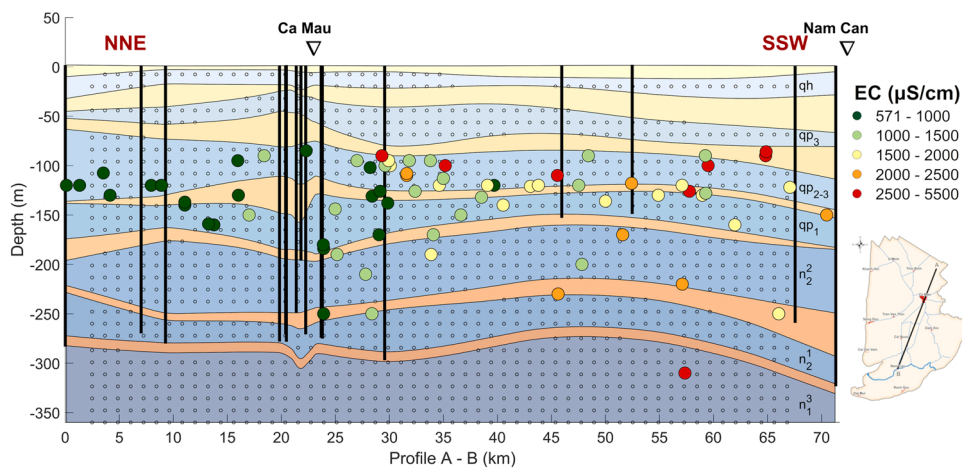


Fig. 6. Visualization of groundwater samples EC plotted in the hydrogeological north-northwest to south-southwest cross section trough CMP. Aquifer (blue colors, dotted) and aquitard (orange colors) delineations based on 27 well logs (black vertical lines) (see chapter 2.2.4). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

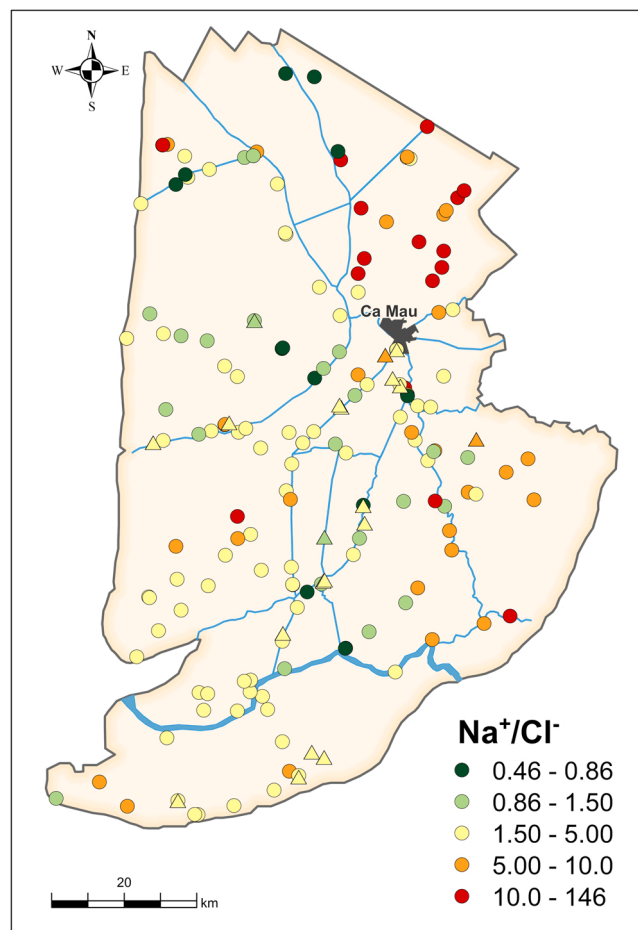


Fig. 7. Spatial distribution of Na^+/Cl^- molar ratio of ● Pleistocene ▲ Pliocene samples in CMP.

4. Discussion

4.1. Groundwater composition

The shift of the fresh-saline water boundary further inland is a major concern for water management in CMP, as an increase of salinity would significantly degrade groundwater resources and limit their use. 40 out of 190 samples exceed the Vietnamese limit for total dissolved solids (TDS) of 1500 mg/L (MONRE, 2015), which is equivalent to an EC value of 1850 $\mu\text{S}/\text{cm}$ (see chapter 3.1). 47 samples exceed the threshold for Cl^- of 250 mg/L. Thus, some groundwater is already unsuitable for direct drinking purpose. Data collected in this study, however, also show that locations with elevated EC are randomly distributed across CMP and are most often represented by more than one sample at each location from both Pleistocene and Pliocene aquifers. This leads to the conclusion that locations of elevated EC are not a single well phenomenon but a local spatial pattern. This is also true for other ions and ion ratios, as shown in Figs. 5 and 7. This indicates that aquifers are to some extent connected, at least partly, either through natural discontinuities in the stratigraphy, as also recently proposed by other authors (Doan et al., 2018; Pechstein et al., 2018; Pham et al., 2019), or hydrological short circuits caused by well leakage or well failure (Doan et al., 2018), which are rarely considered. In a regional perspective, no significant correlation between geochemical patterns and depth or aquifer was found, as shown by the correlation analysis (Table A1 in appendix A) and by the geological cross section (Fig. 6). In addition, locations with higher EC are not correlated to the distance to the coast.

As a simple and straightforward measure of salinity, EC is a useful parameter to characterize and classify groundwater resources in coastal regions potentially affected by seawater intrusion, especially when detailed analysis is not available. Seawater of Na-Cl type is largely uniform with a TDS of around 35 g/L, while freshwater is often defined with a TDS concentration below 1 g/L (Vengosh, 2013), meaning that even slight seawater intrusion is detectable. However, groundwater composition is often more complex and other parameters than Na^+ and Cl^- are affecting EC as well (Jones et al., 1999). This also applies to data presented in this study. As shown in Fig. 5a-c, elevated levels of EC in the southern part of the study region cannot solely be attributed to Cl^- associated with seawater but rather to the presence of high HCO_3^- concentrations. In fact, around Nam Can groundwater with $\text{EC} > 2000 \mu\text{S}/\text{cm}$ is of Na- HCO_3 and Na- HCO_3 -Cl type (Fig. 3) and HCO_3^- concentrations are lowest inland in the northeastern area, where recent freshwater inflow is estimated to occur, even though it might be limited (Fig. 5a). This indicates that the source of HCO_3^- is not freshwater intrusion. Almost all samples are oversaturated to calcite ($n = 158$), especially in the south and central south between CMC and Nam Can (Fig. A5 in appendix A), which should lead to calcite precipitation. Only a few samples in the northern part of the study area are slightly undersaturated to calcite ($n = 5$) or in equilibrium ($n = 27$). One reason for the oversaturation of calcite might be the addition of Ca^{2+} due to cation exchange processes or the dissolution of gypsum (Plummer et al., 1990), which has a SI between -1.56 and -6.21 . This contradicts typical hydrochemical facies evolution in coastal areas, where $\text{SI}_{\text{calcite}}$ tends to decrease towards the sea (Custodio and Bruggerman, 1987). Ca^{2+} and HCO_3^- have a negative correlation and while HCO_3^- concentrations increase, Ca^{2+} concentrations are relatively low, probably because Ca^{2+} is involved in complex ion exchange processes (Jones et al., 1999). It is therefore concluded that observed high concentrations of HCO_3^- in the south of the study area cannot be explained by simple mixing and calcite dissolution. Another possible source of HCO_3^- in coastal aquifers is dissolved organic carbon derived from organic matter, which is oxidized to dissolved inorganic carbon. It was shown in other studies that the concentration of HCO_3^- originating from organic matter oxidation can surpass the concentration in fresh groundwater at recharge areas multiple times (Chapelle and McMahon, 1991; Orem and Gaudette, 1984). In addition, organic matter reduction also shifts the calcium carbonate equilibria due to an increase in P_{CO_2} as well as changes in pH, and causes dissolution (Custodio and Bruggerman, 1987; Jones et al., 1999). Due to their marine and estuarine origin, high amounts of organic matter are consistently found across all stratigraphic layers in CMP (Doan et al., 2018; Nguyen et al., 2010; Pechstein et al., 2018) and could therefore account for high HCO_3^- concentrations. Furthermore, sulfate reduction directly produces HCO_3^- and leads to sulfate depletion, which is typical for freshening aquifers rich in organic matter and might therefore also apply to

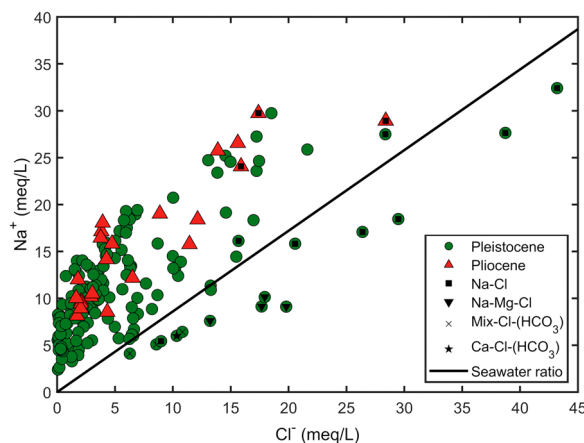


Fig. 8. Na^+/Cl^- plot of groundwater samples including water type markers associated with salinization of freshwater aquifers.

CMP where as a consequence sulfate concentrations are rather low (Kim et al., 2017; Chapelle and McMahon, 1991). Overall, this is an important finding, demonstrating that the increase of EC values in coastal areas are not necessarily an evidence of recent seawater intrusion, but can also be attributed to the generation of additional HCO_3^- .

4.2. Salinization and freshening processes

Coastal aquifers are influenced by marine transgression and regression cycles leading to seawater or freshwater intrusion, respectively (Custodio and Bruggeman, 1987; Han et al., 2020). Fig. 8 reveals that the Na^+/Cl^- molar ratio of most samples in the study area is well above the seawater ratio of 0.86. Only a few samples show ratios lower than seawater. It is remarkable that the water type of those samples below the seawater ratio line is changing with increasing Cl^- concentration from Mix-Cl-(HCO_3) and Ca-Cl-(HCO_3) over Na-Mg-Cl and finally to Na-Cl, while almost all samples above the seawater ratio are of Na- HCO_3 and Na- HCO_3 -(Cl) type. This observation in surveyed data convincingly demonstrates the impact of cation exchange processes during salinization and freshening. The customized water type is well suitable to reflect different stages and the geochemical processes associated with salinization. It can be observed that Na-Mg-Cl seem to occur at higher Cl^- concentrations compared to Ca-Cl-(HCO_3) (see Fig. 8), probably because seawater contains more Mg^{2+} over Ca^{2+} with a $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratio of 4.5–5.2 (Vengosh, 2013). The $\text{Mg}^{2+}/\text{Cl}^-$ ratio is shown in Fig. 9 and highest ratios correlate with those of lowest Na^+/Cl^- ratios and salinization water types, again demonstrating the cation-exchange processes. The same pattern can be observed for $\text{Ca}^{2+}/\text{Cl}^-$ (Fig. 10) but with a wider spread and deviation from the mixing line, as Ca^{2+} concentrations are more influenced by other factors such as calcite precipitation and dissolution, which in turn depend on HCO_3^- concentrations.

In conclusion, freshwater intrusion is, or was, the predominant process leading to the abundant Na- HCO_3 and Na- HCO_3 -(Cl) type groundwater in CMP. The rarely occurring groundwater of Na-Cl type above the seawater line might be in a less advanced stage of freshening, where Cl^- is still the dominant anion. Further freshening produces waters of Na- HCO_3 type and Cl^- below 25 mg/L, as found in the northeast of the study area. Due to the general hydrogeological conditions, it can also be assumed that the freshening process has progressed furthest in this region. This assumption is supported by Na^+/Cl^- molar ratios greater than 10.0 in the north-east and Na^+/Cl^- between 5.00 and 10.0 in the central east (Fig. 7).

It can be expected that both processes, cation exchange reactions and the release of organic carbon by organic matter decomposition, contribute to observed Na- HCO_3 groundwater in CMP. Detailed water type analysis in combination with the evaluation of Na^+/Cl^- molar ratios and the consideration of cation exchange processes proved to be an appropriate tool to identify signs of salinization, even in early stages at low Cl^- concentrations. Focusing on total salinity via EC analysis alone, however, is not a suitable method. For example, three samples in the central north (Fig. 5c) have EC values below 1000 $\mu\text{S}/\text{cm}$ (Fig. 5c). However, based on their Na^+/Cl^- ratio, which is below the seawater line (Fig. 7), and their water type (Fig. 3), particular these samples seem to be in an early stage of salinization.

4.3. Groundwater evolution and development

Marine transgression and regression phases in the Quaternary (Fig. A1 in appendix A) caused numerous cycles of alternating saltwater and freshwater intrusions in the MD and coastal regions worldwide (Delsman et al., 2014; Pham et al., 2019; Spratt and Lisiecki, 2016; van Engelen et al., 2021). In this period, phases of sedimentation during marine transgression were alternating with phases of extensive erosion during marine regression. Derived and edited after Pham et al. (2019), Fig. 11a-c illustrate three characteristic stages of past hydrogeological situations in the lower MD. The formation of Na- HCO_3 type groundwater dominant in CMP at moderate EC levels with high Na^+/Cl^- ratios supports the assumption of Pham et al. (2019) that extensive freshwater intrusion occurred in the aquifer system of the MD. Previously, this assumption was only covered by the distribution of TDS. It furthermore

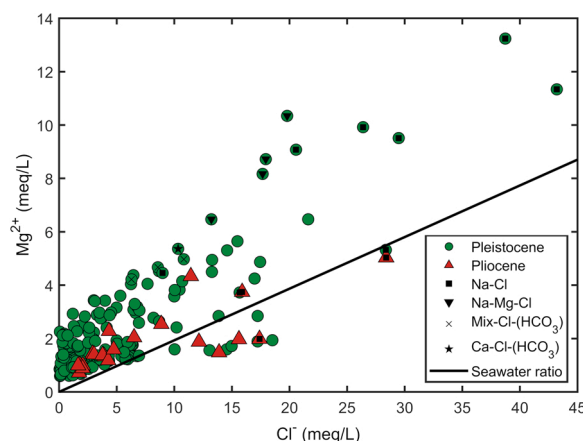


Fig. 9. $\text{Mg}^{2+}/\text{Cl}^-$ plot of groundwater samples including water type markers associated with salinization of freshwater aquifers.

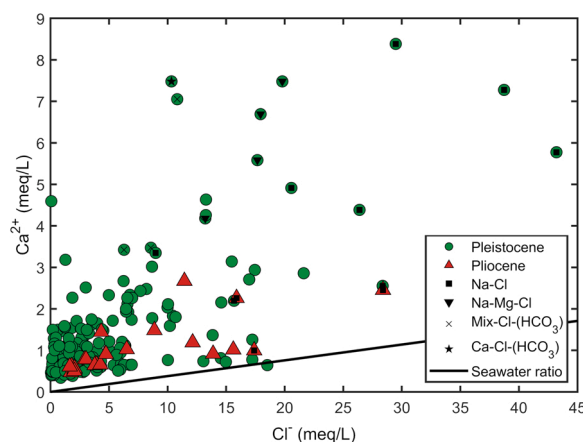


Fig. 10. $\text{Ca}^{2+}/\text{Cl}^-$ plot of groundwater samples including water type markers associated with salinization of freshwater aquifers.

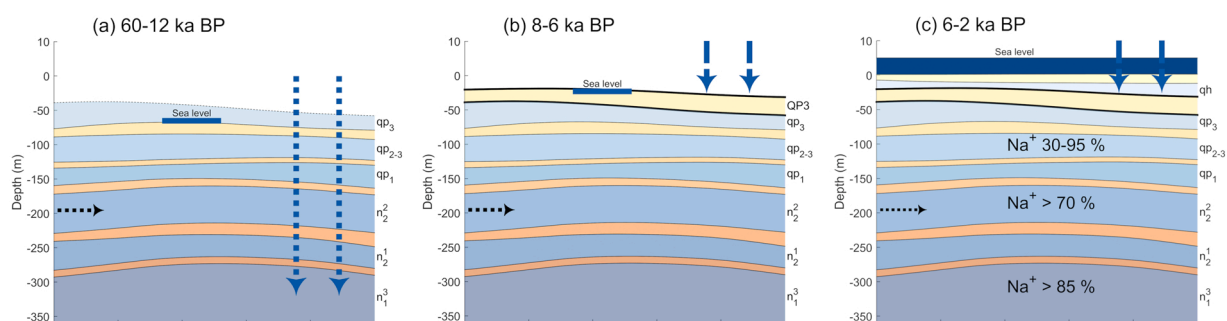


Fig. 11. Scheme of the past hydrogeological situations in CMP edited after Pham et al. (2019). Black horizontal dotted arrows indicate lateral aquifer recharge from outside the study area (exemplary displayed for aquifer n_2^2). The blue vertical arrows indicate depth of vertical direct freshwater recharge. Sea levels were correlated with the paleo surface using sediment dating techniques (summarized in Pham et al., 2019). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

proofs that the system was saline before freshwater intrusion occurred through permeable top layers. These findings are evident in both shallow and deep aquifers concurrently. The freshening event presumably happened in the last marine regression phase 60–12 ka BP, especially during the LGM when sea levels were extremely low (Fig. 11a), which would explain groundwater ages in that range (Pham et al., 2019).

The formation of large-scale impermeable Holocene aquitards, particularly QP3, between 8 and 6 ka BP prevented extensive seawater intrusion, which otherwise would have been expected due to rapidly rising sea levels in the Holocene transgression phase (Fig. 11b) and would have also led to the respective salinization signatures, namely $\text{Na}^+/\text{Cl}^- < 0.86$ and associated water types. The phenomenon of Pleistocene freshwater conservation can also be observed in other coastal areas worldwide (Cohen et al., 2010; Delsman et al., 2014; Han et al., 2020; Post and Kooi, 2003; van Engelen et al., 2021). However, such salinization signatures are present at a few locations. Due to the high groundwater exploitation rates as well as the high hydraulic connectivity within and apparently across the aquifers it is rather unlikely that these samples reflect remnants of older saline groundwater unaffected by the latest freshening event. Furthermore, these samples plot below the conservative mixing line at low to moderate EC levels, which indicates that they developed from freshwater and are in an early stage of salinization (Fig. 8) rather than in a less advanced stage of freshening, as it is the case for same samples of Na-Cl type above the mixing line. Therefore, it is more likely that former freshwater mixed with saline water more recently. However, the origin of this recent salinization is not further examined in this study, but it should be noted that the MD was completely inundated at around 5.5 ka BP and CMP until estimated 2 ka BP (Fig. 11c) (Nguyen et al., 2000; Pham et al., 2019). The current stratification with high-density Holocene saline aquifers on top of low-density deep freshwater aquifers reflects an unstable aquifer situation, which might lead to a downward migration of the younger saline groundwater along natural and anthropogenic pathways (Custodio and Bruggerman, 1987; Post and Kooi, 2003). It must be noted that the subsurface in the study region is virtually perforated with abandoned as well as active wells of different construction quality and reliability.

The Piper diagram (Fig. 4) shows that in average the proportion of Na^+ is notably higher in Pliocene than in Pleistocene samples, which is illustrated in Fig. 11c. This finding might indicate the heterogeneous downwards migration of saline water from top to bottom, which leads to the release of divalent cations in Pleistocene aquifers, which therefore show a wide range of Na^+ (%). In addition, differences in geomorphology and discontinuities in the stratigraphy probably resulted in non-uniform downward migration

of freshwater, which would explain highly heterogeneous geochemical patterns and partly inconsistent groundwater ages observed over the whole MD (Anderson, 1978; Pham et al., 2019; Wagner et al., 2012).

Although information on Miocene groundwater in CMP is rare, one sample probably originating from the Miocene aquifer n_1^3 (Fig. 6). With EC of 3090, Na^+ over 86%, Na^+/Cl^- of 1.5 and Na-Cl water type, the sample is also in a less advanced stage of freshening. In addition, this sample is consistent with samples from the n_1^3 aquifer in Soc Trang Province bordering the southern Mekong River mouth. They have similar geochemistry and are described as slightly brackish but generally more uniform. Pleistocene samples in Soc Trang do also show a wide range in Na (%) (Hoang and Bäumle, 2019; Tran et al., 2020), which demonstrates the applicability of the concept to other coastal provinces in the MD, even outside the Ca Mau Peninsula. Considering that direct vertical freshwater intrusion must have passed through several layers of various permeability, intensity of freshening is estimated decrease with depth (Doan et al., 2018; Pham et al., 2019).

In addition to the depth-dependent observations the spatial component in surveyed data can be further examined. Freshening signatures are more pronounced in the northern part inland of CMP with Na- HCO_3 water type, $\text{Cl}^- < 25 \text{ mg/L}$ and high Na^+/Cl^- ratios. This cannot be explained by seaward-directed, naturally occurring lateral freshwater recharge northeast to southwest parallel to the delta propagation axis, which is controlled by the minor marine regression in the last 5.5 ka, until recently. Due to the confined aquifer situation and the extremely low hydraulic gradient in the flat low-lying MD, the natural recharge is estimated to be negligible. Therefore, the almost completed freshening may be the result of accelerated freshwater inflow from outside the study area due to the significant drop of hydraulic heads in recent decades, mainly around CMC. Decreasing hydraulic heads lead to steeper hydraulic gradients and depression cones promoting more recharge at higher velocities from outside the pumping area. Furthermore, the random distribution of groundwater with high Cl^- concentration and salinization signatures highlights that recent large-scale seawater intrusion into deep aquifers is not occurring and these samples are rather the result of the aforementioned local downwards migration of shallow saline water. There is no correlation between these samples and the distance to the coast or any other consistent pattern, which are regularly observed in other coastal areas and are mostly related to one or more discrete saline sources, such as the upwelling of old saline brines or anthropogenic sources (Marie and Vengosh, 2001; Vinson et al., 2011). A clear fresh-saline boundary was not identified. As pointed out by Delsman et al. (2014), coastal groundwater is only rarely in equilibrium with present boundary conditions and some processes are slow. However, aquifer system salinization can be a fast process under some circumstances (Post and Kooi, 2003; Russak et al., 2016). The direct intrusion of seawater due to pumping would result in accelerated groundwater salinization (Vengosh, 2013) while the downwards migration of shallow saline groundwater might be much slower. Observed geochemical patterns might be more related to a disturbed hydrological system due to pumping rather than direct lateral seawater intrusion. In a short term, appropriate counter measures should be considered at locations where a significant increase in salinity is evident. In a longer term, however, it should be expected that salinization of deep aquifers will arise or continue and that the quantity of freshwater will decline if current practices are not reconsidered.

5. Conclusions

Groundwater data and detailed evaluation of geochemical signatures, including water types, salinity and element distributions, as well as element ratios, allowed for the development of a comprehensive model for the evolution of groundwater geochemistry in CMP. Based on the predominance of Na- HCO_3 water types, salinity patterns, and the distribution of Na^+/Cl^- , the groundwater evolution in the study area can be explained by the downward dilution of infiltrating freshwater into an initial saline system. The freshening event happened during the last marine regression phase 60–12 ka BP and especially during the LGM, 26 ka BP to 18 ka BP, and shows slightly decreasing intensity from Pleistocene to Miocene aquifers. Element ratios of Na^+/Cl^- , $\text{Ca}^{2+}/\text{Cl}^-$, as well as $\text{Mg}^{2+}/\text{Cl}^-$ and their deviation from the seawater line were used to determine cation exchange processes between groundwater and aquifer sediments, and thus to characterize salinization and freshening processes. As demonstrated, evaluation of characteristic element ratios is a powerful tool to determine groundwater state and evolution in coastal environments. This is particularly valid in contrast to the sole analysis of salinity via EC measurements, which has not proven to be a suitable indicator of seawater intrusion.

Moreover, hydrogeological layers in CMP are estimated to be connected, at least partly, either through natural discontinuities or anthropogenic influences. Even though the formation of impermeable aquitards in the Holocene marine transgression phase prevented extensive seawater intrusion, some samples show distinct salinization signatures of unknown origin. Salinization due to seawater intrusion would result in accelerated groundwater degradation. Therefore, it is important to distinguish direct seawater intrusion from mixing with other saline water sources, like the slow downwards migration due to unstable aquifer conditions, to establish a sustainable water management plan necessary to provide clean freshwater to the people. These findings have a direct implication to the whole MD region.

More work about the current state of salinization and freshening in the MD will be conducted using geochemical fingerprinting methods like ion ratios, trace elements, stable isotope techniques and geochemical models. By considering the new insights on natural drivers leading to the current groundwater composition in CMP presented in this study, the effect of pumping induced changes in hydraulic parameters and geochemistry can be appropriately evaluated in a future study, also considering pumping induced land subsidence. Lastly, concepts for alternative water resources substituting groundwater should be considered and developed to mitigate negative environmental impacts.

CRediT authorship contribution statement

Jonas Bauer: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Nicolas Börsig:** Formal analysis, Investigation, Writing – review & editing, Visualization, Project administration. **Van Cam Pham:** Investigation, Writing – review & editing. **Tran Viet Hoan:** Investigation, Writing – review & editing. **Ha Thi Nguyen:** Writing – review & editing, Resources, Project administration. **Stefan Norra:** Writing – review & editing, Resources, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was conducted in the frame of the project ViWaT-Engineering, funded by the German Federal Ministry of Education and Research (BMBF) under grant No. 02WCL1474A. We gratefully thank the Vietnamese National Center for Water Resources Planning and Investigation for contributing with the project “Research on improvement for efficiency of water resources monitoring system for early warning of depletion and saline intrusion in the Mekong Delta plain”, which is funded by the Vietnamese Ministry of Science and Technology (MOST) (grant No. ĐTDL.CN-46/18) and we thank the Department of Natural Resources and Environment Ca Mau (DONRE Ca Mau) for their support in the field and the scientific and personal exchange. A special thanks goes to the laboratory staff of the Institute of Applied Geosciences at KIT, Karlsruhe, and all project partners contributing to this work. We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology.

Appendix A. Supporting information

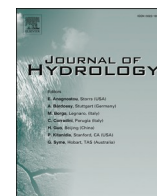
Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ejrh.2022.101010](https://doi.org/10.1016/j.ejrh.2022.101010).

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Seawater intrusion in river delta systems. Inter-annual dynamics and drivers of salinity variations in the southern Mekong Delta, Vietnam

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ARTICLE INFO

This manuscript was handled by D. Han, Editor-in-Chief, with the assistance of Ryan T. Bailey, Associate Editor

Keywords:

Seawater intrusion
Time series analysis
Hydrology of delta systems
Water management
River discharge
Land subsidence

ABSTRACT

Amidst intensifying impacts of climate change and anthropogenic pressure, seawater intrusion (SWI) emerges as a growing threat for delta systems worldwide, compromising freshwater resources and ecosystem stability. The Mekong Delta (MD) and its southernmost province Ca Mau are at the frontline of climate change impacts and anthropogenic modifications of the hydrological regime. To assess the inter-annual variability of river SWI, factors contributing to changes of the hydraulic pressure gradient between freshwater and seawater are analyzed. By utilizing long-term hydro-meteorological data from 2000 to 2022, the collective impact of catchment-scale and local-scale factors on salinity is evaluated. While salinity gradually increases by more than 10 g/L during the dry season, significant inter-annual differences of up to 15 g/L in peak salinity occur, regularly reaching and exceeding seawater salinity levels. Upstream freshwater discharge patterns were identified as major control for coastal water levels and resulting salinity levels. While climate variability governs natural upstream discharge fluctuations, dam constructions and operational responses to low-rainfall years lead to unfavorable conditions along the Mekong River, shifting and prolonging the low discharge period in the delta. This intensifies hydrological drought conditions and triggers extreme SWI events. Land subsidence of up to 2 cm per year, derived from water level records, is driving relative sea level rise and increasing the MD's vulnerability to future SWI. Mitigation strategies for SWI are examined from new perspectives, highlighting the benefits of increasing early dry-season discharge through rethought upstream reservoir operations and water storage concepts, as well as adapted local sluice gate management.

1. Introduction

Freshwater availability is a major challenge worldwide and the occurrence of regions with freshwater scarcity is rapidly increasing (Huggins et al., 2022). Coastal areas and in particular the large delta systems, inhabited by more than 500 million people worldwide, are threatened by progressive seawater intrusion (SWI) accelerated by

climate change and anthropogenic interventions (Bucx et al., 2014; Nicholls et al., 2021; Rahman et al., 2019). Seawater is characterized by high concentrations of total dissolved solids with a global average concentration of 35 g/L, which in case of inland progression degrades valuable freshwater resources and ecosystems (Vengosh, 2013; White and Kaplan, 2017).

The pressure gradient between rivers and the sea defines the inland

Abbreviations: CM, Ca Mau; CMP, Ca Mau Province; GH, Ganh Hao; LDP, Low discharge period; MD, Mekong Delta; NAWAPI, National Center for Water Resources Planning and Investigation, Hanoi, Vietnam; NCHMF, National Center for Hydro-Meteorological Forecasting of Vietnam, Hanoi; RSLR, Relative sea level rise; SD, Song Doc; SIWRR, Southern Institute of Water Resources Research, Vietnam; SLR, Sea level rise; SWI, Seawater intrusion.

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<https://doi.org/10.1016/j.jhydrol.2025.133745>

Received 9 January 2025; Received in revised form 14 June 2025; Accepted 20 June 2025

Available online 26 June 2025

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extent of SWI (Park et al., 2022; Savenije, 2012). For a given topographic setting, the hydraulic pressure gradient in coastal rivers originating from the sea is regulated by the seawater level, while the freshwater gradient is determined by river discharge. Within this framework, natural and human-induced factors, such as climate variability, water management infrastructure and land subsidence due to groundwater exploitation affect relative seawater levels and river discharge, thereby modifying the hydraulic pressure gradient and influencing SWI dynamics.

The Mekong River Basin and in particular the Mekong Delta (MD) in Vietnam, Southeast-Asia, was classified as a hotspot for severe freshwater stress and storage loss, and ranked amongst the highest socio-ecological vulnerable regions globally (Bucx et al., 2014; Huggins et al., 2022). The region is seriously affected by numerous environmental stressors, which contribute to the progressive “loss of land and freshwater” phenomenon (Bauer et al., 2022), inevitably leading to progressive SWI. The causes for SWI are complex and cannot solely be attributed to rising sea levels (Eslami et al., 2019a). Recent studies identified several, interconnected drivers for SWI in the MD: (i) Relative sea level rise (RSLR) comprising sea level rise (SLR) due to global warming (Smajgl et al., 2015) and accelerated land subsidence rates (Erban et al., 2014; Minderhoud et al., 2020), (ii) adverse effects of upstream hydropower dam construction including variations in discharge of the Mekong River (Dang et al., 2019; Lu and Chua, 2021) as well as sediment starvation (Anthony et al., 2015; Brunier et al., 2014; Karlsrud et al., 2017; Liu et al., 2017; Jordan et al., 2020) and (iii) riverbed level incision due to sand mining (Jordan et al., 2019; Eslami et al., 2021a, 2019b; Kumar et al., 2024; Loc et al., 2021a; Park, 2024).

In the coastal areas of the monsoon-influenced MD, SWI is a natural process recurring every dry season, which spans approximately from December to April. Over decades and centuries, people have adapted to that phenomenon by integrating brackish and saltwater aquaculture into their socio-economic activities (Nguyen et al., 2019a). Recent observations of accelerated SWI, with seawater conditions in the coastal zones and brackish water extending more than 90 km upstream (Gugliotta et al., 2017; Park et al., 2022), give rise to great concerns. In the course of El Niño events in 2010, 2015–2016 and 2019–2020, the MD experienced extreme droughts and SWI conditions, which had a severe impact on livelihoods (Binh et al., 2025; Hoang-Phi et al., 2020; Park et al., 2022; Van Tho, 2022). Even though farmers have the adaptive capability to change to salt-tolerant crops or brackish aquaculture, they struggle to cope with the rapid change, and especially the large variability of conditions (Binh et al., 2025; Vu et al., 2022a). For example, SWI directly controls the rice crop calendar in the coastal zones (Ferrer et al., 2022; Hoang-Phi et al., 2020; Tri et al., 2019a) and unpredictable water quality poses a high risk for shrimp farmers (Joffe et al., 2018).

Variations in river discharge driven by factors such as climate variability and precipitation patterns, upstream reservoir management as well as water consumption by agriculture and industry impact the extent of SWI in the MD. In that regard, the occurrence of hydrological drought and SWI conditions is concurrent (Park et al., 2022). Although these drivers of SWI in the MD are widely discussed in literature (e.g. Eslami et al., 2021a), a detailed analysis of inter-annual salinity variability over an extended time period is missing. Previous studies utilized a range of modeling approaches for SWI, typically relying on short time frames of in-situ observations for calibration and validation, sometimes only encompassing a few days (Eslami et al., 2021b; Khang et al., 2008; Lam, 2020; Nhung et al., 2019; Tran et al., 2024a,c). This deficiency in long-term observational data leads to limited confidence in model performance, lacking the capability to encompass the full range of inter-annual salinity variations. Moreover, the southernmost region of the MD is underrepresented in SWI studies, and processes and dynamics there are expected to differ from those in the main estuary zone of the Mekong River.

In April 2024, Ca Mau Province (CMP), along with other regions, announced an emergency in some of its districts due to water scarcity

and SWI accelerated by the 2023–2024 El Niño event (VnExpress, 2024). In the light of that event, the present study provides a comprehensive assessment of inter-annual SWI variability and aspects controlling SWI in the southernmost MD on straightforward in-situ monitoring data evaluation from 2000 to 2022. Thereby, the temporal and spatial variability of SWI is investigated in CMP. CMP was selected as the study region for SWI due to its unique geographical characteristics and socio-economic relevance. Surrounded by the sea on three sides and featuring a low topography, CMP is already characterized by a saline environment (Khang et al., 2008; Minderhoud et al., 2019a) and is at the frontline of climate change impacts, facing severe challenges from sea level rise and land subsidence. The convergence of natural and anthropogenic challenges makes CMP a valuable model region for other at-risk coastal areas (Khang et al., 2008; Minderhoud et al., 2019a).

This study incorporates supporting data, including local precipitation, river water levels, and upstream discharge time series, to systematically characterize river salinity dynamics and identify the major drivers of SWI fluctuations and their evolution in the southern MD. Particular emphasis is placed on analyzing the causes of extreme SWI events and understanding their connection to hydrological droughts, land subsidence, and upstream water management practices. Furthermore, the progression of SWI under the combined influence of natural variability and anthropogenic interventions is assessed, and novel perspectives on previously introduced mitigation strategies are critically evaluated. The methods and insights developed here are intended to support evidence-based water management and are transferable to other coastal provinces within the MD, as well as to similar deltaic regions in Southeast Asia and globally.

2. Study area

2.1. Overview

Fig. 1 shows the location of the MD and CMP as well as main features and points of interest relevant for this study. The Vietnamese MD, one of the largest river delta systems globally, and the metropolis Ho-Chi-Minh-City together are inhabited by over 27 million people (GSOV, 2024). Vietnam is the world's third-largest rice exporter, accounting for nearly 15 % of global exports, with the MD contributing up to 90 % of the country's export capacity (Huong et al., 2022; Maitah et al., 2020). The MD is characterized by a tropical monsoon climate where the rainy season lasts approximately from May to November and annual precipitation can reach up to 2500 mm/a in CMP (Dang et al., 2020; Pham-Thanh et al., 2021). The rainy season is followed by a pronounced dry season from December to April. The mean relative humidity is around 80 % throughout the year and mean monthly temperatures range between 25 °C and 30 °C (GSOV, 2024). The study area CMP, inhabited by around 1.2 million people (GSOV, 2024), is the southernmost province of the MD and is located on the Ca Mau Peninsula, which includes the neighboring provinces Bac Lieu in the northeast and Kien Giang in the north. CMP covers an area of 5,221 km² with an estimated average elevation below 0.8 m above mean sea level (Minderhoud et al., 2019a; Zoccarato et al., 2018). Land use dynamics in the MD, and in CMP in particular, are key factors to understand the environmental impact, economic aspects, as well as potential social conflicts of progressive SWI (Binh et al., 2025). CMP has a leading role in the agricultural sector of Vietnam, especially for shrimp farming (Nguyen et al., 2019b; Thong et al., 2010). After the land use transformation in the year 2000, high-value brackish and saline aquaculture or other cash-crops basically replaced traditional rice farming (Phan et al., 2021; Vu et al., 2022a). Depending on available freshwater resources, various farming practices exist in CMP, including shrimp permaculture or various aquaculture-rice rotation systems, and rarely two-crop rice cultivation in the protected zones like the U Minh freshwater zone (Le et al., 2018; Loc et al., 2021b; Nguyen et al., 2020).

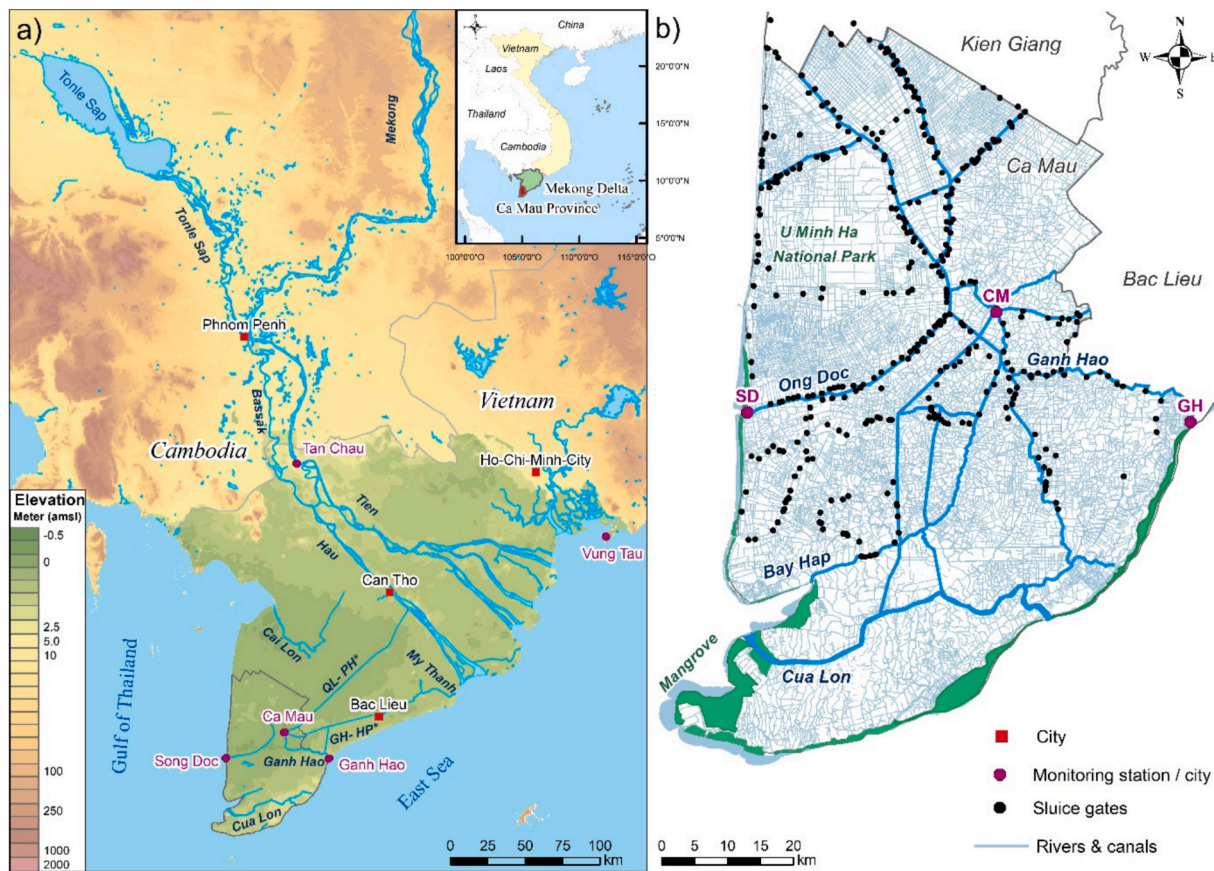


Fig. 1. a) Overview of the Mekong Delta, including points of interest for this study. *QL-PH: Quan Lo – Phung Hiep Canal. BL-CM: Bac Lieu – Ca Mau Canal. GH-HP: Ganh Hao – Ho Phong Canal. Monitoring stations are Song Doc (SD), Ca Mau (CM) and Ganh Hao (GH). Surface elevation (not linear) in the Mekong Delta by Minderhoud et al. (2019a) with a grid size of 500x500 m (Minderhoud et al., 2019b). Surface elevation outside the Mekong Delta from the Global Topographic 30 Arc-Second Digital Elevation Model GTOPO30 (EROS, 2017). b) Ca Mau Province and its hydrological infrastructure 2022 (river network data provided by the National Center for Water Resources Planning and Investigation, Vietnam (NAWAPI)).

2.2. Hydrological regime

In the Vietnamese MD, the quantity of water resources is mainly controlled by the discharge of the Mekong River (Eslami et al., 2021a; Ha et al., 2018). The Mekong River's discharge is governed by precipitation in its catchment area and is subject to significant seasonal and inter-annual variations (Mohammed et al., 2018). Precipitation in the Mekong River Basin is influenced by climate phenomena, like El Niño Southern Oscillation (ENSO) and climate change (Lee and Dang, 2018; van der Linden et al., 2016). Beginning in late April to mid-May, the discharge of the Mekong River in the middle and lower basin undergoes a gradual increase, attributed to higher precipitation rates during the summer monsoon. The peak of river water levels in the coastal zones is observed towards the end of the rainy season, typically between October and November and up to December in the southern Ca Mau Peninsula (Nguyen, 2020; Nguyen et al., 2023). With the beginning of the dry season, discharge of the Mekong River sharply decreases, whereas minimum river water levels in the delta are observed in June to July (Schwarzer et al., 2016). Since the construction of upstream dams in China, Laos and Cambodia, river discharge and seasonality have been altered significantly to ensure stable conditions for hydropower production and water availability (Ang et al., 2024). Dry-season discharge has more than doubled in Cambodia and Laos and increased by around 20 % in the Tien River in Vietnam to accommodate double and triple rice cropping in the Mekong River Basin. On the contrary, discharge is limited during the rainy season to prevent flooding of agricultural areas (Binh et al., 2021; Le Huy et al., 2021; Lu and Chua, 2021). Over 90 % of the river's discharge is directed towards the East Sea, also known as

South China Sea, or used for irrigation, with less than 5 % reaching the Gulf of Thailand via the southern MD plain and the Ca Mau Peninsula (Renaud and Kuenzer, 2012).

The southern MD plain is characterized by tidal rivers and an extensive network of man-made channels, intensively utilized for transportation and irrigation purposes. Primary channels convey water from the tidal rivers into agricultural areas, while secondary channels further subdivide these networks, directly supplying water for agriculture and aquaculture. The main rivers in the study region, which particularly contribute to SWI, are Ganh Hao in the east, Ong Doc and Bay Hap in the west as well as Cua Lon, which directly connects the East Sea with the Gulf of Thailand (Fig. 1). On regional scale, the rivers My Than northeast and Cai Lon northwest of CMP in Kien Giang Province contribute to SWI in the area (Hoanh et al., 2009; Tho et al., 2006). These rivers provide water for the secondary channel systems but due to SWI and conflicting demands between freshwater rice farming and saltwater related aquaculture, water flow and quality in tributary channels is controlled by numerous sluice gates of varying size and pumping activities (Di Giusto et al., 2021; Hoanh et al., 2009; Nguyen et al., 2020). The gates and pumps are operated on seasonal or tidal scale. To provide freshwater for the saltwater zones, straight canals parallel or perpendicular to the Hau River were constructed through the Ca Mau Peninsula (Nhung et al., 2019). As soon as SWI is expected, large sluice gates, like in Ho Phong in Bac Lieu Province or the Cai Lon-Cai Be sluice in CMP, are closed, typically near the end of February (Hoanh et al., 2009). Within CMP, no large sluices control SWI in the Ong Doc and Ganh Hao rivers. On average, river depth is about 3–5 m except for Cua Lon River (5–19 m) and Ganh Hao River (5–14 m). The depth of

secondary channels and irrigation canals are generally shallower.

3. Data and methods

In the Vietnamese MD, environmental data is generally scarce, and many studies utilize the same or similar datasets on salinity, water level and discharge provided by governmental institutions to investigate various research questions. Amongst others, parts of the datasets used in this study were previously used to study flow dynamics (Eslami et al., 2019b), water level evolution and tidal characteristics (Nguyen, 2020; Phan et al., 2019), saline intrusion (Dang et al., 2019; Loc et al., 2021a; Tri, 2012), land use impacts and water quality (Minh et al., 2020; Tri et al., 2019b), as well as land subsidence (Nguyen et al., 2023; Khang et al., 2008). To comprehensively assess inter-annual salinity variability in CMP, the utilization of available models as employed in previous studies was intentionally avoided in favor of a straight-forward evaluation of in-situ monitoring data. The time series data was quality-checked, and obviously false values that fell outside reasonable ranges were removed, while decimal errors were corrected manually. These corrections affected only isolated data points and accounted for less than 1 % of the dataset. For the continuous datasets, resulting short-duration gaps were linearly interpolated. To ensure better comparability with previous studies, linear regression analysis was chosen for the trend analysis of the different time series. The figures in this article use *ColorBrewer2*-inspired color schemes (Brewer et al., 2013).

3.1. Salinity

Daily maximum salinity values from 2000 to 2022 are available for three monitoring stations in CMP and were provided by the National Center for Hydro-Meteorological Forecasting of Vietnam (NCHMF). The stations are located in Ca Mau (CM) and Ganh Hao (GH), both situated along the Ganh Hao River, approximately 40 km and 1 km from the East Sea, respectively, and Song Doc (SD), located along the Ong Doc River about 2 km from the Gulf of Thailand (Fig. 1). In the MD, the standard sampling procedure involves collecting grab samples of surface water, followed by measuring salinity concentrations using a handheld meter.

The salinity records contain data gaps of one to four days and

typically cover the period from January to July, which includes the dry season when salinity levels are highest. The limited temporal coverage reflects the operational focus of monitoring for water management and SWI control, with less emphasis on long-term scientific continuity. The available records were combined into a dataset of daily maximum salinity values and are presented in Fig. 2. The highest recorded salinity occurred at SD in May 2020 with 44 g/L, followed by peak years 2016 and 2010. In contrast, salinity at CM consistently reached seawater levels in the early 2000 s, with major peaks in 2010 and 2016. No peak was observed at CM in 2020, unlike at SD. At CM, a clear pattern of increasing and decreasing salinity phases is present in most years. Similar dynamics were observed at SD in several years (e.g., 2010, 2015, 2016, and 2020), whereas in other years, such as 2017 to 2001, and more recently in 2021 and 2022, the increase was more gradual. GH, located on the eastern coast, exhibited the lowest inter-annual variability, especially in recent years where salinity measurements were more tightly clustered. The distinct seasonal salinity patterns observed at CM and SD were less pronounced at GH.

To analyze long-term trends, monthly mean values of daily maximum salinity were calculated for February, March, and April, covering the period June 2000 to May 2020. These months were selected to ensure consistent data availability and to focus on the peak dry season. Linear trends for each station and month were derived using the *fitlm* function in MATLAB.

3.2. Water level

Continuous 1-hourly surface water level data from the river monitoring stations SD and GH were provided by NCHMF and the National Center for Water Resources Planning and Investigation (NAWAPI). For CM, no water level data was available, as continuous measurements over the entire study period are lacking. Sand mining and dredging largely influences water levels in the Tien River (Jordan et al. 2020, Eslami et al., 2021a), but is considered negligible for CMP due to lower extraction activity in the study area. Continuous RSLR, combining SLR and land subsidence, significantly contributes to SWI in coastal regions, including the MD (Eslami et al., 2021a; Savenije, 2012; Tran et al., 2021; Vu et al., 2018). Therefore, both factors are assessed via trend analysis.

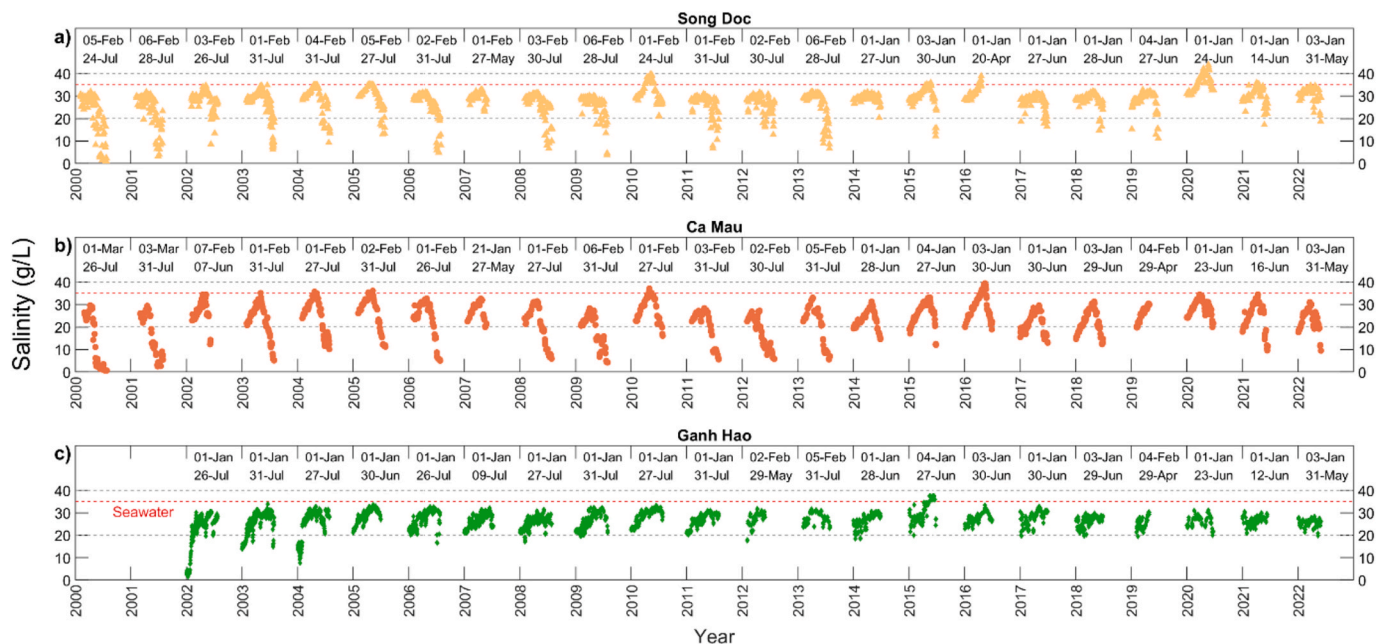


Fig. 2. Daily maximum salinity data for Song Doc, Ca Mau and Ganh Hao from 2000 to 2022. Each year's starting and ending dates are indicated above the time series. Seawater salinity is indicated by the red dashed line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Land subsidence is one of the most recognized threats to the MD and is locally one magnitude higher than SLR due to global warming (Dörr et al., 2024; Minderhoud, 2019). When assessing SLR by tidal gauge stations, subsidence of the station itself can be a major source of error and contributes to observed SLR at tide gauges in many coastal settings, potentially overestimating SLR (Liu et al., 2020; Saramul and Ezer, 2014). Nguyen et al. (2023) estimated subsidence rates for the time period October 1987 to September 2015 utilizing monthly averaged changes in water level records from eleven stations in the MD by comparing them with rates of SLR at the Vung Tau station, which is considered tectonically stable. At Vung Tau station a RSLR of 2.2 ± 0.3 mm/a was determined, and by subtracting the value at Vung Tau from the RSLR of 13.5 ± 0.7 mm/a in GH, a yearly subsidence of 11.3 mm was obtained. Monthly averages are commonly used in assessing SLR to reduce short-term water level fluctuations and data noise (Church and White, 2011; Kim and Cho, 2016). Therefore, monthly averages of water level data for the two periods January 2000 to December 2019 and January 2010 to December 2019 at GH and SD were used to calculate RSLR by linear regression analysis using Matlabs's *fitlm* function. These two time frames were selected to capture the pre-dam period (before 2009) and the post-dam era, marked by a sharp rise in the number of dams along the Mekong River since 2010 (Tran et al., 2021, Lu and Chua, 2021). To ensure that long-term trends are not influenced by recurring seasonal fluctuations, the data was deseasonalized by subtracting the monthly mean for each calendar month over the study period, providing a clearer identification of inter-annual variability. The resulting anomalies highlight deviations from the long-term seasonal cycle, enabling trend assessment independent of predictable seasonal patterns. Due to varying methodologies and time frames of previous SLR calculations at Vung Tau, an average value of 3.10 mm/year was derived from available studies, including Nguyen et al. (2023: 2.20 ± 0.3 mm/year, linear regression analysis of deseasonalized monthly mean sea-level data, 1987–2015), Hak et al. (2016: 3.50 mm/year, linear regression analysis of annual mean sea-level data, 1985–2010), and MONRE (2016: 3.19 mm/year, linear regression analysis of annual mean sea-level data, 1978–2014). Since land subsidence in the MD locally exceeds 30 mm/year, SLR, which is approximately one order of magnitude lower, plays only a minor role in the overall estimation of RSLR (Minderhoud et al. 2020).

The use of linear regression on deseasonalized monthly mean sea-level data provides an estimate but does not account for other causes of sea level variation, such as large-scale oceanic-atmospheric interactions, including fluctuations driven by the Pacific Decadal Oscillation and ENSO-related wind and circulation changes (Cheng et al., 2023). Nguyen et al. (2023) selected a 28-year analysis period (1987–2015) to effectively eliminate biases from the 18.6-year lunar nodal tidal cycle, which periodically affects tidal amplitudes and coastal water level records. In contrast, the 1.5-cycle timeframe was not applied in this study. Instead, a more recent period was chosen to better capture the influence of increasing subsidence rates on current RSLR estimates (Allison et al., 2017; Dunn and Minderhoud, 2022). Additionally, consistent with the salinity trend analysis, water level trends were calculated separately for the months of February, March, and April. These months represent the peak of the dry season, when water levels are low and SWI effects are most pronounced.

Tides were not explicitly considered in the analysis of inter-annual water level changes and salinity variations, as their predictable short-term fluctuations have minimal influence compared to river discharge and RSLR on longer timescales (Baranes et al., 2023; Kvale, 2006).

3.3. Upstream river discharge and water level at Tan Chau

Since discharge is not measured at the monitoring stations SD, CM, and GH, available data on seasonal streamflow variations from the Mekong River, which supplies freshwater to the delta, is instead used as a proxy. Daily mean discharge [m^3/s] and water level data at the

monitoring station in Tan Chau close to the Cambodian border (Fig. 1) was provided by the Southern Institute of Water Resources Research (SIWRR) for the years 2000 to 2022. The station is located at the Tien River, which accounts for more than 80 % of the Mekong's annual discharge to the delta (Binh et al., 2021). The discharge of the Tien River at Tan Chau has a linear relationship with that of the parallel Hau River (Le et al., 2007). Even though discharge at Tan Chau does not directly represent discharge at the coastal stations in CMP, it serves as a good proxy for hydrological conditions in the delta. The station captures freshwater inflow before significant tidal effects and local water diversions alter streamflow conditions downstream, making it a representative site for analyzing seasonal discharge variations.

The length of the dry season is an important aspect when assessing SWI in the MD and is associated with the onset and cessation of the monsoon season. In this study, the duration of the dry season was not assessed based on precipitation but instead defined through a low discharge period (LDP). The LDP was identified when the weekly average discharge at Tan Chau station consistently exceeded or fell below a threshold of $4000 \text{ m}^3/\text{s}$ for two consecutive weeks. To our best knowledge, no universally recognized critical discharge value for SWI in the MD exists. The $4000 \text{ m}^3/\text{s}$ threshold represents approximately 10 % of the annual average peak flow (Binh et al. 2020) and 20 % of the average monthly discharge during the rainy season. The LDP serves as a reliable proxy for freshwater availability in the system rather than indicating a direct, short-term physical relationship between discharge at Tan Chau and salinity levels at SD, CM, and GH, given the time lag in water transport, which can be a few weeks during low flow conditions in the dry season (Birkinshaw et al., 2010; Hung et al., 2012; Le et al., 2007). As the LDP defined here typically begins between mid-January and late February and ends between late April and mid-May, it encompasses the dry season.

To compare with local surface water levels in CMP, the water level trend at Tan Chau station, which is directly related to discharge, was also calculated. The trend analysis followed the same approach as described for salinity, using linear regression on monthly averages and deseasonalized data to ensure comparability and to identify long-term changes while minimizing short-term fluctuations.

3.4. Precipitation

Daily precipitation data is available for Ca Mau City, close to the river monitoring station CM, and was provided by NCHMF. CMP receives the highest annual rainfall in the MD, reaching up to 2500 mm (Pham-Thanh et al., 2021). By choosing the optimal set of rainy season onset detection parameters, including the total rainfall amount during the initial wet spell, the number of wet days within this period, and the duration of a control period ensuring sustained wet conditions, Pham-Thanh et al. (2021) found that the onset of the rainy season is strongly controlled by local rainfall characteristics and shows significant regional correlation, with the initial wet spell being the most robust indicator. Therefore, it can be assumed that the rainy season begins simultaneously in the southern MD with a mean onset between the end of April and early May and shifts to the northeast part of the delta (Pham-Thanh et al., 2022). Precipitation from the meteorological station in Ca Mau City is thus considered sufficiently representative for the study region CMP.

4. Results

4.1. Inter-annual variability of salinity and hydrometeorological drivers

To understand the progression and severity of SWI in the southernmost MD, seasonal patterns and inter-annual salinity variations from 2000 to 2022 were analyzed in relation to local and catchment-scale hydrometeorological factors. While inter-annual differences in salinity maxima exceed 15 g/L , seasonal dynamics are characterized by gradual increase and decrease phases within each year (Fig. 2), with an abrupt

turning point at the onset of the monsoon season, when continuous rainfall and rising local discharge decrease salinity. The years that stand out in terms of low precipitation and high salinity, described previously as periods of pronounced drought and SWI (Park et al., 2022), are presented in Fig. 3. Fig. 3a-i presents daily maximum salinity for the three monitoring stations and daily precipitation from the Ca Mau meteorological station for the drought years 2010, 2016 and 2020, along with data from the preceding and following years. The average total precipitation in the dry-season months of January to April from 2000 to 2022 is 160 mm, with maximum values reaching up to 400 mm due to an early monsoon onset in April, as occurred in 2012 and 2022 (not shown). In contrast, during the dry years 2010 and 2016, total rainfall was below 10 mm (Fig. 3b, e), while in 2020, rainfall was similarly low except for a single heavy rain event with almost 80 mm in March (Fig. 3h). At the onset of the rainy season in April 2020, the salinity at CM and GH stations, situated along the Ganh Hao River, began to decrease, while the salinity at the SD station continued to rise, culminating in a peak value of 44 g/L. In 2015, salinity at GH almost reached 37.5 g/L, much higher than at the other stations, which only occurred in this particular year. In the drought years, salinity in CM is higher than at GH, but lower than at SD. In contrast, in normal and wetter-than-normal years, salinity in GH is higher than at CM or equal, like in 2011 or 2017. Single, yet strong, irregular rain events amid the dry season, like in 2009 or March 2020, momentarily halt the salinity rise, only for it to resume shortly after at a relatively steady pace.

The Mekong River's discharge significantly contributes to the

adverse shift in the pressure gradient impacting SWI. Recent studies showed that SWI in the MD is co-occurring with hydrological drought conditions caused by variations in discharge of the Mekong River (Park et al. 2022). Fig. 4 shows the monthly mean discharge at Tan Chau station (see Fig. 1) and monthly maximum salinity values at the three monitoring stations in CMP (see Fig. 2). The lowest discharge between 1760 m³/s and 2,200 m³/s occurred in March and/or April 2004, 2005, 2007 and 2010, followed by February and March of 2020. Dry-season discharge was highest in March 2019 and 2017, with 4,621 m³/s and 4,182 m³/s, respectively, and in April 2022 with 5,012 m³/s and around 4,550 m³/s in April 2017 and 2019. For comparison, during wet years, the monthly rainy season discharge peaks between 22,000 m³/s and nearly 25,000 m³/s. The lowest river discharge in May was measured in the years 2003 to 2006, and 2010, ranging between 2,400 m³/s and 2,800 m³/s, while in more recent years 2017 to 2022 discharge is more than doubled in May compared to the pre-2010 period. The lowest discharge in June and July corresponds to the years with the highest salinity. In order of lowest discharge, these years are 2010, 2020, 2019, 2015, 2007, 2005, and 2003. Lowest discharge in December and November occurred in 2019 and 2015, prior to severe drought years 2020 and 2016, indicating the relevance of early dry season conditions.

Fig. 5 illustrates the onset, end, and duration of the LDP, defined as the annual recurring period when the weekly average discharge of the Mekong River at Tan Chau station drops below 4000 m³/s. In addition, discharge volume during the LDP as well as total discharge volume in the early dry season for the period November to February are shown in

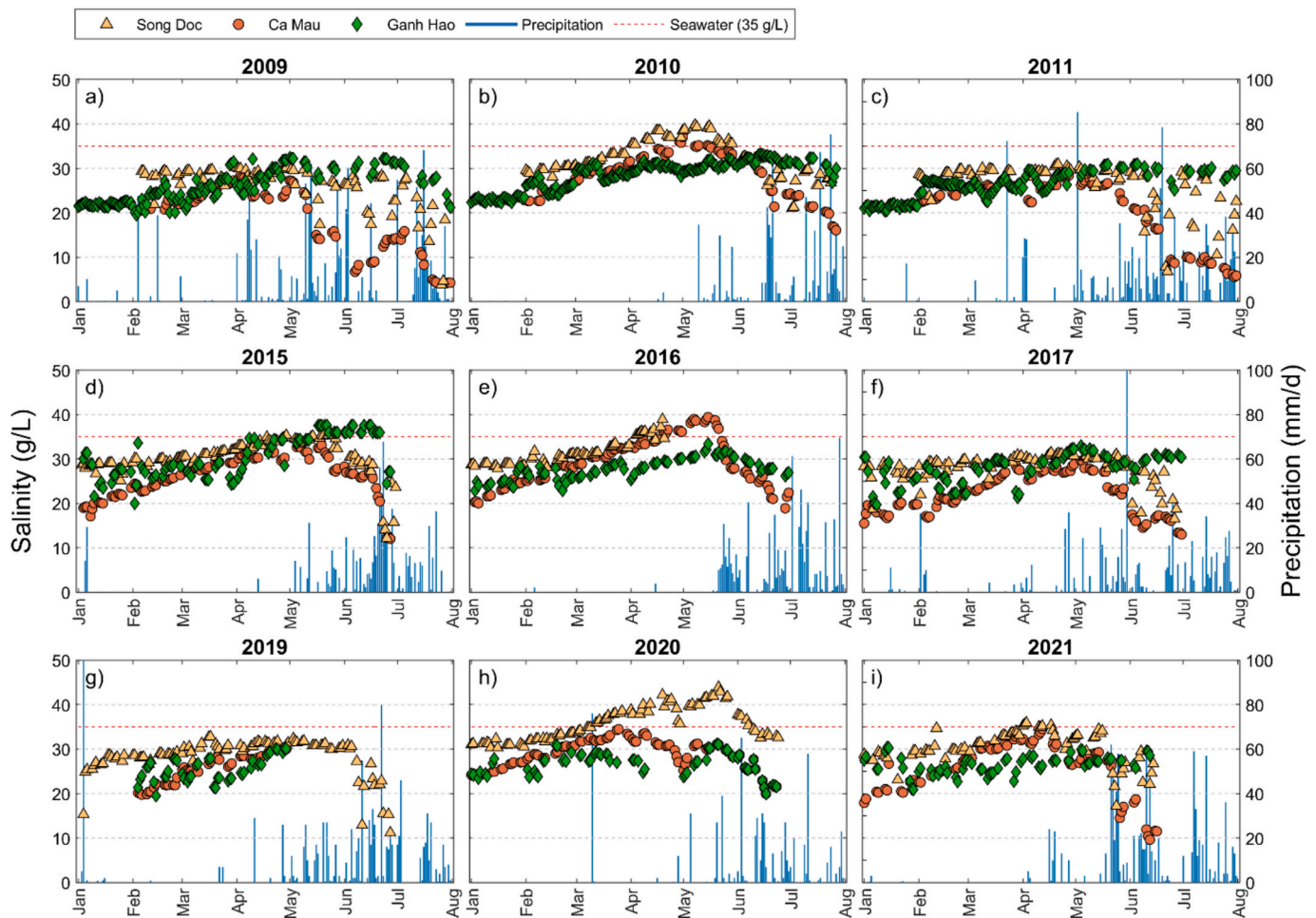


Fig. 3. Daily maximum salinity at Song Doc, Ca Mau and Ganh Hao and precipitation at the Ca Mau meteorological station between January and July in the drought years 2010, 2016 and 2020 as well as the previous and subsequent years. The red dashed line indicates seawater salinity levels with 35 g/L. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

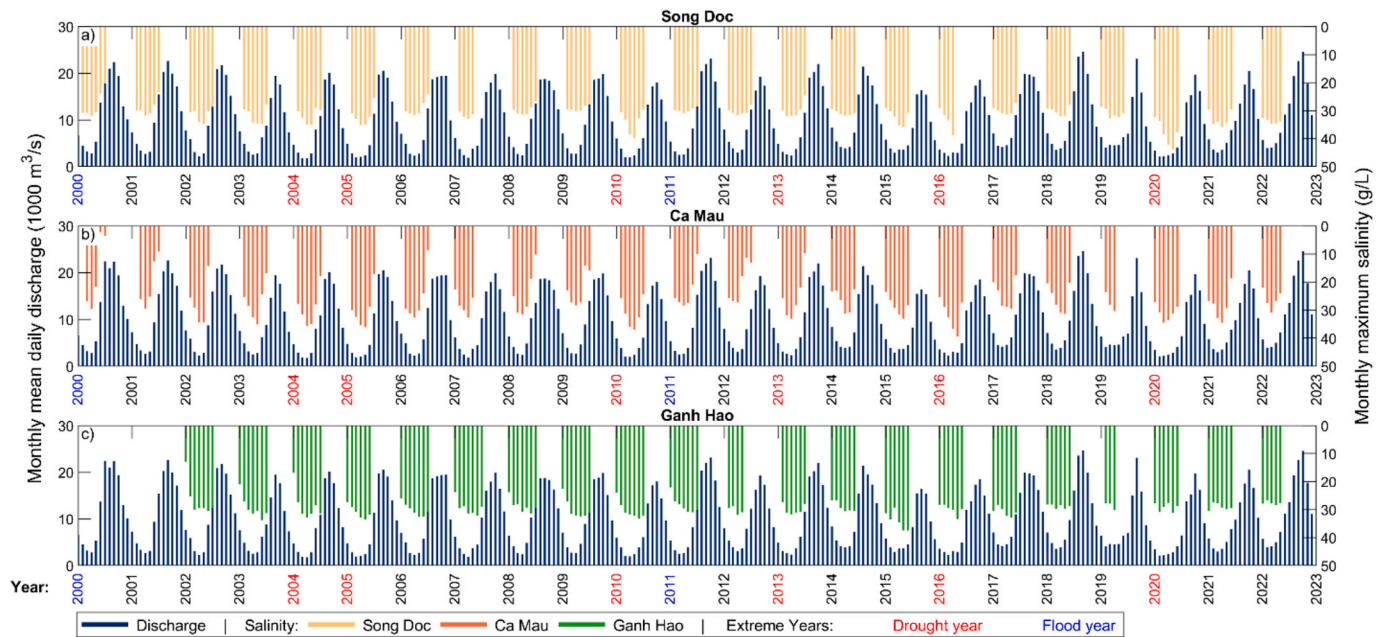


Fig. 4. Monthly mean discharge at Tan Chau station and monthly dry season maximum salinity at Song Doc, Ca Mau and Ganh Hao from 2000 to 2022 (compare Fig. 2). No salinity data are available during the rainy season. Drought and flood years are indicated (Loc et al., 2021a; Van et al., 2024).

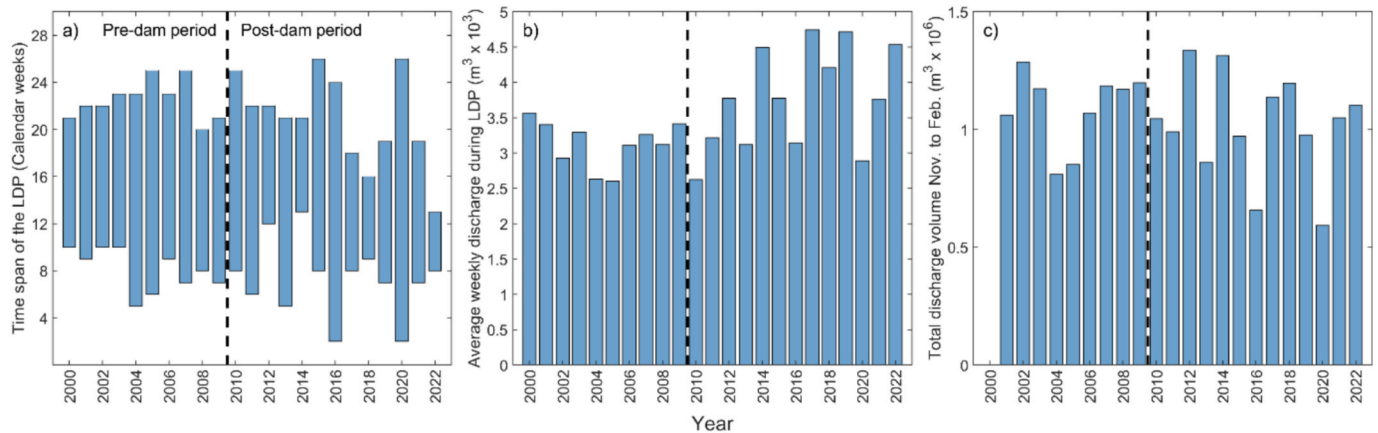


Fig. 5. Discharge patterns at Tan Chau station showing a) starting and ending calendar weeks of the low discharge period, with its duration calculated as the difference between the two, b) average weekly discharge volume during the Low discharge period, and c) total discharge volume between November and February. The black dashed line separates the pre-dam and post-dam era.

Fig. 5b, c. The LDP varies significantly between 2000 and 2022, ranging from a minimum of five weeks in the dry season of 2022 to a maximum of 24 weeks in 2020. In the pre-dam era, the data in Fig. 5a-c show relatively stable patterns, whereas the post-dam era is characterized by greater variability, including pronounced minima and maxima and more distinct year-to-year fluctuations. Significant earlier onsets and longer durations of the LDP were observed in 2013 and particularly in 2016 and 2020 (Fig. 5a), coinciding with ENSO-related low rainfall during the monsoon seasons of 2015 and 2019. Notably later onsets and earlier ends, resulting in shorter LDP durations, were also recorded in more recent years, such as 2012, 2014, 2018, and 2022, with a tendency of decreasing LDP duration in that order. Lowest average weekly discharge volume was detected in 2004, 2005 and 2010, while in extreme SWI years 2016 and 2020 discharge during the LDP is slightly higher (Fig. 5b). In rainy years, average discharge is significantly higher after 2013. The increase of inter-yearly discharge fluctuation is pronounced for the total discharge volume between November and February, with a decrease of discharge from 2010, 2013 to 2016 and finally 2020

(Fig. 5c). Although 2004 and 2005 also experienced low discharge during these months, SWI conditions were not as pronounced as in 2016 and 2020.

Fig. 6 shows the duration of the LDP and mean salinity in April, when highest salinity levels are expected, at all three stations. Fig. 6 also shows information about the maximum salinity observed in each year. In years marked by extreme mean and maximum salinity levels, such as 2010, 2016, and 2020, the LDP tends to be longer, indicating a notable relationship between extreme salinity levels and prolonged LDPs. Overall, salinity levels at SD and CM show a moderate to good Spearman correlation, with $\rho = 0.61$ and $\rho = 0.66$, respectively, while GH shows a weaker correlation with $\rho = 0.34$. In years with record low total discharge like 2004 and 2005 (Fig. 4) and a long LDP, salinity levels are high at SD and CM. In the years 2002, 2003 and 2021 salinity levels are increased despite an average LDP. Even though the LDP in 2022 is only five weeks and mean salinity is low, the maximum salinity is high at SD, but low at CM and GH. At GH, highest mean salinity level occurred in 2004, 2005 and 2010. In 2016 and 2020, salinity levels are significantly

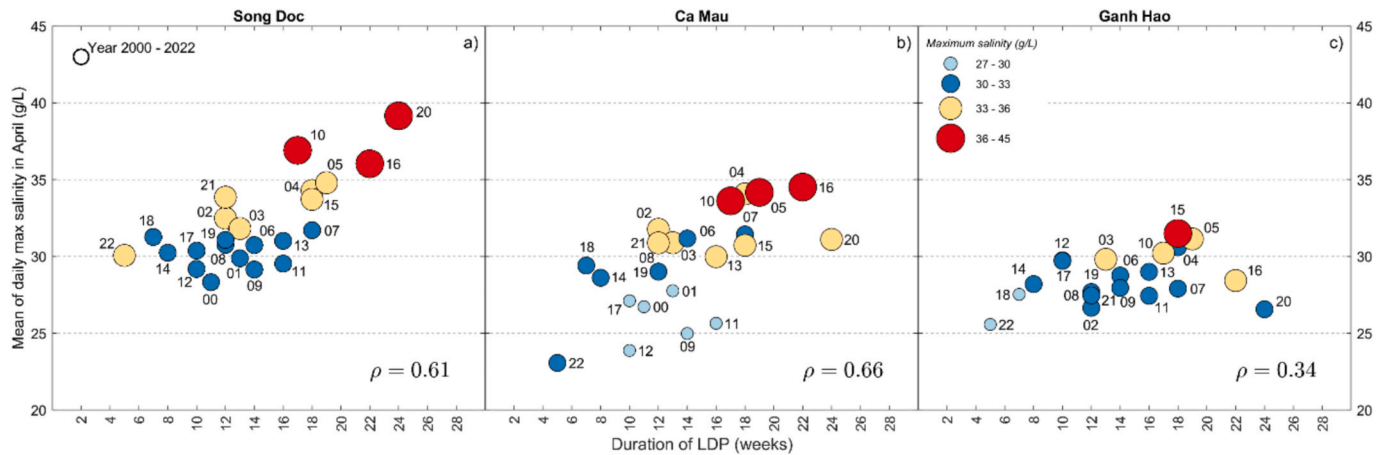


Fig. 6. Correlation (Spearman ρ) between the duration of the low discharge period (as defined in chapter 3.3) and mean of daily maximum salinity in April at Song Doc, Ca Mau and Ganh Hao for the period 2000 to 2022. Years are indicated next to the data points in two-digit format.

lower at GH than at SD and CM, despite the long LDP. The spatial differences in observed salinity levels are discussed further in Chapter 5.1.

4.2. Trends for salinity, water level and land subsidence

The analysis of water level trends and land subsidence rates provides valuable insights into long-term hydrological and topographic changes at Tan Chau, located 220 km inland from the river mouth, for the period January 2000 to December 2022, and at the coastal stations SD and GH from June 2000 to May 2020, with implications for salinity trends. Using linear regression on both the original and deseasonalized data, annual rates of change were calculated and are presented in Fig. 7.

At Tan Chau, the long-term trend reveals a steady decline in water levels, with an annual decrease of 2.67 cm based on the original data and 2.72 cm for the deseasonalized data. At SD and GH, the trends show an increase in water levels, with rises of 1.58 cm and 2.06 cm, respectively, for the deseasonalized data, aligning closely with the original data. In the post-dam era (2010–2019), the trends show a more pronounced

increase. At SD and GH, water levels have risen at accelerating rates of 2.32 cm and 2.66 cm per year, respectively, since 2010. During the study period from 2000 to 2022, seasonal water level differences at Tan Chau ranged between 300 and 400 cm prior to 2010 (Fig. 7a). In more recent years, this range decreased significantly to below 250 cm, with the smallest seasonal variations observed in 2020 and 2021, both recording less than 100 cm. After deseasonalizing the monthly water level time series, anomalies at Tan Chau reached up to plus 150 cm in 2011 and minus 150 cm in 2020 and 2021 relative to the long-term trend (Fig. 7b). This indicates that a substantial portion of the discharge variability observed in the original water level data upon entering Vietnam is influenced by non-seasonal factors. In comparison, deviations from the trend at the coastal stations are smaller (Fig. 7d, f). Distinct anomalies with negative values in 2010, 2015, and 2016 reaching up to 9 cm, and positive values in 2000 and 2011 between 9 and 11 cm, reflect the non-seasonal influences. These account for approximately one-third to one-half of the total water level fluctuation, similar in relative magnitude to those observed at Tan Chau.

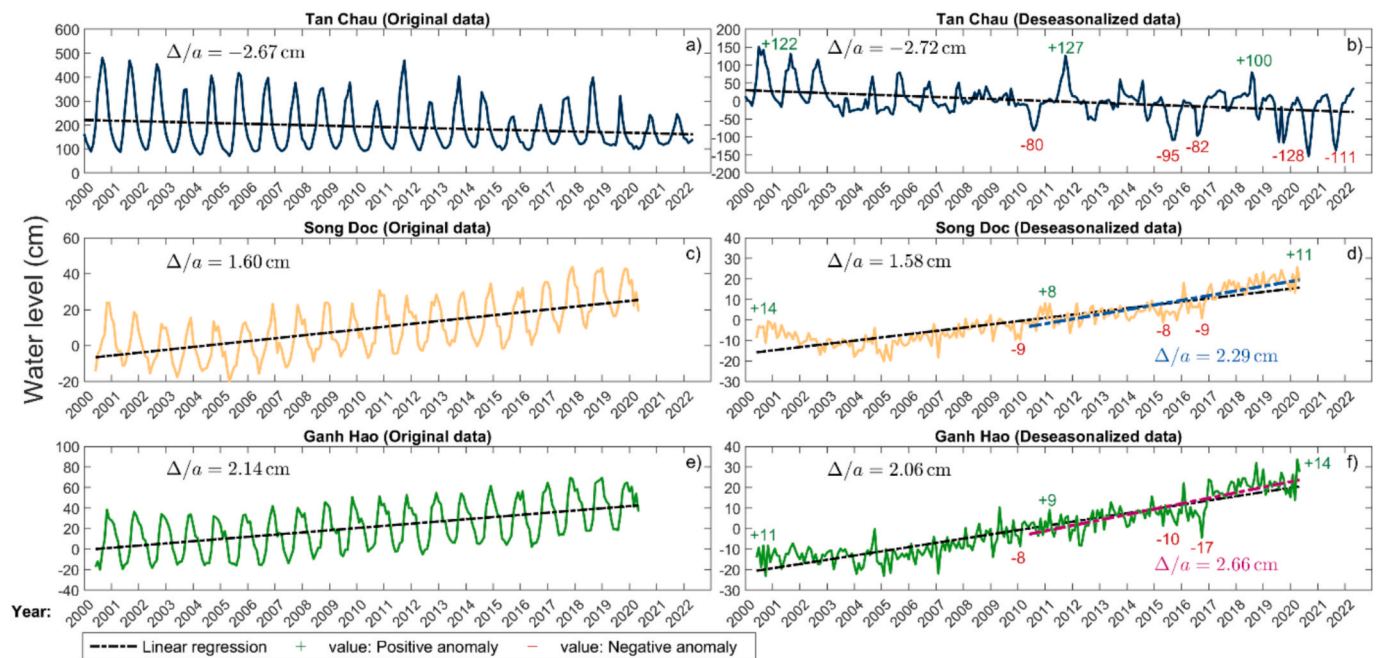


Fig. 7. Water level trend from 2000 to 2020 at the monitoring stations Tan Chau, Song Doc and Ganh Hao. Fig. 7a, c, e show the original data, while Fig. 7b, d, f show the deseasonalized trend. Fig. 7d, f includes the trend for 2010 to 2019 at SD and GH.

Land subsidence rates were estimated by subtracting the SLR at Vung Tau (0.31 cm/a) from RSLR trends at SD and GH, following the methodology of [Nguyen et al. \(2023\)](#). For the period 2000 to 2019, land subsidence was calculated at 1.27 cm/a at SD and 1.75 cm/a at GH. However, during the more recent period from 2010 to 2019, this used method suggests an increase of land subsidence rates to 1.98 cm/a at SD and 2.35 cm/a at GH, reflecting more pronounced land subsidence rates in the past decade.

To evaluate long-term trends and variability in salinity in relation to water levels and their inter-annual fluctuations, [Fig. 8](#) presents linear trends for monthly mean water levels in February, March, and April, analysed for the period 2000 to 2022 at Tan Chau and 2000 to 2020 at SD and GH. It also shows trends in monthly mean salinity, derived from daily maximum values, for the same months at CM, SD, and GH from 2000 to 2022. Notably, no water level data was available for CM. At Tan Chau, the trends diverge from the overall declining water levels shown in [Fig. 7](#). Water levels exhibit a positive trend, increasing by 0.45 cm/a in February, 0.85 cm/a in March, and 1.75 cm/a in April. For SD, the water level trends in February and April align closely with the annual average rates of increase, while the trend in March shows a comparatively smaller rise. At GH, the increases in February and April are substantially higher than the annual trend, reaching 2.70 cm/a in February. In March, the rate of increase is significantly lower than in the previous and subsequent months. At CM, no significant salinity trend is observed for February, while a 0.09 g/L increase in March and a 0.10 g/L decrease in April are noted. For SD, salinity trends show an annual increase of 0.09 g/L in February, which rises to 0.15 g/L in March before reverting to 0.09 g/L in April. At GH, February salinity increases by 0.05 g/L, while March and April exhibit decreases of 0.03 g/L and 0.10 g/L, respectively.

5. Discussion

5.1. Dynamics and drivers of salinity variability

The inter-annual variability of salinity is of great concern for local stakeholders, governing water management and agricultural practices ([Nguyen, 2017](#)). While salinity gradually increases during every dry season, significant inter-annual differences, as shown in [Fig. 2](#), create high uncertainty in regional conditions and, consequently, in the planning of dry-season agricultural practices, including sowing and harvest timing, crop selection, and the management of aquaculture species such as fish and shrimp. The primary factor controlling progressive SWI

within many coastal and deltaic environments is the volume of freshwater contributing to river discharge at the river mouth ([Pokavanich and Guo, 2024; Savenije, 2012](#)). Naturally and anthropogenically influenced variability of river discharge persists in many large catchments worldwide, causing both periods of flood and drought ([Hansford et al., 2020](#)), and eventually SWI. In the Mekong River Basin, peak rainfall during the rainy season, which is typically highest in August and September, triggers the annual rise in water levels at Tan Chau. As the Mekong's discharge propagates downstream, peak water levels on the Ca Mau Peninsula occur between November and December ([Nguyen, 2020; Nguyen et al., 2023](#)), with a time lag ranging from one to several weeks relative to Tan Chau due to the low slope of the delta. ([Fig. 4](#)). In contrast, local rainfall in CMP provides an immediate freshwater source to counteract the seawater hydraulic gradient, as is evidenced by a pronounced drop in salinity as soon as continuous monsoon rainfall starts ([Fig. 3](#)). A time lag occurs between the onset of rainfall in the delta and the rise of discharge in the Mekong River Basin and Tan Chau, and the timing of both freshwater sources influence the salinity gradient. Within the dry season, local rainfall typically plays a minor role, as delta water levels depend mainly on upstream discharge. However, single heavy rain events, like in 2009 or March 2020, can temporarily reduce surface salinity ([Fig. 3](#)). This may result from surface dilution or short-term increases in local or upstream discharge due to regionally correlated rainfall. Since salinity is measured from surface grab samples, values at depth may remain high, and the quick return of high salinity suggests limited mixing. This underscores a methodological limitation and points to the need for follow-up studies to better understand how short-term salinity dynamics are affected by rainfall.

The inter-annual variability in water levels and corresponding upstream discharge, including both the total discharge and the timing of the LDP, directly contributes to salinity variability in the delta ([Fig. 6](#)). In particular, pronounced negative water level anomalies occurred in 2015–2016 and 2019–2020 ([Fig. 7a](#)), coinciding with salinity extremes at the monitoring sites ([Fig. 2](#) and [Fig. 4](#)). Therefore, the non-seasonal factors contributing to discharge fluctuations are assessed. While ENSO controls much of the rainfall patterns in the Mekong River Basin and is the primary natural cause of drought and flood conditions, as seen in the monsoon seasons of 2015 and 2019 and their respective subsequent dry seasons ([Apel et al., 2020; Fok et al., 2018; Xue et al., 2011](#)), anthropogenic interventions can amplify these discharge fluctuations. This amplification in discharge fluctuations since the onset of the mega-dam era in 2010 has led to either very long or very short LDPs ([Fig. 5a](#)). Additionally, early dry-season discharge levels have become highly

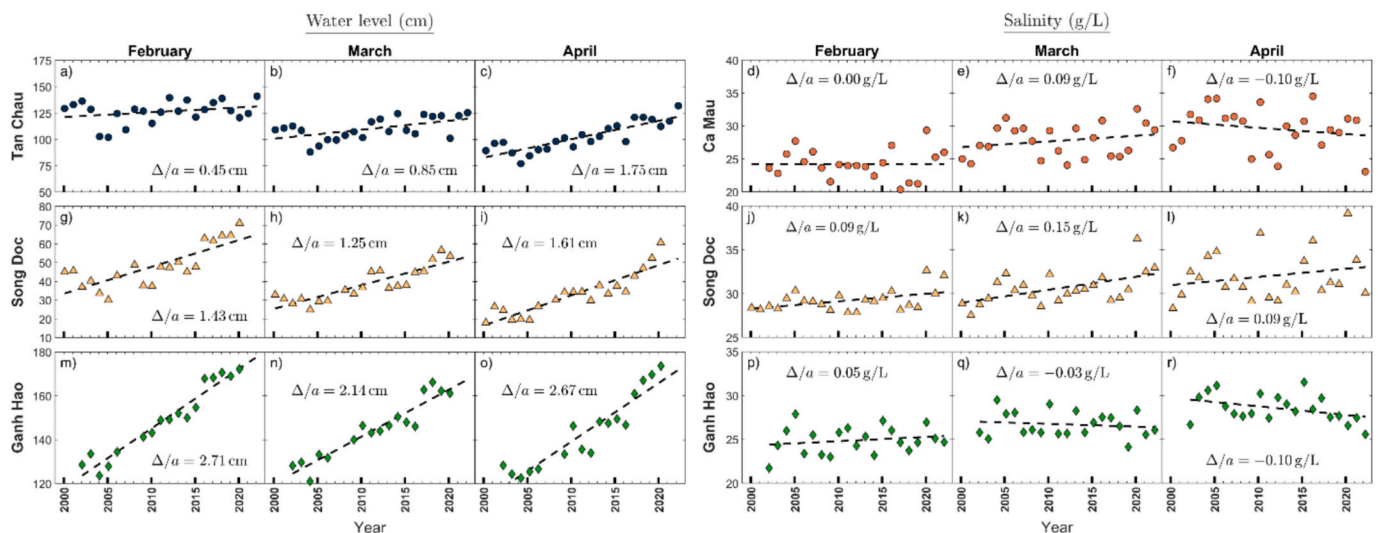


Fig. 8. (a-c, g-i, m-o) Monthly mean water level trend for February, March and April at the monitoring stations Tan Chau, Song Doc and Ganh Hao and (d-f, j-l, p-r) monthly mean salinity trend (of daily maximum values) for February, March and April at the monitoring stations Ca Mau, Song Doc and Ganh Hao.

variable, sometimes being similar to or higher than those of the pre-dam era (e.g., 2012 and 2014), and sometimes reaching unprecedentedly low discharge levels (Fig. 5a, c), promoting extreme SWI (e.g., 2016 and 2020).

Dam operation and the management of reservoirs significantly alter the yearly distribution of discharge volume to mitigate extreme floods and low flows (Binh et al., 2020; Lu and Chua, 2021). As demonstrated by trend analysis, water levels at Tan Chau are increasing in the dry season months February to April (Fig. 8), despite an overall declining trend (Fig. 7). Throughout the study period, early dry season discharge minima have declined steadily, with new record lows reached repeatedly (Fig. 5c), particularly in the post-dam era. At the same time, peaks in higher-discharge years, such as 2012, 2018, and 2022, also show a decreasing volume of early dry season discharge in that chronological order. The coastal stations SD and GH show an increasing trend in salinity in February (Fig. 8j, p), which, based on the analysis presented here, is likely attributable to reduced early dry season discharge between November and February due to upstream water management (Fig. 5c). While CM has also experienced high variability in salinity levels, the trend for February suggests a more consistent pattern (Fig. 8d). In March, the rate of salinity increase becomes significantly more pronounced at CM and SD (Fig. 8e, k). During this month, water levels at SD and GH show notably slower rates of increase compared to the preceding and following months (Fig. 8h, n). At the same time, water levels at Tan Chau continue to rise (Fig. 8b), indicating that the lower water levels at SD and GH are due to local sluice gate management rather than upstream discharge, which typically close at the end of February to prevent SWI (Hoanh et al., 2009). While sluice gates help to reduce SWI in protected zones, they can lead to higher salinity downstream (Danh et al., 2024). This effect is evident in the increased salinity levels, as numerous sluice gates were constructed along the Ganh Hao and Ong Doc Rivers to protect secondary channels from SWI, as well as in the neighbouring provinces of Kien Giang and Bac Lieu, to protect them from SWI originating in CMP. (Nguyen and Nguyen, 2023). At GH station, a slight declining trend is observed for salinity in March (Fig. 8q), which can be explained by the increased upstream discharge starting in February, gradually reaching GH through the canal network connected to the Hau River (Fig. 1), but not at SD or CM yet. In April, the increased discharge begins to affect salinity at CM as well, leading to a shift in the trend to a decline (Fig. 8f), similar to GH (Fig. 8r). However, SD continues to show increasing salinity rates (Fig. 8l), not benefiting from increased upstream discharge. The increase in salinity at SD and the decrease at CM and GH in April, as observed in the long-term trend analysis (Fig. 8f, l, r), are reflected in the 2020 case, where salinity levels at GH and CM decreased rapidly in April, while at SD, salinity continued to rise, reaching nearly 45 g/L in May (Fig. 3h). At SD, hypersaline conditions with salinity well above seawater levels of 35 g/L occurred in 2010, 2016 and 2020 (Fig. 3b, e, h). During periods of low river discharge, high temperature and low humidity conditions, accelerated in those years by El Niño episodes (Nguyen et al., 2014), elevated evaporation rates can lead to the accumulation of solutes and therefore salinity levels well above 35 g/L (Mikhailov and Isupova, 2008). At river mouths, where the monitoring stations are located, the development of a maximum salinity zone can evolve, temporarily blocking freshwater from reaching the sea (Wolanski, 1986). In addition, differences in tidal amplitude between the Gulf of Thailand and the East Sea can alter river flow direction during the dry season, potentially creating stagnant water zones in CMP when opposing forces reach equilibrium (Hoanh et al., 2009; Le et al., 2007), eventually promoting evaporation and concentration of solutes. In addition, while salinity levels are expected to decrease landwards, in the drought years of 2010, 2016, and 2020, salinity levels at the inland station CM exceeded those at the coastal station GH. Since both stations are located along the Ganh Hao River, additional processes, particularly evaporation, are likely factors contributing to this observation. Regarding observed salinity extremes, this phenomenon has not been previously documented for the MD and is

typically observed in arid regions, such as the reversed estuaries in Western Africa and Australia (Mikhailov and Isupova, 2008; Wolanski, 1986). These salinity extremes are likely confined to areas near river mouths and further inland, where stratification and evaporation are more pronounced, and are not expected to extend into the Gulf of Thailand or the East Sea, where salinity levels are generally more stable and remain at or below 35 g/L (Ascharyaphotha et al., 2008; Guo et al., 2021; Limsakul et al., 2023; Zeng et al. 2018). Furthermore, complexities of salt transport, such as mixing and stratification as well as estuarine circulation might add to observed salinity conditions (Tran et al., 2024c; Eslami et al., 2021b; Geyer, 2010). However, these processes must be further investigated.

Extreme events can cause abrupt and significant impacts that may be overlooked when focusing solely on trends and gradual changes (Vogel et al., 2019). As shown in Fig. 5, years of extreme salinity share an early onset and long duration of the LDP, along with persistently low water levels and discharge at Tan Chau (Fig. 7). In 2010, 2016 and 2020, discharge remained low over the entire period from November to June (Fig. 4). The large Xiaowan and Nuozhadu reservoirs, together accounting for around 85 % of the Lancang Basin's total storage, operated normally during the 2019–2020 dry season despite low rainfall in 2019 (Vu et al., 2022b). The Lancang Basin, located in China and also referred to as the Upper Mekong River Basin, forms the upper reach of the Mekong River and contributes about 55 % of the average annual flow measured in Northern Thailand, making it a key driver of the river's hydrology. By the end of 2019, most reservoirs showed reduced storage, and it is suggested that, due to concerns over another dry year and its potential impact on hydropower production, water releases were limited (MRC, 2022), which likely contributed to an early onset of the dry season, as indicated by the LDP (Fig. 5a). The large reservoirs in China usually start filling up in June and July (MRC, 2022) and are refilled until the end of October (Li et al., 2017). When rainfall began in the monsoon season of 2020, reservoirs were replenished first, rapidly reaching the same storage levels as in the rainy year of 2018 (MRC, 2022), which arguably contributed to the prolongation of the LDP in the delta, resulting in extreme salinity in 2020. In addition, Lu and Chua (2021) noted that the untimely filling of the newly constructed Xayaburi dam in October 2019 in Laos had a significant influence on extreme salinity levels in the MD in the dry season of 2020 as well.

In conclusion, reduced rainfall during the preceding monsoon season results in low reservoir storage levels across the Mekong River Basin, prompting reservoir operators to prioritize reservoir replenishment at the start of the early monsoon season, thus delaying the transition from the LDP to the high discharge period. Since depleted reservoir conditions typically coincide with more intense dry seasons, the reduced early monsoon discharge caused by this management practice exacerbates SWI in the delta, as observed by Bui et al. (2023) and illustrated in Fig. 4. Furthermore, the monsoon onset has been shifting later by approximately two to four days per decade (Pham-Thanh et al., 2021) and the early monsoon period coincides with the lowest annual water levels in the delta (Hoang et al., 2019). The simultaneous occurrence of these conditions prolongs the LDP in some years (Fig. 5a) and causes extreme SWI events (Fig. 6), while in other years the increase in late dry season discharge (Fig. 5c) mitigates SWI.

Similar to the situation observed in 2019–2020, the same processes likely contributed to the severe SWI event of 2015–2016, with 2015 showing reduced rainfall due to El Niño. In the dry season of 2015 to 2016, critical SWI occurred 1.5 months earlier than usual (Nguyen, 2017). The case of the extreme SWI event in 2010 differs slightly as the preceding year 2009 was not particularly dry, but the commissioning of the large Xiaowan dam during this period may have contributed to the late end of the LDP in week 24 (Fig. 5a), and especially to the lowest average discharge recorded during the LDP in the study period, thereby promoting SWI. The Nuozhadu Dam, which has the highest capacity in the entire Mekong River Basin (5,850 MW) and the second largest reservoir volume (23,703 Mm³), required nearly half a year to fill after

its completion in 2012 (Lu & Chua, 2021; Ang et al., 2023). This may explain the early onset of the LDP in 2013, as no climatic explanation is apparent, given that the period from May 2010 to early 2014 was dominated by La Niña conditions, typically associated with increased rainfall. Together, these examples underscore the critical role of reservoir management in controlling the hydrological regime of the Mekong River and its influence on SWI in the delta.

Another impact of water management becomes evident at the Tonle Sap Lake in Cambodia, where reduced monsoon-season discharge has led to less frequent flood pulses, which historically filled the lake (Lu and Chua, 2021). Therefore, the Tonle Sap Lake does not reach sufficient water levels necessary to discharge freshwater into the delta during the dry season, when the water level in the Mekong River should be lower than that of the lake (Arias et al., 2014; Cochrane et al., 2014; Eslami et al., 2021a). As a result, the reduced discharge from Tonle Sap Lake does not contribute to the freshwater gradient and, therefore, fails to counteract SWI. For instance, during the 2015/2016 drought event, the MD experienced extreme low peak flow and volume, which can be partly explained by the decreased inflow and outflow of the Tonle Sap Lake (MRC, 2022). Data show that the reverse flow from the Tonle Sap Lake into the Mekong River in 2010, 2015 and 2016, as well as 2020, was significantly reduced compared to historical data (MRC, 2022). On the other hand, in rainy years such as 2014, 2017 and 2018, the duration of the LDP was only between seven and ten weeks, much shorter than in the pre-dam era (Fig. 5), highlighting that upstream reservoir management can also be beneficial for SWI control. In conclusion, it appears that upstream reservoir management amplifies discharge patterns in both directions.

Overall, the data analyses indicate that the main drivers altering the hydraulic pressure gradient between freshwater and seawater in favor of SWI events are reduced rainfall in the previous year across the Mekong River Basin, combined with little to no rainfall during the affected dry season. Additionally, an early onset of the dry season and a delayed onset of the rainy season, resulting in a prolonged LDP, appear to have significantly contributed to extreme salinity levels. Finally, these drivers are strongly influenced by anthropogenic interventions, such as upstream dam operations and local sluice gate management, causing substantial inter-annual salinity variability.

5.2. Future development of seawater intrusion

As demonstrated for the locations SD and GH, land subsidence calculated through RSLR trends after Nguyen et al. (2023) amount to 1.27 cm/a and 1.75 cm/a for the period 2000 to 2019, respectively, and increasing rates of 1.98 cm/a and 2.35 cm/a in the period 2010 to 2019. The more recent subsidence rates are notable higher than previously calculated at GH (Nguyen et al., 2023) and in the same value range at SD, which was not assessed before. However, the calculated rates are consistent with recent remote sensing land subsidence studies in the area (Dörr et al., 2021, 2024). In general, continuous land subsidence substantially contributes to increased RSLR and therefore promotes increasing rates of SWI (Loc et al., 2021a; Savenije, 2012). Each successive decrease in total dry-season discharge in 2010, 2016, and 2020 led to progressively higher record salinity levels (Fig. 5), and RSLR can be considered a major factor for this observation. In the aforementioned years, the effect of RSLR could not be compensated for. In addition, after 2016, water levels at SD and GH show no negative anomalies in the long-term trend (Fig. 8d, f), not even in 2020, despite a pronounced negative discharge anomaly at Tan Chau (Fig. 8b), suggesting that land subsidence is having an increasingly significant and lasting impact on coastal water levels and, consequently, salinity. Continuous land subsidence amplifies the impact of extreme events, while extreme events can, in turn, accelerate land subsidence (Miller et al. 2020, Huning et al. 2024). The analysis conducted here suggests such a relationship for the 2016 event, though further investigation using post-2020 water level data is needed to determine whether this also applies to the 2020 event.

From this perspective, three major conclusions can be outlined:

- 1) To mitigate the impacts of continuous RSLR, maintaining sufficient upstream dry-season discharge in the future is crucial, as current water management practices and competing demands already limit discharge availability. As RSLR continues to increase, discharge must also be increased to balance the hydraulic forces to effectively counteract SWI.
- 2) The reduction of discharge in the early dry season, November to February, promotes SWI for the southernmost MD. The dry season starts notably earlier in dry years, and while dam operations during the late dry season increase discharge along the main branches of the Mekong River in the MD, these higher discharge levels do not reach CMP quickly enough, causing high SW levels. Sufficient discharge in the early dry season is crucial, which is strongly affected by upstream reservoir filling, predominantly in October (Li et al., 2017). Amongst other negative effects of upstream dams (Binh et al., 2020), altered discharge patterns caused by upstream reservoir operation apparently contribute considerably to hydrological drought and SWI events in the southernmost MD, which was previously suspected but had not been confirmed through salinity data analysis (Lu and Chua, 2021).
- 3) In years when upstream discharge is significantly reduced, either due to negative rainfall anomalies and/or reservoir management, an immediate salinity rebound effect must be expected, leading to gradually more severe SWI events in the upcoming years, progressively accelerated by RSLR, which is already visible in the data (Fig. 2 and Fig. 5). Overall, cumulative factors, including continuous SLR, land subsidence, a later onset of the rainy season, intensifying rainfall anomalies, rising temperatures and lastly anthropogenic interventions such as sand mining and the construction of additional upstream dams are expected to further exacerbate SWI in the MD and CMP (Allison et al., 2017; Nguyen et al., 2014; Park, 2024; Pham-Thanh et al., 2021; Phan et al., 2020; Tamura et al., 2020; Yuen et al., 2022). The delta has become increasingly vulnerable, even to mild natural events (Eslami et al., 2021b), likely due to these contributing factors that add upon each other. This vulnerability may be amplified by human-induced cascading feedback loops. For instance, reduced rainfall prompts adjustments in upstream reservoir management, as seen in 2019 affecting the 2020 dry season, and increases agricultural water demand, further worsening the initial water shortage. In conclusion, as variability increases, long-term trends become increasingly less reliable. Extreme events have a lasting impact that extends beyond its duration. For example, progressive SWI leads to the accumulation of solutes in farmland soils, which often cannot be flushed out at the same rate as they are being introduced, thereby persistently affecting soil quality adversely (Loc et al., 2021b; Tarolli et al., 2024). In addition, farmers often cannot financially compensate a year of yield loss, which might explain the high rates of outmigration in CMP, with nearly 3 % in 2010 and between 1 % and 2 % after 2018 (GSOV, 2024).

5.3. Mitigation approaches for seawater intrusion

Risks and adaptation strategies are widely discussed for many large delta systems worldwide (Cremin et al., 2023), with the MD and CMP being no exception (Gustafson et al., 2018; Karlsrud et al., 2017; Nhung et al., 2019). In summary, these measures include protective constructions such as sluice gates, seawalls and breakwaters (Danh et al., 2024; Luom et al., 2021; Vu et al., 2022c), as well as natural solutions such as mangrove reforestation and increasing the sediment budget for delta stabilization (Besset et al., 2019; Tinh et al., 2022; Veettil et al., 2021). Adaptation strategies encompass land use and crop change and the utilization of alternative water resources in the dry season, such as rainwater harvesting and storage (Loc et al., 2021b; Pham et al., 2023; Tran et al., 2024b; Vu et al., 2022a). Lastly, research often highlights the

need to reduce or stop sand mining to prevent SWI as well as groundwater overexploitation to mitigate land subsidence (Dörr et al., 2023; Eslami et al., 2019a; Kondolf et al., 2022; Loc et al., 2021a). Building on the findings and insights from this study, concepts for reducing the risk of SWI extremes in the MD can be enhanced and further developed. In particular, Binh et al. (2020) proposed an early release of water from upstream reservoirs in case of emergency. As the present study shows, an increase of early dry-season discharge would greatly benefit the MD and is crucial for CMP to reduce SWI extreme events (e.g., Fig. 5). In the long run, a managed increase of dry-season discharge is necessary in any case, as RSLR will further promote SWI. As shown here, adapted and integrated upstream water management is already reducing SWI in some years and has a large potential for overall SWI control, but mismanagement must be avoided as it triggers and enhances extreme SWI like in 2020. Therefore, storage of sufficient freshwater volumes to overcome critical episodes of water scarcity is crucial. While it is questionable if this can be achieved within the delta alone, transboundary efforts are necessary to rethink upstream reservoir operation. The results of this study suggest that restoring the Tonle Sap Lake's past capacities, as it once played a significant role in supporting dry-season discharge, especially between November and February (Pokhrel et al., 2018). The lake could serve as an optimal buffer for managing discharge variability. This would benefit not only the delta, but also the farmers and ecosystems in Cambodia, which have been struggling with decreasing water levels since major upstream dam operations began in 2010 (Sithirith, 2024). Under the current conditions, the Tonle Sap Lake does not receive enough freshwater to provide these functions (Jiang et al., 2024) and therefore engineering and infrastructure solutions are proposed to sufficiently fill the lake in the rainy season. However, the inland waterway project Funan-Techo Canal in Cambodia, intended to be finalized in 2028 and suspected to further reduce river flow into Vietnam, just recently increased tensions about water resources and environmental impact in the region (Normandin et al., 2024; Tran et al., 2024b). In addition to transboundary solutions, local efforts are necessary to cope with SWI (Tran et al., 2021). Building on previous studies (e.g., Tran et al., 2024b), which suggest that effective sluice gate management is crucial in preventing SW, especially further inland, this study provides new support for this concept from a different perspective. Analyses have shown that river system complexity and vulnerability to water flux variations shows an inverse relationship (Tejedor et al., 2015a,b). In the lower MD, the main pathways for SWI involve relatively few rivers (Fig. 1), characterizing the MD as less complex compared to many other delta systems. This inherent vulnerability, in fact, presents an opportunity for effective management and prevention of SWI by constructing well-managed sluice gates.

6. Conclusion

By combining long-term salinity, upstream discharge, and coastal water level records with a focus on inter-annual dynamics, this study developed a novel and integrated approach to assess the drivers of SWI in the MD. The use of time series analysis, including monthly dry-season trends in water level and salinity, long-term trends from both original and deseasonalized water level records (2000–2022), the introduction of the LDP concept, and the estimation of relative sea level rise proved effective in capturing both natural variability and anthropogenic influences.

The results demonstrate that SWI dynamics are primarily governed by fluctuations in the total volume and timing of upstream freshwater discharge. Non-seasonal fluctuations, driven increasingly by anthropogenic factors such as reservoir operations and flow regulation, now control a significant portion of the Mekong River's hydrological regime. This shift alters the freshwater–seawater gradient and amplifies SWI risks. At the same time, the findings show that rethought and adapted upstream water management presents a strong opportunity to mitigate SWI impacts by strategically increasing freshwater discharge early in the

dry season, thereby enhancing the MD's resilience. In parallel, land subsidence continues to accelerate relative sea level rise, further exacerbating salinity intrusion. These findings reveal the cumulative impacts of multiple stressors acting across spatial and temporal scales and underscore the need for adaptive, coordinated water management strategies. The study provides new insights into the long-term vulnerability of monsoon-influenced coastal deltas to SWI. Beyond the MD, the applied approach and identified interactions offer valuable lessons for other regions where climate change, land subsidence, and upstream water use affect the freshwater–saltwater balance.

Within the MD, future work should build on these insights through integrated long-term SWI modelling. At the same time, detailed analyses of short-term salinity fluctuations in relation to tidal regimes and local water management will be essential to complete the understanding of salinity variability across all time scales. The methods applied here can also be extended to additional monitoring stations, and the relative impact of individual contributing factors should be further quantified.

Ultimately, strengthening delta resilience to future SWI challenges will require not only effective local measures but also the recognition of transboundary hydrological linkages and the integration of dynamic pressure factors into flexible responsive water governance frameworks.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability of the study. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Jonas Bauer: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Felix Dörr:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Hoang Thai Duong Vu:** Writing – review & editing. **Andreas Schenk:** Writing – review & editing, Investigation. **Hoan Viet Tran:** Writing – review & editing, Data curation. **Van Cam Pham:** Writing – review & editing. **Nicolas Börsig:** Writing – review & editing, Project administration. **Roderick van der Linden:** Writing – review & editing. **Ngoc Hoa Nguyen:** Writing – review & editing. **Elisabeth Eiche:** Writing – review & editing, Resources, Project administration. **Stefan Norra:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We gratefully thank the National Center for Hydro-Meteorological Forecasting of Vietnam, the Southern Institute of Water Resources Research, the National Center for Water Resources Planning and Investigation Vietnam as well as the Department of Natural Resources and Environment Ca Mau for providing monitoring data used in this study as well as their support in the field, scientific and personal exchange. A special thanks goes to all project partners contributing to this work. This research was conducted in the frame of the project “ViWaT – Vietnam Water Technologies” funded by the German Federal Ministry of Education and Research (funding reference: 02WCL1474A). We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology, Germany.

Data availability

Data used in this study can be provided on request to NCHMF and/or NAWAPI, Hanoi, Vietnam, or by directly contacting the authors of this study, who can assist with access and facilitate contact with the aforementioned institutions.

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Tidal Control of Salinity Dynamics and Seawater Intrusion in the Southern Mekong Delta, Vietnam

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Abstract

As sea levels rise and freshwater resources decline, seawater intrusion (SWI) poses an increasing threat to many delta systems worldwide. Effective mitigation strategies for SWI require a fundamental understanding of underlying processes, which classical numerical and machine learning models often struggle to provide yet. In the Vietnamese Mekong Delta, SWI recurs annually during the dry season, adversely affecting agriculture and ecosystems. Building on previous work that analyzed interannual salinity variations in Ca Mau Province from 2000 to 2022, this study examines the sub-seasonal interplay between tide-driven water level fluctuations and salinity. Time series analyses, including harmonic analysis, were applied to data from three monitoring stations in Ca Mau Province between January and June in 2017 and in 2018. Results show that co-oscillations of two different tidal regimes in the east and in the west influence water level patterns and ultimately salinity dynamics. Frequency analyses revealed salinity variations at major tidal frequencies. A sliding window Harmonic Least Squares approach captured the non-stationary behavior expected in estuarine systems at all three stations, with weighted R^2 values of 0.85 to 0.98 for water level and 0.53 to 0.73 for salinity. The

findings of this study highlight the spatiotemporal complexity of salinity variations in the study region and underscore the importance of process-based understanding for developing reliable numeric models and effective SWI mitigation strategies.

Keywords: Seawater Intrusion, Estuaries, Time Series Analysis, Harmonic Analysis, Tides, Mekong Delta, Ca Mau Province

1 Introduction

Seawater intrusion (SWI) amplified by climate change and anthropogenic modifications of hydrological regimes is a major challenge for coastal regions and delta systems globally (Lee et al., 2025; Mohammed and Scholz, 2017). The inland progression of seawater into river and surface water systems is a dynamic and complex process with distinct temporal and spatial characteristics. SWI leads to the degradation of valuable freshwater resources and agricultural farmland (Bucx et al., 2014; Nicholls et al., 2021; Rahman et al., 2019). The high socio-ecological impact of SWI is particularly pronounced in the low-lying Asian mega-deltas (Bucx et al., 2014), adversely affecting drinking water resources and agricultural production, threatening food security both regionally and beyond (Schneider and Asch, 2020). The Vietnamese Mekong Delta (MD) inhabits more than 17 million people and ranks among the most agriculturally productive river deltas in the world (Eslami et al., 2021b; GSOV, 2024; Park et al., 2022). Farmers in the MD critically depend on sufficient freshwater resources for agriculture (Pham et al., 2023), but these resources are sharply declining due to SWI (Binh et al., 2025; Normandin et al., 2024). Meanwhile, groundwater is being heavily overexploited, leading to a sharp decline in hydraulic heads (Duy et al., 2021; Hoan et al., 2025) and triggering both land subsidence and salinization (Bauer et al., 2022; Dörr et al., 2025a; Minderhoud et al., 2017). As land subsidence is an existential threat in the low-lying MD (Dörr et al., 2025b; Kondolf et al., 2022), a further decline of freshwater resources due to riverine SWI must be prevented.

Consequently, given that progressive SWI driven by multiple factors poses a major challenge to sustainable development in the MD, research efforts in recent years have intensified to identify its drivers and to develop mitigation strategies (Bauer et al., 2025; Loc et al., 2021b; Park et al., 2022; Tran et al., 2024a).

In estuarine systems, riverine SWI occurs across multiple time scales as a result of variations in the hydraulic pressure gradient between river discharge and sea levels (Savenije, 2012). Understanding long-term trends and interannual fluctuations is critical for establishing baseline conditions, detecting emerging risks, and for informing sustainable development strategies. In the MD, seasonal salinity levels and interannual variations are primarily controlled by upstream river discharge (Bauer et al., 2025; Binh et al., 2020a).

Superimposed on these large-scale patterns are high-frequency salinity variations driven by tidal-controlled water level fluctuations on the diurnal to fortnightly scale, which are equally essential to understand (Cai et al., 2025), particularly in a complex multi-channel system such as the MD (Eslami et al., 2019; Nguyen and Savenije, 2006). Short-term, tide-driven water level dynamics influence key estuarine processes, which are not simple residuals of gravitational forcing but result from nonlinear interactions, which can reshape the net salt transport and modulate the inland extent of SWI even under stable upstream conditions (Geyer and MacCready, 2014). Nonlinear interactions between tidal forcing and river discharge can amplify or dampen SWI (Savenije, 2012). Short-term excursions, especially during spring-neap cycles or low-discharge periods, can push the system over critical ecological or management thresholds, exposing freshwater-dependent ecosystems, agricultural areas or water supply facilities to sudden and extreme salinity levels that cannot be predicted from long-term averages alone (Wang et al., 2022). In periods that are characterized by reduced river discharge and precipitation, the tidal influence on salinity levels increases (Gaiolini et al., 2023). Due to upstream reservoir management and intensifying hydrological droughts, low discharge periods of the Mekong River can emerge earlier and last longer (Bauer et al., 2025). Accordingly, a recent study found that the

tidal influence along the Mekong River is accelerating due to anthropogenic influences (Nguyen et al., 2025).

Understanding short-term dynamics is essential for improving process-based models and numerical simulations under both current and changing boundary conditions, thereby supporting adaptive management, early warning systems, and community resilience (Chen, 2023). In the MD, this is particularly crucial because hydrological conditions are heavily influenced by ongoing extensive dam development, sand mining and canal projects (Jordan et al., 2020, 2019; Kumar et al., 2024; Tran et al., 2024b), resulting in alterations to the Mekong River's discharge and coastal morphology (Ang et al., 2024; Lu and Chua, 2021).

Most previous studies directly employed various modelling approaches to simulate and predict water-level-dependent salinity levels and the extent of SWI in different areas of the MD, but mostly relied on short periods of in-situ observations used for calibration and validation, often ranging between a few days to weeks (Eslami et al., 2021a; Khang et al., 2008; Lam, 2020; Tran et al., 2024b; Tran et al., 2019). Assuming a straightforward relationship between the two parameters and extrapolating it over the long term may result in inaccuracies and potentially false predictions, as this approach overlooks the full spectrum of sub-seasonal variability driven by spring-neap cycles and nonlinear interactions between tidal forcing and upstream discharge. So far, tidal characteristics along the MD and water level fluctuations in the tide influenced rivers are mostly described with a seasonal resolution (Nguyen et al., 2023; Phan et al., 2019), overlooking finer-scale diurnal and fortnightly tidal dynamics.

In this context, machine learning techniques hold considerable potential for both short- and long-term predictions (e.g. Guillou et al., 2023; Qian et al., 2022). But without a fundamental understanding of the underlying processes, the implementation of countermeasures will remain ineffective.

Therefore, the objective of this study is to analyze short-term, high-frequency salinity variations and the hydrodynamic interactions that govern them, with particular emphasis on the role of tide-driven water-level fluctuations. Harmonic analyses are employed to identify major periodicities and to

delineate stationary as well as non-stationary dynamics for water level and salinity in the periods January to June in 2017 and in 2018. This work complements previous work on interannual SWI dynamics in CMP (Bauer et al., 2025), and completes the picture of salinity dynamics in the southern MD across multiple timescales.

The methods and insights developed in this study will support the implementation and improvement of current SWI mitigation strategies and are transferable to other coastal provinces of the MD, as well as to comparable deltaic regions across Southeast Asia and beyond where similar tidal and hydrological dynamics prevail.

2 Study area

2.1 Overview

Figure 1 shows the location of the MD in Southeast-Asia as well as the river network and the location of the monitoring stations in CMP used in this study. The Vietnamese MD, one of the largest river delta systems globally, together with the adjacent metropolis of Ho-Chi-Minh-City, is home to 27 million people (GSOV, 2024). The region is renowned for its vast patches of rice fields and aquaculture production, which play a crucial role in ensuring the nation's food security and enhancing its export capacity. Located on the Ca Mau Peninsula, CMP is the southernmost province of Vietnam, covers an area of 5,221 km² and inhabits around 1.2 million people (GSOV, 2024). Please note that the administrative structure of the MD provinces was reorganized in 2025. The nomenclature and representation used in this study refer to the former provincial boundaries.

Outside the provincial capital, Ca Mau City, most residents live in rural areas along an extensive network of rivers and channels (Figure 1b). They are primarily engaged in diverse small-scale aquaculture and agricultural activities, including traditional rice farming in areas protected from SWI and various forms of aquaculture and adapted crop rotation systems, with shrimp farming being particularly prominent (Nguyen et al., 2019a; Thong et al., 2010; Vu et al., 2022). These activities

depend on sufficient water resources, and in the past, local water conflicts have emerged over the competing needs for freshwater in rice farming and brackish water in shrimp farming (Hoanh et al., 2009; Nguyen et al., 2019b).

The region's climate is governed by the tropical monsoon, characterized by a dry season from approximately December to April and a rainy season from May to November. Most precipitation occurs during the rainy season, with annual rainfall reaching up to 2,500 mm in CMP (Dang et al., 2020; Pham-Thanh et al., 2021). Mean monthly temperatures range between 25 °C and 30 °C with humidity levels above 80 % throughout the year (GSOV, 2024). The average elevation in 2018 was below 0.8 m above mean sea level, with many areas in CMP below that average (Minderhoud et al., 2019a; Zoccarato et al., 2018). The study area is surrounded by the sea on three sides, making it exceptionally prone to SWI and coastal erosion.

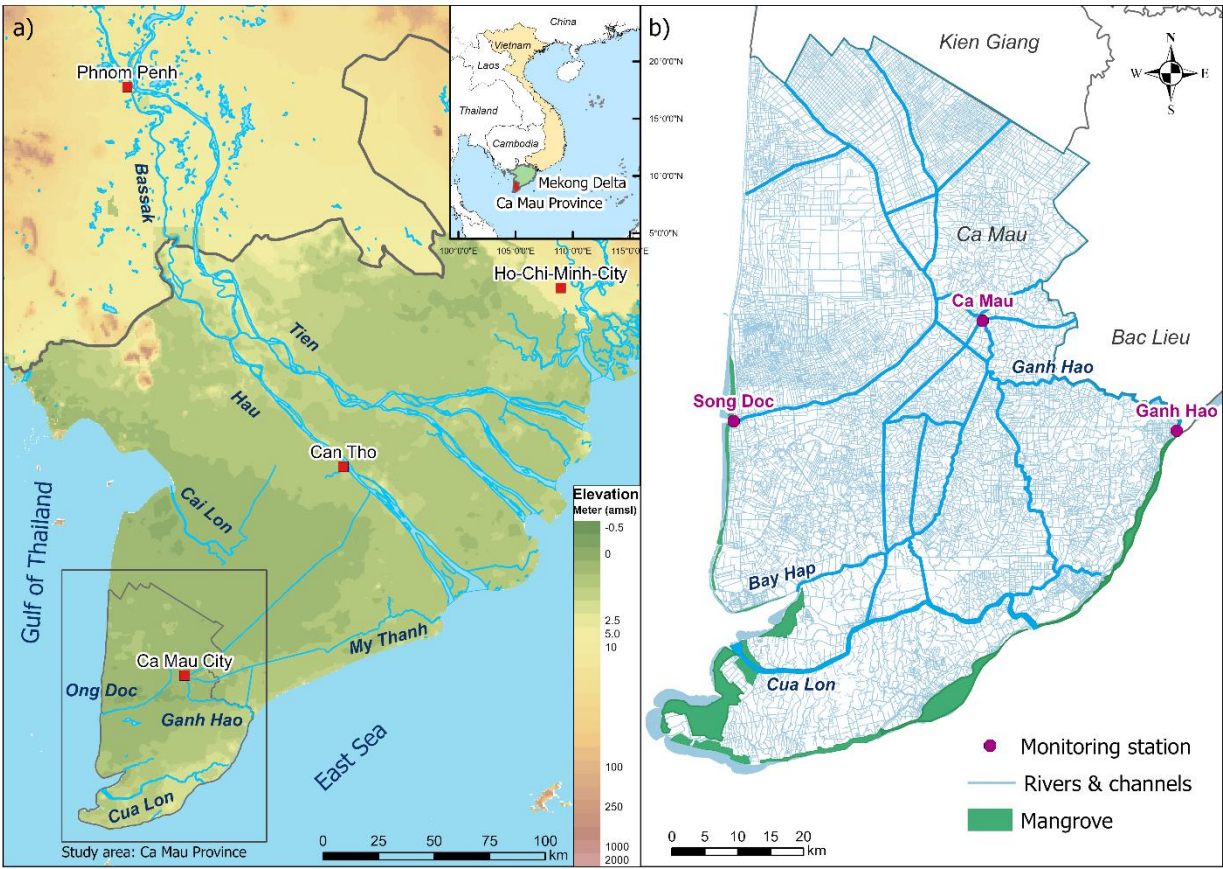


Figure 1 a) Overview of the Mekong Delta and its location in Southeast Asia. Surface elevation in 2018 (not linear) in the Mekong Delta from Minderhoud et al. (2019b). Surface elevation outside the MD from the Global Topographic 30 Arc-Second

Digital Elevation Model GTOPO30 (EROS, 2017). b) Ca Mau Province and its river network as well as the location of the monitoring stations Song Doc, Ca Mau and Ganh Hao.

2.2 Hydrological regime and seawater intrusion

Originating from the Tibetan Plateau and flowing through China, Thailand, Laos, and Cambodia, the Mekong River finally enters Vietnam, delivering freshwater and sediments to the delta before ultimately discharging into the East Sea (South China Sea). Discharge of the Mekong River controls water levels in the delta and is subject to strong seasonal as well as interannual variations (Mohammed et al., 2018). Peak water levels in the coastal areas occur at the end of the rainy season, typically between October in the upper delta and in December in the Ca Mau Peninsula. As the dry season begins, discharge sharply decreases, resulting in lowest annual water levels in the coastal areas in June to July (Schwarzer et al., 2016). The largest proportion of the Mekong River's discharge, almost 90 %, is discharging into the East Sea via its eight main branches, while only a small proportion is flowing through the southern MD plain via the large irrigation canals parallel and perpendicular to the Hau River (Renaud and Kuenzer, 2012). Water infrastructure is omnipresent as the region is characterized by tidal rivers and an extremely dense network of man-made canals, which are used for transportation and irrigation purposes.

Since 2010 an increasing number of upstream hydropower dams and reservoirs substantially alter the discharge patterns of the Mekong River (Binh et al., 2020a). To ensure hydropower production and to mitigate downstream water shortages for agriculture, discharge in the dry season almost doubled in the upper and middle Mekong River Basin and decreased in the rainy season to prevent floods. As a consequence, however, discharge from the Mekong River entering Vietnam slightly decreased in the early dry season (Binh et al., 2021, 2020b), promoting an early dry season onset, an increased duration of the dry season and therefore higher salinity levels (Bauer et al. 2025).

Beyond the seasonal impact of Mekong River discharge on deltaic water levels, tidal forces drive fluctuations on timescales ranging from daily to fortnightly. The MD is classified as a tide-wave

dominated regime (Ta et al., 2002b), with the western part at the Gulf of Thailand (GOT) being more influenced by waves attributed to the southwest monsoon and the eastern part by the tidal regime of the East Sea (Phan et al., 2019). Tidal signals in the dry season, when river discharge is low, can reach as far as Phnom Penh, the capital of Cambodia, which is located 300 km upstream (Hung et al., 2012; Nguyen et al., 2023). Tidal fluctuations are significantly affected by bathymetry and the shape of the coast or basin they propagate (Phan et al., 2019). In the study area, two distinct tidal regimes can be distinguished, with the GOT having a mixed, mainly diurnal system and the East Sea having a mixed semi-diurnal system (Nguyen et al., 1998; Phan et al., 2019). The mixed semi-diurnal tide in the East Sea is identified by two high waters and two low waters of varying amplitude per tidal day. Due to seasonal effects and the spring-neap tide cycles, tidal amplitudes at the eastern coast vary between 1.0 m and 3.8 m, while at the western coast in the GOT tidal amplitudes are much lower with a maximum of about 0.7 m (Hoanh et al., 2009; Phan et al., 2019). In general, the tidal range decreases from the central MD coast along the East Sea southwestward, with lowest tidal ranges at the West Coast and in the GOT (Vu et al., 2025).

In CMP, the rivers Ong Doc and Bay Hap in the west, Ganh Hao in the east, and Cua Long directly connecting the GOT and the East Sea are the primary rivers in the study area affected by SWI (Figure 1). The secondary irrigation channels along these rivers are locally managed via sluice gates and pumping operation to control salinity levels for freshwater rice farming and saltwater related aquaculture (Di Giusto et al., 2021; Hoanh et al., 2009; Nguyen et al., 2020).

On average, river depth is about 3-5 m except for Cua Lon River (5-19 m) and Ganh Hao River (5-14 m). The depths of secondary channels and irrigation canals is generally shallower.

188 **3 Data and Methods**

189 **3.1 Monitoring sites and data acquisition**

190 Salinity and water level data from January to June in 2017 and 2018 were obtained by the National
191 Center for Hydro-Meteorological Forecasting of Vietnam, Hanoi, from three hydrological monitoring
192 stations in CMP: Song Doc (SD), Ca Mau (CM), and Ganh Hao (GH) (Figure 1). These two years were
193 chosen as they provide the most recent continuous datasets for the region and were not affected by
194 severe droughts, reducing complexity in analyzing the salinity–water-level relationship. SD lies about
195 one kilometer upstream on the Ong Doc River near the Gulf of Thailand, GH is located two kilometers
196 upstream on the Ganh Hao River adjacent to the East Sea, and CM is situated roughly 40 kilometers
197 further inland along Ganh Hao River, centrally within CMP (Figure 1). Salinity was measured manually
198 or semi-automatically every two hours, at odd-numbered hours, over approximately three consecutive
199 days, followed by pauses of two to four days. Therefore, approximately half of the days within the
200 measurement period are missing.

201 Measurements were conducted during the dry season and at the onset of the rainy season, between
202 January and June, when the data directly supported local water management decisions, particularly
203 sluice gate operations. Water levels were available in 1-hourly resolution without gaps.

204 Shape files for the river network (Figure 1) were provided by the National Center for Water Resources
205 Planning and Investigation, Hanoi, Vietnam.

206 **3.2 Time series preprocessing**

207 In order to evaluate diurnal to fortnightly salinity variations via harmonic analysis, where 1-hourly
208 timesteps are generally recommended in the context of tidal analysis (e.g. Foreman, 2004), and for the
209 purpose of better overall comparability with the 1-h water level data set, a continuous 1-hour data set
210 for 2017 to 2018 was obtained from the original 2-hour data record with missing days intervals by a
211 two-step linear interpolation. First, data from missing days were interpolated using linear interpolation

with tidal phase alignment to ensure tide-synchronous reconstruction. Missing observations at a given time of a missing day (e.g., measurements at 01:00 am) were estimated by linearly interpolating data recorded at the same time on adjacent days with available observations.

Subsequently, the data was recombined to a continuous 2-hour dataset and linear interpolation was used once more to obtain a continuous salinity dataset with 1-hour sampling. Examples of a two-week period and a one-week period at SD, CM and GH stations with missing days in between is displayed in

Figure 2.

Nguyen et al. (2023) presented an alternative approach to obtain a continuous dataset, in which missing consecutive days of less than one week were spatially interpolated from neighboring monitoring stations. For the present study, this approach is considered inappropriate because local differences between stations in regard to water level dynamics and differences in salinity, as well as different tidal regimes, are too high to justify cross-station interpolation. In addition, data gaps at other monitoring stations in the MD may further impair interpolation. Eslami et al. (2021a) employed model computations to generate 1-hourly datasets for six stations at the mouth of the Mekong River, yet there is potential to enhance the accuracy of their method as the model encountered some challenges to accurately represent the scattered observation values derived from the irregular 2-hourly data. The method presented here can very well replicate the salinity dynamics for missing days at all three stations. However, it must be noted that this interpolation naturally cannot replicate extremes caused by short-term events, such as heavy precipitation or storm surges, and assumes a day-to-day periodicity. In the next step the dataset was synchronized so that each time series spans the period from 4th January to 21st June of 2017 and 2018, respectively, ensuring consistency for direct comparisons.

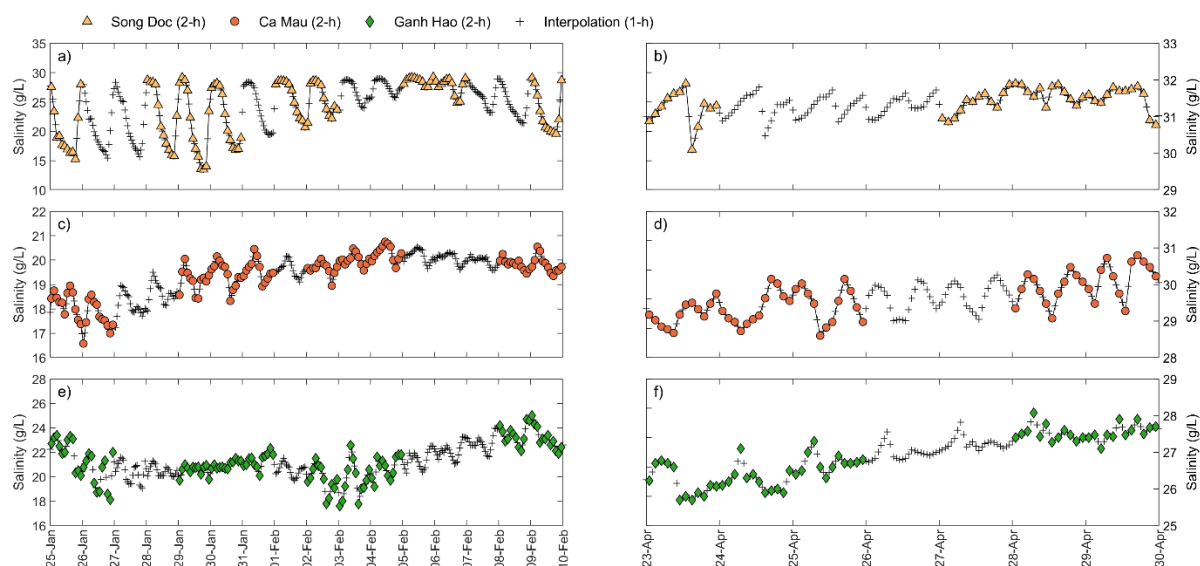


Figure 2. Representative examples of interpolation of discontinuous salinity data at Song Doc, Ca Mau and Ganh Hao monitoring sites in 2018 from 25 January to 10 February (a, c, e) and 23 April to 30 April (b, d, f).

The relationship between tidal water level fluctuations and salinity changes was analyzed using harmonic analysis. The timeseries were detrended using a 45-day moving average (MATLAB's *movmean* function). Detrending improves frequency, amplitude and phase estimates, which can be masked or biased by long-term trends and low-frequency variations, and is a common step in harmonic analysis (e.g. Baranes et al., 2023). A 45-day window is commonly used as a filter or window length in tidal analysis, as it captures three cycles of fortnightly modulation and adequately resolves the major tidal constituents (Lobo et al., 2024). The original time series, the trendline and the detrended time series are shown in Figure 3.

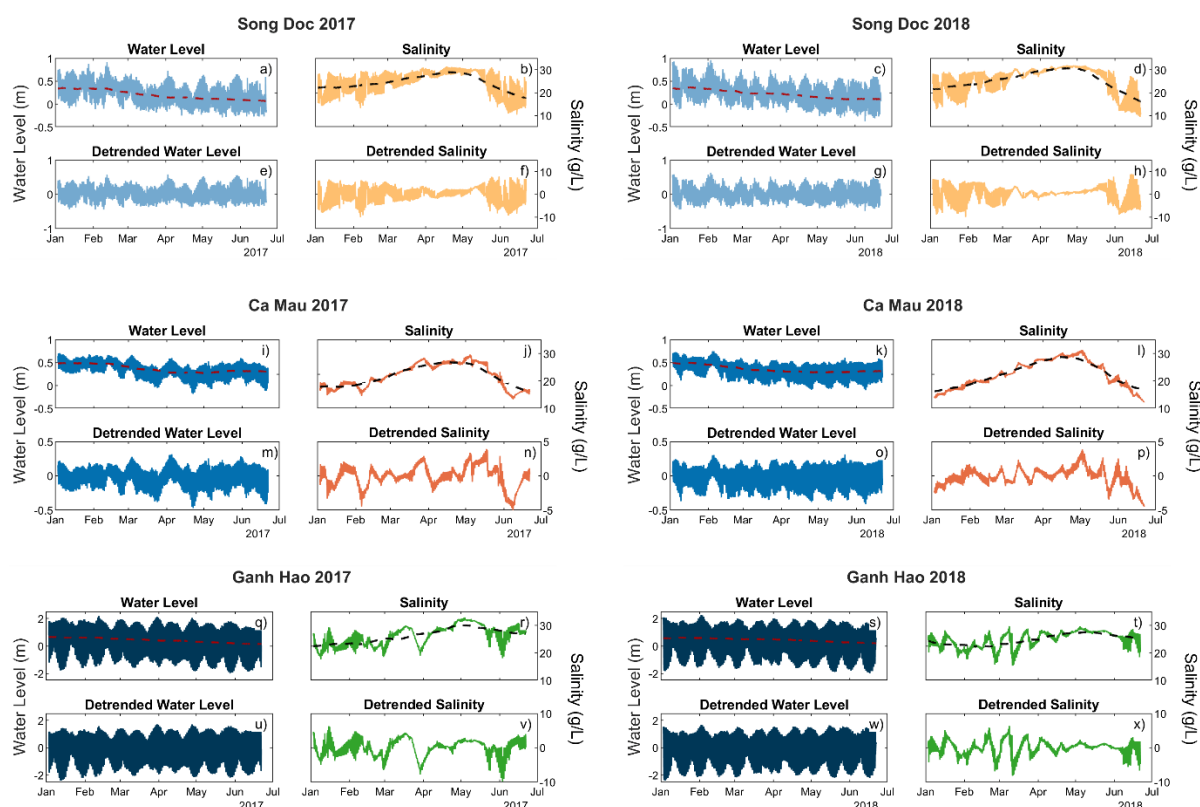


Figure 3 Original time series for water level and salinity at Song Doc (a) to (h), Ca Mau (i) to (p) and Ganh Hao (q) to (x) for January to June 2017 and 2018. The original time series were detrended with a 45-day moving mean. For each station and year, the upper charts show the original data with dashed trendlines and the lower charts the detrended time series respectively.

3.3 Harmonic analysis

In this study, Fast Fourier Transform (FFT) was used to identify dominant periodicities, whereas Harmonic Least Squares (HLS) provided more accurate amplitude estimates, enabled time-series reconstruction to quantify tidal control on salinity, and facilitated the computation of transfer functions to determine time lags of selected tidal frequencies between water level and salinity. All tidal frequencies considered in this study across the different analytical approaches are listed in Annex A.

FFT was applied on the interpolated and detrended timeseries (MATLAB's *fft* function), effectively converting time-domain data into its frequency-domain representation (e.g. Foreman et al., 2009). Dominant frequencies for salinity and water level were identified and well-known tidal constituents

260 (in cycles per day, cpd), including M2 (1.9323 cpd, semi-diurnal lunar), S2 (2.0000 cpd, semi-diurnal
261 solar), K1 (1.0027 cpd, diurnal lunar/solar) and O1 (0.9295 cpd, diurnal lunar) (Kvale et al., 1995;
262 Pawlowicz et al., 2002; Phan et al., 2019) were assigned to obtained dominant peaks. Both amplitudes
263 as well as phases were obtained for each constituent.

264 FFT decomposes the signal into fixed, equally-spaced frequency bins and the obtained frequencies
265 might differ from theoretical frequencies, and across stations and years. However, for the calculation
266 of phase lag between water level (input) and salinity (output), uniform and precise frequencies are
267 necessary, as otherwise the direct relationship is not accessible. To overcome this, HLS estimation was
268 used. HLS is fitting a set of sinusoidal functions with precise and predefined target frequencies, e.g.
269 tidal constituents, to the time series and estimates their amplitudes and phases. HLS has the advantage
270 that it fits exact frequencies into the time series rather than scanning over fixed frequency bins like
271 FFT, effectively separating noise and other non-target constituents to avoid amplitude loss. In addition,
272 HLS can handle gaps and irregular sampling (Schweizer et al., 2021). Therefore, HLS amplitudes are
273 assumed to be closer to the real physical oscillation.

274 HLS was configured with a comprehensive set of fixed astronomical constituents (Mm, MSf, Q1, O1,
275 M1, K1, N2, M2, S2, M3, MK3, M4, MS4). Tidal constituents P1, K2 and MF are not considered
276 individually to meet the Rayleigh criterion, as constituents should be separated by $1/T$, where T is the
277 length of the time series (Foreman et al., 2009; Pawlowicz et al., 2002). If two fitted frequencies are
278 closer than $df=1/T=0.0059$, the columns of the HLS design matrix become nearly collinear, causing
279 large parameter covariance, unstable amplitudes, phases and producing noise-sensitive fits (Codiga,
280 2011).

281 HLS was applied to multiple salinity datasets, including (i) the original 2-hourly timeseries with gaps,
282 (ii) the original 2-hourly timeseries with gaps but detrended, and (iii) the interpolated 1-hourly
283 detrended timeseries previously used for FFT. For each dataset, HLS amplitudes at O1, K1, M2, and S2
284 were extracted from the full-basis fit and compared with FFT amplitudes. Based on the results (see
285 chapter 4.3.2), the 1-hourly detrended series was selected for subsequent analysis as 1-hourly

timesteps are generally recommended for tidal analysis (e.g. Foreman, 2004) and obtained amplitudes are the most consistent. Tidal components were reconstructed from the HLS coefficients and tidal control was quantified as explained variance (R^2) relative to the detrended series. HLS reconstruction was done with two separate approaches to answer two research questions. First, a stationary HLS model over the full time series record was estimated, e.g. SD 2017, and R^2 was calculated for water level and salinity. With this approach it is clarified how well one stationary harmonic model explains the whole time series. Nguyen et al. (2025) pointed out that non-stationary analyses are necessary to capture more dynamics. Therefore, the second approach involves a sliding HLS calculation to investigate how well a local harmonic model explains the water level and salinity data, as non-stationary behavior and phase shifts can be expected in an estuary setting (Lobo et al., 2024; Matte et al., 2013). While longer time series separate frequencies more effectively, shorter windows are able to resolve time variations of tidal patterns (Lobo et al., 2024).

Additionally, for each tidal constituent, a transfer function derived from the HLS coefficients summarizes the salinity response in time, expressed as phase lag, relative to water-level forcing at that frequency. The phase lag was translated into a time lag by taking the fraction of the constituent's cycle represented by the phase and converting it to hours using that constituent's period. Lags were wrapped to the range minus half to plus half a cycle.

For the sliding HLS approach, the harmonic regression in overlapping 45-day windows, advancing by one day, was calculated in the same way as the global HLS fit was calculated. Even though frequency resolution decreases for $T=45$ days, the Rayleigh criterion is still met for the used tidal frequencies.

In each window, a weighted HLS fit was calculated using a Hann taper, where points near the center are weighted higher to effectively reduce spectral leakage and edge artefacts (Babadi and Brown, 2014). The Rayleigh criterion is still met considering a potential increase up to $1.5/T$, as tapering reduces the nominal spectral resolution (Harris, 1978).

Each window's fitted tidal components were then used to generate predictions for every original timestep of that window. As windows overlap, most timesteps receive multiple predictions. To form the final HLS reconstruction, the multiple results for each individual timestep were averaged, improving overall robustness of the fit. As coverage increases in the first 22.5 days and is then constant until it decreases in the last 22.5 days, timesteps in the beginning and end of the time series have less predictions. Therefore, model performance was summarized for each station and year for water level and salinity using two global coefficients of determination. The first is the straightforward unweighted R^2 computed over all timesteps, assigning each timestep equal weights. The second is a coverage-weighted R^2 that uses the number of overlapping windows as weights, giving more weight to time periods supported by more window fits where the estimator is best supported. The coverage-weighted method effectively suppresses poor model performance at edges.

Uncertainty of the 45-day sliding HLS reconstruction was quantified using the analytic covariance of the regression coefficients in each window. From this, two complementary uncertainty measures were derived for every timestep (Matte et al., 2013; Pawlowicz et al., 2002): (i) the mean-fit uncertainty, describing uncertainty of the reconstructed harmonic signal itself, and (ii) the prediction uncertainty, which additionally includes residual variability and thus represents the expected scatter of observations around the HLS reconstruction. In addition, per-constituent amplitude and phase standard errors were estimated using linear error propagation via the delta method (Oehlert, 1992; Pawlowicz et al., 2002). Median values per station and year were summarized to characterize overall HLS reconstruction precision.

4 Results

4.1 Salinity variability

The diurnal amplitude of maximum and minimum salinity values for the 1-hourly salinity time series for January to mid of June in 2017 and in 2018 is shown in Figure 4. Salinity dynamics vary distinctly across the three sites SD, CM and GH. Varying between around 10 g/L and 30 g/L, the maximum diurnal differences of up to 16 g/L are observed in SD during the early dry season in January and the transition period between the dry and rainy seasons in June (Figure 4a). As the dry season progresses, salinity levels at all stations increase in both years, leading to a prominent decrease in the diurnal range. In the course of the dry season, the daily minimum salinities increase faster than the maximum values at all stations in 2017 and 2018. The CM inland station exhibited the smallest diurnal range, not exceeding 5 g/L for the observed years (Figure 4b). In both years and at all stations, salinity does not reach seawater salinity levels of 35 g/L, which was previously observed in years with hydrological drought (Bauer et al., 2025; Park et al., 2022).

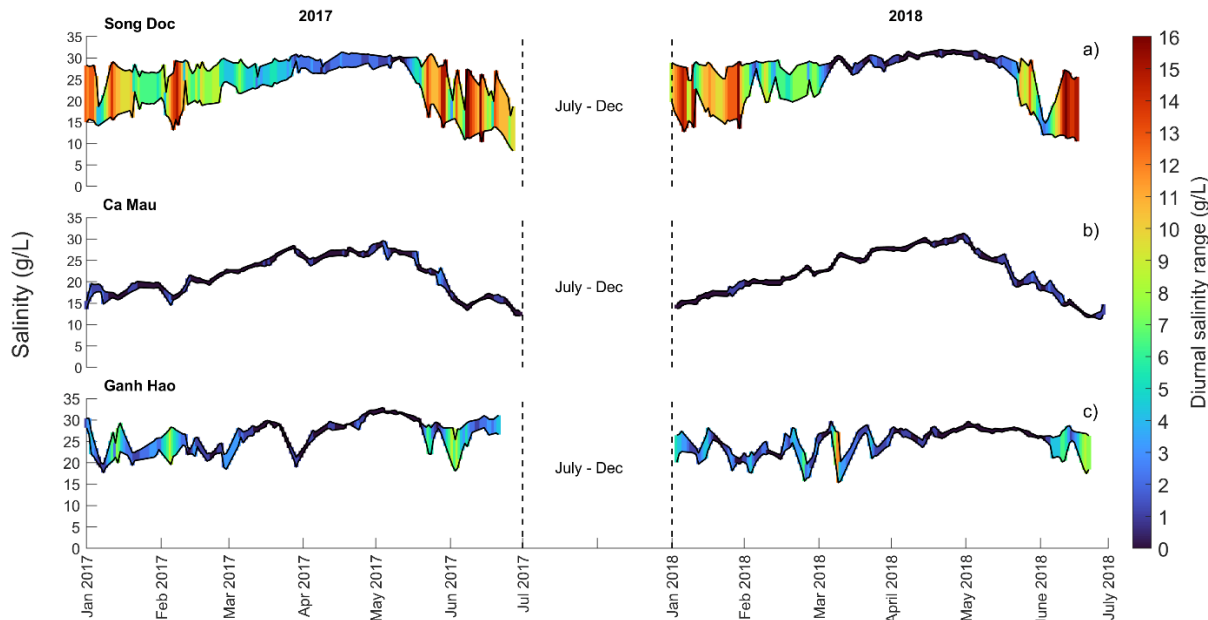


Figure 4. Diurnal salinity range of the continuous 1-h dataset at the three monitoring stations (a) Song Doc, (b) Ca Mau and (c) and Ganh Hao for 2017 and 2018.

4.2 Water level and tides

Variations in water levels and their dynamics can greatly influence salinity in tide-affected rivers, with salinity often responding to the periodic shifts in water levels (van Keulen et al., 2025). To explain the different diurnal salinity dynamics, a detailed characterization of the two tidal regimes in the GOT and East Sea was conducted, represented by SD and GH. Additionally, the water level characteristics at CM were analyzed. Results are presented in Figure 5 exemplary for the year 2018. At GH a tidal cycle with two highs and two lows of different magnitude are observed, while at SD both diurnal and sometimes semi-diurnal tides are present. Tides in the East Sea have a higher amplitude of almost 4 m at GH compared to SD with maximum amplitudes of less than 1 m. Spring tides in the East Sea, when water level and amplitude are highest, occur one to a few days after full and new moon, when the gravitational forces on Earth are at their peak due to the alignment of the moon and the sun (Kvale, 2006). Subsequently, neap tides with lower water levels and amplitudes occur after the first and third quarter. In contrast, at SD station located at the GOT, highest and lowest water levels respond to the declination change of the moon (Figure 5b).

Another aspect observed at GH is diurnal inequality, where one high tide is either higher or lower than the subsequent high tide within the same day (Figure 5f). In addition, semi-monthly inequality is caused by constituents M2 and N2 being in phase every 27.55 days (Kvale, 2006). This can be well observed at GH, as a weaker spring tide is followed by a stronger spring tide (*Figure 5e, f*). Therefore, the tide at GH can be referred to as mixed tide (Mukherjee et al., 2023). In conclusion, tides in the East Sea can be characterized as synodical, mixed-semidiurnal tides with an ideal cycle of 29.53 days and the tides in the GOT as tropical mainly diurnal tides, or equatorial tides, with an ideal cycle of 27.32 days.

In general, these findings are consistent with previous studies (Hoanh et al., 2009; Nguyet-Minh et al., 2025; Phan et al., 2019). However, while previous studies mainly analyzed the tidal regimes on the seasonal scale (Phan et al., 2019), this study analyzed the tidal characteristics in higher resolution for 2017 and 2018, evaluating sub-seasonal deviations. Notable variations in these patterns due to the interaction of both tidal regimes are evident, and resulting tidal characteristics for CM can be

376 described. Sea water flows from the East Sea to the GOT and vice versa (Cui et al., 2019; Hoanh et al.,
377 2009), around and through CMP, and seem to cause complex tidal interaction observed at the coastal
378 stations and connecting rivers. The gradual interplay of synchronous and asynchronous occurrences of
379 spring and neap tides in the East Sea and the GOT results in complex water level responses at all three
380 stations. The co-oscillation of both tides is particularly visible during spring tides at GH, for example
381 mid of April 2018, as during this time mixed-semi-diurnal features replace the diurnal tides at SD
382 (Figure 5a, c). In the subsequent neap tide at GH, the diurnal features at SD are restored. Water level
383 fluctuations at CM seem to respond to both the East Sea and the GOT tidal patterns. Around the 26th
384 of March and the 9th of April 2018, water levels at CM remained elevated as spring tides from the East
385 Sea and the GOT occurred in close succession, overlapping during the low-water phase and amplifying
386 water levels (Figure 5d).

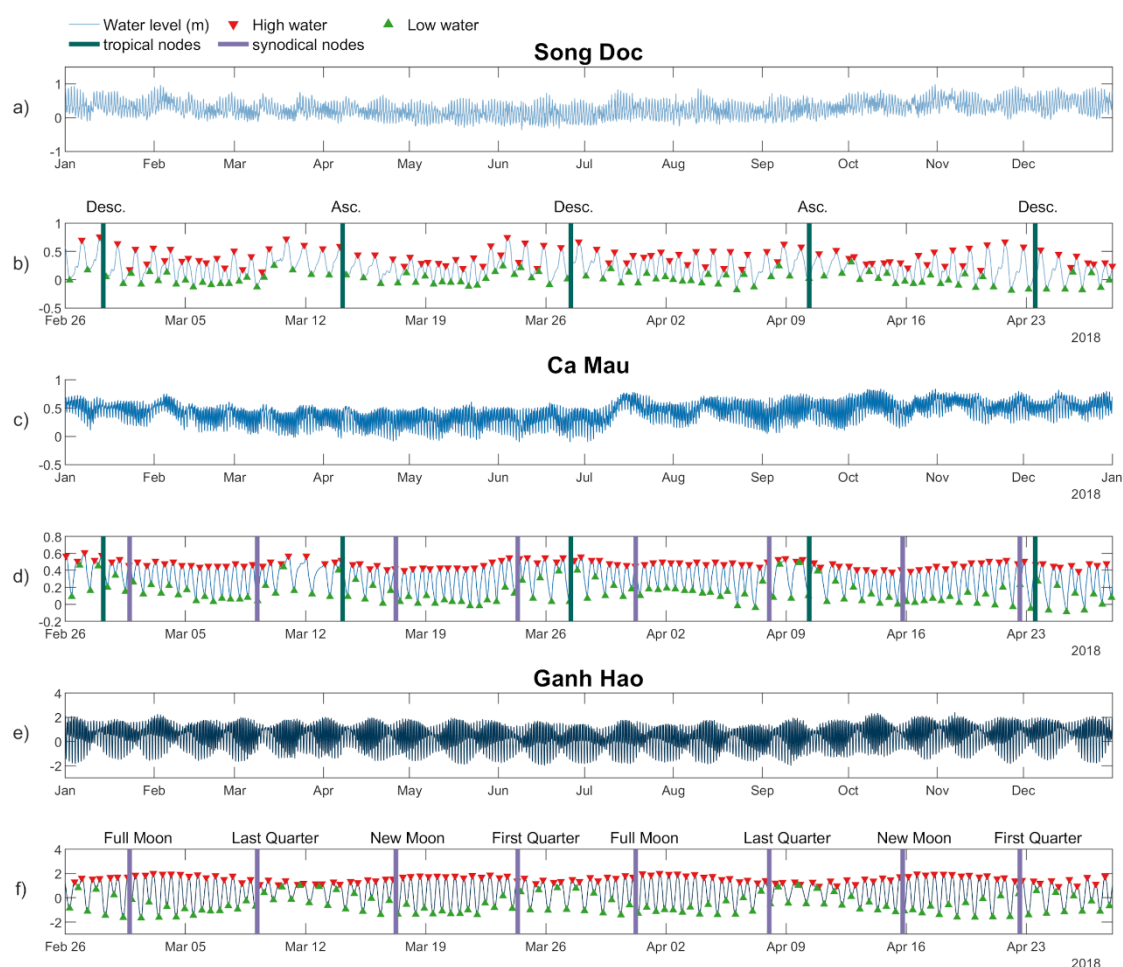


Figure 5. Changes of water levels due to tidal influence in 2018 at the monitoring sites of Song Doc, Ca Mau and Ganh Hao.

Tiles b, d, f include indicators for high and low water peaks as well as bars representing moon cycle nodes for synodical and tropical tides.

4.3 The relationship between water level and salinity

4.3.1 General observations

Figure 6 shows the relationship between water levels and salinity during representative spring and neap tides at SD, CM, and GH in January and April 2018. In mid-January (Figure 6a), spring tides occur at SD and GH. At SD, diurnal water level peaks coincide with salinity peaks, although salinity decreases more slowly than the water level. The time lag between peak water level and peak salinity is approximately four hours at SD. At GH, semi-diurnal water level peaks are observed, where two peaks form a plateau until the water level drops to its minimum, and salinity follows the same pattern. In terms of response times, the first peak has an immediate salinity response, while the second peak

400 shows a response delay of about four hours. A third salinity peak at GH appears concurrent with the
401 water level minimum. At CM, the water level pattern is similar to GH, with a plateau and an immediate
402 salinity response after the first peak, followed by a four-hour delay for the second peak. However, a
403 distinct third salinity peak during ebb tide is absent. The concurrent water level peak at SD and GH
404 occurs at 2 AM local time on January 16th, with the peak at CM happening six hours later at 8 AM.

405 During the subsequent neap tide at the end of January (*Figure 6b*), semi-diurnal features develop at
406 SD for both water level and salinity, with salinity peaks delayed by two to three hours. At GH, besides
407 a small increase in salinity during water level peak, highest salinity peaks occur during ebb tides every
408 twelve hours and appear uncorrelated with the preceding water level peaks.

409 In early April 2018 (*Figure 6c*), spring tides in the East Sea, with pronounced semi-diurnal water level
410 peaks, result in semi-diurnal water level peaks at SD, where neap tides are present. The delay between
411 water level and salinity peaks at SD remains four hours, but only every second water level peak leads
412 to a distinct salinity peak. At CM, well-defined semi-diurnal features dominate for both water level and
413 salinity, with an almost immediate response. During the subsequent spring tide in the GOT (*Figure 6d*),
414 diurnal water level patterns are restored at SD, and double-peak plateaus form at GH and CM during
415 neap tides. While salinity at CM closely follows water level changes, at GH, several salinity peaks occur
416 with some responding to water level peaks, while others appear unrelated and irregular.

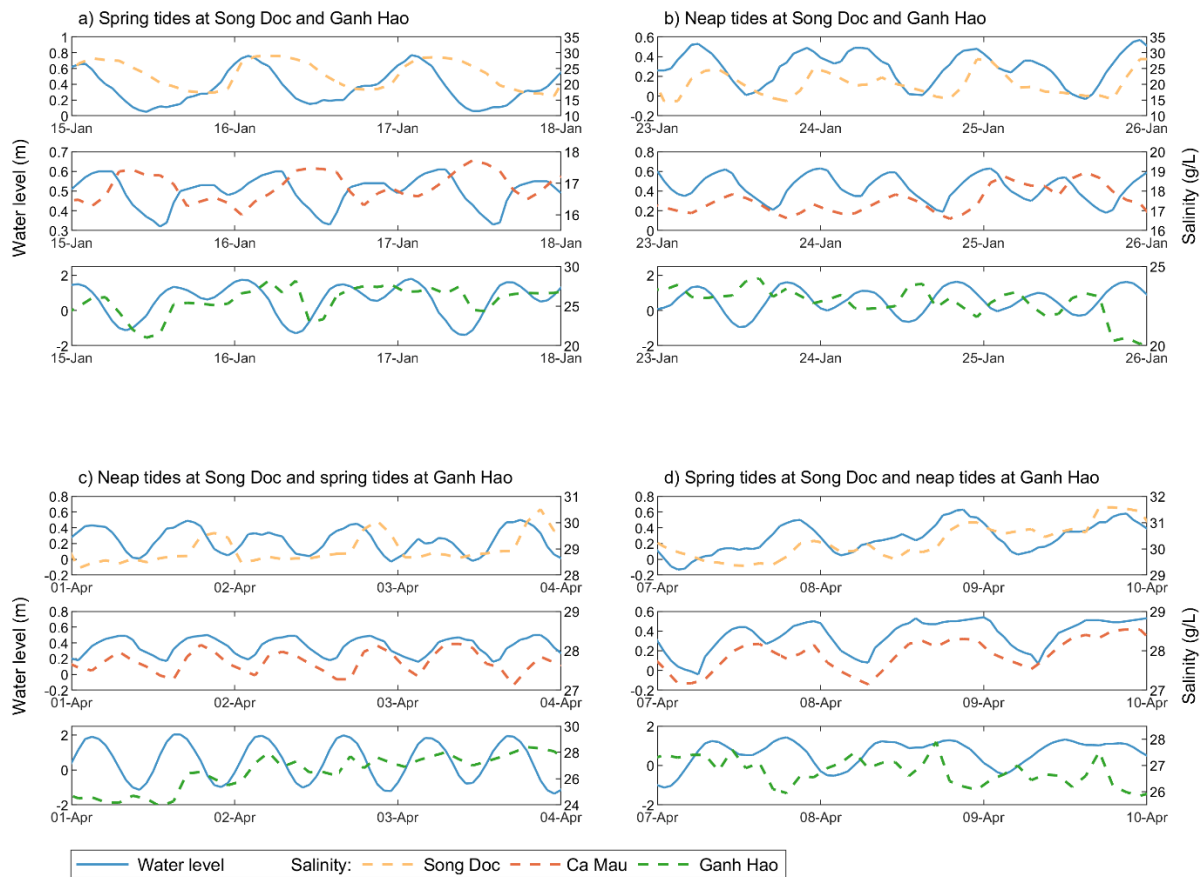


Figure 6. Water level (blue) and salinity at Song Doc, Ca Mau and Ganh Hao (colored) during synchronous and asynchronous spring tides in January and April 2018. Please note that y-axis scales differ.

4.3.2 Frequency analysis – Identifying periodic patterns

To further assess the periodic patterns of both water level and salinity, and to quantify their relationship displayed in Figure 6, harmonic analyses were performed. Results are presented in Figure 7, showing the FFT amplitude spectra for water level and salinity in 2017 and 2018. The most prominent diurnal (O1, K1), semidiurnal (M2, S2) and compound tides at around 3 cpd (MK3) and 4 cpd (MS4) are indicated. In addition, fortnightly constituents Mf and MSf, which are close to each other and cannot be resolved by FFT resolution here, are indicated by “F”. Other constituents, like N2 or P1 are not labeled, but are present.

The water level at SD is mainly controlled by the diurnal tidal constituent K1, and to a lesser extent by O1. The semi-diurnal constituents M2 and S2 are also significant. Conversely, at GH the semi-diurnal constituent M2 shows the highest amplitude. This result is consistent with results shown in Figure 6.

For the salinity time series, K1 is also dominant at SD, and M2 has a four times smaller amplitude. At GH, while water level is dominated by M2, K1 and M2 are almost equal for salinity (Figure 7f). For CM, salinity frequencies are comparable to GH with much smaller amplitudes and M2 explains more of the variability than K1. For water levels, the semi-monthly frequencies noted as “F” have smaller magnitudes compared to the high-frequency components. On the other side, for salinity the fortnightly band shows high magnitudes and the low-frequency peaks are higher than the high-frequency peaks. At CM, peaks at diurnal and semi-diurnal tidal frequencies are smaller than the peaks occurring in the low-frequency part. In general, salinity peaks in the low-frequency domain beyond fortnightly frequencies hint to a seasonal trend, representing the gradual increase of salinity in the dry season associated with changes in river discharge and precipitation. Detrending with a 45-day window (see section 3.2) could not completely remove longer trends, manifesting as high peaks in the low-frequency domain. These peaks are much smaller for water levels, which are also subject to strong seasonality (Binh et al., 2020b).

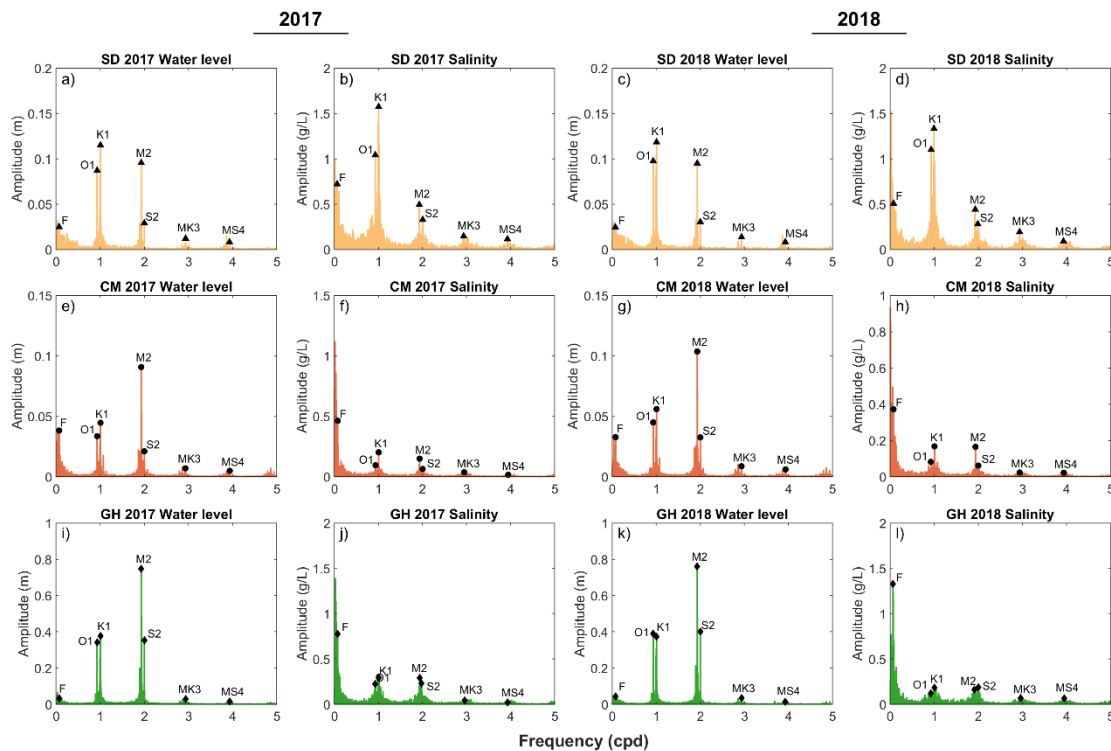
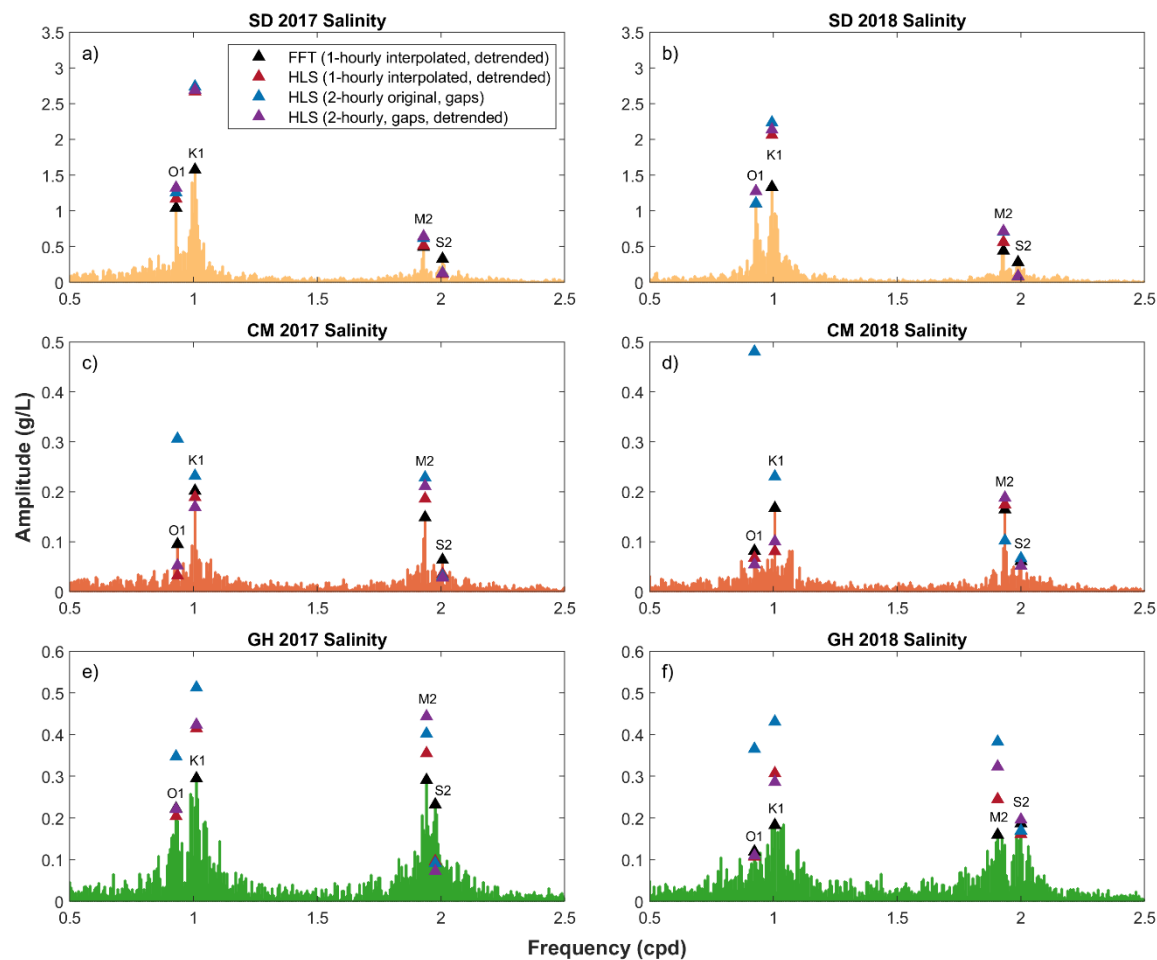


Figure 7. FFT analysis of water level and salinity at Song Doc (a-d), Ca Mau (e-h) and Ganh Hao (i-l). Significant tidal constituents are indicated for frequency ranges between 1 cpd to 4 cpd as well as fortnightly.

447 In addition to FFT, HLS was applied on differently pre-processed versions of the dataset to compare
448 amplitudes, select the optimal dataset to assess HLS model performance and to compute the transfer
449 function. In Figure 8, the amplitudes of FFT and HLS calculations are shown. For SD the O1 and M2
450 amplitudes are close to each other, while the HLS results for all datasets collectively are substantially
451 higher at K1, and lower at S2. The HLS results using the original untreated salinity dataset is
452 inconsistent. For example, at CM, using this dataset for HLS results in the highest amplitude for M2 in
453 2017, but the lowest amplitude in 2018. At CM and GH, the HLS amplitudes for O1 are unreasonably
454 high, suggesting a diurnal dominance. Typically, K1 would indicate diurnal dominance and the water
455 level record is clearly not diurnal for both locations (Figure 6).

456 The HLS results on the 1-hourly interpolated detrended dataset align well with the FFT results. At GH,
457 the HLS amplitudes show a more pronounced variance. K1 and M2 amplitudes are notably higher than
458 the FFT amplitudes in both years, while HLS S2 amplitudes are low in 2017. At CM and SD, the 1-hourly
459 interpolated detrended dataset is closest to the FFT result. For consistency with the water-level
460 records and due to more consistent amplitudes (Figure 8), the detrended, interpolated 1-hourly salinity
461 series was further analyzed and evaluated with HLS.



464 *Figure 8 Comparison of amplitudes calculated by Fast Fourier Transform and Harmonic Least Squares for different versions*
465 *of the salinity timeseries in 2017 and 2018 at Song Doc, Ca Mau and Ganh Hao.*

466 **4.3.3 Harmonic Least Square approaches to determine tidal control on water level and salinity**

467 Tidal control was quantified as the explained variance (R^2) of the HLS reconstructions, and constituent-
468 specific phase lags were derived from the transfer function relating water level (input) to salinity
469 (output). Results for the global R^2 and phase lag are presented in Table 1, and the global HLS fit is
470 shown in Annex B. All R^2 values refer to the detrended timeseries and quantify variance explained by
471 the tidal-band HLS reconstruction. HLS reconstructions of water level reproduced the observed records
472 well across all stations. Maximum R^2 was 0.94 in both 2017 and 2018 at GH. At SD, R^2 was 0.77 (2017)
473 and 0.78 (2018), with slightly lower values at CM. In contrast, salinity R^2 varied more across the
474 stations. At SD, R^2 is 0.40 for 2017 and 0.29 for 2018, while CM 2017 and 2018 as well as GH 2017 have

R² values below 0.15, and GH 2018 R² is 0.34.

Time lags between water level and salinity are also shown in Table 1. In general, the M2 responses are faster compared to the diurnal frequencies at all stations, at around two hours at SD, below one hour at CM and in average three hours at GH. At the K₁ frequency, water level leads salinity by approximately four to five hours, and by about one hour less at CM. For O1 negative values were obtained for GH.

Table 1. R² for the global Harmonic Least Squares approach for water level and salinity and time lag (h) between water level (input) and salinity (output) for main tidal components for Song Doc, Ca Mau and Ganh Hao for 2017 and 2018.

Station	Year	HLS R ² global		Time lag (h)			
		Water level	Salinity	O1	K1	M2	S2
SD	2017	0.77	0.40	4.96	4.20	2.08	5.09
	2018	0.78	0.29	6.08	4.39	2.10	2.48
CM	2017	0.69	0.13	0.93	2.74	-0.05	0.08
	2018	0.76	0.07	3.01	3.98	0.60	0.57
GH	2017	0.94	0.11	-4.50	4.65	2.73	3.70
	2018	0.94	0.34	-9.90	5.04	3.50	1.95

Across all stations and years, mean-fit uncertainties for the sliding windows HLS reconstruction were small, ranging from 4–13 mm for water level and 0.07–0.18 g/L for salinity, indicating a well-constrained harmonic signal. Prediction uncertainties, which include observational noise, were larger, ranging from 4–12 cm and 0.37–1.53 g/L, respectively. The prediction uncertainties reflect natural short-term variability not captured by the HLS reconstruction. Median amplitude standard errors were 2–5 mm for water level and 0.02–0.05 g/L for salinity, while phase standard errors corresponded to 5–7° and 10–21°, equivalent to timing uncertainties of roughly 10–40 min for the M₂ constituent.

To assess the sub-seasonal tidal control on water level and salinity, the fits for the 45-day-windowed HLS reconstructions are shown in Figure 9, and R² are reported (also see Annex C). The sliding HLS approach results in even higher R² for water level compared to the global HLS fit, ranging between 0.84

and 0.98, with only slight differences between unweighted and coverage-weighted R^2 . For salinity, the sliding HLS fits improve R^2 substantially. For SD and GH, unweighted R^2 ranges between 0.50 and 0.60 in both years, and around 0.30 at CM. Largest differences in scale and amplitudes occur in the end of the time series, from end of May to end of June. As the coverage-weighted approach suppresses this time frame, the coverage-weighted R^2 is notable higher, with all stations showing R^2 between 0.51 and 0.73 for salinity (Figure 9, Annex C).

The temporal evolution of R^2 as a proxy for tidal control for the sliding window fit is shown in *Figure 10* with the detrended, interpolated salinity time series in the background. A version of the figure with water level shown as background is provided in Annex D. While R^2 for water level is stable throughout the time series, R^2 for salinity shows larger variations. In mid of April 2017, R^2 for salinity at CM and GH drop sharply from around 0.9 to 0.2 and below, and at SD from slightly above 0.8 to almost 0.5. A few days later, R^2 increases again, followed by another, smaller drop, and another increasing phase. A similar drop occurs at SD in April 2018 and to a lesser extent at CM, while at GH R^2 decreases more gradually. Positive peaks of R^2 seem to correlate with peaks of salinity itself as well as phases of higher fortnightly amplitudes, as seen mid of March 2017 at CM and GH (Figure 10c, e), beginning of May 2018 at CM (Figure 10d), or in general at GH in 2018 (Figure 10f).

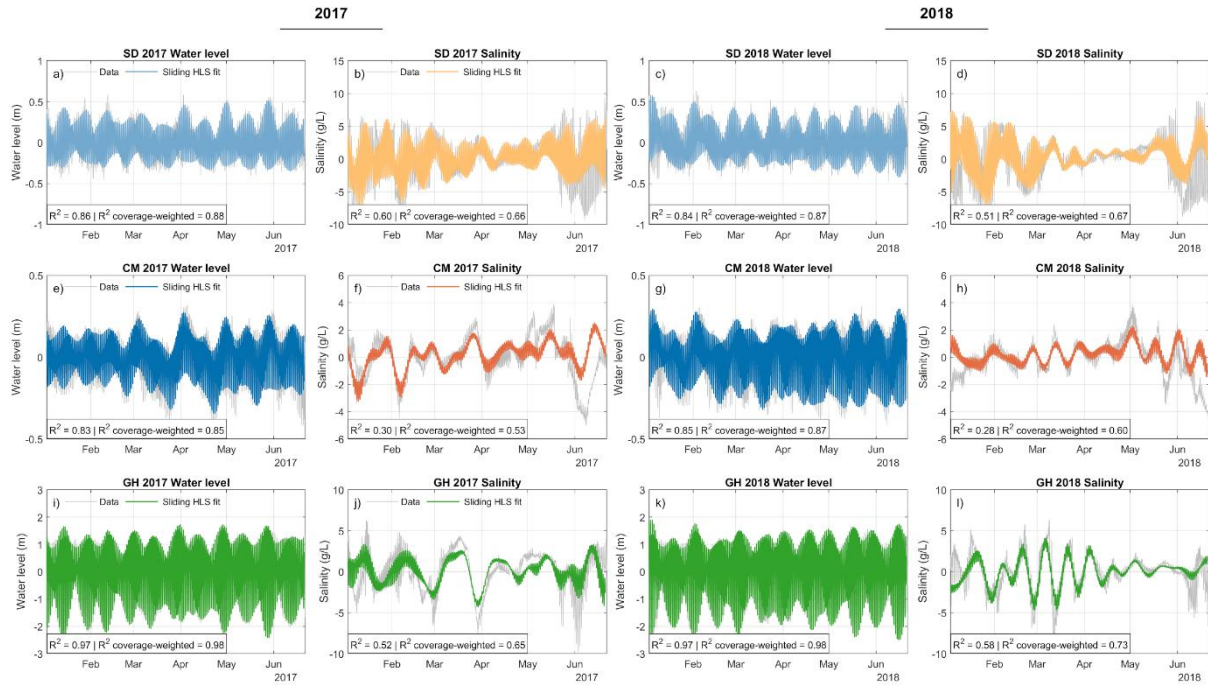


Figure 9 HLS reconstruction (sliding 45-day window, step size of 24h) using 13 tidal constituents (see section 3.3) and fit for water level and salinity at Song Doc, Ca Mau and Ganh Hao for 2017 and 2018.

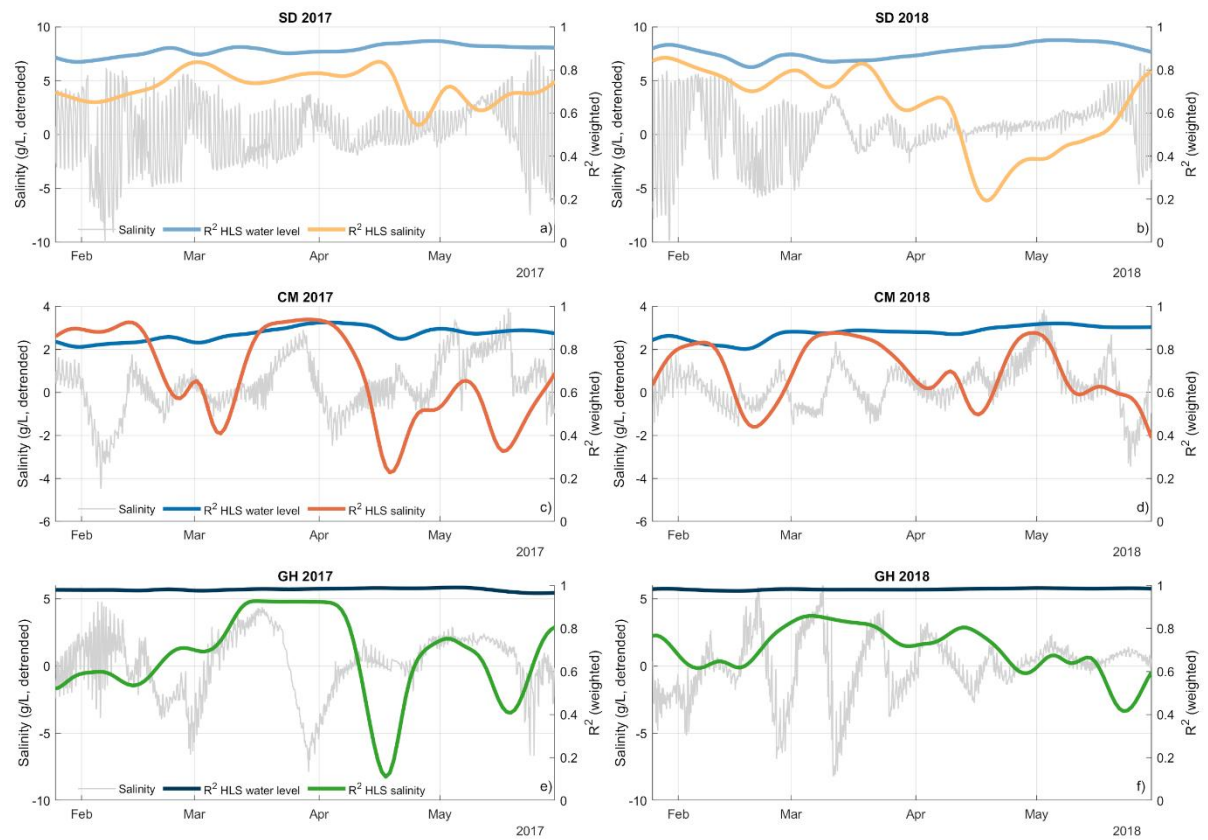


Figure 10 Tidal control expressed as explained variance R^2 of the sliding HLS reconstruction (45-day window, 24h step size) for water level and salinity at Song Doc, Ca Mau and Ganh Hao for 2017 and 2018.

5 Discussion

5.1 Salinity variability in response to tidal regimes

Superimposing seasonal trends, the salinity time series at SD, CM, and GH for January to June in 2017 and in 2018 reveal pronounced diurnal variation of salinity amplitudes, which are highest at the beginning of the dry and rainy seasons, reaching up to 16 g/L at SD, but stay below 5 g/L at the other two stations. (Figure 4). In addition, spring-neap cycles cause fortnightly variations (Figure 6). Farmers must plan ahead when using surface water for agriculture and aquaculture due to specific salinity requirements. However, as the results show, salinity fluctuations and the underlying dynamics are complex. This is especially crucial at the saline-freshwater boundary, where water may be suitable for rice farming during ebb tide or neap tide conditions but not six hours later during flood tide or during strong spring tides in general (Figure 6). This is also true for persistently brackish conditions during the dry season in aquaculture, as different fish and shrimp species require distinct salinity conditions for growth and survival (Duy et al., 2012; Gao et al., 2016; Li et al., 2017), as well as for disease resilience (Duc et al., 2015). Water in ponds, regardless of the farming practice, whether intensive, extensive or natural, needs to be replaced every few weeks (Duy et al., 2012). Unpredictable salinity conditions pose a substantial threat to yield stability. This study shows that salinity condition uncertainty is not exclusive to strong interannual salinity variations but also occurs on diurnal to fortnightly scales.

To better understand the causes for observed salinity variations, tidal influences on water level and salinity in the region were examined. Harmonic analyses show that salinity responds to the same tidal constituents as water level (Figure 7) and follows water level fluctuations (Figure 6) with a time lag ranging between two and six hours at the coastal stations and with more immediate responses inland at CM (Table 1, Figure 6). However, as shown in Figure 5, the different tidal regimes in the GOT and the East Sea, particularly their interaction caused by differences in amplitude and synchronous and asynchronous spring tides, result in complex water level and salinity patterns across a fortnightly scale (Figure 6). Most notably, during spring tides in the East Sea, semi-diurnal water level and salinity

patterns dominate in the GOT, which otherwise experiences diurnal tides. This pattern is pronounced during synchronous neap tides and weakens during spring tides in the GOT. During weaker neap tides in the East Sea, the east to west flow appears to reverse, restoring the original diurnal tide and salinity patterns in the GOT. While previous studies examined the interaction between the GOT and the East Sea, particularly resonant frequencies and amplitude responses (Cui et al., 2019; Phan et al., 2019), the impact of this interaction on salinity variation has not yet been addressed before.

The changes in hydraulic pressure gradients caused by tidal forcing and differences in tidal amplitudes between the GOT and the East Sea result in dynamic water flow conditions and varying solute transport in CMP (Phan et al., 2019). The changing water flow conditions cause the east-to-west freshwater-seawater front to not only shift in response to tidal forcing but to sometimes disappear on the southern peninsula, particularly during the dry season. Thereby, water flows directly through CMP, from the East Sea to the GOT, and vice versa, via large rivers, such as Ganh Hao, Ong Doc and Cua Lon (Figure 1) (Hoanh et al., 2009). Consequently, depending which tidal regime is dominant, both semi-diurnal and diurnal water level and salinity patterns occur at CM, representing the inland areas (Figure 6). The occurrence of changing water flow conditions in CMP has been reported before (Hoanh et al., 2009) and is also well-known among local people navigating these rivers, as the strong currents can pose significant danger to small boats. Changing water flow conditions, referred to reversing estuarine conditions, underscore the complexity of the hydrological regime in CMP and partly explain the observed irregular salinity patterns.

Furthermore, the interaction between the tidal regimes can create stagnant water zones in CMP when the opposing forces reach equilibrium (Le et al., 2007). During periods of extremely low river discharge, high temperature and low humidity, conditions that are exacerbated in El Niño years (Nguyen et al., 2014), elevated evaporation rates can lead to the accumulation of solutes and therefore salinity levels well above 35 g/L. At SD and CM, salinity levels exceeded seawater salinity levels in the El Niño years 2010, 2016 and reached 45 g/L at SD in May 2020 (Bauer et al. 2025). These high salinity levels cause

adverse effects on the ecosystem and agriculture, potentially having a lasting impact that extends beyond its duration as solutes accumulate in soils and sediments (Loc et al., 2021a; Tarolli et al., 2024).

5.2 The complexities of tides and its effect on seawater intrusion

Changes of water level and salinity patterns caused by changes in the hydraulic pressure gradient between river discharge and seawater due to tidal forcing account for much of the observed diurnal to fortnightly salinity variability. The time series analysis shows that the relationship between water level and salinity is complex, and that besides the interaction of the two tidal regimes in the GOT and the East Sea, other processes are likely contributing as well. Tidal control on both water level and salinity was quantified as the explained variance (R^2) of the HLS reconstruction using a comprehensive set of tidal constituents. Water level can already be well described by the global fit over the whole time series, with R^2 ranging between 0.69 and 0.94, while the sliding-window HLS approach, which allows to incorporate non-stationary variations, elevates the explained variance slightly (Figure 9).

In contrast, in the stationary model, tides do only partly explain salinity variations at SD and GH and only in 2018, and not at all in CM (Table 1). The low explained variance shows that other effects control salinity variations, especially further inland. The complexities of salt transport, such as mixing and stratification, as well as tidal amplification and tidal asymmetry, and estuarine circulation in general, can alter observed salinity levels and dynamics substantially (Eslami et al., 2021a; Geyer, 2010; Geyer and MacCready, 2014). In shallow coastal rivers and estuarine zones, asymmetric tidal cycles, storage effects, tidal distortion and non-linearities can occur (Simpson et al., 1990; Speer and Aubrey, 1985; Zhang et al., 2025). In addition, human-controlled water diversions and sluice gate operations introduce additional non-linear behavior, further complicating the system response. For that reason, the non-stationary HLS approach, using a sliding window of 45 days combined with a Hann taper and reporting coverage-weighted R^2 , substantially improves the model fit for salinity and therefore the explained variance caused by tides. R^2 (weighted) was calculated at 0.53 and 0.60 for CM in 2017 and 2018, respectively, and ranges between 0.65 and 0.73 at SD and GH (Figure 9). This improvement reflects better representation of the temporal variability and is indicative for a strong tidal control, but

can still not capture the entirety of processes involved. Due to the lack of data on vertical salinity profiles at the monitoring stations and the absence of detailed information on morphology and river geometry, processes such as stratification and mixing could not be directly investigated with the data used in this study. However, such processes have been documented in many estuaries worldwide, including the MD (Eslami et al., 2019; Hendrickx et al., 2023; Hendrickx and Pearson, 2024; Wünsche et al., 2024). The analyses conducted in this study suggests that certain observed water level and salinity patterns may be indicative of these processes.

Quadratic friction and estuarine geometry lead to non-linear effects, which, for example, are manifested as pronounced overtides, such as M4, and compound tides, including MS4 and MK3 (Friedrichs and Aubrey, 1988; Lafta, 2022; Ray et al., 2023). At SD, located at the shallow Ong Doc River, the amplitudes of the exemplary compound tides MS4 and MK3 are relatively high for salinity and water level (Figure 7) and are also distinctly visible at CM and GH. Another compound tide, which can be pronounced in shallow water, is the fortnightly constituent MSf, which reflects the spring–neap modulation of semidiurnal tides with a frequency of 14.765 days, originating from the difference between M2 and S2 ($2.00000 \text{ cpd} - 1.93227 \text{ cpd} = 0.06773 \text{ cpd} = 14.765 \text{ days}$) (Garel et al., 2021). At GH and CM, where M2 is more dominant than K1, salinity at CM and GH as well as water level at GH show significant peaks at the fortnightly frequency band, indicating a strong neap-spring tide control on salinity (Figure 7), which is also clearly visible in the time domain (*Figure 6, Figure 3m-p, u-x*).

In case of large salinity gradients, which can be expected in the MD, density-induced pressure differences in the water column promote gravitational circulation, also known as estuarine circulation, meaning that less saline water at the surface is directed towards the sea, while the saline water at the river bottom moves further upstream, creating complex mixing patterns (Geyer, 2010; Savenije, 2012). This behavior can be observed in many estuary systems, such as the Danshuei River estuary in northern Taiwan, where strong salinity stratification was observed in a deep river during ebb flow when river discharge from upstream was largest (Liu et al., 2022). Another shallower river in the Danshuei River

estuary did not show this behavior (Liu et al., 2022). In the Amazon estuary, strong stratification and estuarine circulation is favored during neap tides (Molinas et al., 2014). These effects can largely impact observed salinity levels in CMP. The reduction of vertical mixing and the evolution of stratification caused by the described estuarine circulations (Geyer, 2010), especially during ebb tides and neap tides (MacCready and Geyer, 2010), is estimated to also apply to the MD and the Ganh Hao river (GH station), which is significantly deeper compared to the Ong Doc River (SD station), with a mean depth of 5 to 14 m compared to 3 to 5 m, respectively. In general, deeper river channels promote the extent of SWI and stratification (Ralston and Geyer, 2019), which is also why channel deepening due to sand mining in the main branches of the Mekong River is extremely critical (Park, 2024).

In the beginning of April 2016, a particularly dry year with reduced discharge from the Mekong River, Eslami et al. (2021a) encountered that during neap tide, when tidal forcing is reduced, salinity at the river mouth and up to 40 km upstream in the Dinh An channel, a secondary channel of the Mekong River, was actually higher compared to the subsequent spring tide. During neap tide, strong salinity stratification was observed in the deeper Dinh An channel, but not in the neighboring, shallower Tran De channel, where highest salinity levels were indeed measured during the spring tide. The authors concluded that salinity cannot solely be attributed to simple discharge and tidal forcing but that other physical processes, such as stratification, are involved as well (Eslami et al., 2021a). Similar observations were made in the Ben Tre Province at the river mouth of the Hau River (Tran et al., 2024c). Elaborating on these patterns, at GH, salinity peaks can be observed concurrent or shortly after the ebb tide during neap tides in the East Sea (*Figure 6b, d*). Such a peak was also observed by Muoi et al. (2022) during a one-day field campaign on the 5th of September 2019 during the rainy season only a few kilometers upstream Ganh Hao River, but not on the 22nd of March 2019 in the dry season. Based on the current evaluation of the issue, the observation by Muoi et al. (2022) can be explained, as the 22nd of March 2019 coincided with a strong spring tide in the East Sea (not shown), and therefore the salinity peak during ebb tide does not occur.

643 The low slope of the MD amplifies estuarine circulation by allowing denser saline water to intrude
644 more easily and remain in the deeper river channels, as the gentle gradient provides insufficient
645 gravitational force to push the saline water seaward, particularly in the dry season. Near-shore
646 stratification of salinity is characteristic during periods of reduced water movement (Pokavanich and
647 Guo, 2024), which in case of the MD is true in the dry season, further altering observed salinity
648 dynamics. Additionally, intertidal flats, defined as areas submerged during high tides and exposed
649 during ebb tides, may significantly affect the salinity patterns (Hendrickx and Pearson, 2024). In CMP,
650 these flats are especially abundant along the Ong Doc and Ganh Hao rivers, where they temporarily
651 store already saline water, which is subject to strong evaporation during the dry season. This
652 evaporated saline water flows back into the rivers during low tide, potentially contributing to elevated
653 salinity levels und irregular timings of salinity peaks.

654 Additionally, sluice gates, designed to protect certain areas of the MD from SWI during the dry season
655 (Nguyen and Nguyen, 2023), also influence observed salinity patterns. By potentially cutting off some
656 coastal areas from freshwater influx and altering water flow, these structures can reduce buffer zones
657 and allow seawater to persist in the system (Binh et al., 2020b; Danh et al., 2024). A recent study for
658 the Hudson River showed that closing gates for three or more days, stopping or limiting streamflow,
659 promotes SWI and stratification well above naturally occurring extremes (Chen, 2023). As neighboring
660 provinces of CMP operate sluice gates to prevent SWI originating from CMP to protect agricultural
661 areas, SWI and stratification could be increased downstream in CMP.

662 The sliding HLS approach employed here was able to capture some of the non-stationary processes
663 and substantially improved the overall salinity model fit compared to the stationary fit over the entire
664 time series, which could not capture non-linear effects. The temporal evolution of R^2 was also
665 considered here, showing that in mid of April 2017 and 2018, marking the peak of the dry season, R^2
666 sharply drops. During this time, water levels are low, diurnal salinity amplitudes are lowest (*Figure 4*),
667 and salinity levels almost reach seawater conditions (*Figure 3*). During this time, storage effects,
668 stratification and other non-linear effects can be expected, potentially causing the sharp drop of R^2 . In

addition, water management, such as sluice gate management and water diversion practices impact total water levels (Bauer et al., 2025), and potentially influence periodic patterns as well.

Lastly, during the Holocene, the MD transitioned from a tide-dominated system to a wave-tide dominated system (Ta et al., 2002a), meaning that waves driven by wind also add to water level fluctuations and can alter salinity patterns and SWI, increasing the non-tidal signal.

5.3 Implications for modelling and mitigation measures

The findings of this study demonstrate that the depth of monitoring equipment installation, the measurement period as well as the frequency of water sampling must follow a standardized protocol to ensure robust and meaningful results. Without such consistency, models and predictions risk being weakened or misleading, particularly given the large diurnal amplitudes, fortnightly fluctuations, and seasonal trends observed. (*Figure 4*). Modeling salinity using short in-situ observation periods of just a few days for calibration and validation, taken during random time intervals, is inadequate. This study suggests that a simple stationary water level to salinity relationship is oversimplified, with significant irregularities caused by complex interaction of tidal regimes, physical processes and human infrastructure. For instance, Vu et al. (2024) calibrated a MIKE 21 SW model with multiple station data in the MD utilizing data limited to February 2020, and achieved an acceptable R^2 of 0.74 and good fits for water level, salinity and current speed. However, the short calibration time certainly did not capture all the variability and irregularities of the considered system. Therefore, the certainty of model results for the SLR-salinity relationship up to the year 2100 should be carefully reconsidered, especially when combining sub-seasonal salinity variability with interannual salinity variability.

Analyzing varying time scales reveals an ambivalent relationship between water level and salinity. Simplified, it is shown that high tides drive salinity peaks on a diurnal scale, while seasonal water level highs from river discharge counteract SWI. However, long-term water level increases due to RSLR ultimately promote SWI (Mohammed and Scholz, 2017)

693 The susceptibility to salinity fluctuations can be regarded as a proxy for system vulnerability and
694 exposure to seawater (Guillou et al., 2023). Therefore, as salinity variability is very high on all
695 considered time scales, the vulnerability of the MD must be considered as very high, particularly in the
696 broader context of the numerous environmental stressors threatening the region (e.g. Binh et al.,
697 2020b; Kondolf et al., 2022; Minderhoud et al., 2021; Park, 2024; Park et al., 2022). Hendrickx et al.
698 (2023) concluded that the complex interplay of estuarine processes and features controls SWI events.
699 Identifying these processes and evaluating their relevance allows for developing meaningful models
700 and effective, evidence-based mitigation measures. A purely data- or model- driven approach could
701 be misleading. In general, there is consensus that measures counteracting RLSR, negative river
702 discharge anomalies caused by climate change and upstream reservoirs as well as a stop to sand mining
703 are essential to mitigate long-term SWI and stabilize salinity conditions for local stakeholders, or at
704 least make them predictable (e.g. Kondolf et al., 2022). On a local scale, within the delta and within
705 CMP, sluice gates operating on a seasonal to tidal scale are often the solution of choice, but they are
706 also often managed only locally and potentially less effective (Hoanh et al., 2009). Based on the tidal
707 analysis and salinity patterns presented in this work, further options should be explored. Observations
708 from other estuaries and modeling approaches suggest several options in addition to measures that
709 aim to increase upstream river discharge during critical periods. For instance, the tidal rivers and
710 especially the canals in CMP are often straight, but meanders would enhance ebb-dominance and
711 reduce SWI as they increase turbulence and mixing (Pein et al., 2018). This effectively counteracts
712 gravitational circulation with high density saline water moving upstream at the river bottom.
713 Furthermore, intertidal areas play an important role for SWI, but depending on the mixing processes
714 of the river, they can enhance or mitigate SWI (Hendrickx and Pearson, 2024), which should be
715 carefully considered when implementing measures that alter the extent of these areas. In areas where
716 estuarine circulation is dominant and the river is partially mixed or forms a salt wedge, assumable in
717 the deeper Ganh Hao River, intertidal flats can disrupt this circulation and thereby limit salt transport.
718 Conversely, in well-mixed rivers, where tidal oscillation is the dominant process, such as the shallow
719 Ong Doc River, intertidal flats can enhance SWI (Hendrickx and Pearson, 2024), which is arguably

supported by salinity levels beyond 35 g/L in dry years (Bauer et al., 2025). In addition, increasing hydraulic drag dampens tidal energy and limits intrusion lengths. This can be achieved by modifying river characteristics, such as increasing bed roughness and bottom friction, reducing water depth and stop dredging as well as widening the river through floodplains and wetlands (Winterwerp et al., 2013). Studies show that increasing bottom friction reduces tidal energy, enhanced vertical mixing and weakens tidal propagation, ultimately mitigating SWI (Veerapaga et al., 2020). Increasing hydraulic drag can be achieved through various approaches, including engineering solutions such as the construction of inclined roughness elements in the river (Badr and Azzubaidi, 2023), air curtains like inflatable dams or gates (Haralambidou et al., 2018), submerged weir and rubber dams (Sriratana and Bisalyaputra, 2019) but also nature-based solutions, including earthen sills, sand dunes and water diversions (Geerts et al., 2025; Hendrickx et al., 2024; Sriratana and Bisalyaputra, 2019). This abundance of options shows that stakeholders in the MD have various tools to mitigate SWI, besides sluice gates and other hard measures often preferred (Nguyen et al., 2024). To date, none of these options have been implemented on a larger scale. The main obstacles stem from fragmented administrative structures and conflicting stakeholder interests, but also from limited expertise, public awareness, and financial resources (Ha et al., 2018; Minkman et al., 2022; Quang et al., 2024). Through an in-depth analyses of tidal water level fluctuations and salinity responses in CMP, this study provides fundamental insights needed to develop and evaluate effective countermeasures, and to transfer these approaches to other areas along the Mekong Delta coastline.

6. Conclusion

Salinity levels were found to vary substantially on the sub-seasonal scale in the southern MD. Estuarine tidal dynamics are inherently complex and non-stationary, leading to equally complex spatiotemporal salinity patterns. The results presented here are indicative of some of these processes. A sliding HLS approach is capable of reconstructing water level and salinity dynamics. While this approach captures more of the non-stationary process dynamics compared to a global HLS fit, the gain in statistical

representation cannot substitute for process-based understanding. Shallow-water effects revealed through frequency analysis, as well as indications of stratification and tidal co-oscillations, were inferred from distinct time series patterns but require follow-up field investigations for confirmation. The insights gained in this study provide a foundation for further sub-seasonal SWI investigations in the MD. They offer a framework for deepening the understanding of the water level–salinity relationship and encourage the development of more reliable, explainable models for SWI prediction that incorporate both stationary and non-stationary effects. Short-term salinity variability is as critical as long-term trends, since sudden events can push the system beyond ecological or management thresholds, threatening freshwater-dependent livelihoods and economic stability. Predictive models and mitigation strategies must therefore account for both temporal scales.

Finally, the findings of this study are transferable to other estuarine systems worldwide, particularly low-lying deltas strongly influenced by tides, where non-stationary salinity dynamics pose similar challenges for water resources planning.

CRediT authorship contribution statement

Jonas Bauer: Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization.

Felix Dörr: Formal analysis, Investigation, Writing – review & editing

Andreas Schenk: Formal analysis, Writing – review & editing

Vũ Hoàng Thái Dương: Writing – review & editing

Hoan Tran Viet: Investigation, Writing – review & editing

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770 Elisabeth Eiche: Writing – review & editing, Resources, Project administration

771 Stefan Norra: Writing – review & editing, Resources, Supervision, Project administration, Funding
772 acquisition

773

774 **Declaration of Competing Interest**

775 The authors declare that they have no known competing financial interests or personal relationships
776 that could have appeared to influence the work reported in this paper.

777 **Declaration of generative AI and AI-assisted technologies in the writing process**

778 During the preparation of this work the authors used ChatGPT in order to improve language and
779 readability of the study. After using this tool/service, the authors reviewed and edited the content as
780 needed and take full responsibility for the content of the publication.

781 **Data availability**

782 Data used in this study can be provided on request to NCHMF and/or NAWAPI, Hanoi, Vietnam, or by
783 directly contacting the authors of this study, who can assist with access and facilitate contact with the
784 afore- mentioned institutions.

785 **Acronyms and Abbreviations**

786 CM: Ca Mau

787 CMP: Ca Mau Province

788 FFT: Fast Fourier Transform

789 GH: Ganh Hao

790 GOT: Gulf of Thailand

791 HLS: Harmonic Least Squares

792 MD: Mekong Delta

793 NCHMF: National Center for Hydro-Meteorological Forecasting of Vietnam, Hanoi
794 RSLR: Relative sea level rise
795 SD: Song Doc
796 SLR: Sea level rise
797 SWI: Seawater intrusion
798

799 **Acknowledgments**

800 The authors thank the National Center for Hydro-Meteorological Forecasting of Vietnam, the Southern
801 Institute of Water Resources Research, the National Center for Water Resources Planning and
802 Investigation Vietnam, and the Department of Natural Resources and Environment Ca Mau for
803 providing the monitoring data used in this study and for their valuable support during fieldwork, as
804 well as for the scientific and personal exchange. We also gratefully acknowledge the contributions of
805 all project partners involved in this work. This research was carried out within the framework of the
806 project “ViWaT – Vietnam Water Technologies,” funded by the German Federal Ministry of Education
807 and Research (funding reference: 02WCL1474A). Publication support was provided by the KIT-
808 Publication Fund of the Karlsruhe Institute of Technology, Germany.

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1205 **ANNEX**

1206 **A**

1207 Major tidal constituents (Kvale, 2006; Kvale et al., 1995; Pawlowicz et al., 2002) used for:

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- Fast Fourier Transform (FFT) to identify major periodicities of water level and salinity and to determine amplitudes of major diurnal and semidiurnal tidal constituents.
 - Harmonic Least Squares (HLS) to compare amplitudes of major diurnal and semidiurnal tidal constituents with FFT results using differently preprocessed datasets.
 - Based on HLS results, time lags between major diurnal and semidiurnal tidal constituents were calculated for water level (input) and salinity) using transfer functions.
 - HLS to determine tidal control on water level and salinity. A global, stationary HLS and a sliding window HLS reconstruction to capture non-stationary behavior was calculated with a comprehensive set of tidal constituents.

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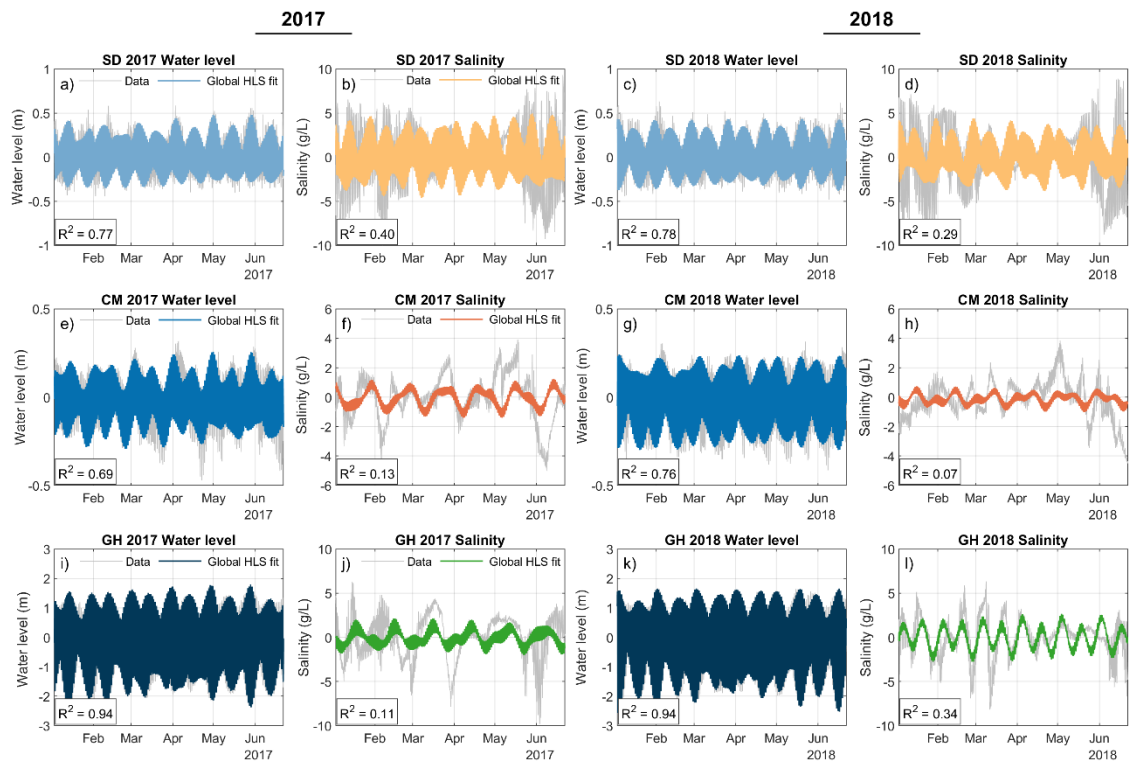
Tide	Frequency (cycles per day, cpd)	FFT (amplitudes)	HLS (amplitudes)	HLS (time lag)	HLS (reconstruction)
Mm	0.03629				✓
MSf	0.06772				✓
MF	0.07319				
Q1	0.89324				✓
O1	0.92954	✓	✓	✓	✓
M1	0.96614				✓
P1	0.99726				
K1	1.00274	✓	✓	✓	✓
N2	1.89598				✓
M2	1.93227	✓	✓	✓	✓
S2	2.00000	✓	✓	✓	✓
K2	2.00548				
M3	2.89841				✓
MK3	2.93501				✓
M4	3.86455				✓
MS4	3.93227				✓

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1221 **B**



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1223 HLS reconstruction over the full time series and fit for water level and salinity at Song Doc, Ca Mau

1224 and Ganh Hao for 2017 and 2018.

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1233 **C**

1234 R^2 for the global HLS fit and sliding HLS fit using unweighted and coverage weighted estimates

		Water level			Salinity		
Station	Year	R1 global	R2 sliding	R2 sliding, weighted	R1 global	R2 sliding	R2 sliding, weighted
SD	2017	0.77	0.86	0.88	0.40	0.60	0.66
	2018	0.78	0.84	0.87	0.29	0.51	0.67
CM	2017	0.69	0.83	0.85	0.13	0.30	0.53
	2018	0.76	0.85	0.87	0.07	0.28	0.6
GH	2017	0.94	0.97	0.98	0.11	0.52	0.65
	2018	0.94	0.97	0.98	0.34	0.58	0.73

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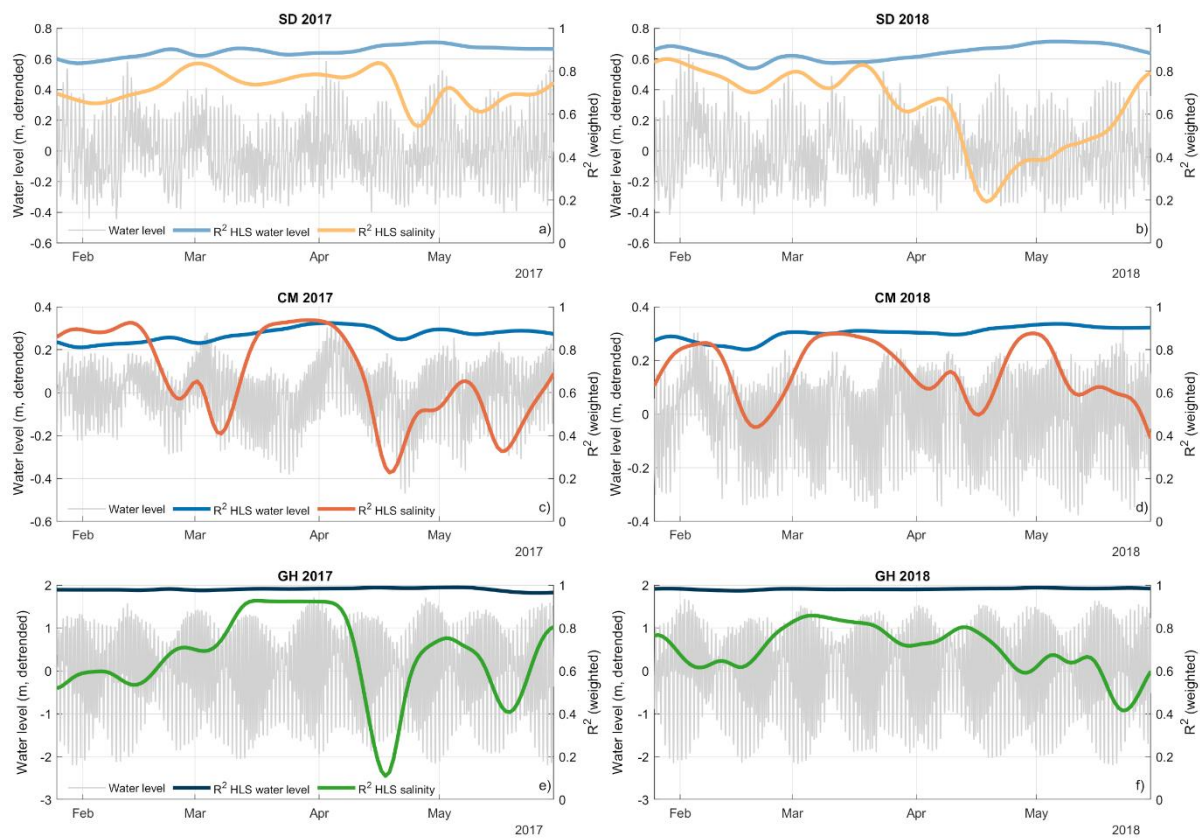
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1246 **D**



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1248 Tidal control expressed as explained variance R² of the global HLS reconstruction for water level and
1249 salinity at Song Doc, Ca Mau and Ganh Hao for 2017 and 2018.

Article

An Improved Groundwater Model Framework for Aquifer Structures of the Quaternary-Formed Sediment Body in the Southernmost Parts of the Mekong Delta, Vietnam

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Citation: Hoan, T.V.; Richter, K.-G.; Börsig, N.; Bauer, J.; Ha, N.T.; Norra, S. An Improved Groundwater Model Framework for Aquifer Structures of the Quaternary-Formed Sediment Body in the Southernmost Parts of the Mekong Delta, Vietnam.

Hydrology **2022**, *9*, 61. <https://doi.org/10.3390/hydrology9040061>

Academic Editors: Md Jahangir Alam, Monzur A. Imteaz and Abdallah Shanbleh

Received: 18 February 2022

Accepted: 3 April 2022

Published: 6 April 2022

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Abstract: The Ca Mau peninsula (CMP) is a key economic region in southern Vietnam. In recent decades, the high demand for water has increased the exploitation of groundwater, thus lowering the groundwater level and leading to risks of degradation, depletion, and land subsidence, as well as salinity intrusion in the groundwater of the whole Mekong Delta region. By using a finite element groundwater model with boundary expansion to the sea, we updated the latest data on hydrogeological profiles, groundwater levels, and exploitation. The basic model setup covers seven aquifers and seven aquitards. It is determined that the inflow along the coastline to the mainland is 39% of the total inflow. The exploitation of the study area in 2019 was 567,364 m³/day. The most exploited aquifers are the upper-middle Pleistocene (qp₂₋₃) and the middle Pliocene (n₂²), accounting for 63.7% and 24.6%, respectively; the least exploited aquifers are the upper Pleistocene and the upper Miocene, accounting for 0.35% and 0.02%, respectively. In the deeper aquifers, qp₂₋₃ and n₂², the change in storage is negative due to the high exploitation rate, leading to a decline in the reserves of these aquifers. These groundwater model results are the calculations of groundwater reserves from the coast to the mainland in the entire system of aquifers in the CMP. This makes groundwater decision managers, stakeholders, and others more efficient in sustainable water resources planning in the CMP and Mekong Delta (MKD).

Keywords: groundwater modeling; hydrogeology; aquifers system; water balance; validation of model; Ca Mau peninsula; Kien Giang; Soc Trang; Hau Giang; Bac Lieu

1. Introduction

Nearly 600 million people are living in river delta areas worldwide [1–3], of which about 17 million live in the Mekong Delta (MKD) [4]. River deltas are important for human civilization, as they are major agricultural production and population centers. Different natural and human-related activities led to enormous changes to the hydrogeological processes in delta areas, which are described in the following sections.

Vietnam is a country with a long coastline consisting of Quaternary sediments. Two large rivers transport sediments from the Himalayas toward Vietnam and discharge into the Pacific Ocean via the Red River Delta (RRD) and the MKD. Geomorphologically, the mouths of both rivers form typical deltas. Both deltas have witnessed transgression and regression phases and consist of complex sediment structures. More than the RRD, the MKD is of geopolitical concern, since it forms sediment bodies expanding southwards into

the free ocean and extends the exclusive economic zone 200 miles from the coast toward the open sea, determining the borders of Vietnam.

The southernmost part of the MKD, the Ca Mau peninsula, is under intensive stress in terms of erosion processes. The coastline is eroded up to 50 m each year [5], and intensive erosion occurs along the banks of the rivers and channels. One driver of this erosion is the change in land use since coastline-stabilizing mangroves were replaced by intensive agricultural activities such as rice and shrimp farming [6]. Another stress driver is the intensive land subsidence of up to 3 cm each year due to a lack of sediments from monsoon flooding, which is no longer occurring due to dam-based flood management. Nguyen et al. [7] used the MODFLOW model to simulate shallow aquifers on Tay Island in the Mekong River (Dong Thap province, near Hong Ngu city). The authors showed that the groundwater flow system is strongly affected by the interannual variation of the water levels in the Mekong River, especially by floodwater during the rainy season. The Ca Mau peninsula formerly was a mangrove area. Now, the management and the saltwater policy have decreased the mangrove population. Many dams are built to keep out saline water and freshen the ecosystem. In addition to this, many hydropower plants upstream of the Mekong are built against the natural streamflow. In former times, much more sediment was deposited during floods. The amount of sediment deposited due to floods every year is reduced by the aforementioned measures, and sedimentation almost no longer exists.

An additional stress driver for land subsidence is the intensive overexploitation of groundwater resources from the different confined aquifers in this region. Thus, overexploitation is one of the most relevant drivers of land subsidence. Numerous privately installed groundwater wells pump groundwater from the different aquifers without any supervision. According to the report of the project “Statistical and assessment of the current status of groundwater exploitation in the Ca Mau peninsula” [8], the whole Ca Mau peninsula comprises a total of 521,911 household wells and 1632 pumping stations, of which 3200 wells are damaged or abandoned.

Minderhoud et al. [9] used the open-source MODFLOW to set up a model for the large MKD area on a regional scale, within a grid size of 1×1 km. The results showed that their groundwater model is able to simulate the processes of land subsidence dependent on overexploitation with high accuracy in comparison to in situ measurements from space. Minderhoud et al. [10] projected extraction-induced subsidence and elevation of the MKD for the 21st century. The model result showed that the largest abrupt change in the subsidence rate happens in scenario M4, where the subsidence rate drops sharply from 8.9 (range: 5.5–12.5) to 1.6 (range: -1.3 – 4.9) mm/year because of the abrupt stop of all groundwater extraction. With current overexploitation, the amount of groundwater extraction in the delta is about twice the amount of recharge. The maximum recovery of the hydraulic heads in the MKD’s aquifer system is achieved when extraction is completely stopped (scenario M4).

This overexploitation not only results in land subsidence processes but also has the potential to promote the salinization of groundwater aquifers. Due to unstable aquifers, conditions with high-density saline water on top of deep freshwater aquifers, and the general drop of hydraulic heads, saline water may infiltrate from the ocean, channels and river systems, and shallow saline Holocene aquifers [11]. Contaminated surface water may infiltrate the groundwater and cause pollution. Saline water cannot be used for living purposes (salinization), such as cooking, drinking, or washing. Freshwater sources are mainly rainwater and groundwater. The overexploitation [12] of freshwater for domestic use and saltwater for aquaculture has depressed the groundwater levels, causing land subsidence [10] and saline intrusion [13]. Thus, overexploitation reduces the hydraulic pressure and contributes to the compaction of the sediment layers, resulting in land subsidence [14]. During the period 2010–2015, Vuong et al. [13] researched salinity intrusion into the MKD by GMS-MODFLOW with a grid size of 2×2 km and calibrated groundwater monitoring data from 2000 to 2010. The climate change scenario together with an increase in estimated exploitation of groundwater until 2100 shows that the saline

intrusion occurs strongly under the impact of climate change and overexploitation. Many other authors deal with salinity modeling in the MKD, such as Thu et al. [15], Hoan [16], and Trung [17], with special adaptations to different issues.

These studies mainly focus on land subsidence and saline intrusions due to groundwater extraction. Additionally, the models do not show hydrogeological windows or complex geological structure (with many fine-grained lenses, coarse grains intercropped with powdered clay) due to the limitation of hydraulic conductivity data. Moreover, the majority of relevant studies conducted in Vietnam, as well as internationally, concern hydrogeological strata, and hydrogeological parameters have not been collected fully and reliably. Along with that, with only a few monitoring wells in a large area with many aquifers, it will be difficult to accurately assess the water balance of the study area.

In order to manage for sustainable exploitation of water resources, the government of Vietnam has installed a national monitoring network for groundwater, with up to [18] 457 monitoring stations (941 observation wells in aquifers). In southern Vietnam, there are 50 monitoring locations (including 223 observation wells), and in the Ca Mau peninsula, there are 22 locations.

Sustainable groundwater protection needs a comprehensive scientific understanding of the complex processes and structures of the sediment layers acting as aquifers, aquitards, and aquicludes. The process of land subsidence in a delta is a complex process, having different causes and taking place in different hydrogeological structures (aquifers). These processes and the detailed processes of salinization on a local scale are unknown.

Thus, a well-founded model of the groundwater bodies is urgently needed, since until now, only a rudimentary understanding of the sediment body has been available. This is the basis of our study. Based on available new drilling data, a finite element FLOW (FEFLOW) approach was used to develop a model for groundwater in the complex structures of the sediment bodies of the Ca Mau peninsula. Therefore, a detailed high-resolution hydrogeological model for the Ca Mau peninsula must be set up to investigate the different processes on a local scale in different aquifers. In this paper, we describe the setup and calibration of this new model, FEFLOW, with an extension of the boundary to the sea. In the future, this **model** will be adapted to **salinity and land subsidence modeling**.

2. Study Area

2.1. Location and Situation

Ca Mau, Bac Lieu, and Kien Giang are located in the southern MKD region (Vietnam, see Figure 1). The terrain is low and flat with many rivers and canals. Most of the area has a low elevation, between 0.4 and 2.0 m.s.l. The terrain gradually slopes from north to south and from the northeast to the southwest. The Ca Mau peninsula has an interlacing river and canal system, which facilitates the exchange between surface water and groundwater of the shallow aquifers.

The tidal system in the Ca Mau peninsula is affected by the irregular semi-diurnal tidal regime of the East Sea, with an amplitude change of about 3.5 m, and the irregular diurnal tidal system of the West Sea (Gulf of Thailand), with an amplitude change of only 1 m [19].

The hydrological regime is directly affected by the tidal system with broad river mouths leading to the sea. Moving inland, the effect of the tides is reduced gradually, which causes the tidal amplitude and the propagation speed in the river to decrease. The systems of interlaced rivers and canals form a wetland that is suitable for agriculture. Saltwater intrusion into the surface water of the Ca Mau peninsula river system occurs during the dry season due to reduced freshwater flow in the canals and is directly related to the sea tides [20].

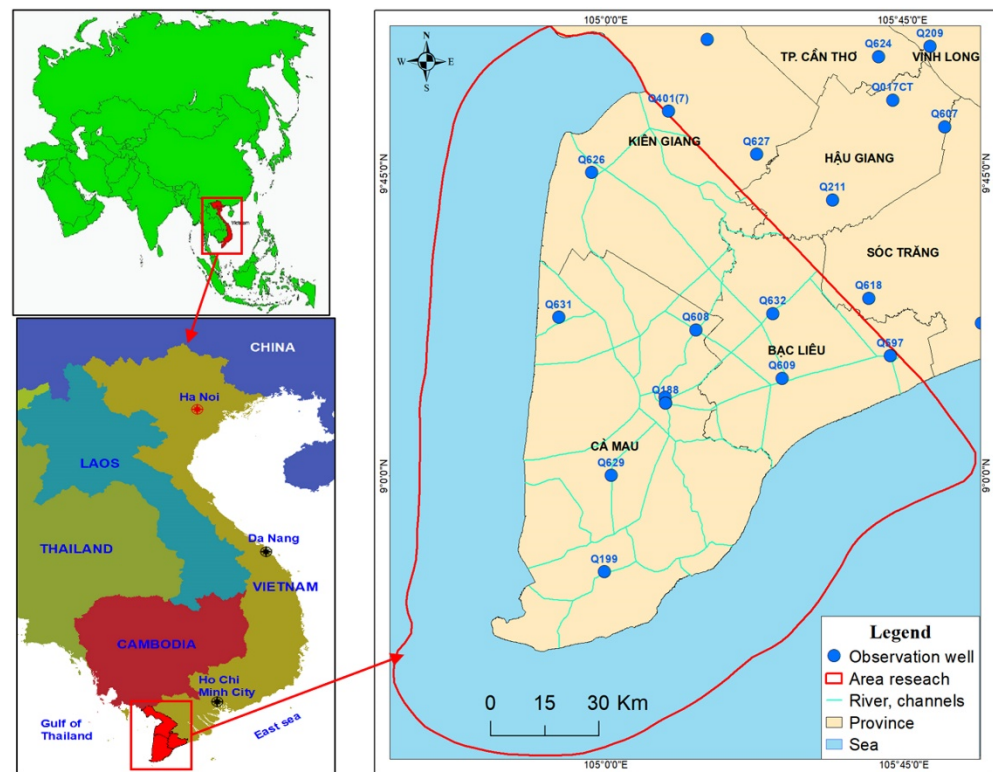


Figure 1. Location of the study area in the Ca Mau peninsula (sources of data: MONRE, NAWAPI, Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community).

2.2. Climatic Situation in Ca Mau Peninsula

According to the statistics of Ca Mau station 2015–2019 [4], the Ca Mau peninsula has a high average temperature (28 °C); the average temperature of the whole area is relatively homogeneous. The highest average temperature is in April (29.6 °C) and the lowest is in January (26.9 °C).

The annual average comparative relative humidity is from 82.2% to 87.2%. In September and October, the highest relative humidity levels occur (86–89%). In January and February, the relative humidity levels are the lowest (75.6–83.2%).

The area of research has two seasons: the rainy season, which lasts from May to November, and the dry season, from December to April. The total annual rainfall is about 2008–2304 mm/year. The rainfall is concentrated mainly in the rainy season, accounting for about 90–92% of total annual rainfall.

The evaporation level in the research area is substantial, with an annual average above 1000 mm (Picher-mm). In the dry season, due to the extensive sunshine and low humidity levels, the evaporation is the highest, particularly in March–April, with 130 mm. In the rainy season, the evaporation is lower, and October has the lowest evaporation level of 60 mm.

2.3. Hydrogeology

In the MKD, a series of unconsolidated Cenozoic sediments (marine transgression cycles) cover a Mesozoic basement. In the Ca Mau peninsula, these Cenozoic deposits are 300–400 m thick on average. The subsidence of the Ca Mau peninsula in the Neogene was caused by the uplift of the Himalayan orogenesis, with high erosion rates in the mountains that provided large amounts of debris transported by the Mekong River to its delta, where it formed, due to sedimentation, the Ca Mau peninsula. Several cycles of marine transgression and regression during the Pleistocene led to a stratification of marine and alluvial faces. The change between high sea levels, which caused saltwater intrusion into the Ca Mau peninsula sediments, and the low sea levels during the glacial

events, which caused the freshwater lenses, comprised the hydrogeological situation (Figure 2b). The mostly fine-grained Holocene sediments protected the deeper layers against recent salinization. The situation is described in Figure 2b. There are seven aquifers (Holocene—qh, upper Pleistocene—qp₃, upper-middle Pleistocene—qp₂₋₃, lower Pleistocene—qp₁, middle Pliocene—n₂², lower Pliocene—n₂¹, and upper Miocene—n₁³) and seven aquitards (Figure 2c).

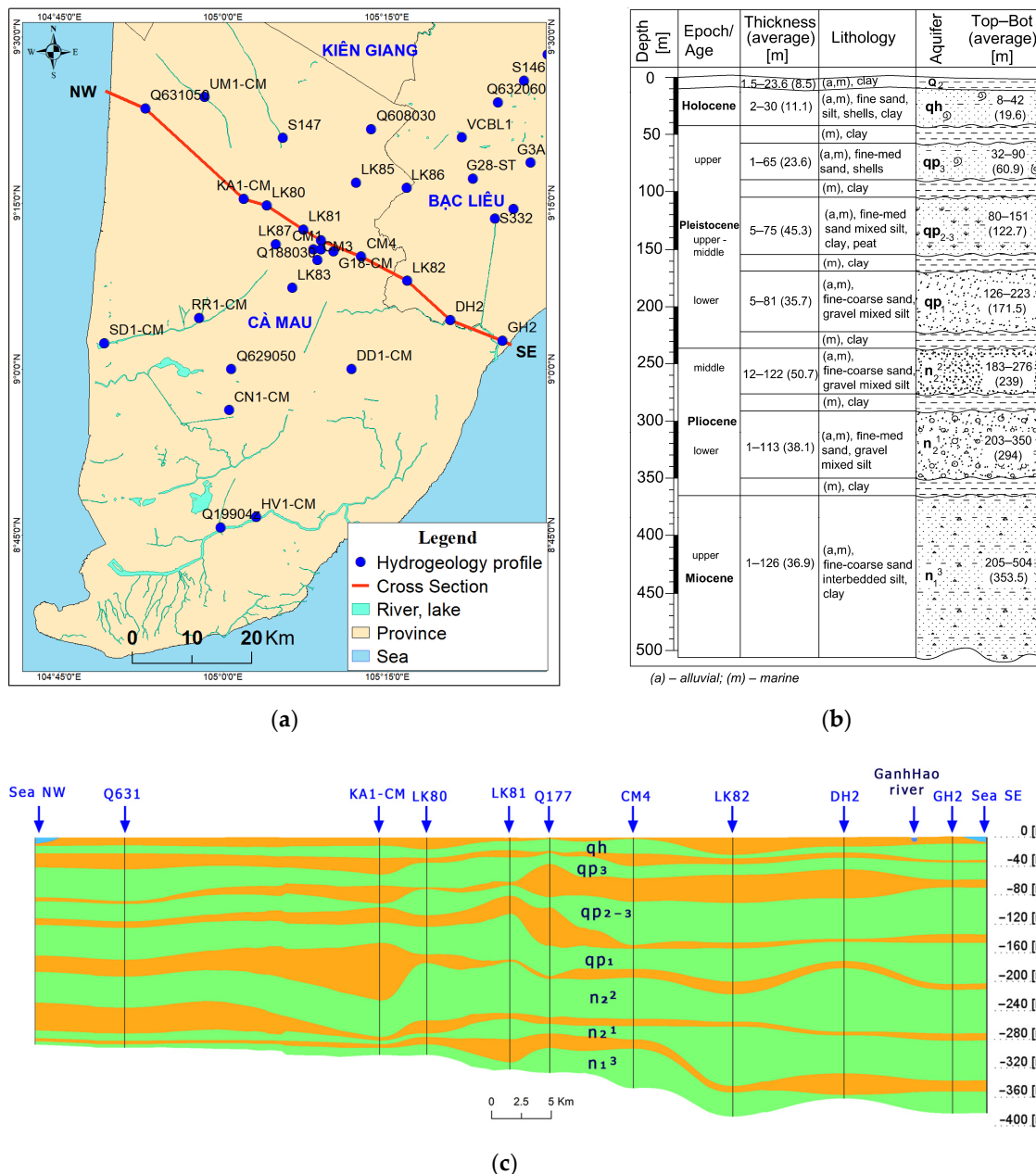


Figure 2. Position of cross-section NW–SE (a). Schematic representation of sedimentary aquifer succession in Ca Mau province (b). Cross-section of Ca Mau peninsula following the path NW–SE (c). (Sources of data: hydrogeological profiles collected by NAWAPI [21].)

2.4. Groundwater Exploitation

The exploitation of groundwater in the Ca Mau peninsula mainly supplies domestic use in urban areas as well as rural areas, industrial parks, and services. In addition, groundwater (including saline water) is used for aquaculture, agriculture, and other purposes. A summary of data collected in six provinces shows that the total amount of groundwater

exploited in the whole region is 453,850 m³/day [8]. In the research area, the exploitation of the various aquifers is very different, depending on the area. Households (unlicensed wells) mainly concentrate on shallow aquifers such as qp₃ (Kien Giang) and qp₂₋₃ (Kien Giang, Ca Mau, Bac Lieu). Licensed exploitation wells are concentrated mainly in deeper aquifers, such as qp₂₋₃ (Kien Giang), qp₁ (Ca Mau, Bac Lieu), and n₂² (Ca Mau). Based on data collected starting in 2010 by the ViWaT project, Ca Mau groundwater exploitation is mainly concentrated in the n₂² aquifer with a flow of 40,000 m³/day; in part of the Kien Giang area, with concentrated exploitation of the qp₂₋₃ aquifers of 12,600 m³/day; and Bac Lieu, with concentrated exploitation of the qp₂₋₃ aquifers of 56,300 m³/day.

3. Data Collection

For the Ca Mau peninsula study area, many data from previous projects are available. The quality and accuracy of the data collected depend primarily on the responsible organizations (DONRE's Ca Mau, MONRE, and NAWAPI) and officials who conduct their surveys and report on their results. Although some of the projects were conducted in the same research area, they produced different results about the groundwater extraction volume due to the estimation of the source from households [22]. In the research area, for the exploitation data, we rely on DONRE's licensed exploitation data. The unregistered extraction volume data from households is interpolated when calibrating the model.

The following data were collected for the evaluation of the hydrogeological model:

- Seventy-eight hydrogeology profiles [21,23];
- Fifty-four surface water profiles [13];
- Rainfall from six different stations (1990–2018) [18];
- Surface water level data (2011–2018) [18];
- Water exploitation data from DONRE's Ca Mau (2011–2018).

The monthly hydraulic heads were taken over the period January 2011 to December 2019 with a total of 74 observation wells (16 locations with well groups collecting data from different aquifers) from the National Center for Water Resources Planning and Investigation [21] and BGR projects [22]. Forty-one observation wells in the model area and eight locations started recording data from 2019 onward. The information on the observation well groups is shown in Figure 3. For the long period, two locations (Q410 and Q597) with 10 wells were used for the boundary condition, and three locations (Q177, Q188, and Q199) were used in which there are some monitoring wells with a full validation period from January 2011 to December 2019.

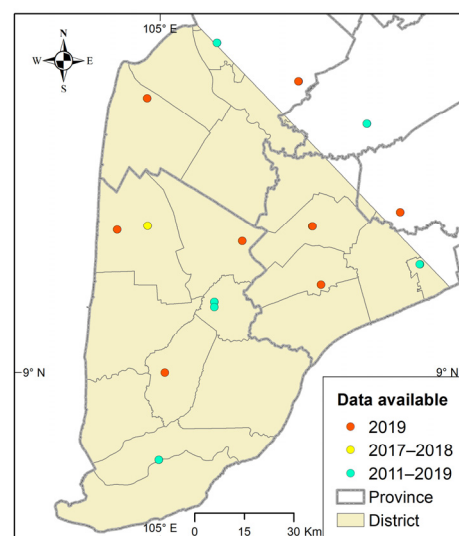


Figure 3. Observation well availability from 2011 to 2019 (source: NAWAPI [21]).

4. Methodology

The modeling process starts with planning, which focuses on gaining clarity on the intended use of the model, the questions at hand, the modeling objectives, and the type of model needed to meet the project objectives. The next stage involves using all available data and knowledge of the region of interest to develop the conceptual model (conceptualization), which is a description of the known physical features and the groundwater flow processes within the area of interest. Then, a mathematical model must be selected with the consistency of mesh, hydrodynamic characteristics, and boundary conditions. Afterward, the initial model will be calibrated by trial and error to understand the response of the model to parameter changes. FePest [24] with the zoning approach was used to achieve optimum calibrations using observation wells as control points. The ongoing procedure is shown on the right side of the flowchart (Figure 4) and is described in detail in the following subsections.

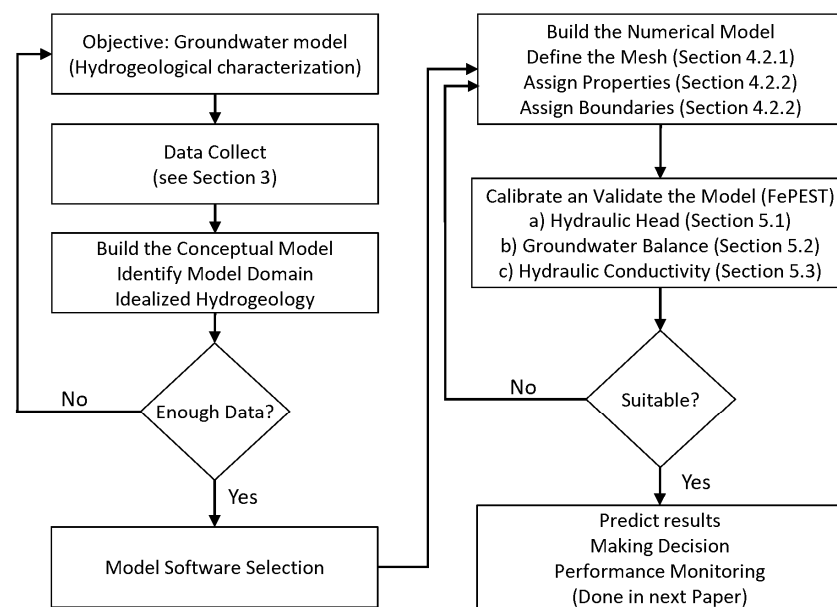


Figure 4. Flowchart of the processing method.

4.1. Model

The MODFLOW model of MKD for an area of approximately 43,000 km² was built by DWRPIS [13] in the GMS environment. The model simulates the situation from 2000 to 2010 and focuses on accessing the influences of climate change and sea level rise. In 2017, Minderhoud et al. [9] used MODFLOW based on environment iMOD (image processing, modeling) [25]. They extended the Mekong model to Ho Chi Minh city and focused on land subsidence. The purpose of the development of a groundwater model in this paper is to design an early warning system for groundwater level depletion and saline intrusion into the aquifers of the Ca Mau peninsula. In the study area, a 3D hydrogeology model was built using the finite element method to simulate the groundwater flow in the Ca Mau peninsula.

Different from using the finite difference method in MODFLOW, the finite element method in FEFLOW [24] shows more advantages in calculating speed and the ability to construct aquifers that are more complex. FEFLOW can create layer-based, partially unstructured, or fully unstructured meshes in 3D and produces precise spatial representations of complex diversity and geometrical settings such as rivers, fractures, pipes, tunnels, and well locations (www.mikepoweredbydhi.com (10 February 2022)). Finite element methods provide a better representation of anisotropy, whereas MODFLOW requires conductivity to be perpendicular to the faces of the finite difference cells [26].

4.2. Model Setup and Calibration

4.2.1. The Modeling Framework

The model area covers the Ca Mau province and parts of the provinces Soc Trang, Bac Lieu, and Kien Giang. A three-dimensional numerical hydrogeological model with finite elements (FEFLOW) was developed to simulate groundwater flow and fluctuations in hydraulic heads over the past 10 years (2011–2020) applying monthly time steps. The modeling area is about 19,900 km², of which the mainland is about 9600 km², with 1,963,276 nodes and 1,056,390 elements (Figure 5b). The finite element meshes are created together with the wells, monitoring points, and rivers. The distance between elements is approximately 10 m to 2.5 km depending on the area.

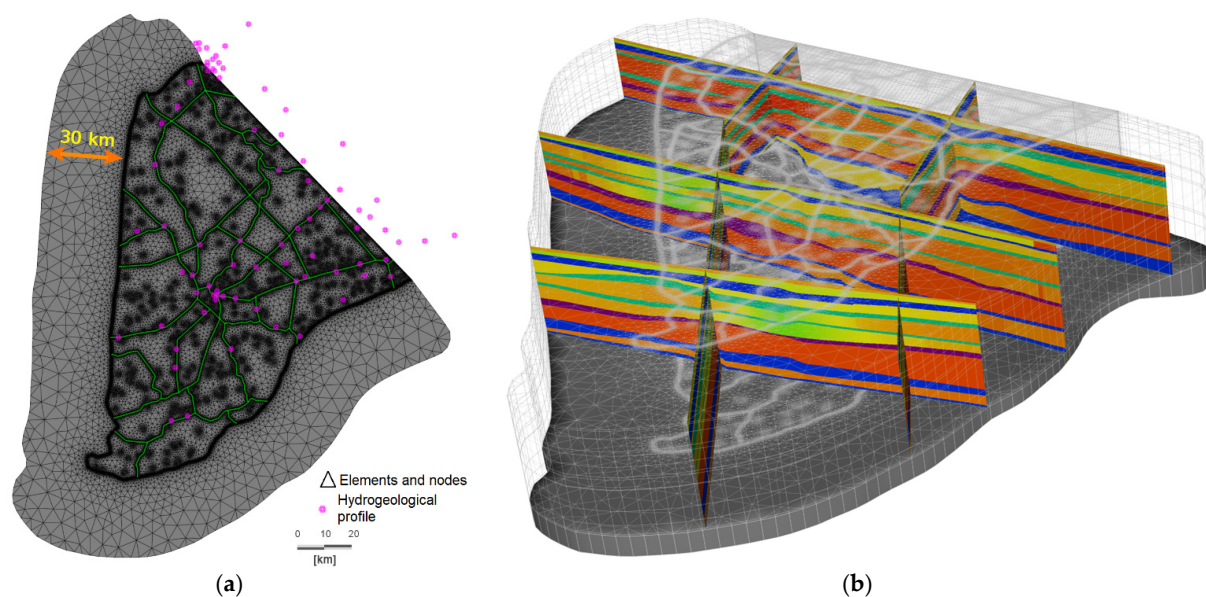


Figure 5. Finite element model areas and 3D hydrogeological model. (a) The mesh and hydrogeological profile; (b) A three-dimensional hydrogeology.

The Ca Mau peninsula subsurface is divided into seven main hydrogeological units using 78 hydrogeological profiles (Figure 5a) and additional information provided by the “Division for Geological Mapping for the South of Vietnam” (governmental organization). Each hydrological profile consists of a permeable bottom layer and the tops for seven aquifers and seven aquitards (Figure 5b). This information was used to create the 3D subsurface model using the linear interpolation method. This resulted in 14 layers comprising the subsurface model, representing seven aquifers, six aquitards, and a phreatic (Q_2) top layer (Figures 2c and 5).

Average hydraulic conductivity (K) values are depicted in Table 1. In addition, the most important rivers are included in the model to calculate the interaction between surface water and the aquifers qh and qp₃. The river widths and river depths were derived from surface water profiles.

Table 1. Statistical average hydrogeology parameters of the aquifers.

Layer (Aquifer)	2 (qh)	4 (qp ₃)	6 (qp ₂₋₃)	8 (qp ₁)	10 (n ₂ ²)	12 (n ₂ ¹)	14 (n ₁ ³)
Number of wells	7	30	64	43	41	25	11
K _h (m/day) *	1.66×10^1	2.78×10^1	2.22×10^1	1.95×10^1	1.81×10^1	1.44×10^1	1.10×10^1
K _v (m/day) **	1.66	2.78	2.22	1.95	1.81	1.44	1.10
Ss	5.00×10^{-4}	3.26×10^{-3}	1.95×10^{-3}	4.20×10^{-4}	2.26×10^{-3}	4.42×10^{-4}	5.00×10^{-5}

* K_h: horizontal hydraulic conductivity, ** K_v: vertical hydraulic conductivity. Data sources: NAWAPI [21] and DWRPIS [23].

To set up the model, the groundwater model must be parametrized by horizontal and vertical K, and by porosity and specific storage for each aquifer and aquitard. According to collected data, the average horizontal conductivity (vertical conductivity is taken as one-tenth [27] of the horizontal conductivity) and specific storage (Ss) are shown in Table 1. These values were interpolated using the inverse distance method to import the model.

4.2.2. Model Boundary Conditions

The boundary conditions (BCs) that are critical for the groundwater flow model of the Ca Mau peninsula are the flow from the northern boundary and the ocean and the surface water levels from the river and channel system. In addition, the recharge from rainfall and the pumping rates are included in the model. The boundary conditions are shown in Figure 6.

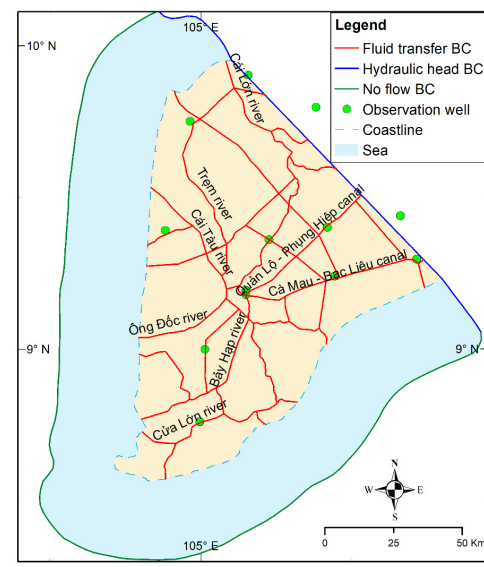


Figure 6. Boundary conditions in the model.

Along the northern boundary of the model, the first type of hydraulic head BC was assigned. The hydraulic head on the northern boundary was determined based on the interpolation of two well groups along the northern line (Q597 and Q401), and for each aquifer, a monthly value from January 2011 to December 2019 was used. The boundary conditions are shown in Figure 7.

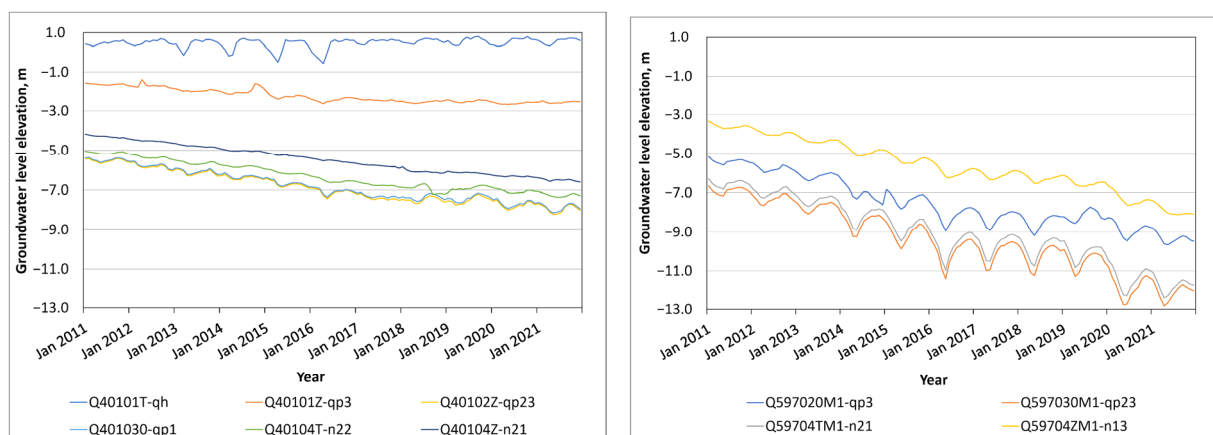


Figure 7. Observation data from different aquifers at Q401 and Q597 (source: NAWAPI [18]).

Figure 6 shows the hydraulic heads for different aquifers. In most of the aquifers, a depletion of the hydraulic head can be seen with an interannual variation. The depletion is caused by an extraordinary increase in exploitation during the past 11 years (Table 2), totaling nearly 30%.

Table 2. Total pumping rates in the model for different aquifers.

Aquifers	Pumping Rate (m ³ /day)			Percentage Increase (%)
	January 2011	December 2019	Difference	
qp ₃	−1649	−1987	−338	20.5
qp ₂₋₃	−294,010	−361,580	−67,570	23.0
qp ₁	−24,801	−33,278	−8477	34.2
n ₂ ²	−104,820	−168,600	−63,780	60.8
n ₂ ¹	−340	−1805	−1465	430.9
n ₁ ³	−100	−114	−14	14.0
Total	−425,720	−567,364	−141,644	33.3

To reduce the influence of the outer boundary on groundwater flow in the mainland, extending the border offshore is a good solution. Its southwest and southeast borders are artificial boundaries in offshore areas where hydraulic heads were assigned no-flow boundary conditions. For the river/canal, fluid transfer BC was chosen as the third kind/Cauchy BC [24]. This flow (infiltration/exfiltration) depends on the water level difference between surface water and groundwater. The boundaries are assigned to phreatic layer 1 and layer 2 (aquifer qh), representing the main rivers/canals and the area around the coast. According to different authors [25], recharge from the river system to the aquifers in the downstream part of the Ca Mau peninsula is expected to be limited due to the presence of a thick, largely impermeable, Holocene aquitard near the surface, effectively sealing off the aquifers below.

Considering recharge from rainfall, the thick aquitard strata at the surface separate the deeper aquifers from the surface water system and may prevent direct aquifer recharge [22]. Moreover, the very dense river and canal network quickly discharges the intensive runoff generated by frequently occurring heavy rainfalls. Therefore, the recharge from rainfall is very small. In the model, initial recharge input amounts to 1% of the mean monthly rainfall (based on two Ca Mau and Bac Lieu stations, in the model divided into three recharge zones).

Regarding pumping from 2011 to 2019, the licensed exploitation of Ca Mau city has increased by 66%. This increase is similar within Bac Lieu province. Unregistered extraction wells grow at an annual rate of 2.5% based on estimates of extraction increase by DWRPIS [10]. The following pumping rates (Table 2) were calculated from the licensed wells for the different aquifers. An interannual variation of the pumping rates is assumed.

5. Results of Model Calibration and Validation

Ahmed Hassan [28] discusses groundwater model validation in detail. He distinguished between scientific, philosophical, operational, and confidence-building views of model validation. The scientific view implies that the model is representing reality. Jackson et al. [29] demand, for specific models, “validation that one might reasonably expect someone with relevant technical knowledge to consider the model acceptable”. From the operational view of model validation, Flavelle [30] argues that most of the validation definitions available in the literature make explicit reference to the need to demonstrate that a model is a good, correct, or sufficient representation of reality and that “these definitions require subjective interpretation”. In addition to this, from the confidence-building view, Davis and Goodrich [31] postulated two acceptance criteria for an existing model: “The first is a measure of the adequacy of the model structure (conceptual model, mathematical model) in describing the system behavior and the second is a measure of the accuracy of

the model input parameters relative to experimental results and field observations.” This leads to the following criteria, which are commonly accepted by groundwater modelers as criteria for an integrated view of a scientific, operational, and confidence-building view of model validation.

To validate a groundwater model, different aspects should be validated:

1. Does the model represent reality (scientific and confidence-building validation)?
2. Best fit to measured and calibrated hydraulic head (confidence-building validation);
3. Validate the groundwater balance (scientific validation);
4. Validate hydrogeological parameters such as conductivity and porosity (scientific and confidence-building validation).

After consideration of the availability, credibility, and distribution in each aquifer/area of the Ca Mau peninsula, 46 monitoring wells were selected for validation. Groundwater model calibration is performed by systematically adapting the model parameters of conductivity, specific storage, leakage factor, and porosity to the measured groundwater levels and the measured discharge in the river system to a plausible estimate of discharge at the hydraulic head boundaries and to a plausible groundwater balance. This results in the error value (positive or negative), which must be minimized during the process of calibration.

The calibration of the model is limited by three different conditions:

1. Interpolation of unregistered extraction wells with an increase in annual growth of 2.5% from 2011 to 2019. Licensed exploitations were compared with the actual licensed exploitation in 2018 from Ca Mau DONRE, in total by 65.7%, so in the model, the corresponding increase was 6.5%/year.
2. Based on the data collected, the transient calibration phase is from January 2011 to December 2019.
3. A reduced information base of groundwater monitoring data for the period January 2011 to December 2019 (only three stations are available: Q199, Q188, and Q177). Since the beginning of 2019, more groundwater measurement stations have been available (Figures 1 and 3).

5.1. Model Validation of Hydraulic Head

The quality of the model is tested in space and time for different aquifers according to Davis and Goodrich's [31] second point mentioned at the beginning of this section.

A usual model test in groundwater modeling can be performed using scatter data plots. These are shown for 46 monitoring wells for two different time steps in Figure 8. In addition to this, the 1:1 line is shown. For January 2018 (dry period) and October 2019 (rain period), values are shown for all the aquifers. The computed hydraulic head is consistent with the measured data. The absolute error E , the root mean square (RMS), and the standard deviation (σ) values are very small; the correlation coefficient is very high in both cases.

Another methodology for testing the model in space is the use of groundwater isohypses, which were used within the error between the measured and calculated hydraulic head points for different well groups. A confidential error of 1.5 m is chosen to verify the quality of model, taking into account the fluctuations of groundwater level during the day and the influence of tides. The difference due to these influences is about 1.5 m and can be up to 2.5 m [14].

In Figure 9, the simulated hydraulic heads from December 2019 for qp_1 and n_2^2 are shown. The green marked error bars show the confidential error for observation wells, and the center of the target corresponds to the observed value. From the isohypses, the continuous hydraulic head in space is shown. The deepest hydraulic heads for both aquifers are shown in the city of Ca Mau, caused by large pumping rates. With a longer period calibrated, Q177 has an important role in the groundwater-monitoring network in the city of Ca Mau with large exploitation.

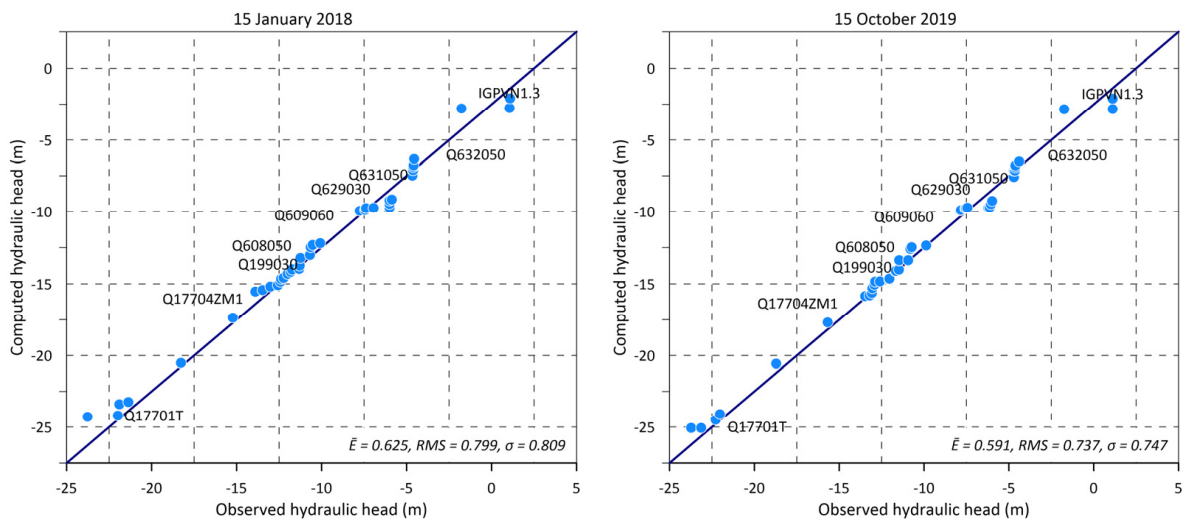
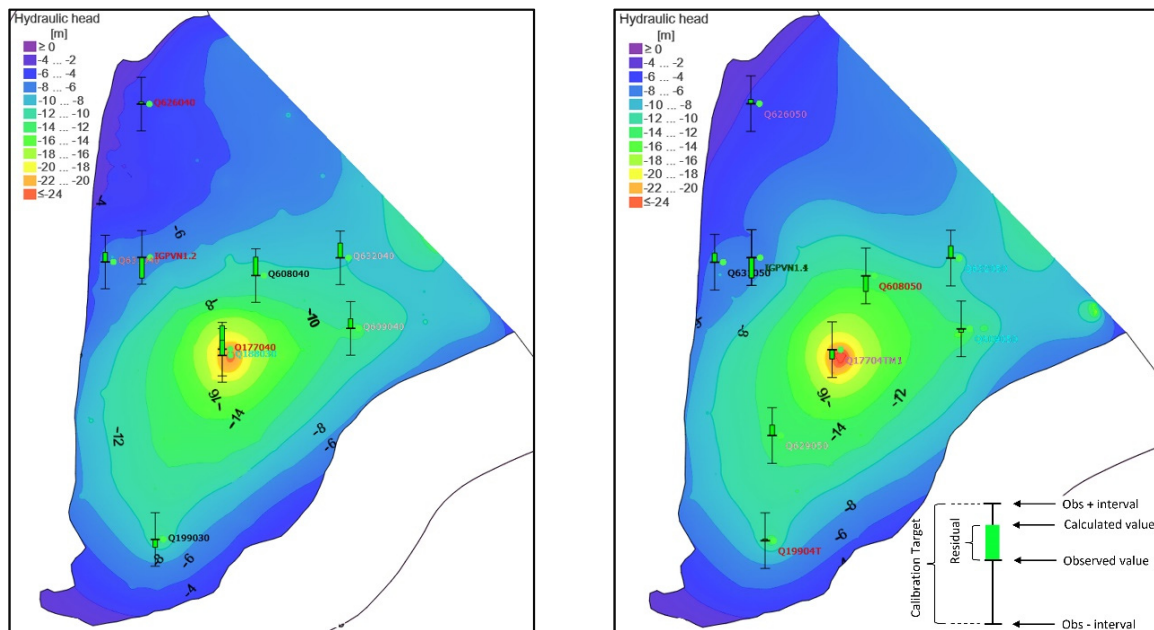


Figure 8. The comparison of computed vs. observed head values in January 2018 and October 2019.



(a) December 2019, qp₁p

(b) December 2019, n₂²

Figure 9. Hydraulic head for aquifers qp₁ and n₂² in December 2019.

In Figure 10, the monthly measured and calculated groundwater levels are shown as a time series. Q177 and Q199 (Figure 10, left side) show the measured and calculated values with the best fits in the model. The aquifers qh and qp₃ show that the fluctuation of the water level tends to be stable, while the qp₁ and n₂² layers are influenced by groundwater exploitation and the dry and rainy seasons of the MKD. Figure 10 (right side) shows simulated (Q608 and Q609) groundwater level trends and captures the groundwater system behavior for a one-year validation period in the complicated exploitation setting.

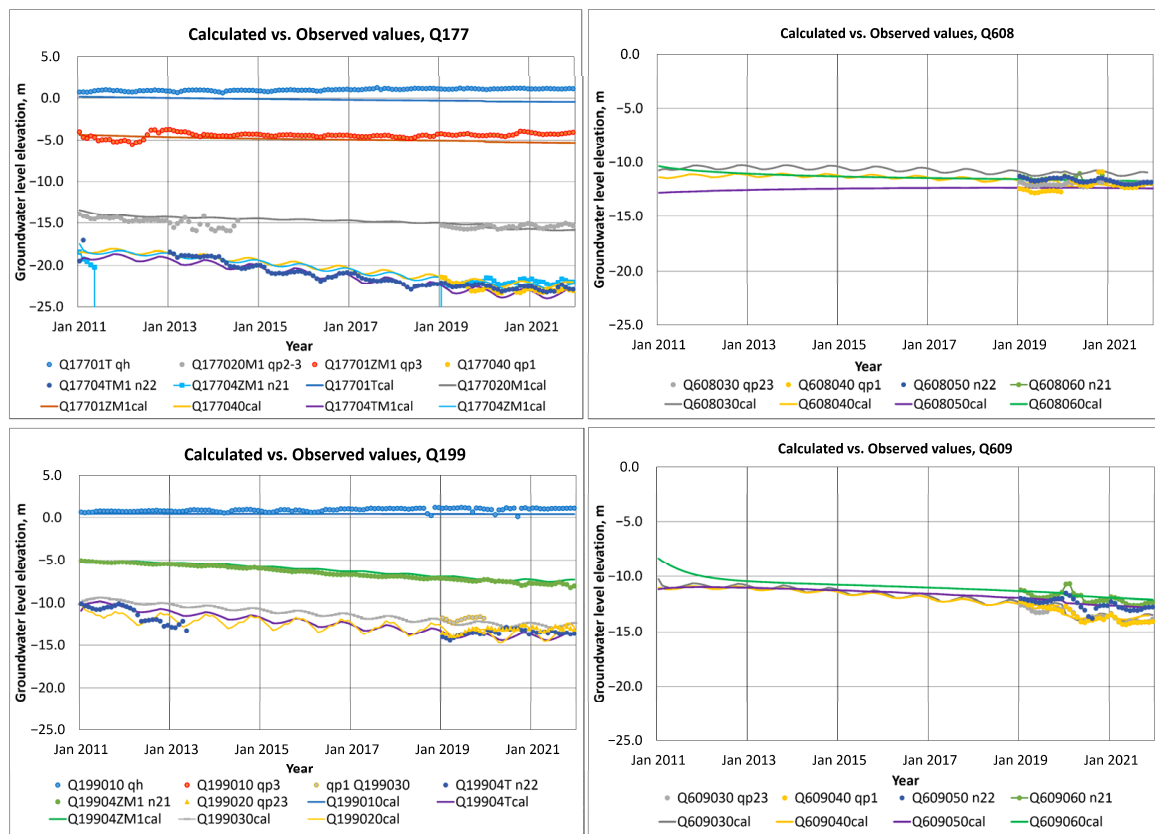


Figure 10. Time-dependent measured and calculated hydraulic heads for different well group and aquitard models.

As a common result of the criteria detailed in the beginning of Section 5, the system behavior described for the hydraulic head is accepted in a confidence-building view of model validation, because the calculated hydraulic head is validated against point measurement hydraulic head data in time and space. This leads to the second criterion for the operational view of model validation, “that a good, correct, or sufficient representation of reality” in time and space (Figures 9 and 10) can be assumed. Moreover, according to the scientific view of validation, which is mentioned above, the authors considered the model as acceptable, considering the knowledge of the hydrogeological situation in the Ca Mau peninsula.

5.2. Valuation of Groundwater Balance

Another important model of quality control is the groundwater balance, which should be plausible. According to the different mentioned criteria for model validation, only the operational and scientific view of model validation occurred, given the fact that underground flow along huge boundaries could not be measured. In Figure 11, the different components are shown for the Ca Mau peninsula. The overall averaged *total sum* (January 2011 to December 2019) in the Ca Mau peninsula is 742,876 m³/day, and the *total sum* out is 742,979 m³/day. The parts of the different components are shown in Figure 11. The *flow in* from the hydraulic head net rate boundary north (see Figure 6) is about 12%, and the inflow along the coastline of the Ca Mau peninsula is about 39%. One important part (approximately 23%) is also the exfiltration from the huge river and channel system. The interaction takes place in the two upper layers. The rainfall (or groundwater recharge) is negligible. Nearly 24% of the *total sum* is part of the positive internal storage flow inside the Ca Mau peninsula.

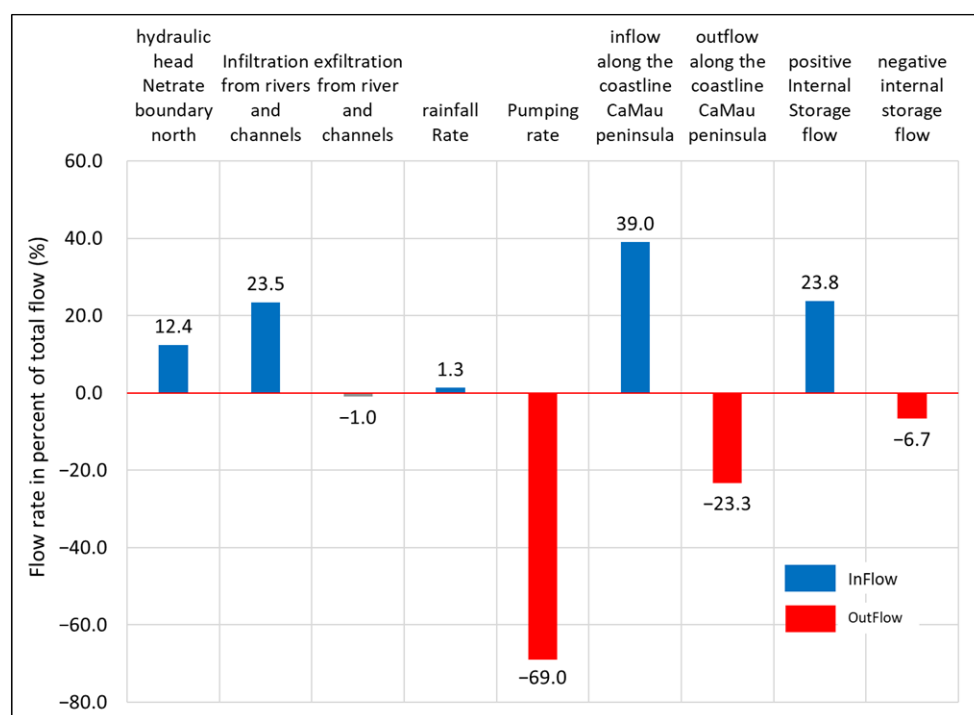


Figure 11. Groundwater balance of the model (components in percent of total flow).

The biggest export out of the model area is the pumping rate, with 69% of the total outflow; approximately 23% is the total outflow flow rate along the coastline of the Ca Mau peninsula into the sea. The exfiltration from the river and channel system is negligible. The negative internal storage flow inside of the model is about 6.5% of the total outflow. To sum up these results, exploitation takes place in the deeper aquifers with nearly 70% of the flow. The filling up of the groundwater system is caused by the positive hydraulic head net rate boundary north, the infiltration from the channel system, and the inflow along the coastline of the Ca Mau peninsula from the ocean, especially for the upper aquifers.

The overall analysis of the groundwater components can be seen on a timescale with variation from January 2011 to December 2019 in Figure 12. There are notable differences in the components. The vertical axis is shown on a logarithmic scale. The most significant component is the pumping rate, within a seasonal variation and an increase from 2011 to 2019. The inflow along the coastline of the Ca Mau peninsula is nearly constant. The hydraulic head net rate boundary north inflow has a high interannual variation, mostly caused by pumping along the northern boundary. In addition, the exfiltration from the river and channel system is assumed constant. There is an interannual variation in the storage, as shown in positive internal storage flow and negative internal storage flow within an increase in the maximum and minimum in the past nine years, which is also caused by pumping.

To conclude, the knowledge of the components of the groundwater balance and their seasonal variation is highly important for groundwater management. Thus, the groundwater balance is considered acceptable from the scientific view of model validation, given the authors' detailed hydrogeological knowledge of the Ca Mau peninsula based on previous studies [9,12,13,32]. The groundwater balance is not mentioned in any known publication.

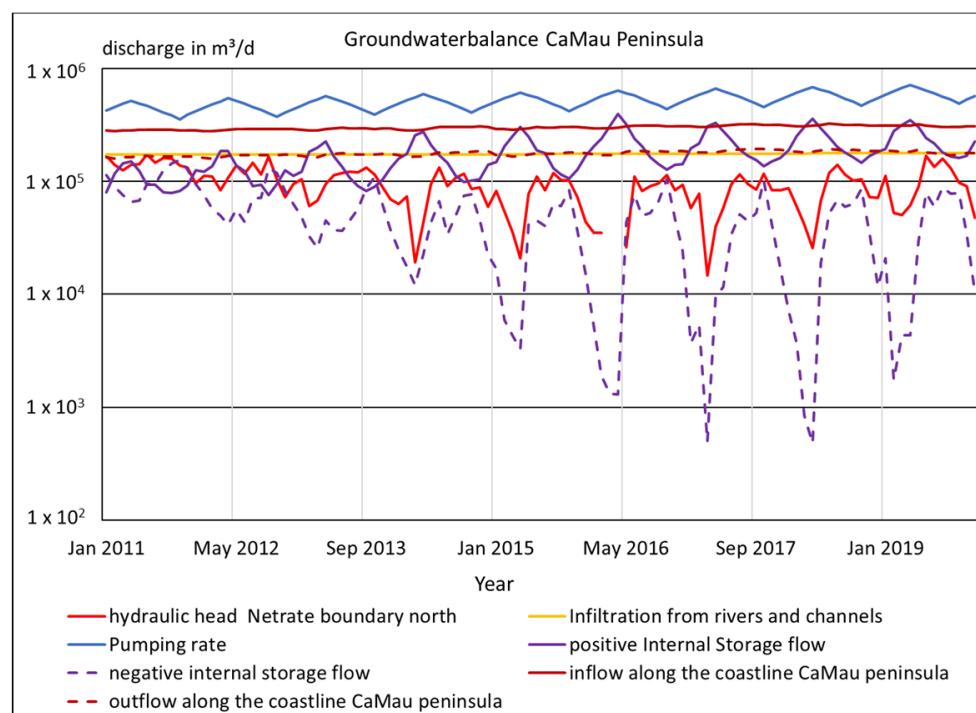
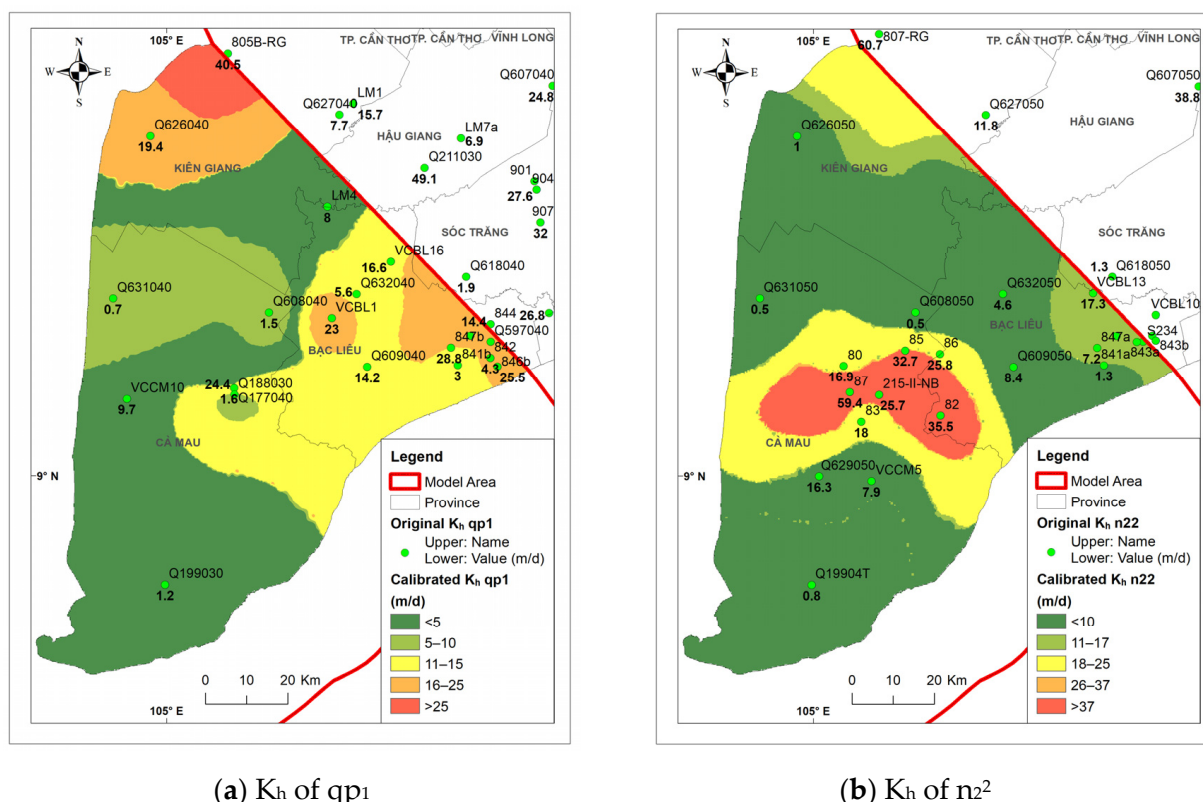


Figure 12. Groundwater balance of the model (monthly variation).

5.3. Valuation of Hydraulic Conductivity

Another possible method of validating the hydrogeological model is comparing the “measured hydraulic conductivities” with the “calibrated hydraulic conductivities”. As an example, the results for the aquifers n_2^2 and qp_1 are shown in Figure 13.



(a) K_h of qp_1

(b) K_h of n_2^2

Figure 13. Calibrated K_h for qp_1 and n_2^2 in comparison with K_h from pumping test.

For the aquifer qp1, the horizontal hydraulic conductivity (K_h) varies between 1.0 and 40 m/day. The highest K_h is located in the northwest in Kien Giang province. The regions with K_h higher than 25 m/day are located at the northern border. The regions with lower K_h (green regions) stretch from the middle of the northern border along the west coast, including the southern part of the Ca Mau peninsula. The comparison of the measured K to the calibrated K shows an overall good correlation.

For the aquifer n_2^2 , the K_h varies between 1.0 and 60 m/day. The highest K_h is located in the surrounding area of Ca Mau city. Moreover, the regions with a K_h higher than 37 m/day (red regions) are located here. The regions with lower K_h (green regions) are located in the north and in the south part of Ca Mau peninsula. Additionally, in this aquifer, the comparison of the “measured K ” to the calibrated K shows an overall good correlation.

Shrestha et al. [32] and Nguyen et al. [7] developed groundwater models for the whole MKD and the Tay Island Region (Dong Thap province). The calibrated hydraulic conductivities used in these models are presented in Table 3 together with those of this study. The values for the K for groundwater layers qh, qp3, qp2-3, qp1, and n_1^3 of Shrestha et al. [32] are similar to those of the recent presentation. The K values from Nguyen et al. [7] are smaller for all aquifers because of limited hydrogeological data collected for the small study area. Both authors did not present a spatially distributed comparison of calibrated and measured K .

Table 3. Comparison average of hydraulic conductivity.

Aquifer	Hoan, 2022	Shrestha, 2016	Nguyen, 2013
Q	0.50	no value	no value
qh	3.57	10.00	6.40
qp3	14.00	25.00	3.70
qp2-3	14.86	18.60	3.20
qp1	9.62	25.00	2.50
n_2^2	12.95	22.00	1.50
n_2^1	6.65	33.80	1.20
n_1^3	5.00	9.40	no value

6. Discussion

The results presented in this paper are discussed according to the following questions:

1. How realistic are the used estimations on exploitation data?
2. Can we verify the calculated groundwater balance for the Ca Mau peninsula?

The first question is important when considering model calibration and model uncertainty. As described in Section 5.2, the groundwater model is calibrated assuming the correctness of the estimated pump rates. Thus, the pump rates (approved by the maximum delivery quantities of the licensed abstraction wells) have an influence on the hydrogeological model parameters of permeability coefficient and storage coefficient. In order to validate the used pumping rates inside the groundwater model, we compared different literature sources for the groundwater exploitation (Table 4).

To compare the used pumping rates (Table 2), a plausibility check of the pumping rates can be performed using the daily water consumption per inhabitant. These results vary between 108 L/person/day in [13] and 297 L/person/day in the BGR Report 2017 [19] for 2010. In the model presented here, a water consumption rate of 144 L/person/day was used.

The current average urban water use standard (including water loss) is 100 L/person/day; it was 120 L/person/day in 2015 and 130 L/person/day in 2020 and will be 130 L/person/day in 2025 [8].

Table 4. Different sources for pumping data.

Source	Province	Time	Pumping Rate (m ³ /day) in Different Aquifers							Population	Water Usage/Capita
			qp ₃	qp ₂₋₃	qp ₁	n ₂ ²	n ₂ ¹	n ₁ ³	Total		(L/day)
Vuong B.T., 2014	MKD	2010	114,945	977,514	130,077	477,359	87,653	87,653	1,875,201	17,306,700	108
BGR Report 2017 (1)	Ca Mau	2009	-	265,371	49,859	52,570	5532	-	373,332	1,258,788	297
BGR Report 2018 (2)	Ca Mau	2015	-	223,989	92,614	106,728	3021	-	426,352	1,257,788	339
Minderhoud 2020 (3)	Ca Mau	2010	-	160	265,371	49,859	52,570	5532	373,492	1,258,788	297
Minderhoud 2020 (3)	Ca Mau, Bac Lieu, 1/2 Kien Giang	2010	207	17,521	514,206	114,313	68,453	7282	721,982	2,956,583	244
Ca Mau FEFLOW Model	Ca Mau, Bac Lieu, 1/2 Kien Giang	2010	1649	294,010	24,801	104,820	340	100	425,720	2,956,583	144
Ca Mau FEFLOW Model	Ca Mau, Bac Lieu, 1/2 Kien Giang	2019	1987	361,580	33,278	168,600	1805	114	567,364	2,962,401	192
Average			29,697	305,735	158,601	153,464	31,339	20,136			231
Standard deviations			56,837	326,420	177,227	148,399	37,194	37,879			86

(1) Baseline Study Ca Mau Review of Studies on Groundwater Resources in Ca Mau Province, Technical Report No III-2, 2017 [19]. (2) Detailed Investigations on the Hydrogeological Situation in Ca Mau Province, Technical Report III-5, 2018 [22]. (3) Minderhoud, Groundwater extraction may drown mega-delta: Projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century, 2020 [10].

The total sum of groundwater exploitation for industrial use in Ca Mau province was estimated by DWRM to be approximately 13,000 m³/day in 2014 [8]. This means an amount of approximately 10 L/person/day (13,000 m³/1,217,822 persons). For the year 2010, the estimation for the unlicensed wells was (1/3 of 100 L/person/day = 34 L/person/day). These three components are summed as follows:

+ 100 L/person/day (from statistics)
+ 10 L/person/day (industrial use)
+ 34 L/person/day from unlicensed wells
= 144 L/person/day from Ca Mau that is used in the actual model.

Comparable values for industrial water use exist in DWRM [8] for Bac Lieu (15 L/person/day), Kien Giang (4 L/person/day), Soc Trang (20 L/person/day), and Hau Giang (2.5 L/person/day).

The total flow of groundwater exploitation in 2019 in the study area was 567,364 m³/day. The groundwater flow is unevenly exploited in the study area as well as in the aquifers, depending on the real pumping location. The most exploited aquifers are qp₂₋₃, and n₂², accounting for 63.7% and 29.7%, respectively; other significantly exploited aquifers are qp₁ and n₂¹, accounting for 5.9% and 0.3%, respectively.

Table 5 shows the results of calculating the horizontal net flow transfer in cubic meters per day, which mainly occurred from the sea, and the net flow transfer in cubic meters per day from the upper and lower aquitards. For the aquifers qp₂₋₃ and n₂², with the largest pumping rates, the horizontal and vertical net flows are the biggest (q_h = 39,000 m³/day and q_v = 49,892 m³/day for qp₂₋₃ and q_h = 27,100 m³/day and q_v = 36,464 m³/day for n₂²), because these are the ones exploited the most in the study area. The vertical and horizontal net flows in the deepest aquifer, n₁³, are the smallest.

Table 5. Aquifer budget for different aquifers in December 2019.

Aquifer	Net Flow m ³ /day		Pumping		Change in Storage m ³ /day
	Vertical (q _v)	Horizontal (q _h)	m ³ /day	%	
qp ₃	16,141	−4500	−1987	0.35	9654
qp _{2–3}	49,892	39,000	−361,580	63.73	−272,688
qp ₁	21,093	18,300	−33,278	5.87	6115
n ₂ ²	36,464	27,100	−168,600	29.72	−105,036
n ₂ ¹	8368	4100	−1805	0.32	10,663
n ₁ ³	4912	2664	−114	0.02	7462
Sum	136,870	86,664	−567,364	100.00	−343,830

The change in storage is only negative in the aquifers qp_{2–3} and n₂², with the highest exploitation rate. In the other aquifers, the change in storage is positive.

The storage changes in layers 1 and 2 (Q₂ and q_h) are positive. These shallow aquifers are important layers in the system of aquifers in the Ca Mau peninsula and receive recharge from rainfall as well as leakage from rivers and channels.

The model shows that the groundwater level decline is mainly due to an increase in the pumping rate. However, the groundwater level from q_h and qp₃ aquifers mostly tended to stabilize (Figure 10). For the time of the model run, from January 2011 until December 2019, the flow of unregistered extraction wells in the aquifer qp_{2–3} increased in total by 23%. The pumping rate of licensed exploitation wells in the n₂² aquifer increased in total by 61% (Table 2). The assumed pumping rates show a realistic estimate for the water exploitation in the Ca Mau peninsula.

In this study, the first groundwater balance for the Ca Mau peninsula is published in detail for the total area. The results are available for all aquifers. Unlike previous studies by Minderhoud et al. [9,10,14], Vuong et al. [13], and Shrestha et al. [32], which mainly assessed land subsidence and climate change, this study focused on assessing water balance, using newly updated detailed data on groundwater extraction in the period from 2010 to 2018 and a higher number of nine monitoring points (46 monitoring wells all together). The use of homogeneity K for aquitards in previous studies [13,30] has limited the leakage of aquifers. The model area was only developed inland, so the coastal boundary conditions needed to be interpolated. All these results lead to an inaccurate water balance assessment. In contrast to the former studies mentioned in this paper, the aquitards are open in some regions, so that more realistic water exchange between aquifers is possible. Therefore, the model boundary was enlarged to 30 km outside of the mainland. No interpolation of the boundary conditions along the coastline was necessary. This led to a more realistic estimate of the groundwater balance.

According to the international standard of groundwater model validation (see Section 5), the scientific, operational, and confidence-building views of validation are guaranteed in the presented groundwater model.

7. Conclusions

A new 3D hydrogeological structure groundwater model with the latest available information (hydrogeological information from 78 wells, pumping rates from nearly 700 licensed wells, and 40 wells for groundwater measurements) with a high-resolution triangular mesh was built.

The model was calibrated in a way that the differences between the measured and calculated hydraulic heads were consistent with the uncertainties of the measured heads. The increase in a more accurate calibration required additional changes to the K field. These changes led to a more realistic understanding of the hydrogeological situation in the Ca Mau peninsula.

The main aquifers qp₁ and n₂² supply groundwater to Ca Mau city, Kien Giang, and Bac Lieu, but the exploitation status increases rapidly. The increased exploitation is examined in a realistic way and validated against the water use of the inhabitants.

Due to the large exploitation volume of the study area ($567,000 \text{ m}^3/\text{day}$, 2019), recharge from outside the study area is not enough to compensate extraction, leading to declining groundwater levels.

In particular, this article calculated and analyzed the water balance according to the aquifers and identified the sources of reserves (inflow along the coastline, inflow from the north) between offshore and mainland areas.

The reserves were calculated based on the model. However, reserves include both saltwater and freshwater; this study has not calculated the total potential exploitable reserves of freshwater. In the next studies, these results will be confirmed by field studies as well as adapting a saline intrusion model.

These research results show that the model has contributed to promoting the development and innovation of water resources research using the finite element method. With the current exploitation, the groundwater level is continuing to tend to decrease. In addition, the inflow along the coastline to the mainland is 39% of the total inflow. Therefore, groundwater resource managers need to investigate the coastal saltwater sources in detail; develop an early warning system for depletion and saltwater intrusion; protect zones and reduce groundwater exploitation; and increase the use of other water sources, such as artificial groundwater recharge, rainwater harvesting, using surface water, and transporting water from other places, as alternatives to groundwater.

Author Contributions: Conceptualization, T.V.H., S.N. and K.-G.R.; methodology, T.V.H., K.-G.R., N.B. and J.B.; software, DHI WASY; validation, formal analysis, and investigation, T.V.H. and K.-G.R.; resources, N.T.H. and S.N.; writing—original draft preparation, T.V.H. and K.-G.R.; writing—review and editing, T.V.H., S.N., K.-G.R., N.T.H., N.B. and J.B.; supervision, S.N. and N.T.H.; funding acquisition, S.N. All authors have read and agreed to the published version of the manuscript.

Funding: This work is part of the ViWaT Engineering project, funded by the German Federal Ministry of Education and Research (BMBF) under grant No. 02WCL1474A/E. Additional financial support was provided by the Catholic Academic Exchange Service (KAAD) and the Karlsruhe Institute of Technology (KIT).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data provided in this paper are available on the request from the corresponding author. A permission letter (18.3.2022) from NAWAPI for collecting 78 hydrogeology profiles, surface water profiles, rainfall data, surface water level data, and water exploitation data is available.

Acknowledgments: This paper benefitted substantially from the comments and suggestions of two anonymous reviews. Ministry of Science and Technology (MOST), German Ministry of Education and Research (BMBF) and Research ViWaT Engineering project, and Catholic Academic Exchange Service (KAAD) supported the work described in this publication. This work is a contribution to the German-Vietnamese research initiative ViWaT Mekong (http://nawapi.gov.vn/index.php?option=com_content&view=article&id=5995%3Ahp-hi-ng-anh-gia-kim-tra-nghim-thu-nm-2020-cm-tai-vi-wat-1-vi-wat-2-vi-wat-3&catid=2%3Ahoat-dong-cua-trung-tam&Itemid=132&lang=vi or <http://www.vi-wat.info/english/21.php>).

Conflicts of Interest: No conflict of interest.

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Article

The Utilization of a 3D Groundwater Flow and Transport Model for a Qualitative Investigation of Groundwater Salinization in the Ca Mau Peninsula (Mekong Delta, Vietnam)

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Abstract: The Ca Mau Peninsula (CMP), the southernmost region of the Mekong Delta, is increasingly threatened by groundwater salinization, posing severe risks to both the freshwater supply and land sustainability. This study develops a three-dimensional, density-dependent groundwater flow and salinity transport model to investigate salinization dynamics across the CMP's complex multi-aquifer system. Unlike previous studies that largely rely on model calibration, this research introduces a novel approach by systematically deriving the spatial distribution of longitudinal dispersivity based on sediment characteristics. Moreover, detailed land use mapping is integrated to assign spatially and temporally variable Total Dissolved Solids (TDS) values to the uppermost layers, thereby enhancing the model realism in areas where monitoring data are limited. The model was utilized not only to simulate the regional salinity evolution, but also to critically evaluate conceptual hypotheses related to the mechanisms driving groundwater salinization. Results reveal a strong influence of seasonal and land use factors on salinity variability in the upper aquifers, while deeper aquifers remain largely stable, affected primarily by paleosalinity and localized pumping. This integrated modeling approach contributes to a better understanding of regional-scale groundwater salinization and highlights both the potential and the limitations of numerical modeling under data-scarce conditions. The findings provide a valuable scientific basis for adaptive water resource management in vulnerable coastal zones.

Keywords: salinity modeling; groundwater transport modeling; hydrogeology; aquifers system; Vietnam; saltwater intrusion; Ca Mau Peninsula; Kien Giang; Bac Lieu



Academic Editor: Yong Xiao

Received: 25 March 2025

Revised: 10 May 2025

Accepted: 12 May 2025

Published: 20 May 2025

Citation: Hoan, T.V.; Richter, K.-G.; Dörr, F.; Bauer, J.; Börsig, N.; Steinel, A.; Le, V.T.M.; Pham, V.C.; Than, D.V.; Norra, S. The Utilization of a 3D Groundwater Flow and Transport Model for a Qualitative Investigation of Groundwater Salinization in the Ca Mau Peninsula (Mekong Delta, Vietnam). *Hydrology* **2025**, *12*, 126. <https://doi.org/10.3390/hydrology12050126>

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1. Introduction

Groundwater salinization is increasingly recognized as a critical global issue, threatening freshwater resources essential for domestic, agricultural, and economic activities in coastal regions [1–4]. This phenomenon is exacerbated by multiple stressors, including

climate change, rising sea levels, and intensive groundwater extraction [5,6], highlighting the need for the improved understanding and management of coastal groundwater resources [7].

The Ca Mau Peninsula (CMP), located at the southernmost region of the Mekong Delta (MKD), is one of the regions most affected by groundwater salinization [8]. For local communities who rely heavily on groundwater, particularly during the dry season [9], excessive groundwater extraction has led to notable declines in groundwater levels (Figure 1). Additionally, upstream dam construction on the Mekong River significantly reduces freshwater inflow, intensifying dry season saltwater intrusion inland [10,11]. However, saltwater intrusion pathways remain inadequately understood due to geological complexity and data limitations, necessitating detailed hydrogeological modeling.

The hydrogeological structure of the CMP comprises seven aquifers and seven aquitards [12,13]. While aquitards were traditionally viewed as continuous barriers, recent studies highlight significant heterogeneity and interconnectedness among aquifers [6,14]. Observations show synchronized dynamics of the groundwater levels across multiple aquifers, suggesting either hydraulic connectivity or loading effects from external stresses [15].

To underscore the urgency of the situation, Figure 1 illustrates the decline in groundwater levels across various aquifers in the CMP, providing direct visual context for the modeling objectives that follow.

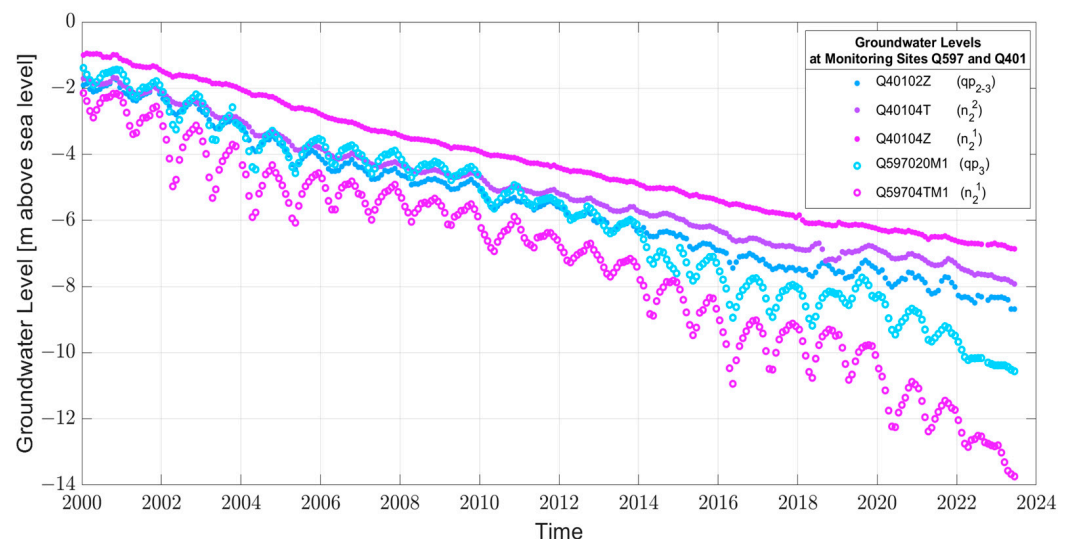


Figure 1. Monthly averaged groundwater levels in monitoring well groups, Q597 and Q401, located in the Ca Mau Peninsula; for the location see Figure 2, and for different aquifers (upper Pleistocene—qp₃; Upper–Middle Pleistocene—qp₂₋₃; Middle Pliocene—n₂²; Lower Pliocene—n₂¹) see Figure 3 (source of data: the NAWAPI).

Over the past decades, groundwater flow and salinization models have been developed for Vietnam [16–18], as well as for the MKD in particular [13,19,20]. Modeling approaches have primarily employed the MODFLOW software [21] and have mostly covered large areas. However, a recent development includes a local high-resolution groundwater model specifically designed for the CMP by [12].

Due to the limited availability of spatially distributed, continuous salinity measurement data, we propose a salinity transport model based on the hydrogeological model of [12] to assess potential salinity pathways.

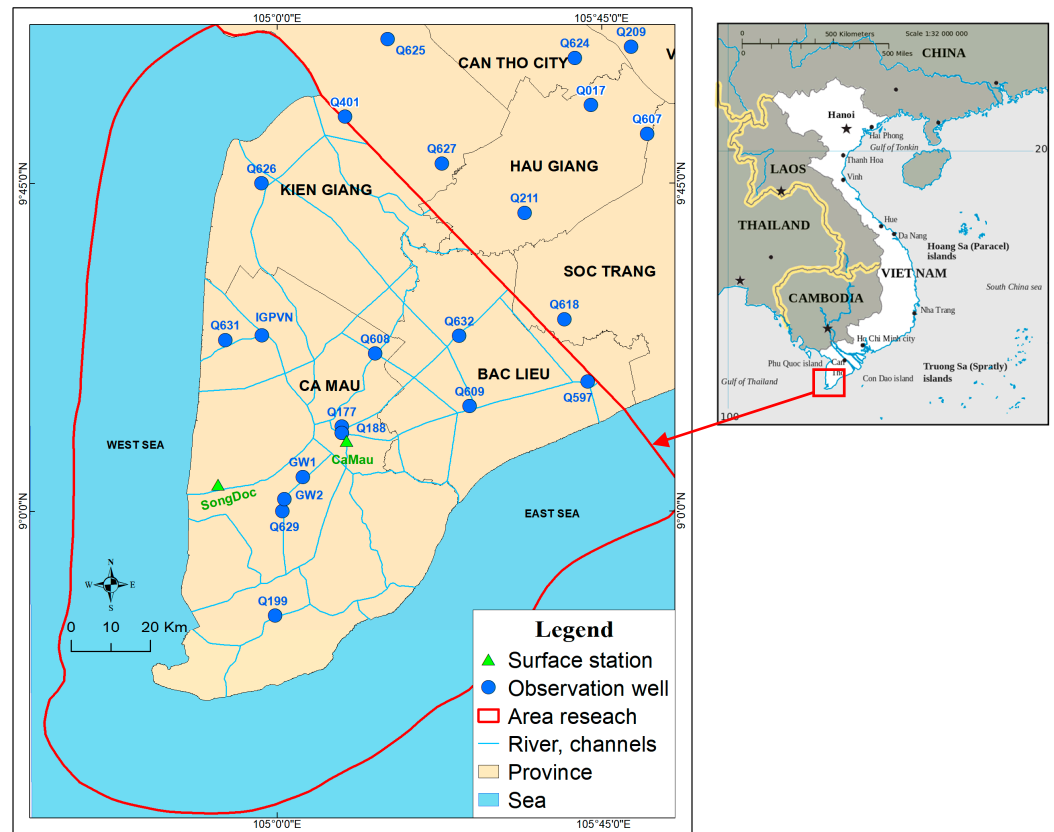


Figure 2. The location of the study area on the Ca Mau Peninsula showing the extent of the model area and observation wells (sources of data: NAWAPI, Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community).

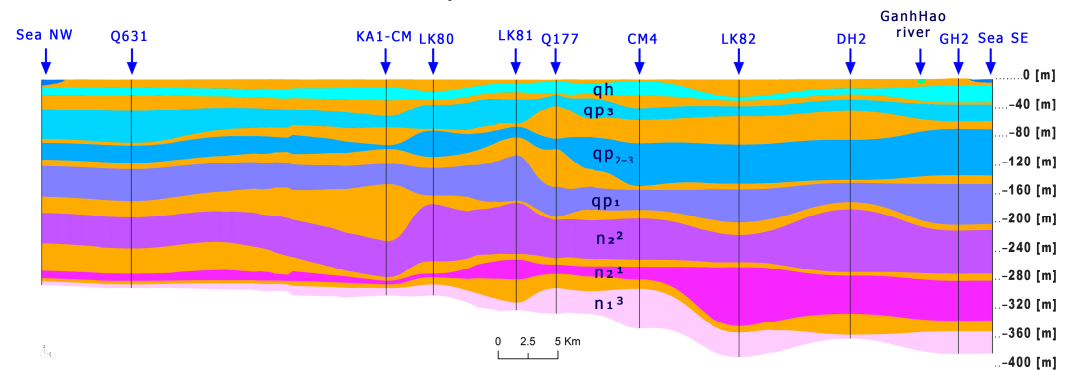


Figure 3. The hydrogeological structure of the Ca Mau Peninsula. Aquitards are shown in orange, and aquifers range in color from blue to magenta (modified after [12]).

Based on the data analysis and the knowledge from the hydrogeological model, we formulate and evaluate the following hypotheses based on observed salinity trends and hydrogeological modeling:

- (a) “There is no lateral saline intrusion from the ocean into the deeper aquifer”.

This hypothesis suggests no horizontal saltwater movement into the deeper aquifer, depending on the geological and hydrological conditions such as the extent and continuity of the aquitards.

- (b) “Different land use classes impact the salinity in the qh aquifer and contribute to the high spatial variability of the salinity in the qh aquifer”.

This hypothesis indicates spatial salinity variability driven by land use impacts on infiltration, runoff, and recharge processes.

- (c) “Interannual variations in the surface water salinity in the river and channel system, as well as in mangrove, rice, and shrimp farming areas, could cause the high variability in the salinity in the qh aquifer”.

This hypothesis emphasizes climatic, precipitation, and anthropogenic influences on salinity dynamics in shallow aquifers.

- (d) “Salinity variations in the deeper aquifers might be caused by the extraction of water during pumping”.

Based on recent field surveys conducted by the ViWaT research program [9,22] and data collected in Ca Mau Province, there has been a noticeable rise in the groundwater salinity levels over the past decade. This has led farmers and water suppliers to drill deeper wells to access freshwater, as previously utilized sources no longer meet quality standards (personal interviews with local farmers, 2022). However, monitoring data from the Vietnamese national groundwater network show no significant increase in salinity within the deeper aquifers [23]. This discrepancy suggests a need for further investigation to identify whether local factors, such as over-extraction or well-drilling practices, could be causing localized increases in salinity.

This study advances the understanding of saltwater intrusion by systematically deriving the spatial distribution of longitudinal dispersivity instead of relying solely on calibration, as commonly practiced in previous groundwater salinity models. Rather than focusing solely on optimizing the fit to available salinity measurements, our approach prioritizes improving the physical understanding of salinity transport processes through a hypothesis-driven methodology. While many studies traditionally adjust porosity to refine model performance, we highlight the critical role of dispersivity in controlling salinity patterns. A particularly notable contribution is the application of detailed land use maps to assign variable TDS values for the uppermost aquifer layer, where direct monitoring data are limited or unavailable. This method significantly enhances the spatial resolution and accuracy of groundwater salinity characterization at regional scales, providing an efficient and cost-effective alternative to traditional field-based measurements and interpolation techniques. The findings offer valuable insights into interactions between aquifer heterogeneity, dispersivity, and land use-driven salinity variations, establishing a refined methodology highly applicable for regional groundwater salinity assessments.

The primary objectives of this study are as follows: (1) to systematically derive the spatial distribution of longitudinal dispersivity; (2) to integrate detailed land use mapping to assign realistic TDS values in shallow aquifers; (3) to elucidate the dynamics and underlying mechanisms of groundwater salinization within a complex multi-aquifer system at the regional scale; and (4) to assess the practical limitations of applying the modeling approach.

2. Study Area

The study area aligns with that employed in our previous study [12]. It is located in the southernmost region of the MKD, Vietnam, covering the provinces of Ca Mau, Bac Lieu, and the lower part of Kien Giang (see Figure 2). The study area is located in a region strongly affected by climate change [24]. The region faces major challenges, described by [9] as the “loss of land and freshwater”, which includes processes such as coastal erosion, land subsidence, and the salinization of the surface and groundwater bodies.

Geologically, there have been multiple transgression and regression periods, resulting in several-hundred-meter-thick sequences of marine and fluvial sediment deposits [14]. In recent geological history, the area was created as a consequence of the uplift of the Himalayan Mountains and the associated erosion. This eroded material was transported by

the Mekong River and deposited in its delta, forming the CMP. These deposits also exhibit a certain degree of salinity from former transgression/regression processes.

With an average elevation of approximately 0.8 m [25] above sea level, the CMP lies at a relatively low altitude. The coastline of the model area is approximately 396 km long. The maximum ocean depth within a range of 30 km beyond the coastline is approximately 80 m. The salinity of the ocean water is 35 g/L on average [13,26]. The channel and river system of the CMP is strongly influenced by the ocean tides. Tidal amplitudes in the western sea reach a maximum of approximately 1 m, whereas in the eastern sea, amplitudes can reach up to 4 m [27]. This causes saline inflow into the channel and river system, with a maximum salinity of nearly 33 g/L in the river system [28]. The river system can be locally connected to the qh aquifer, as described by [29]. However, the surface water–groundwater interaction is considered to be limited in most areas, with the top aquitard being several meters thick [12], Figure 3 (cross-section).

The surface water network comprises a dense system of interlinked channels used for transportation and agricultural and aquacultural activities. However, the hydraulic interaction between the surface water network and the aquifer system does not extend down to qp₂₋₃ [30]. The conceptual model of the groundwater system of the CMP consists of seven aquifers (from top to bottom: Holocene—qh; Upper Pleistocene—qp₃; Upper—Middle Pleistocene—qp₂₋₃; Lower Pleistocene—qp₁; Middle Pliocene—n₂²; Lower Pliocene—n₂¹; and Upper Miocene—n₁³; Figure 3). These aquifers are separated from each other by aquitards. However, the continuity of these aquitards has not yet been fully clarified and is therefore examined in this evaluation.

The groundwater in the deep aquifers in the MKD region consists of brackish, saline, and fresh types. In previous studies, the determination of the groundwater age was inconclusive, ranging from recent to older than 45 ka, but with an increasing trend from the Pleistocene to Miocene aquifers [26,30]. The saline water in the deep aquifers could result from the diffusion of saline pore water and/or past/present salt intrusion into the freshwater resources. The interaction between the deeper aquifers might be caused by the natural conditions (e.g., locally thin aquitard layer, hydrogeological windows, and hydraulic gradients) or anthropogenic factors (e.g., number of production wells, leakage along the well structure, and underground construction) [9].

This study focuses on qp₂₋₃ and n₂² aquifers, as these are the most exploited aquifers in the model area, as mentioned in [12]. The qp₂₋₃ and n₂² accounted for 63.7% (361,580 m³/day in 2019) and 29.7% (168,600 m³/day in 2019) of the total pumping in 2011. According to a survey conducted in 2019, residents in Ca Mau mainly use groundwater for diverse domestic purposes. However, only 25.4% of the respondents in the survey used groundwater from local household wells for drinking purposes [22]. The higher salinity in the qp₂₋₃ aquifer is one reason for the minor use of its groundwater for drinking. In addition, high concentrations of other parameters (e.g., Fe, Mg, etc.) have been reported [4], leading to a reduced use of water from qp₂₋₃ for drinking. Therefore, this study emphasizes the importance of qp₂₋₃ and n₂².

Due to the presence of a thick clay layer at the top, the recharge to deeper aquifers in the study area is severely restricted. Consequently, groundwater in deeper aquifers primarily comprises paleowater, accumulated tens of thousands of years ago during historical transgression and regression periods. Over thousands of years, variations in transgression and regression have shaped the current salinity patterns in deep aquifers, leading to complex interactions between ancient saline water and present groundwater dynamics. This characteristic strongly influences the groundwater salinity distribution and dynamics within the system.

3. Data Collection

Despite these modeling advancements, the available data for the evaluation of ground-water salinity in the CMP remain limited. Groundwater salinity data in the CMP have been collected primarily through two distinct approaches:

- Sampling campaigns at various observation wells in different aquifers, with the laboratory analysis of Total Dissolved Solids (TDS) since 2011 with two measurements per year (dry and rainy season);
- Electrical Conductivity (EC) measurements (data logging sensor) with a calibration factor for TDS calculations, implemented since 2019, at various observation wells in different aquifers.

To ensure comprehensive data coverage, salinity data were collected from multiple sources, including the national groundwater monitoring network [31] and international research cooperation projects, such as the ViWaT project (<https://www.viwat.info/english/21.php> (accessed 20 August 2023)) and the IGPVN (<https://igpvn.vn/> (accessed 20 August 2023)) project from 2013 to 2022, which cover key study areas, including Ca Mau, Kien Giang, Soc Trang, and Bac Lieu.

For salinity measurements, two distinct methodologies were employed in the study area. The first approach entailed the laboratory analysis of water samples utilizing standard procedures. While some samples were collected biannually during both the dry and rainy seasons [32], others were based on one-time sampling. In contrast, the second method involved continuous measurements using Electrical Conductivity.

It should be noted that EC and TDS values obtained over long-term monitoring periods can exhibit certain inaccuracies due to various factors, including the prolonged observation of well operations, sampling technique, pumping duration, and analytical procedures [33,34]. These factors inherently increase uncertainty in EC and TDS measurements. Nevertheless, this variability reflects the natural complexity and inherent uncertainty of real groundwater systems, particularly in shallow aquifers (qh). Therefore, these discrepancies are considered an inevitable component in the analysis and evaluation of modeling results.

These salinity measurements are crucial for assessing seawater intrusion in coastal areas. The assessment of seawater intrusion into the groundwater in the coastal areas of Vietnam relies predominantly on the TDS and EC measurements. However, our data collection process revealed the existence of numerous conversion factors between the EC and TDS across different studies, which creates a larger uncertainty in the data.

To address this uncertainty and improve the spatial resolution of the salinity data, various interpolation methods can be employed. Saline and freshwater areas can be distinguished using the interpolation method in space for point measurements. Alternatively, regionalizing methods can be used, as presented by [35]. The dataset, available on a 1 km by 1 km grid, incorporated groundwater points with TDS and wells with geophysical logging via indicator kriging. An additional dataset for Ca Mau Province is from [23]. To regionalize these data for each aquifer, a detailed data analysis and interpolation using the “Ordinary kriging [36] in the ArcGIS geostatistical analyst toolbox, as the best linear unbiased estimator” [23] was carried out. The result was a homogenized dataset of salinity distributions for each aquifer. Therefore, in principle, two homogenized datasets are available for the CMP.

The time series of the measured data from 2011 to 2021 did not reveal any significant trend in the lower aquifers regarding salinization [23]. In Figure 4a, the measured TDS data for aquifer qh are presented, illustrating the entire period of observation from 2011 to 2024. While the assessment focuses on the 2011–2021 period, some monitoring wells in aquifer qh, such as Q177 and Q632, exhibited fluctuations in TDS concentrations over time; however, no clear increasing or decreasing trend was evident, particularly for well Q401

(Figure 4a). Overall, the available data do not suggest a long-term increase in salinity in aquifer qh on a regional scale.

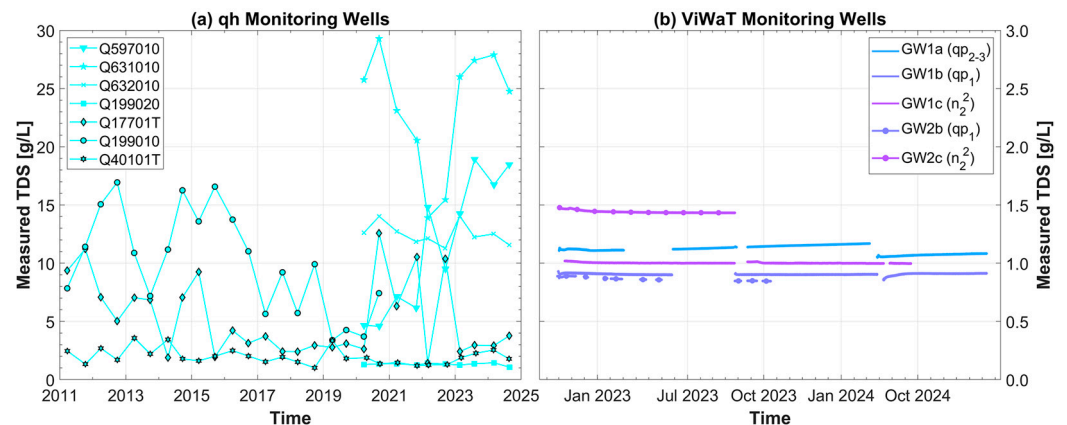


Figure 4. Examples of TDS time series of groundwater monitoring wells from (a) the NAWAPI (aquifer qh; period 2011–2024) and (b) the ViWaT project (well groups installed in 2022).

In Figure 4b, the automated EC monitoring data (converted to TDS) of groundwater wells in the ViWaT projects at two monitoring locations, GW1 and GW2, are visualized. The data showed that different levels of TDS were established at two sites in different aquifers over time. However, the observed change in the TDS in the aquifers was not significant.

4. Methodology

4.1. Approach to Salinity Transport Modeling

An adapted method for the assessment of saline intrusion was employed, based on numeric modeling but deviating from the conventional approach of calibrating the parameters for a transport model, due to the limited data availability (Figure 5). The method involves developing a simple model to calculate the longitudinal dispersion coefficient using a global dataset and verifying it with regionally developed coefficients, which were derived from the data collected in the study area. The main goal of our approach was to improve the understanding of the physical processes involved, rather than achieving the best fit for the few available salinity measurements.

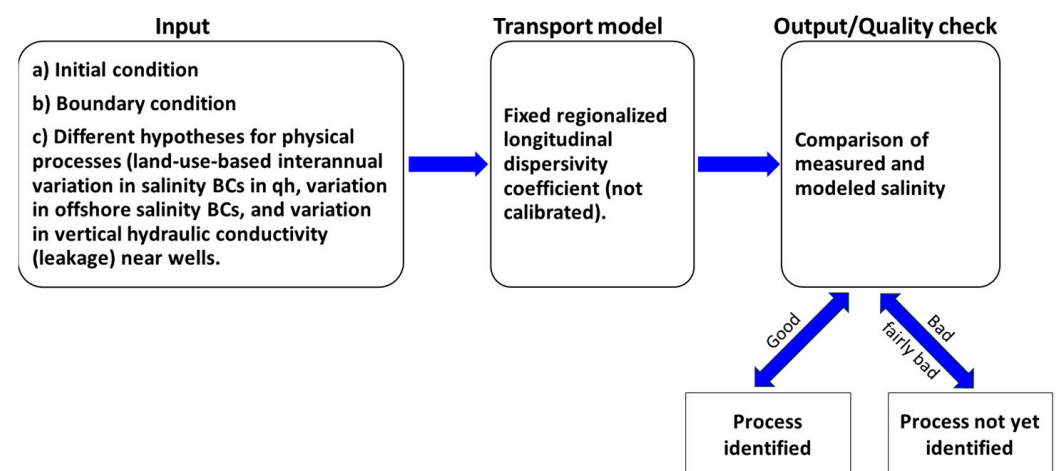


Figure 5. Conceptual framework for evaluating longitudinal dispersion coefficients in saltwater intrusion processes in the Ca Mau Peninsula. *Note: The four processes outlined in the model include additional mechanisms that may not fully correspond to the initial hypotheses but are considered relevant based on field observations.*

Our aim was to assess the significance of these hypotheses and glean insights into the dynamic processes governing groundwater salinization through the examination of various hypotheses against both measured and calculated salinity data. This approach emphasizes a more exploratory and hypothesis-driven analysis of salinity transport, allowing for the identification of important processes. Such an approach is promising and potentially insightful, particularly in situations with limited available salinity data.

Figure 5 illustrates the conceptual framework we used for evaluating salinity transport in the study area. While the initial hypotheses provided a foundational framework for evaluating salinity transport processes, the model incorporates additional mechanisms based on the field data and observed variability in the study area. These mechanisms, including the mixing and dispersion along the flow path and leakage through hydraulic windows, are considered essential for a comprehensive analysis of potential salinization pathways. The conceptual framework also accounts for the historical context of the groundwater system. Given the predominance of paleowater in deeper aquifers, initial salinity conditions in the groundwater model reflect historical salinity patterns resulting from past marine transgression and regression events. This assumption aligns with the field evidence showing distinct salinity interfaces and mixing patterns, as detailed in the Section 4.2.2, which are critical for understanding current salinity dynamics driven by hydraulic gradients from intensive groundwater extraction.

The output of the transient transport model is the concentration at each node in the model domain during the considered time period. The calculated concentration values can be compared to observed concentrations as well as to qualitative information (e.g., reports showing increasing salinity in some production wells). Our approach highlights the iterative nature of model development and refinement. If the simulation results show a good agreement between the measured and calculated salinity in terms of the trend and the order of magnitude, it suggests that the identified processes and the model parameters used could represent real-world conditions. This alignment provides confidence in our model's ability to predict salinity transport within the study area. The spatial discretization of the model was designed to support large-scale and long-term salinity simulations. A spatially variable mesh with local refinement was applied in sensitive areas; the details of the mesh configuration are provided in Section 4.2.1.

In contrast, if the simulation results do not match the measured salinity well, it signals the need for further investigation. This may involve the identification of additional or alternative physical processes that impact salinity transport but were not adequately considered in the initial model. It could also prompt a re-evaluation of the chosen model parameters and assumptions.

The goal of this study was to continuously refine and improve the model by incorporating new insights, data, and adjustments to better capture the complexities of the salinity transport system. This iterative process is common in scientific modeling, where the feedback loop between model predictions and real-world observations helps enhance the accuracy and reliability of the model over time.

4.2. Saline Intrusion Model Setup

Figure 6a illustrates the process of enhancing the existing flow model [12], transforming it into a variable-density transient transport model with a subsequent sensitivity analysis. Figure 6b provides a three-dimensional conceptual representation of the aquifer–aquitard system used in the model, helping visualize the spatial structure and layering relevant to salinity transport.

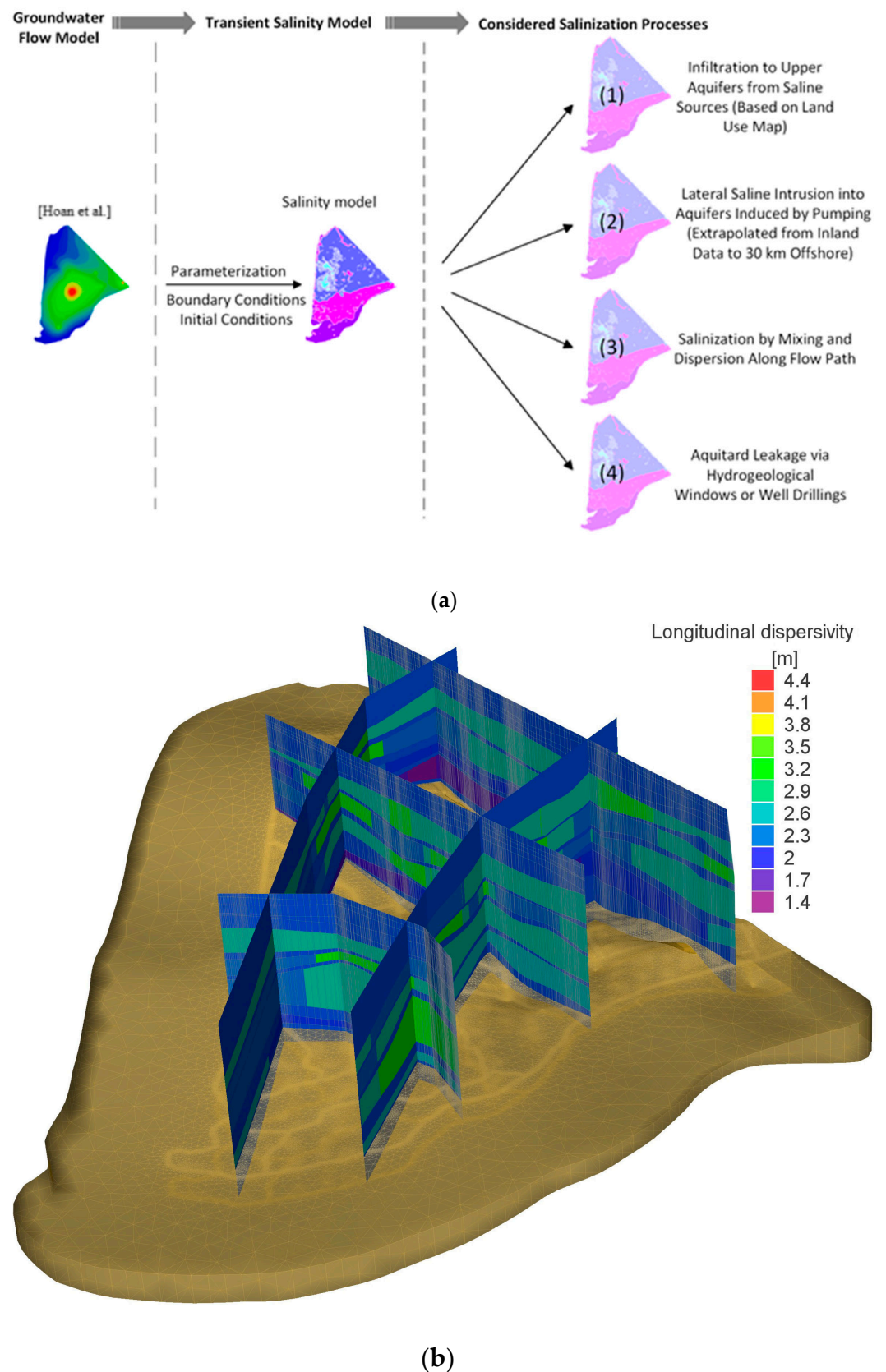


Figure 6. (a) The flowchart of the integrated groundwater flow [12] and salinity modeling approach for evaluating potential saltwater intrusion processes in the MKD. (b) A three-dimensional schematic representation of the hydrogeological model, showing the spatial layering of aquifers and aquitards with corresponding longitudinal dispersivity values assigned to each sediment type.

The density-dependent transient transport model for the CMP was set up with the software FEFLOW [37] for the time period from 2011 to 2024. The following salinization processes in the CMP were considered in the model:

1. Infiltration from saline surface water sources (rivers, canals, aquaculture ponds, salt production, and tidal inundations) into the upper aquifers as identified by the land use map;
2. Lateral saline intrusion from the offshore areas into the aquifer system induced by pumping, assuming that freshwater/saline water in deep aquifers is extrapolated from inland data up to 30 km offshore;
3. Salinization by mixing and dispersion from areas with higher salinity to areas with lower salinity along the flow path;
4. Downward or upward leakage from one aquifer to another through hydraulic windows in the aquitard, either naturally or from drilled wells. Although not included in the current model, this process is considered relevant to understanding salinity changes in the region.

4.2.1. Groundwater Flow Model

The groundwater flow model used as the basis for the salinity transport simulation was originally developed for the CMP by [12]. The original model covers a total area of approximately 19,900 km², including Ca Mau Province and parts of adjacent provinces, with approximately 9600 km² representing the land area. It was constructed using the finite-element software FEFLOW with a triangular finite-element mesh, featuring a spatially variable resolution. The mesh was refined to element sizes of 2–10 m near monitoring wells, extraction wells, rivers, and channels. Elsewhere, element sizes were gradually increased up to 2.5 km. Vertically, the model is structured into seven aquifers and seven interbedded aquitards. The boundary conditions of the flow model consist of a Dirichlet boundary condition (hydraulic head BC) at the northern boundary based on observed groundwater levels, no-flow boundary conditions along offshore boundaries, and Cauchy-type boundary conditions representing surface water–groundwater interactions in rivers and channels. The groundwater recharge was applied at a rate of approximately 1% of the monthly average precipitation. The flow model was simulated as a transient model from January 2011 to December 2020, using monthly time increments.

The understanding of the salinization process in the CMP is important for the model. Salinization in the upper aquifers (q_h , q_{p3}) is influenced by the intrusion from the river and channel system above and from the interaction between the sea and land beneath the ground surface. Additionally, we assume an influence from shrimp and rice farming practices, salt production, and groundwater abstraction. We also assume the presence of freshwater below the sea floor. These processes are simulated with the model setup.

4.2.2. Mass Transport Model

For the mass transport model, the TDS was used to represent salinity, as it is a widely accepted proxy in groundwater studies, particularly in coastal aquifers where detailed ionic composition data may be limited. This approach follows previous studies [13,26,35], which have demonstrated that the TDS provides a reliable spatial representation of salinity. During the model validation period, the observed TDS values from a total of 14 well groups were used for the period of 2011–2024. The transient transport model was run using monthly time steps to capture seasonal and interannual variations throughout the simulation period. For model comparison and analysis, observed TDS data were incorporated twice per year (representing the dry and rainy seasons) at each monitoring location. This approach enabled the model to effectively reflect seasonal salinity dynamics, particularly strongly

expressed in the shallow aquifer (qh), while also capturing long-term salinization trends observed in deeper aquifers (qp₃, qp₂₋₃, qp₁, n₂², and n₂¹).

Model Boundary Conditions

The following boundary conditions (BCs) were considered:

- (1) Seawater intrusion was implemented as Dirichlet BCs with defined concentrations. For Layer 1–Layer 5, representing aquifers qh and qp₃, this was set to 35 g/L (similar to the current TDS of seawater), while for Layer 6–Layer 14, which represent the main exploited aquifers (freshwater to slightly brackish water), this was set to 3 g/L [38] at the model boundary offshore.
- (2) No boundary conditions for salinity were defined at the northern model boundary. As there is a flow boundary condition defined at the northern model boundary, the FEFLOW software automatically generates a salinity boundary condition to adapt the concentration of the inflowing water to maintain the concentration near the boundary.
- (3) The land use-based estimation of human activities influencing the salinity in the qh aquifer was determined using land use maps [39] (Figure 7, left side). For most land use classifications, a constant salinity concentration BC was used (see Figure 7, right side) for the top layer and the qh aquifer depending on the predominant land use class in each region. At selected locations, these boundary conditions were refined to time-varying fixed-concentration BCs according to the interannual dynamics illustrated in Figure 8 with monthly data.
- (4) Surface water–groundwater interaction: The channel and river system in the CMP is strongly influenced by the tidal system of the ocean as well as seasonal (dry/rainy) interactions. The water levels in the river and channel system were interpolated from measurements based on the mean monthly change in the water level. In addition, we used the measured mean monthly salinity data (Ca Mau and Song Doc stations) to interpolate the interannual variation in the surface water bodies, mangrove, and semi-intensive shrimp and salt production zones and implemented them as time-varying fixed-concentration BCs (shown in Figure 8).

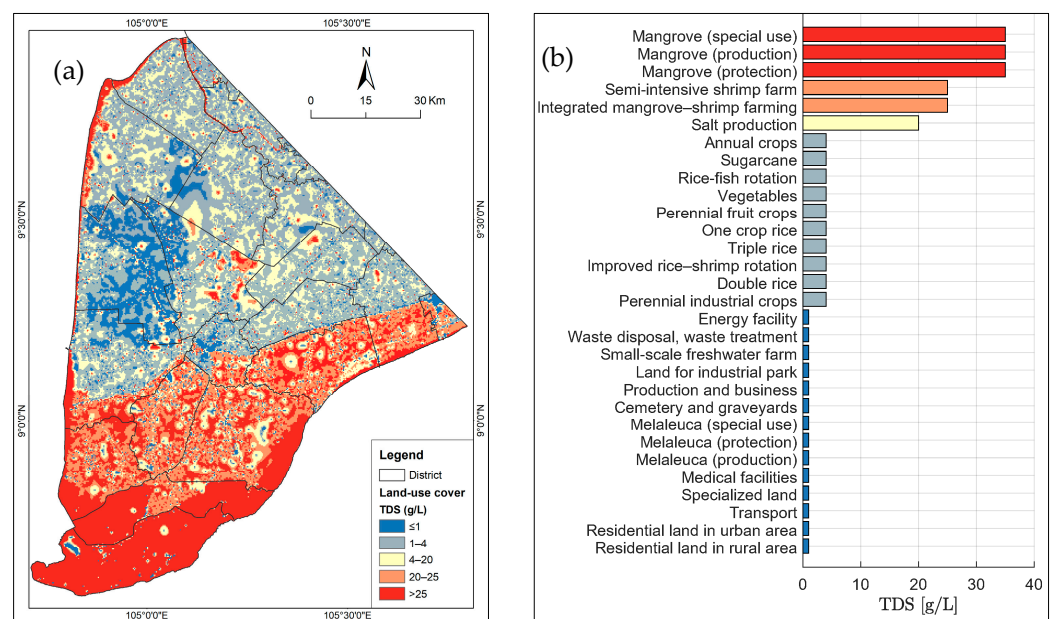


Figure 7. Land use-dependent salinity initialization (a) based on [39] and TDS classification based on land use (b).

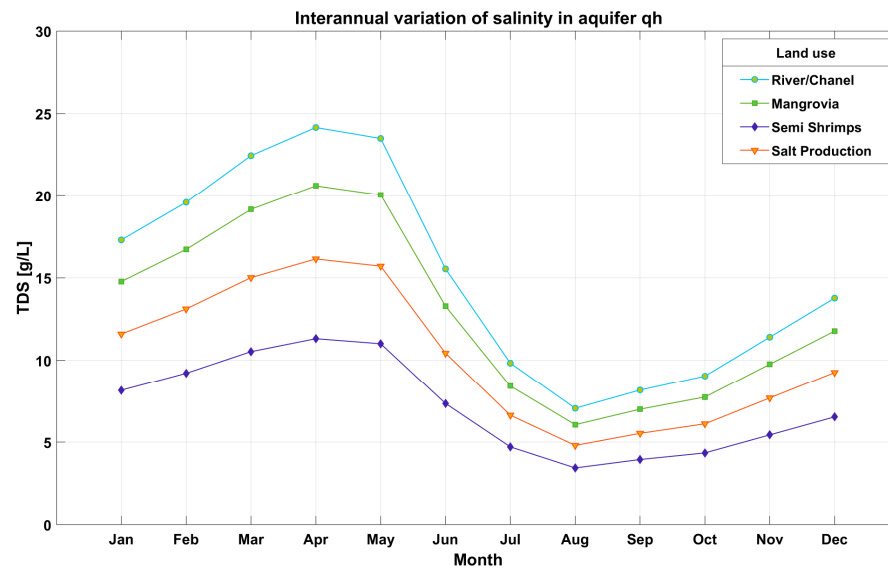


Figure 8. Mean monthly salinity for different land use types applied for model boundary conditions in aquifer qh and the top layer (derived from the salinity of surface water monitoring stations of Song Doc and Ca Mau, period 2012–2020).

Initial Conditions

At the beginning of the simulation (January 2011), the initial TDS concentration had to be defined for every node in the model. The initial conditions were determined based on the limited information available, specifically the salinity data collected simultaneously across different locations. All the salinity data available in different locations were utilized to establish the initial horizontal salinity values.

A combined dataset was established from the regionalized data of the IGPVN project [23] for the aquifers qp₃, qp_{2–3}, qp₁, n₂², and n₂¹ inside Ca Mau Province and interpolated values outside of Ca Mau Province based on the values measured during our data collection.

One of the challenges was determining the initial TDS concentration for the upper layers. There are many lakes, ponds, and rivers/channels, covering approximately 60% of the study area. However, their common feature is that the salinity varies seasonally. Data on these changing salinity levels are not available.

Therefore, the salinity in Layer 1 and Layer 2 (qh) was determined according to the zoning of the land use types, combined with survey data from some specific point groups. For the upper aquitards, the same initial conditions as in the upper aquifer were applied. For areas controlled by sluice gates, salinity measurements vary within a relatively small range. Consequently, the TDS value is considered to be a boundary condition that is constant over time for areas controlled by sluice gates. As for the remaining regions and land use types, their salinity variations were estimated through interpolation based on seasonal changes throughout the year (as depicted in Figure 8). The initial conditions for the aquifers are illustrated in Figure 9.

Dispersivity Parameter Adaptation

Flow velocities and hydrodynamic dispersion coefficients are key parameters for the description of fluid and solute transport in porous media. The topic of dispersivity has been of great interest in the scientific community, particularly among those studying hydrology and contaminants and flow through porous media (e.g., [40–43]). Hydrodynamic dispersion includes both mechanical (advective) dispersion and molecular diffusion. For low fluid velocities, solute dispersion is dominated by molecular diffusion; for high velocities,

advection becomes dominant, but the contribution of diffusion cannot be neglected. In this study, we did not calibrate the longitudinal dispersion coefficient but instead derived the spatial distribution of the longitudinal dispersion coefficient.

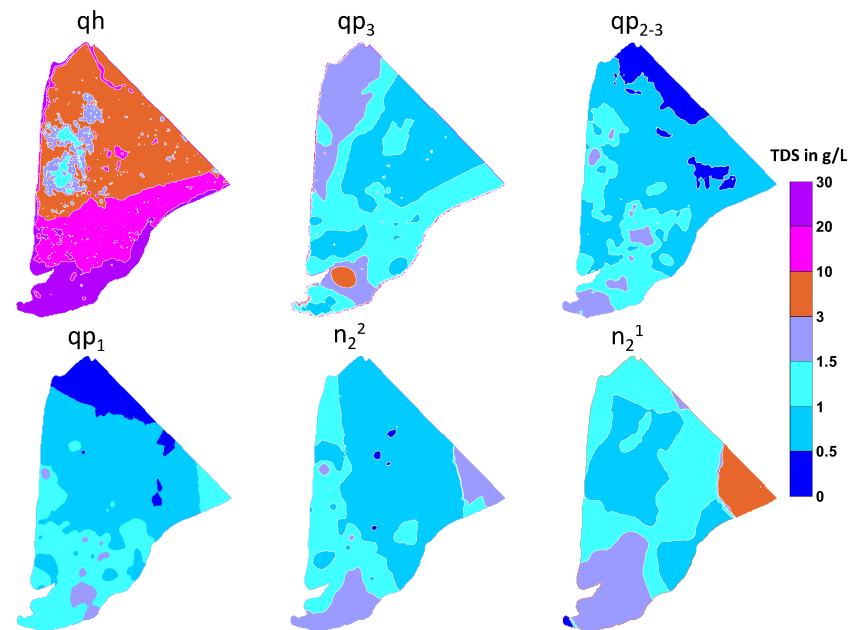


Figure 9. The spatial distribution of the initial salinity (January 2011) for the aquifers qh, qp₃, qp₂₋₃, qp₁, n₂², and n₂¹.

The following dependencies of the longitudinal dispersion on the soil and sediment are known from the literature:

1. The longitudinal dispersivity coefficients for homogeneous soil and layered heterogeneous sediments show that stratification affects the longitudinal dispersivity coefficient, and the longitudinal dispersivity coefficients for layered heterogeneous sediments are nearly half than those in homogeneous sediments [44–47].
2. The longitudinal dispersion coefficient is influenced by the distance of travel, and its values undergo changes as the distance increases. In both homogeneous and layered heterogeneous sediments, the dispersion coefficient's values increase by a factor of 2.5 with the expansion of the horizontal travel distance [47–49].
3. There is also a dependency of the longitudinal dispersivity coefficient on the sediment type. From sand to clay, the longitudinal dispersion coefficient decreases with the smaller grain size of the material.

We set up a simple regionalized model for the calculation of the longitudinal dispersion coefficient in terms of average parameters from the Waterloo Hydrologic Enviro-Base, modified by the mentioned dependencies 1 and 2. We verified this regionalized longitudinal dispersion coefficient with local literature values [50].

Therefore, in this study, the Waterloo Hydrogeologic Enviro-Base [50] was used to calculate the average longitudinal dispersivity coefficients and average flow distances for different sediment types in the multilayered aquifer system of the CMP.

These averaged longitudinal coefficients were normalized (i.e., normalized dispersion coefficient) by dividing by the averaged flow distance (Figure 10a). The dependency of the normalized dispersion coefficient was fitted by the regression shown in Figure 10a. To recalculate the longitudinal dispersion coefficient for every soil type, an estimated flow distance of about 50 m was selected.

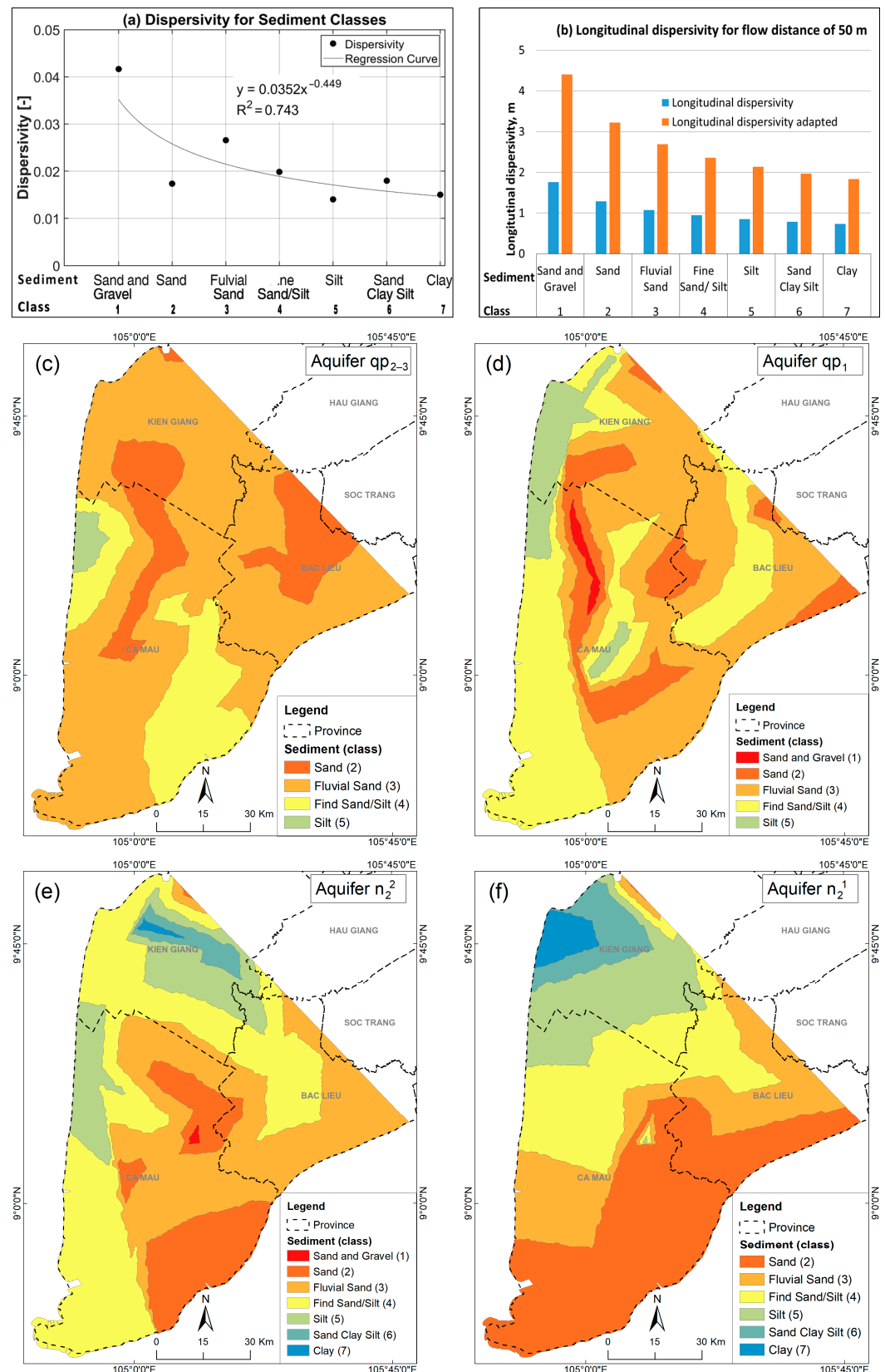


Figure 10. (a) The dependency of longitudinal dispersivity on the sediment class as demonstrated by [26], based on flow meter data; (b) longitudinal dispersivity coefficient (m) for different sediment classes based on a flow distance of 50 m for different sediment classes; and (c–f) sediment classes for different aquifers, qp_{2-3} , qp_1 , n_2^2 , and n_2^1 [51], used for the regionalization of the longitudinal dispersivity coefficient.

According to point one, we assumed that the sediments were homogeneous within the sediment classes presented in Figure 10, because detailed information about the sediment structure was not available. Thus, the longitudinal dispersivity was multiplied by a factor of 2.5 and by a 50 m flow distance. The regional distributions for the sediment type-based coefficients for aquifers qp₂₋₃, qp₁, n₂², and n₂¹ are shown in Figure 10c–f.

To validate the derived longitudinal dispersivity coefficients for the study area, they were compared to those in the previous literature. Ref. [52] described a groundwater fieldwork pumping and tracer injection test in the Nghiem Xuyen commune, Thuong Tin district, Hanoi, where a salinized and fresh groundwater boundary exists in the Pleistocene aquifer. The tracer experiment was conducted during a 60 h pumping test. The result was a longitudinal dispersivity value of 2.5 m, with an effective porosity of 0.32. In four other reports [53–56] (Table 1), the longitudinal dispersivity was estimated from 20-day-long tracer tests using 150 kg of salt. The salt was injected during pumping tests after the water level reached a steady state (after 48–72 h). These longitudinal dispersivity coefficient results differ significantly due to many influencing factors, such as the pump rate throughout the pumping test, the pumping well not being cleaned before the experiment, the salt injection process, and asynchronous machinery. In addition, there are natural factors such as the heterogeneous nature of the sediment types.

Table 1. Overview of dispersivity coefficients from different reports in Vietnam.

Well Name	Aquifer	Longitudinal Dispersivity	Effective Porosity	Specific Storage	Average Filtration Velocity	Flow Distance	Location
		α_L (m)	n_e (%)	μ (m ^{−1})	V (m/min)	m	
CM2E ⁽¹⁾	n ₂ ²	1.14	14.0	7.53×10^{-4}	4.54×10^{-2}		Ca Mau
BL4D ⁽²⁾	n ₂ ²	0.02	16.0	4.58×10^{-3}	4.20×10^{-3}	8.0	Bac Lieu
BL2B ⁽³⁾	qp ₂₋₃	0.12	19.4	5.58×10^{-4}	8.90×10^{-4}	8.0	Bac Lieu
IGPVN 1.4 ⁽⁴⁾	n ₂ ²	0.09–1.1	11.5–29.50		$4.0\text{--}9.9 \times 10^{-5}$	10.09	Ca Mau
CHN5 ⁽⁵⁾	qp ₁	2.5	32.00				Hanoi

Note: ⁽¹⁾ [56], ⁽²⁾ [54], ⁽³⁾ [53], ⁽⁴⁾ [57], and ⁽⁵⁾ [52].

The longitudinal dispersivity coefficient varied between 0.02 m and 2.5 m, with an effective porosity between 11.5% and 32%. Thus, the aforementioned dispersion coefficients were within the range of the derived sediment-based coefficient without applying the layer-based factor (blue columns in Figure 10b). The transverse dispersivity in the model was applied as 0.5 m.

In addition to dispersivity, porosity is another critical parameter influencing salinity transport in groundwater systems. In this study, a uniform effective porosity value of 0.3 was applied to both aquifers and aquitards. This choice aligns with values commonly reported for sandy aquifers [58,59] and is consistent with previous regional-scale groundwater models in the Mekong Delta, which typically adopted effective porosity values in the range of 0.25–0.30 without differentiating between aquifers and aquitards [6,13,26]. Although some studies, such as [35], assigned distinct porosity values to aquifers and aquitards based on the sediment type, the application of a single representative value remains a common and acceptable simplification in large-scale models aiming for consistency and tractability.

We acknowledge, however, that the effective porosity of aquitard materials such as clay is generally lower, typically ranging from 0.01 to 0.18 [60,61]. Nevertheless, as our model focuses primarily on horizontal transport processes in sandy aquifers, the impact of this simplification on the overall salinity distribution is expected to be limited. Future studies may benefit from implementing spatially variable porosity fields derived from detailed

lithological data to better capture vertical transport and retardation effects, particularly in fine-grained aquitard layers.

4.3. Limitations of the Model

In order to evaluate the groundwater salinization processes in the CMP, the model was adapted accordingly based on the available dataset. However, the model incorporates some limitations due to the limited available data.

No private household wells are included in the model, since household wells operate with very small flows. Instead, the water consumption for each commune is based on the population and an average rural water demand of 34 L/person/day [12]. This water consumption for each commune is implemented in the model by several wells with a total flow rate equivalent to the derived water demand. With this method, the assumed amount of the water extraction by a large number of private household wells is represented by fewer wells in the model.

The drilling time of wells is not considered during the transient model calculation: all wells are included in the model throughout the whole calculation period. However, in reality, many of the deeper wells are drilled later than the shallow wells. This time dependency could be considered in further evaluations.

Additionally, the use of a spatially uniform effective porosity value for both aquifers and aquitards, while consistent with several previous regional studies, may not fully represent the heterogeneity of fine-grained aquitard layers and their limited contribution to advective transport. Furthermore, the use of uniform porosity values may underestimate the effects of fine-scale heterogeneities, which are especially relevant in layered systems.

5. Salinity Model Results

The groundwater flow model validation was discussed in detail in [12]; thus, the following discussion focuses on the aspects of the transport model only. The longitudinal dispersivity parameters of the transport model are not calibrated. They have been estimated by a regionalized method using representative literature values and correction methods. According to the described validation criteria, salinity modeling can be performed for the purposes of confidence building and scientific validation. As stated by Ref. [62], confidence building “is a measure of the adequacy of the model structure (conceptual model and mathematical model) in describing the system behavior” and “is a measure of the accuracy of the model input parameters relative to experimental results and field observations”. For regional validation at different time steps, the scientific view postulated by [63] demands the validation of specific models “that one might reasonably expect someone with relevant technical knowledge to consider the model acceptable”.

As described in the Data Collection Section, there are only very limited continuous salinity data available that could be used for a transient model calibration. Therefore, as an alternative approach, the comparison of measured and modeled salinity concentrations was used to validate the implemented salinization processes and assess their relevance. In Figure 11, the values measured twice a year, as well as the modeled TDS concentrations, for different aquifers are shown as time series.

Figure 11 illustrates that the modeled TDS concentrations at the presented monitoring wells align closely with the observed values, both in terms of magnitude and temporal trends. The modeled salinity concentrations at monitoring well Q199 qh (Figure 11a) show seasonal variations as a result of the applied boundary conditions with interannual variations (as shown in Figure 8). This indicates that part of the measured variability may be caused by the interannual variation in salinity assumed in the rivers system. Thus, we identify this process as a potential contributor to the salinization pathway, but other

impacts on the variability remain unclear. This can also be observed in Figure 11b for well Q177 qh, where the model simulates the general trend well but the observed variations in the TDS concentrations are not reflected, indicating that a further consideration of locations with interannual variations in the TDS boundary conditions in qh could improve the model results, such as the Q177 site, where constant TDS boundary conditions are applied.

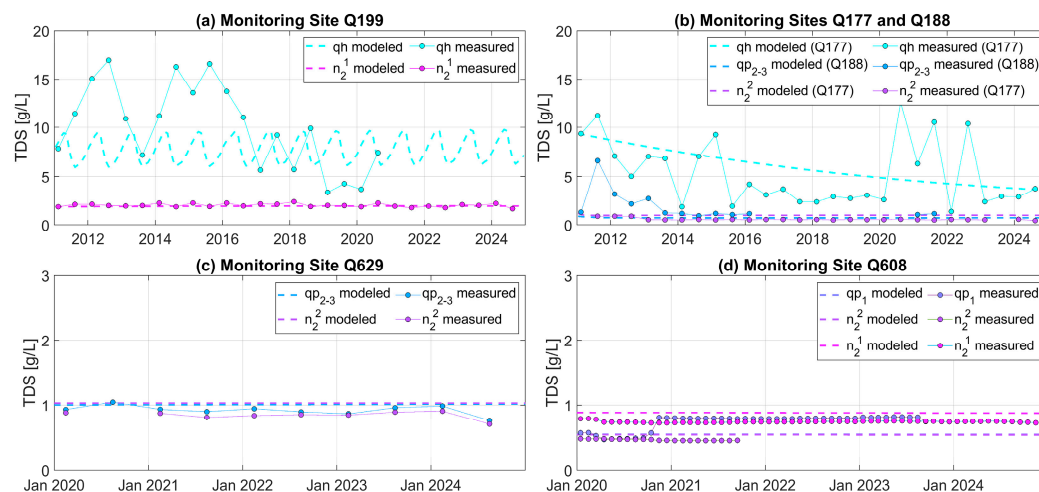


Figure 11. Time-dependent comparison of measured and modeled salinity for different well groups and aquifers. (a) Q199 (qh)—Seasonal and interannual variation captured; (b) Q177 (qh)—General trend matched; short-term variability not reproduced; (c) Q629 (qp₂₋₃, n₂)—Stable salinity indicates limited vertical transport; and (d) Q608 (deep)—Consistent salinity primarily driven by initial conditions.

Figure 11c (monitoring site Q629) shows a more stable trend in the observed and modeled TDS concentrations for the aquifer layers qp₂₋₃ and n₂². The model captures the general trend, with slight deviations observed during the period from 2020 to 2024. This consistency suggests that vertical transport processes in deeper aquifers may be limited or occur at a much slower rate. However, minor discrepancies, especially near the end of the time series, may still arise from sampling conditions, laboratory handling, or other external influences that require further investigation.

The salinity in the deeper aquifers qp₁ and n₂² tends to be stable in the monitoring wells, without interannual variation. Figure 11a–d show that the simulated (Q199, Q188, Q177, Q629, and Q608) TDS concentrations effectively depict the behavior of the groundwater system over an extended validation period (from 2011 to 2024) in the complex exploitation setting. This indicates that only the initial condition is responsible for the well-simulated salinity in the deeper aquifers. It also suggests that during this extended period, the vertical transport of salinity remains very slow, further confirming the stability observed in deeper aquifer systems.

A common method for evaluating model performance in groundwater modeling is through scatterplots. Figure 12 presents the scatterplot comparing modeled and measured TDS concentrations at observation wells during various time intervals from 2011 to 2024. The 1:1 line represents a perfect agreement between modeled and measured values, while the $\pm 10\%$ and $\pm 20\%$ boundaries highlight regions of underestimation or overestimation by the model. This scatterplot offers a qualitative assessment of the model's performance.

It is important to note that the larger discrepancies seen in Figure 12 are primarily associated with observation wells located in the shallow aquifer (qh), which were deliberately separated from other wells for targeted evaluation. This is due to the high seasonal variability and surface influence affecting TDS concentrations in qh, particularly given the model's reliance on land use data to estimate the recharge salinity in these shallow zones.

In contrast, wells in deeper aquifers show a much closer match to observed values, with the majority falling within the $\pm 10\%$ or $\pm 20\%$ deviation bands. This distinction highlights both the complexity of modeling shallow systems and the overall robustness of the model in representing deeper groundwater salinization processes. Despite some discrepancies in absolute values in qh, as observed in Figure 11a,b, the model effectively captured the overall trends and variability in the TDS at the shallow aquifer level.

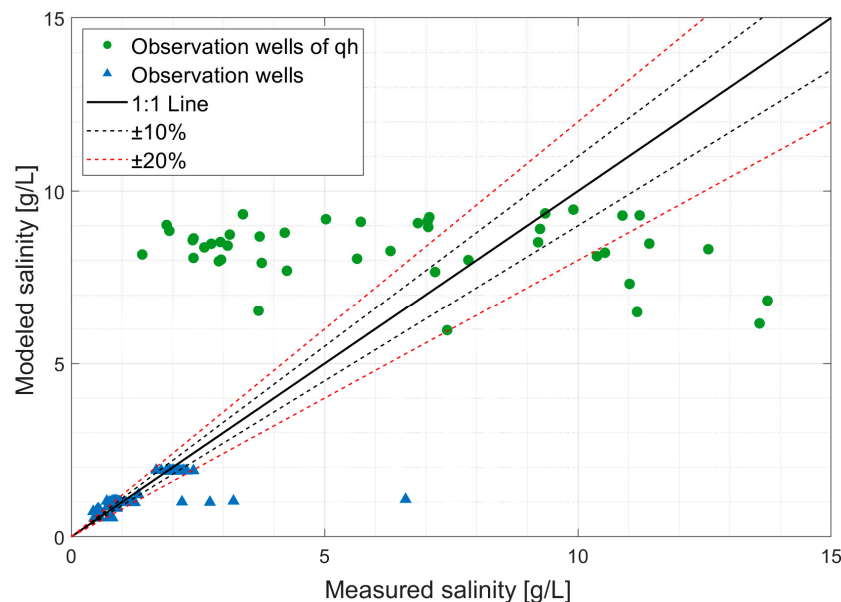


Figure 12. A comparison between measured versus modeled average TDS concentrations (g/L) at observation wells during the simulation period (2011–2024). The solid black line represents a perfect 1:1 match, while dashed lines indicate $\pm 10\%$ and $\pm 20\%$ deviations. Green circles represent qh wells affected by surface processes and land use variability, while blue triangles indicate deeper aquifers with a generally closer agreement.

The salinity distribution in January 2011 served as the initial conditions for aquifers qh and qp₃, as outlined in the Section Initial Conditions. Subsequent simulations captured changes in the TDS concentrations, with Figure 13 providing a visual representation of these variations. In the top-right portion of Figure 13, the influence of the boundary conditions with interannual variations is evident, resulting in a reduction in the salinity of the qh aquifer during the rainy season. This reduction is likely attributed to the dilution caused by the influx of freshwater from precipitation events. Conversely, for August 2022, the bottom-right portion of Figure 13 illustrates an increase in salinity in aquifer qp₃. This increase is attributed to the substantial transport of salinity from aquifer qh to qp₃. Furthermore, the long-term simulation uncovered additional dynamics in the salinity distribution. In the top-right portion of Figure 13, there is an indication of salinity import from the top, possibly influenced by external factors or processes affecting the upper part of the aquifer. Simultaneously, the bottom-right portion shows ongoing salinity transport from the top down, suggesting the continuous downward movement of saline water within the aquifer system.

Figure 13 shows that the salinity transport was dominated by input from the surface, and the modeled salinity in the two upper aquifers qh and qp₃ shows a strong change over the simulation between January 2011 and August 2022. In contrast, the lower aquifers qp₂₋₃ and n₂² show fewer changes in salinity over time (for comparison, see two lower maps in Figure 14a–e). The scale is defined within an interval of 1.0 g/L. For the deeper aquifers qp₂₋₃ and n₂² (Figure 14a–e), no significant lateral change in salinity can be obtained from the model results for the simulation period. In the current model described above, only a

small-scale variation in salinity due to pumping can be detected. However, this is consistent with the time series measurement of the salinity, as no significant changes in salinity over time could be observed (see Figure 11). Figure 14c,f show the modeled spatial changes in the freshwater zones (<1 g/L) between 2011 and 2022. Both time steps include the 1 g/L isolines to allow the direct comparison of the salinity extent between 2011 and 2022. In qp₂₋₃ (Figure 14c), region 1 shows an increase in salinity along the border of the original salinity inflow from the ocean, while region 2 presents a northward expansion of salinity from the northern boundary (Bac Lieu Province), likely induced by intensive groundwater extraction. In regions 3 and 4, salinity levels exceed 1 g/L due to the lateral transport of brackish water, rendering the groundwater unsuitable for drinking. In aquifer n₂² (Figure 14f), changes are less pronounced, but a local increase in salinity is noticeable in the eastern parts (regions 5 and 6), following the direction of the horizontal groundwater flow.

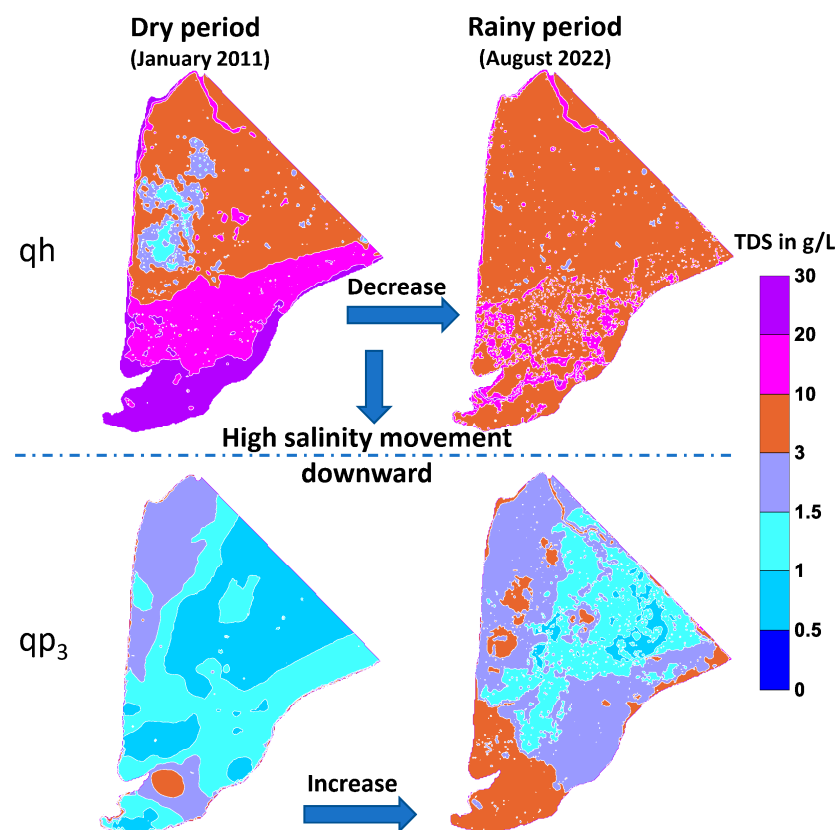


Figure 13. The modeled salinity distribution (TDS in g/L) in aquifers qh and qp₃ during the dry period (January 2011) and the rainy period (August 2022).

These patterns of lateral salinity increase—particularly in the northeast (Bac Lieu) and west—may reflect the influence of anisotropic aquifer properties, where a horizontal hydraulic conductivity dominates. In the Mekong Delta’s stratified aquifer systems, interbedded clay or silt layers tend to impede vertical flow while allowing horizontal movement. This likely limits the downward salt transport from qp₃ to deeper units like qp₂₋₃ and n₂², despite pumping activity. However, due to the coarse resolution of the model, such anisotropic behavior is not explicitly represented.

In the southern part of the CMP, the model also indicates vertical salinity transport from qp₃ to qp₂₋₃, originating from the mangrove regions in the upper layers (Figure 9). As a result of the model, we only observe small influences on the vertical salinity movement in qp₂₋₃ and n₂², which result from pumping. Exploitation is simulated based on area-wide values rather than specific points. In regions with high pumping rates, such as Ca Mau City,

the results therefore suggest a stable salinity as compared to other regions, as illustrated in Figure 14d,e.

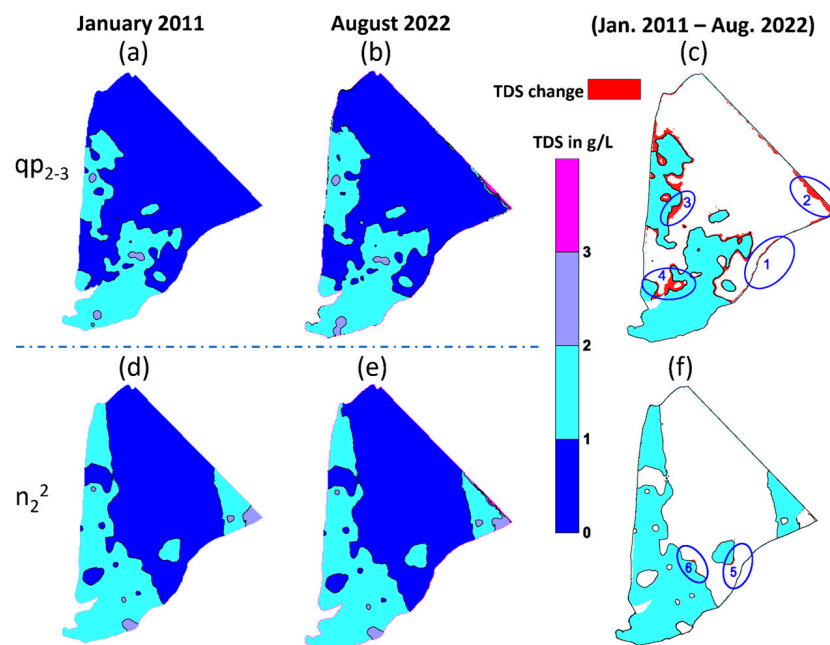


Figure 14. The development of the salinity from 2011 up to 2022 for aquifer qp₂₋₃ (a,b) and n₂² (d,e); (c,f) illustrate the difference between simulation results from 2011 to 2022.

In the study by [22] it was found, among 144 participants who completed questionnaires in Ca Mau, that the percentage of exploited groundwater allocated for cooking purposes constituted 65.7% of the water usage, while 97% of respondents used groundwater for washing purposes. These freshwater areas are depicted as dark-blue regions in Figure 14a,b, representing the northeastern Ca Mau Province. In the future, the number of areas with higher salinity is likely to increase due to similar pumping-induced effects, as illustrated in Figure 14c. Thus, the possibility of pumping freshwater from qp₂₋₃ will decrease. In this area, freshwater has to be substituted from other sources, such as rain-water harvesting or water diversion structures from other sites. In regions with brackish groundwater, with a salinity exceeding 1 g/L but below 3 g/L, it will be possible to use water from the qp₂₋₃ aquifer for cleaning and washing in the near future.

For aquifer n₂² (Figure 14d,e), the model showed a local increase in the saline water area in the east from January 2011 to August 2022 (Figure 14f, red color), due to the horizontal salinity movement along the direction of the groundwater flow.

6. Discussion

6.1. Key Controls on Salinity Dynamics

As previously mentioned in the Methodology Section, our approach was primarily exploratory, aiming to elucidate dominant physical mechanisms rather than achieving a perfect fit to limited observational data.

The complex interaction between surface water salinity and the upper aquifer qh in the CMP remains inadequately characterized, despite its importance for regional water management. Elevated salinity concentrations in both sediments and water bodies are a ubiquitous problem in the CMP. The salinity varies at the local scale (5–10 m), but the relative effects of land use and surface geology on the salinity variation in the near-surface zone (<5 m) are still unclear. Reference [64] identified that “the influence of surface water salinity (associated with different land uses) on the groundwater salinity regime is

pervasive". They found that areas underlying a shrimp farm/tidal flat displayed a higher salinity regardless of the near-surface sediment characteristics, while areas underlying drinking water ponds or inhabited areas had a relatively low salinity. In this study, the impact of land use and the infiltration of surface water into the qh aquifer was implemented in a numeric model to simulate the relationship between land use and groundwater salinity.

In addition to the spatial variability driven by land use patterns, temporal variations in salinity also present significant complexity, particularly in the shallow aquifer system. Our analysis indicated that significant fluctuations primarily occurred within the shallow qh aquifer, which were strongly influenced by seasonal factors and surface activities such as irrigation, aquaculture, and the tidal-induced salinity intrusion through rivers and canals. Deeper aquifers generally exhibited stable salinity trends both in observational data and model simulations. However, our model also revealed localized temporal variations at certain production wells, where increasing or decreasing trends in TDS were observed (as explicitly presented in Figure 15). These findings underscore the complexity of groundwater salinity dynamics, which are driven by both natural hydrological processes and anthropogenic activities. Beyond surface-driven influences, the internal structure and connectivity of the aquifer system also play a crucial role in shaping salinity behavior.

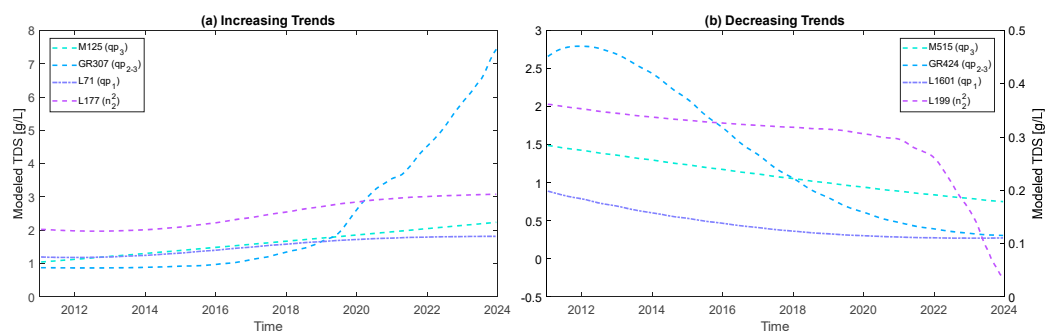


Figure 15. Modeled TDS variations at selected wells across aquifers (2011–2024) (upper Pleistocene—qp₃; Upper–Middle Pleistocene—qp₂₋₃; Middle Pliocene—n₂²; and Lower Pliocene—n₂¹); see Figure 3 (source of data: NAWAPI).

Other key factors influencing salinity dynamics are geological heterogeneity and anisotropy. Variations in hydraulic conductivity, the presence of semi-permeable aquitards, and preferential flow paths across layers may significantly influence saltwater migration patterns. These physical features, combined with anthropogenic stresses such as intensive groundwater abstraction, can alter vertical and lateral salinity gradients. In multi-aquifer systems like Ca Mau, long-term pumping can enhance inter-aquifer leakage, mobilizing deeper or trapped paleo-saline water towards abstraction zones. Consistent with this, ref. [65] demonstrated through numerical modeling that the presence of preferential flow pathways in heterogeneous aquifers significantly accelerates saltwater intrusion processes under groundwater pumping conditions, emphasizing the combined impact of geological heterogeneity and human-induced stresses.

However, a detailed quantitative assessment of individual parameters, such as the hydraulic conductivity, porosity, and geological structure, was beyond the scope of this exploratory study. In addition, due to the coarse spatial resolution of the regional-scale model, preferential flow processes were not explicitly resolved. These mechanisms are often better captured in high-resolution 2D or localized 3D models. For instance, [65] illustrated the influence of preferential flow on pumping-induced salinity intrusion using a focused modeling approach. Future research should aim to combine detailed vertical salinity analyses, parameter sensitivity assessments, and high-resolution subregional models to

better quantify the roles of aquifer heterogeneity, anisotropy, and preferential pathways in salinity dynamics across the CMP.

6.2. Model Representation and Applicability

As shown in the scatterplot (Figure 12), the modeled salinity values generally align well with the measured data. However, discrepancies are evident, particularly in the qh aquifer, where the errors are more pronounced. These deviations suggest that while the model effectively captures general trends, it does not accurately replicate localized variations in salinity. This limitation can be attributed to the scarcity of detailed observational data for the upper layer, regionalized longitudinal dispersivity parameters, and potential unknown local factors that remain beyond the scope of the current model.

Interannual variations in the TDS concentrations at observation wells are most evident for the qh aquifer. Nevertheless, even in deep aquifers (e.g., in n_2^1 at Q199 (Figure 11a)), such interannual variations are observed. In order to model these dynamics, interannually variable TDS boundary conditions were applied at selected locations in the model for the qh aquifer. Nonetheless, these dynamics in the TDS concentration did not propagate to the lower aquifers in a sufficient magnitude in the model.

To address this, the model's intent is not to focus on the detailed representation of the uppermost layer but to propose a conceptual framework. This framework leverages land use maps with varying salinity levels for the surface layer, combined with seasonal salinity variations, to simulate broader regional patterns effectively. Such an approach is a pragmatic solution for a wide-scale analysis, especially when high-resolution data are unavailable.

As highlighted by ref. [64], the distance from rivers can influence groundwater salinity, but the presence of saline water within the rivers themselves often plays a more significant role. Their study identified that areas located approximately 400–500 m from rivers exhibited groundwater salinity levels ranging from 2.8 to 3.8 g/L (4100–5500 $\mu\text{S}/\text{cm}$, with a conversion factor EC to TDS of $k = 0.7$). In this study, we observed similar patterns at well Q199010 in the qh aquifer, where interannual salinity levels varied between 6 and 10 g/L (Figure 9, top left). This well, located approximately 100 m from the nearest river, experiences a significant influence from the tidal system and seasonal variations, including rainy and dry periods. The modeled interannual variability in the TDS at this location (4–8 g/L, as shown by the green dashed line in Figure 11a) aligns closely with Rahman et al.'s observations, reinforcing the critical role of river proximity and tidal influences in shaping groundwater salinity dynamics.

6.3. Management Strategies and Research Priorities

Effective groundwater salinity management requires a nuanced understanding of both regional and local dynamics. In this context, Figure 15 below illustrates modeled TDS variations across selected representative wells, helping to visualize localized salinity trends across aquifers. For these wells, salinity increases when pumping induces the movement of saline water from the surrounding areas toward the well due to a steeper hydraulic gradient. Conversely, salinity decreases where freshwater inflow dominates, diluting the salinity in the pumping wells. These localized trends reflect the complexity of salinity dynamics, driven by the interplay between groundwater exploitation, hydrogeological conditions, and the spatial distribution of freshwater and saline water lenses. Field surveys further confirmed that these changes align with the influence of paleowater mixing and extraction-induced hydraulic gradients, emphasizing the need to consider ancient trapped saline water in evaluating long-term salinization risks.

Additionally, Figure 15 demonstrates that among the 1101 pumping wells in the model, salinity fluctuations—both increases and decreases—are observed at many locations, depending on local conditions. These dynamics emphasize the need for site-specific strategies to effectively manage groundwater resources in areas impacted by saltwater intrusion. Such strategies should consider localized variations and the broader regional dynamics to ensure sustainable groundwater use.

Moreover, data resolution plays a crucial role in shaping the observed salinity patterns. According to the ref. [23], salinity maps with higher point densities—such as in the qp₂₋₃ aquifer—exhibited greater spatial complexity compared to deeper aquifers like n₂¹, where fewer data points were available. This suggests that some apparent homogeneity may result from data scarcity rather than actual aquifer uniformity. The report recommends acquiring at least 50 spatially distributed sampling points per aquifer for provinces with areas exceeding 5000 km². Implementing such monitoring strategies would enhance our ability to characterize heterogeneity and improve model reliability for groundwater salinization assessments.

Based on the criteria detailed in Section 4.2.2, the system's salinization behavior is reasonably well represented in the model from a confidence-building perspective. The calculated salinity was validated against point-measured data, with the simulated results showing a reasonable agreement in terms of magnitude and temporal evolution. This aligns with the operational aspect of model validation, i.e., “that a good, correct, or sufficient representation of reality” in time and space can be achieved with the model. Moreover, the model can be considered acceptable as it incorporates knowledge of the hydrogeological and salinity context in the CMP for its setup.

Ref. [66] obtained salinity forecasts covering the period up to 2026, focusing on a 1.5 g/L shift (below 1.5 g/L and above 1.5 g/L) in the saline boundary line in two different regions. The work described in this study presents a salinity distribution with improved detail. Due to the initialization dataset used for each aquifer, more monitoring data would be needed for a more accurate salinity forecast model. Our model indicated that the salinity movement in the deeper aquifers appeared to be slow, which is consistent with the predictions made by ref. [66].

As illustrated in the cross-section in Figure 3, the aquitard thicknesses vary significantly in the southernmost region of the MKD. This variation in thickness, along with the small number of available drilling logs upon which the layer interpolation is based, can be considered an indicator that hydrogeological windows may indeed exist in different aquitards, even though they have not yet been identified in drilling logs. This observation points to the need for further investigation into the potential salinization pathways in this area.

Building on this finding, as neither the observed TDS concentrations in the monitoring wells nor the modeled concentrations showed a significant increase in salinity during the simulation period from 2011 to 2024, it becomes evident that further potential pathways of groundwater salinization need to be evaluated. To achieve this, a sensitivity analysis of the vertical hydraulic conductivity interaction between the aquifers should be conducted to better understand the dynamics of salinity movement.

Further an investigation regarding the comparison of the TDS concentrations of monitoring wells, active production wells, and abandoned production wells is necessary to better understand the impact of pumping and well construction on the local groundwater salinity.

7. Conclusions

Building on the groundwater flow model of [12], this study developed an enhanced 3D density-dependent transport model to investigate the understanding of saltwater dynamics

and salinization processes in the CMP. The model incorporated new approaches, including the determination of longitudinal dispersivity as a function of sediment type and the inclusion of interannual salinity impacts driven by land use, infiltration from river systems, and mangrove areas.

These advancements enabled the detailed identification of high-salinity regions in aquifer qh and their influence on the salinity dynamics in qp₃ and parts of qp_{2–3}. The deeper aquifers predominantly contained freshwater (TDS below 1.0 g/L) with a minimal temporal variation over the analyzed timeframe (2011–2024). However, localized regions in northeast Ca Mau (Bac Lieu) exhibited higher salinity, highlighting potential pathways of salinization through hydrological windows or lateral flow.

Notably, the model results showed a fair correlation between simulated and measured salinity values across different aquifers, validating its reliability in capturing broad salinity trends. The surface salinization from various land use types significantly impacted the qh aquifer, while deeper layers did not exhibit clear top-down salinization trends during the observed period.

Although monitoring wells did not show a clear increase in salinity, the model demonstrated that, based on the analysis of production wells, localized salinity increases were evident in areas impacted by groundwater extraction.

This study confirms that land use-related salinity inputs significantly affect the shallow aquifer, while deeper aquifers remain relatively stable. Model outputs aligned with field observations, indicating the effectiveness of the approach in representing salinization trends across aquifers.

Overall, this study contributes to a nuanced understanding of salinity intrusion pathways and provides valuable insights for managing groundwater resources in regions affected by saltwater intrusion.

Author Contributions: Conceptualization, T.V.H., S.N., K.-G.R. and F.D.; methodology, T.V.H., K.-G.R., F.D. and J.B.; validation, formal analysis, and investigation, T.V.H. and K.-G.R.; resources, V.T.M.L., A.S., N.B. and S.N.; writing—original draft preparation, T.V.H. and K.-G.R.; writing—review and editing, T.V.H., F.D., K.-G.R., J.B., N.B., A.S., V.T.M.L., V.C.P., D.V.T. and S.N.; supervision, S.N.; funding acquisition, S.N.; administrator, S.N. and N.B. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Karlsruhe Institute of Technology; This work is part ViWaT – Engineering project, funded by the German Ministry of Education and Research (BMBF) under grant No. 02WCL1474A; and the Catholic Academic Exchange Service (KAAD).

Data Availability Statement: The data described in this paper are available upon request to the corresponding author. A permission letter was obtained from the NAWAPI for the collection of the rainfall data, groundwater quality data, surface- and groundwater-level data, and water exploitation data.

Acknowledgments: This paper benefitted substantially from the comments and suggestions of the two anonymous reviewers. This publication was supported by the Publication Fund of the Karlsruhe Institute of Technology, the German Ministry of Education and Research (BMBF), the ViWaT Engineering research project, the Ministry of Science and Technology (MOST), and the Catholic Academic Exchange Service (KAAD). This work is was contribution to German– Vietnamese research initiative ViWaT Mekong (<http://www.viwat.info/english/21.php> (accessed on 25 April 2025)).

Conflicts of Interest: Author Karl-Gerd Richter was employed by the company Aquantec Company for Water and Environment GmbH. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Vietnams Mekong-Delta - Landsenkung infolge von Grundwasserübernutzung

Das Mekong-Delta ist Lebensraum für ca. 21,5 Mio. Menschen und sieht sich seit einigen Jahren mit zunehmend existenzbedrohenden Landsenkungsprozessen (bis zu 3 cm/a) konfrontiert. Als einer der Hauptgründe dafür gilt die starke Grundwasserentnahme. Um die Prozessdynamik besser untersuchen zu können, wurde ein im Mekong-Delta bislang einmaliges Messsystem zur tiefendifferenzierten Landsenkungsmessung an einem Pilot-Standort aufgebaut, dessen vorläufige Messdaten eine Korrelation zwischen Landsenkung und dem fallenden Grundwasserspiegel zeigen.

Felix Dörr, Jonas Bauer, Hoan Viet Tran, Stefan Norra und Franz Nestmann

1 Bisheriger Kenntnisstand zur Landsenkung infolge von Grundwasserübernutzung im Mekong-Delta

1.1 Hydrogeologischer Kontext

Das Grundwassersystem (GW-System) des Mekong-Deltas (MD) ist in seiner Gesamtheit noch nicht vollständig verstanden, da vergleichsweise wenig Daten zur Ausdehnung und komplexen Abfolge von GW-Leitern und -Stauern sowie zu deren Interaktion vorliegen. Grundsätzlich wird im MD zwischen sieben GW-Leitern mit jeweils gespannten GW-Verhältnissen differenziert, deren hydraulische Trennung durch GW-Stauer, wie von Hoan et al. [1] dargelegt, meist als durchgehend gewährleistet angenommen wird. Die im südlichen MD häufig >20 m mächtige Tonschicht, die den oberen GW-Leiter überdeckt, verhindert, wie von Bauer et al. [2] erörtert, eine nennenswerte GW-Neubildung. Die Wechselfolge zwischen GW-Leitern und -Stauern endet in 300-400 m Tiefe, doch selbst die tieferen GW-Leiter weisen GW-Druckspiegel von nur 10-20 m unterhalb der Geländeoberkannte (GOK) auf. GW-Stand, -Dynamik und -Trends der verschiedenen GW-Leiter sind trotz der hydraulischen Trennung oft nahezu identisch.

1.2 Landsenkung im Mekong-Delta

In den vergangenen Jahren wurden im MD u. a. von Erban et al. [3] Landsenkungsraten von bis zu 3 cm/a beobachtet. Da sich die GOK des gesamten MD, wie Minderhoud et al. [4] zeigte, im Mittel nur ca. 0,8 m oberhalb des Meeresspiegels befindet, stellt die Landsenkung in Kombination mit dem stetigen Meeresspie-

geanstieg ein akutes existenzbedrohendes Problem für die Bewohner dieser Region dar. Die meisten bislang veröffentlichten Datensätze zu Landsenkung im MD basieren auf der Auswertung von Satellitendaten. Die wenigen bestehenden festinstallierten Monitoring-Systeme, wie von Karlsrud et al. [5] vorgestellt, erlauben keine tiefendifferenzierte Messung der Landsenkung.

1.3 Potenzielle Einflussfaktoren auf die Landsenkung

Landsenkung infolge von sinkenden Grundwasserständen ist ein weltweit bekanntes Phänomen, das bereits seit knapp 100 Jahren untersucht wird [6]. Die extensive GW-Übernutzung führt im MD zu einer Senkung der GW-Druckspiegel in den gespannten GW-Leitern, so dass der damit einhergehende sinkende hydrostatische Druck im Untergrund zu einer Erhöhung der effektiven Spannung in den Sedimentschichten führt. Insbesondere in den GW-Stauern kann dies zu einer Kompaktion der tonhaltigen Sedimente führen, woraus letztendlich eine Senkung der Landoberfläche resultiert.

Wie stark die Kompaktion einer Sedimentschicht infolge einer Erhöhung der effektiven Spannung ist, kann durch ihren Kompressionsbeiwert C_c beschrieben werden. Bindige Sedimente, wie beispielsweise Ton, weisen deutlich höhere Kompressionsbeiwerte auf als nicht-bindige Sedimente wie Sand.

Modellbasierten Untersuchungen von Minderhoud et al. [7] zufolge ist das MD aufgrund der GW-Entnahme innerhalb von 25 Jahren um durchschnittlich 18 cm abgesunken. Wie groß der Anteil der aus der GW-Entnahme resultierenden Landsenkung an der gesamten Landsenkung tatsächlich ist, konnte bislang jedoch noch nicht anhand von Messdaten belegt werden.

Ein weiterer möglicher Einflussfaktor auf die Landsenkung im MD könnte das Ausbleiben von großflächigen Überflutungen infolge von Dammbauten sein, da dies die Deposition von neuen Sedimenten verhindert und so möglicherweise natürliche Kompaktionen der jüngsten Sedimentlagen nicht mehr durch neue Ablagerungen kompensiert werden können [8]. Im Weiteren gelten, wie Galloway et al. [9] erörtert, der Abbau von organischen Bestandteilen im Untergrund sowie das Austrocknen der oberen Bodenschicht infolge von intensiveren Trockenperioden als potenzielle Einflussfaktoren.

Kompakt

- Erstmalig tiefendifferenzierte Landsenkungsmessung im Mekong-Delta.
- Vorläufige Messdaten zeigen mittlere Landsenkungsraten von 9,5 mm/a in 0-164 m Tiefe.
- Vorläufige Messdaten zeigen Korrelation zwischen Landsenkung und fallendem Grundwasserspiegel.

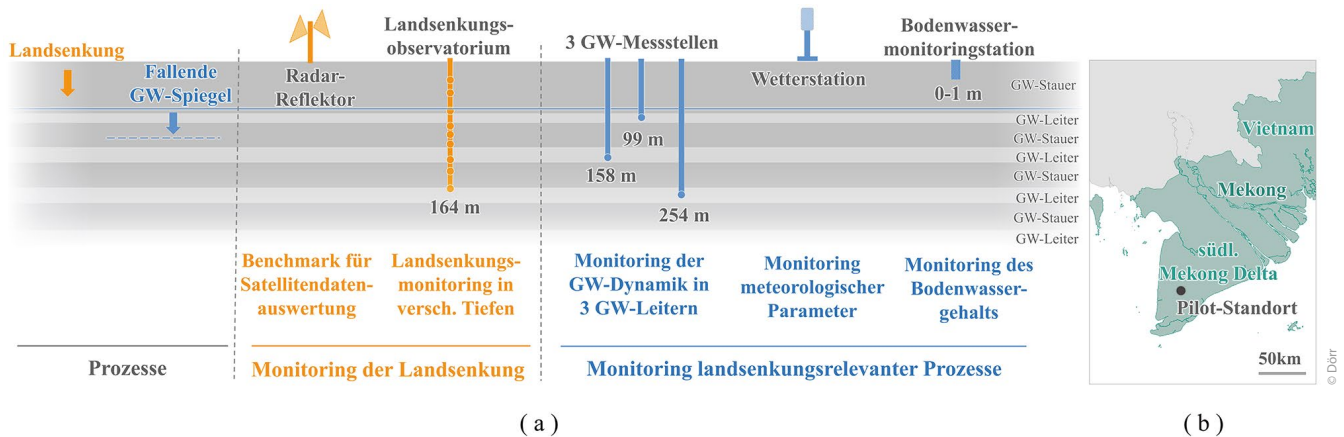


Bild 1: a) Konzeptioneller Querschnitt durch den Pilot-Standort und b) seine Lage im südlichen Mekong-Delta

2 Aufbau des Pilot-Standorts

2.1 Konzeptionierung des Pilot-Standorts

Der Pilot-Standort befindet sich im südlichen MD, in der Provinz Ca Mau, südlich der Provinzhauptstadt Ca Mau-Stadt. Ziel des Pilot-Standorts ist es, dort sowohl die Landsenkung selbst als auch relevante Umweltprozesse, die als mögliche Einflussfaktoren auf die Landsenkung gelten, zu messen. Am Pilot-Standort wurden daher u. a. drei GW-Messstellen errichtet, welche in verschiedenen GW-Leitern verfiltert sind (in 99 m, 158 m und 254 m Tiefe). Ebenfalls wurde am Pilot-Standort eine Wetterstation aufgebaut und eine Profilmesssonde zur Messung des Bodenwassergehalts installiert. Durch eine Kernbohrung bis in 254 m Tiefe liegen darüber hinaus ungestörte Sedimentproben aus

57 Tiefenhorizonten vor, die eine genaue Ansprache sowie geochemische, mineralogische und geomechanische Untersuchungen der Sedimente ermöglichen.

Zur Messung der Landsenkung selbst verfügt der Pilot-Standort über einen Radar-Reflektor, welcher die Auswertung der Landsenkung anhand von Satellitendaten verbessern kann, sowie über das Landsenkungsobservatorium (LSO) zur tiefendifferenzierten Messung der Landsenkung, welches nachfolgend genauer erläutert wird. **Bild 1** zeigt einen konzeptionellen Querschnitt durch den Pilot-Standort (a) und seine Lage im südlichen MD (b).

2.2 Landsenkungsobservatorium

Zur tiefendifferenzierten Messung der Landsenkung wurde am Pilot-Standort ein Messsystem in einer 164 m tiefen Bohrung

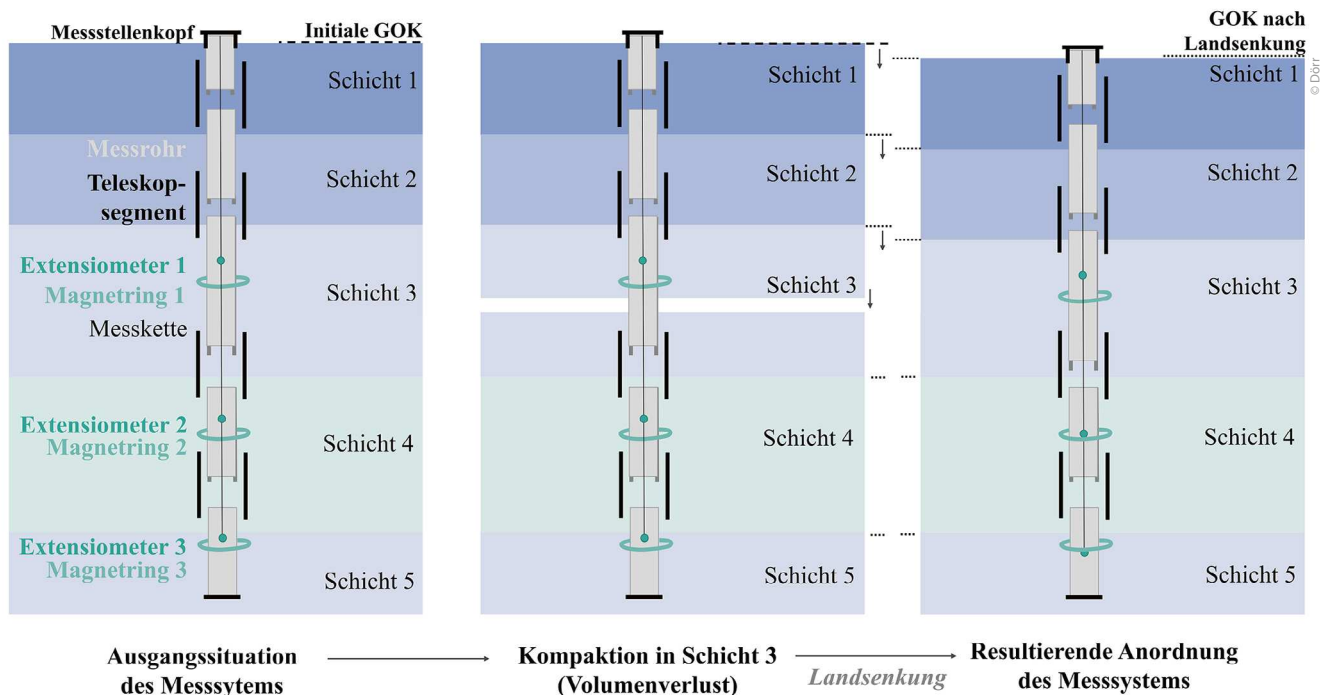


Bild 2: Beispielhafte Darstellung des Messprinzips des Landsenkungsobservatoriums

installiert, das über eine Messkette mit acht digitalen Extensio-
metern verfügt. Die Messkette hängt frei in einem Messrohr,
welches durch Teleskopsegmente in separat bewegliche
Abschnitte gegliedert ist. In verschiedenen Tiefen sind Magnet-
ringe am Messrohr befestigt. Der Raum zwischen Messrohr und
der Bohrlochwand wurde mit einer Bentonit-Zement-Suspen-
sion gemäß ISO 18 674 verfüllt, so dass Festigkeit und Steifigkeit
der Verfüllung bestmöglich den Eigenschaften der anstehenden
Sedimentschichten entsprechen und sich Kompaktionsprozesse
in den Sedimenten auf die Verfüllung und somit das Messrohr
übertragen.

Führt eine Kompaktion in einer Sedimentschicht zu Land-
senkung, senkt sich die gesamte Messkette, welche über den
Messstellenkopf mit der GOK verbunden ist, um das Maß der
erfolgten Kompaktion nach unten. Die Abschnitte des Mess-
rohrs, die sich oberhalb des nächsttieferen Teleskopsegments
befinden, bewegen sich ebenfalls um das gleiche Maß nach
unten und führen zu einer Stauchung des nächsttieferen Tele-
skopsegments. Die darunterliegenden Messrohrabschnitte
mitsamt ihrer Magnetringe verbleiben unbewegt, sodass dort
eine relative Bewegung zwischen Magnetring und den Extensio-
metern an der Messkette zu verzeichnen ist. Oberhalb des
gestauchten Teleskopsegments verschieben sich Magnetringe
und Extensiometer hingegen parallel, so dass dort keine relative
Bewegung zwischen Magnetring und Extensiometer vorliegt.
Somit kann eine tiefendifferenzierte Bewertung der Kompak-
tion zwischen den Tiefenlagen der Teleskopsegmente erfolgen.

Kompaktionen, die im Bereich zwischen dem untersten Tele-
skopsegment und der Endtiefe des Messrohrs erfolgen, führen
zu einer Stauchung des untersten Teleskopsegments. Kompak-
tionen die unterhalb der Endtiefe des Messrohrs erfolgen,
können mit diesem Messsystem nicht erfasst werden. Hierzu
kann jedoch grundsätzlich die Differenz zwischen der mit dem

LSO ermittelten Landsenkung im Bereich 0-164 m und der mit
Satellitendaten ermittelten Gesamtlandsenkung herangezogen
werden.

Das Messprinzip ist konzeptionell für ein Beispiel in **Bild 2**
dargestellt. Dort führt eine Kompaktion der Schicht 3 zu einer
relativen Bewegung zwischen Extensiometer 2 und Magnet-
ring 2 sowie zwischen Extensiometer 3 und Magnetring 3.
Extensiometer 1 und Magnetring 1 bewegen sich parallel, sodass
dort keine relative Bewegung zu verzeichnen ist.

3 Vorläufige Messdaten und erste Erkenntnisse

3.1 Tiefendifferenzierte Messreihe der Landsenkung

Die vorläufigen Messergebnisse des LSO sind für den Betrachtungszeitraum 11.12.2022-02.04.2023 in **Bild 3** dargestellt. Die Messdaten zeigen in diesem Zeitraum eine Landsenkung von ca. 2,9 mm über den gesamten vom LSO erfassten Messbereich (0-164 m Tiefe). Dies entspricht einer mittleren Landsenkungsrate von ca. 9,5 mm/a.

Bild 3a zeigt die Ganglinien der acht digitalen Extensiometer und somit die Dynamik der Kompaktionsprozesse in den abgegrenzten Tiefenhorizonten. **Bild 3b** fasst die zeitlich kumulierte Landsenkung der jeweiligen Tiefenhorizonte im Betrachtungszeitraum zusammen, welche sich aus der Differenz der entsprechenden Ganglinien ergibt. Die Tiefenzuordnung der Messdaten, die sich aus der Lage der Teleskopsegmente ableitet, ist in **Bild 3b** beschriftet.

Die Auswertung der vorläufigen Messergebnisse des LSO zeigt, dass mehr als 60 % der aufgezeichneten Landsenkung auf Kompaktionsprozesse in den Tiefenbereichen 0-13 m und 13-16,5 m zurückzuführen sind. Der Tiefenhorizont 13-16,5 m erfasst den aktuellen Schwankungsbereich der GW-Druckspie-

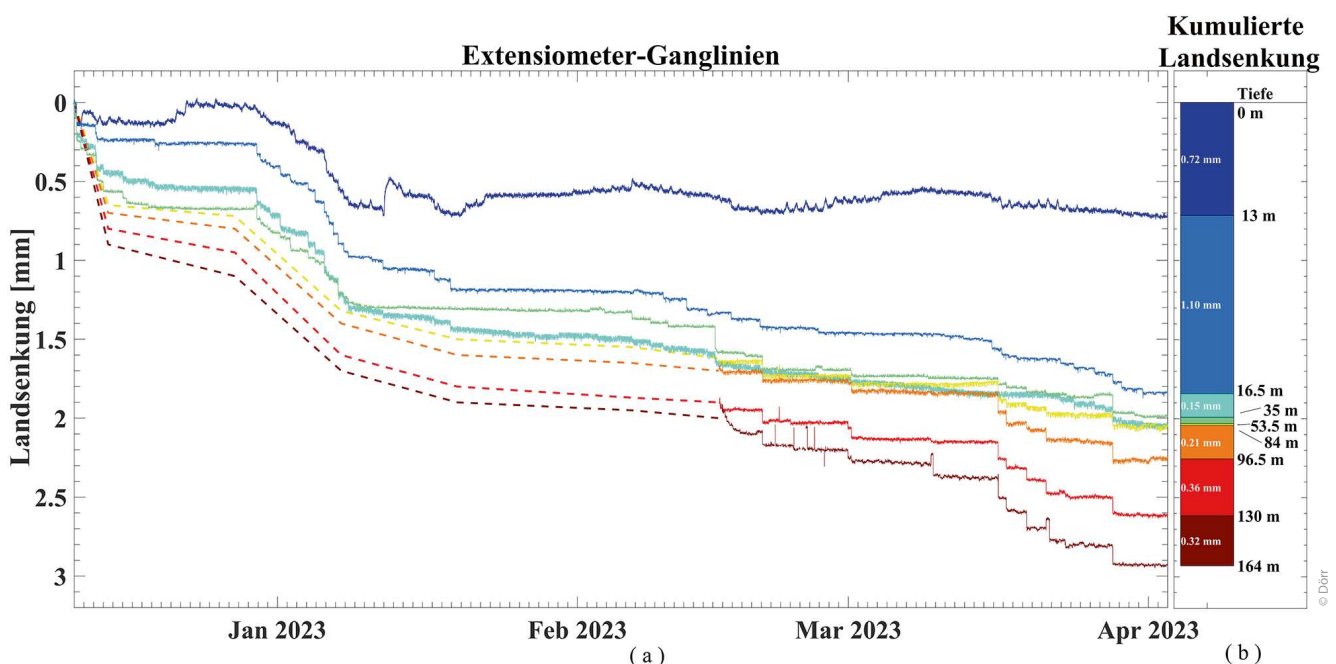


Bild 3: Vorläufige Messdaten des Landsenkungsobservatoriums

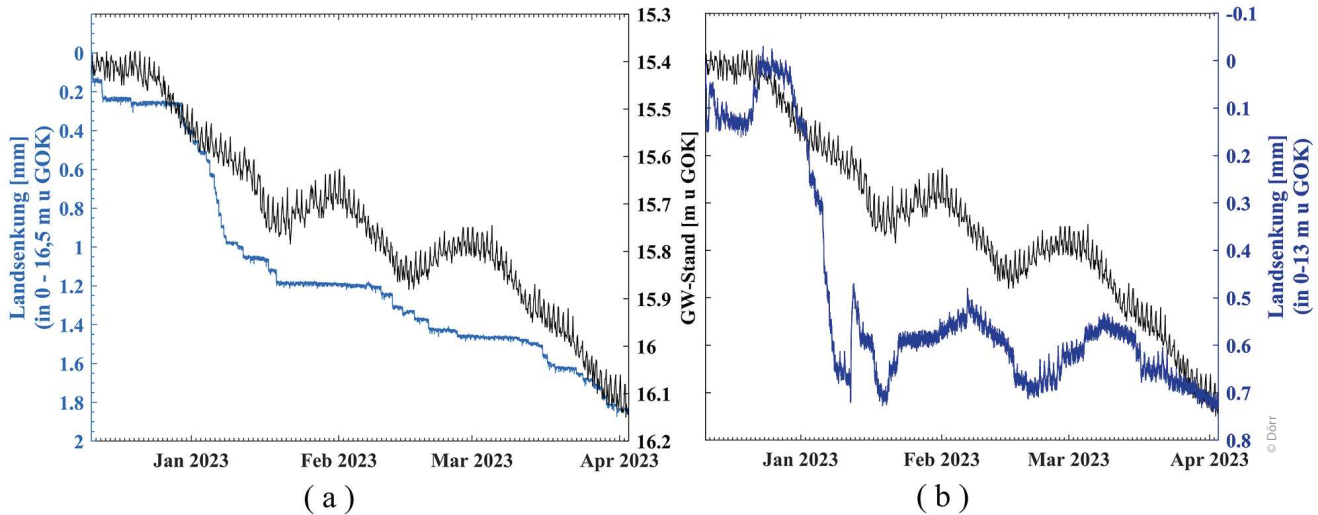


Bild 4: Korrelation zwischen Landsenkung und Grundwasserdruckspiegel

gel in den drei überwachten GW-Leitern. Die Messdaten weisen also darauf hin, dass ein signifikanter Anteil der Kompaktionsprozesse in den Horizonten der fallenden GW-Druckspiegel erfolgt. Aufgrund ihres geringen Alters sowie eines hohen Tonanteils sind diese Horizonte vermutlich durch hohe Kompressionsbeiwerte charakterisiert und weisen daher wahrscheinlich ein großes Landsenkungspotenzial auf.

In den Tiefenhorizonten 35–84 m zeichnet das LSO kaum signifikante Kompaktionsprozesse auf. Während dies für den Tiefenhorizont 35–53,5 m aufgrund der dort vorliegenden hohen Anteile an Sand in den Sedimenten zu erwarten war, liegen im Tiefenhorizont 53,5–84 m bereichsweise Tonschichten mit organischen Anteilen vor, in denen Kompaktionsprozesse infolge der GW-Druckspiegelsenkung erwartbar gewesen wären.

In den Tiefenhorizonten 84–96,5 m, 96,5–130 m und 130–164 m zeichnet das LSO Kompaktionsprozesse auf, die etwa 30 % der aufgezeichneten Gesamtlandsenkung verursachen. Diese Horizonte sind durch Wechselfolgen aus sandigen und tonigen Sedimenten charakterisiert.

Die Dynamik der vier unteren Extensiometer konnte für die erste Hälfte des Betrachtungszeitraums bis zum 15.02.2023 nicht ausgewertet werden (gestrichelte Linien in **Bild 3**), da die Messkette aufgrund einer lokalen Schrägstellung des Messrohrs und einer daraus resultierenden temporären Blockade eines Extensiometers in diesem Zeitraum nach aktuellem Kenntnisstand nicht frei im Messrohr hing.

3.2 Korrelation zwischen Landsenkung und Grundwasserdruckspiegel

In **Bild 4** sind die Ganglinien der beiden oberen Extensiometer (hellblau und dunkelblau) und die GW-Standganglinie der in 99 m Tiefe verfilterten GW-Messstelle (schwarz) dargestellt.

Bild 4a zeigt eine deutliche Korrelation zwischen dem fallenden GW-Druckspiegel und den aufgezeichneten Kompaktionsprozessen im Tiefenhorizont 0–16,5 m. Bei temporär ansteigenden GW-Spiegeln stagniert die Landsenkung in **Bild 4a** so lange, bis wieder ein neuer Minimalwert des GW-

Stands erreicht wird. Die Messdaten zeigen also, dass eine Absenkung des GW-Druckspiegels zu einer Landsenkung führt. Zukünftige GW-Entnahmen, die zu einer Absenkung des GW-Spiegels führen, werden demnach weitere Landsenkung zur Folge haben.

Bild 4b zeigt ebenfalls eine Korrelation zwischen dem fallenden GW-Spiegel und Kompaktionen im Tiefenhorizont 0–13 m; allerdings zeigt diese Ganglinie darüber hinaus auch eine vermeintliche Landhebung infolge von temporär ansteigenden GW-Ständen. Eine solche ist jedoch nach aktuellem Kenntnisstand nicht erfolgt, da eine tatsächliche Hebung der GOK eine Hebung der gesamten Messkette zur Konsequenz hätte, welche sich wiederum in allen acht Extensiometerganglinien zeigen müssten. Da jedoch nur der oberste Extensiometer eine solche Dynamik aufzeigt, ist nach aktuellem Kenntnisstand davon auszugehen, dass diese vom Extensiometer erfasste relative Bewegung aus einer abwärtsorientierten Bewegung des Magnetings und nicht aus einer aufwärtsorientierten Bewegung der Messkette resultiert. Diese Messdaten spiegeln somit keine tatsächlichen Hebungsprozesse des Untergrunds wider, sondern resultieren vermutlich allein aus Bewegungsprozessen des Messsystems selbst. Diese vorläufige Interpretation muss in Zukunft anhand von längeren Zeitreihen verifiziert werden.

3.3 Ausblick

Die vorläufigen Messergebnisse sind in Größenordnung und Dynamik plausibel und erlauben erstmals eine tiefendifferenzierte Bewertung der Kompaktionsprozesse im MD sowie deren Korrelation mit möglichen Einflussfaktoren. Die Auswertung längerer Zeitreihen sowie eine manuelle Messung der Lage der Magnetringe sollte in Zukunft zur Verifizierung der Tiefenzuordnung der Messwerte sowie zur Klärung eventueller Hebungsprozesse herangezogen werden. Eine Messreihe von mindestens 12 Monaten ist hierfür notwendig, um insbesondere auch die Reaktionen des Messsystems auf die Monsunniederschläge und steigende GW-Spiegel zu beurteilen.

Mit den in dieser Studie vorgestellten Daten liegt erstmals eine fundierte Grundlage für kommende politische und wissenschaftliche Bewertungen vor, welche Gegenmaßnahmen hinsichtlich durch GW-Entnahme bedingter Landsenkung ergriffen werden sollten, um die Zukunft des südlichen MD zu sichern.

Dank

Die hier vorgestellten Messdaten wurden im Rahmen des Forschungsprojekts ViWaT-Engineering erhoben, gefördert vom Bundesministerium für Bildung und Forschung (BMBF) unter der Fördernummer 02WCL1474A. Ein besonderer Dank gilt an dieser Stelle allen Forschenden des ViWaT-Engineering-Projekts sowie den vietnamesischen Partnern des Vietnamese Ministry of Science and Technology (MOST) und des Department of Natural Resources and Environment Ca Mau (DONRE Ca Mau). Ein weiterer Dank gilt der Hector Fellow Academy, die im Rahmen eines Stipendiumsprogramms die Finanzierung von Personal- und Forschungsmitteln des Erstautors dieser Studie bereitstellt.

Hinweis

Bei den im Rahmen dieser Studie vorgestellten Messdaten und Interpretationen handelt es sich um vorläufige Erkenntnisse, die in Zukunft weiter verifiziert werden müssen und ggfls. von dem hier Dargestellten abweichen können. Die Rohmessdaten können erst nach Abschluss der Forschungsarbeiten der Autoren veröffentlicht werden.

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Vietnam's Mekong Delta -

Land Subsidence due to Groundwater Overexploitation

The Mekong Delta is home for approx. 21.5 million people and is confronted with existence-threatening land subsidence processes up to 3 cm/a since several years. Groundwater overexploitation is considered to be the main reason for this. In order to investigate the process dynamics of land subsidence, a depth-differentiated land subsidence monitoring system was set up at a pilot site, which is so far unique in the Mekong Delta. The preliminary monitoring data shows a correlation between land subsidence and the lowering groundwater level.

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DOI dieses Beitrags: <http://doi.org/10.1007/s35147-023-1922-3>



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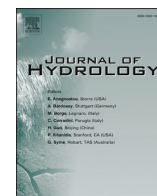
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Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Passive subsurface characterization in subsiding deltas: assessing land subsidence mitigation potential with frequency analyses of groundwater heads and superposing harmonic drivers

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ARTICLE INFO

This manuscript was handled by D. Han, Editor-in-Chief, with the assistance of Xiaolong Geng, Associate Editor

Keywords:

Mekong Delta

Ca Mau

Earth and ocean tides

Tidal subsurface analysis

ABSTRACT

Many of the world's low-lying river deltas are experiencing severe land subsidence, posing significant challenges to sustainable development. Effective mitigation strategies require a thorough understanding of subsurface processes and comprehensive parameterization, which are often hindered by limited investigations and resources. In this context, passive subsurface characterization (PSC) methods are particularly advantageous, as they utilize existing datasets to estimate hydraulic and geomechanical properties of the subsurface. This study conducts a detailed frequency analysis of 43 groundwater head time series in the southern Vietnamese Mekong Delta, revealing harmonic signals and imprints of mechanical loading in groundwater heads. These signals are identified as a superposition of five key drivers: (i) Earth tides, (ii) atmospheric tides, (iii) ocean tides, (iv) river tides, and (v) anthropogenic groundwater extraction. By disentangling Earth and ocean tides from atmospheric tides at the semi-diurnal frequency S_2 , the specific storage and elastic formation compressibility of the intensely exploited middle Pliocene aquifer are estimated to $5.9\text{--}7.8 \cdot 10^{-6} \text{ m}^{-1}$ and $6.4\text{--}7.5 \cdot 10^{-10} \text{ Pa}^{-1}$, respectively. This indicates a low land rebound and water storage potential and therefore an insignificant subsidence mitigation potential of this confined aquifer. By revealing that groundwater pumping may leak into amplitude spectra and corrupt quantitative PSC, this study underscores that accurate parameter estimations require a careful disentanglement of various superposing drivers. While the complex interplay of multiple tidal forcings limited previous PSC-applications in subsiding deltas, the novel integration of ocean tide loading on the solid Earth enables PSC-parameter estimations in coastal groundwater systems.

1. Introduction

Land subsidence is a geohazard of global scale and relevance, with nearly two billion people living in affected areas (Davydzenka et al.,

2024). Groundwater over-exploitation has been identified as one of the main causes for intensive large-scale land subsidence (Motagh et al., 2008; Sun et al., 1999; Poland and Davis, 1969). Coastal plains and river deltas are particularly vulnerable to subsidence-induced land loss due to

Abbreviations: BE, barometric efficiency; FFT, fast Fourier transform; HALS, harmonic least squares; IGPVN, improvement of groundwater protection in Vietnam; MAR, managed aquifer recharge; NAWAPI, National Center for Water Resources Planning and Investigation, Vietnam; NGMN, National Groundwater Monitoring Network of Vietnam; OT_{SE}, ocean tide loading on the solid Earth; OT_{GW}, ocean tide loading on the aquifer's water; PSC, passive subsurface characterization; PT, pressure transducer; TSA, tidal subsurface analysis; VMD, Vietnamese Mekong Delta.

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<https://doi.org/10.1016/j.jhydrol.2025.133844>

Received 18 February 2025; Received in revised form 11 June 2025; Accepted 5 July 2025

Available online 8 July 2025

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their low elevation, and their high demand for freshwater often results in depleting groundwater heads, leading to sediment compaction and causing subsidence (Gambolati and Teatini, 2021). In light of climate change, global economic and population growth, and a resulting increase of groundwater demand and depletion, land subsidence hazards must be expected to exacerbate within the next decades (Herrera-García et al., 2021).

As one of the world's largest deltaic lowlands, the southern Vietnamese Mekong Delta (VMD) is a prominent example for hazardous land subsidence dynamics due to groundwater overexploitation, with rates of more than 3 cm a^{-1} (Erban et al., 2014; Minderhoud et al., 2017; Dörr et al., 2024). Other deltas and their metropolitan cities like the Ganges-Brahmaputra Delta (Dhaka), the Mississippi Delta (New Orleans), the Nile Delta (Alexandria) and the Yangtze Delta (Shanghai) are further examples for deltaic lowlands suffering from land subsidence (Syvitski et al., 2009).

Land subsidence due to groundwater depletion may be mitigated to some extent. However, the effectiveness of mitigation measures varies between the affected regions. In some previously subsiding regions like Tokyo and Osaka, Japan (Sreng et al., 2011), as well as Taipei, Taiwan (Chen et al., 2007), a significant land rebound followed a natural recovery of groundwater heads after a substantial reduction of groundwater extraction. Besides natural groundwater recharge, the injection of water or other fluids into the aquifer, e.g. in the context of managed aquifer recharge (MAR), may yield in significant land rebound, as achieved in the Wilmington oil field, California (Gambolati and Teatini, 2021). In other previously subsiding regions with limited rebound capability, a reduction of groundwater withdrawal substantially reduced further land subsidence, for example in Venice, Italy (Gambolati and Teatini, 2021) and in Shanghai, China (Zhang et al., 2015). In confined aquifer systems, such as in the VMD, the land rebound potential depends on elastic aquifer properties (Allen and Mayuga, 1970) which can be derived from groundwater head responses to harmonic forcings (Merritt, 2004; Cuttillo and Bredehoeft, 2011; Rau et al., 2020).

The responses of groundwater heads to external forcings such as barometric pressure variations or ocean tides have been recognized and described long ago (Klönne, 1880; Veatch, 1906) and are used to derive hydro-geomechanical subsurface parameters since the 1940's (Jacob, 1940). Barometric pressure and ocean tides are subject to periodic variations, enabling an assessment of these effects not only in the time domain but in the frequency domain as well. This is equally valid for the response of groundwater heads to Earth tides (Bredehoeft, 1967). Earth tides are caused by small but effectful variations of gravitational potential due to the movement of celestial bodies, inducing motions in the solid Earth (Agnew, 2007). With the given knowledge of the movement of celestial bodies, Earth tide strains can be calculated for any location on the earth's surface and for any point in time.

Since decades methods in time and frequency domain have been developed and improved to derive hydro-geomechanical subsurface parameters like the specific storage S_s (m^{-1}) and the aquifer compressibility α (Pa^{-1}) from groundwater responses to Earth and atmospheric tides, well summarized by Turnadge et al. (2019) and framed by the terms passive subsurface characterization (PSC) and tidal subsurface analysis (TSA). Particularly in the context of land subsidence mitigation, coastal plains and deltaic groundwater bodies would benefit from the application of PSC methods, given that the elastic compressibility of the subsurface is a proxy for (i) the contribution of elastic aquifer compaction to the overall observed subsidence, (ii) the mitigation potential in terms of land rebound capability (Allen and Mayuga, 1970) and (iii) the elastic aquifer storage and therefore the capability to temporarily receive and store surplus water resources by deformation of the aquifer material (Bouwer, 2002).

This study aims to demonstrate the potential of PSC for assessing land subsidence mitigation in deltaic lowlands by estimating elastic geomechanical properties. The southern VMD serves as an ideal study

area due to three key factors: (i) tidal signals in groundwater heads have not yet been systematically described in the region, (ii) high land subsidence rates and ongoing land loss necessitate an urgent evaluation of subsurface properties and processes, and (iii) the superposition of multiple harmonic forcings provides a unique opportunity to apply PSC in a complex setting influenced by various tidal drivers. While the application of previous PSC methods was restricted in near-coastal aquifers, the novel integration of ocean tide loading on the solid Earth enhances PSC-parameter estimations in such hydrogeological systems. Therefore, the findings of this study highlight the utility of PSC and its potential applicability to other deltaic aquifer systems.

2. Study area

2.1. Land subsidence and water resources in the southern Vietnamese Mekong Delta

The VMD and its adjacent metropolis Ho Chi Minh City (Fig. 1) are home to more than 21 million people (GSOV, 2024) who have been facing local land subsidence rates $>3 \text{ cm a}^{-1}$ for several years, amounting to an existential crisis (Erban et al., 2014; Minderhoud et al., 2017; Dörr et al., 2024). With an average elevation of only 80 cm above sea level measured in 2018 (Minderhoud et al., 2019), such high rates of subsidence require an urgent investigation of the process dynamics, parametrization of subsurface properties and the assessment of potential mitigation strategies. Intensive groundwater overexploitation, leading to a continuous decline in groundwater heads throughout the confined multi-aquifer-aquitard system (Duy et al., 2021) and thus increases the effective stresses in the aquifer and aquitard sediments, is considered to be the greatest single driver for land subsidence in the VMD (Minderhoud et al., 2020; Kondolf et al., 2022). In addition, the construction of upstream reservoirs, dams and hydropower plants, along with sand mining activities in the rivers and channels, cause a sediment deficit in the delta plain, contributing to the overall subsidence by failing to compensate non-anthropogenic subsidence due to natural compaction processes of the young delta sediments (Kondolf et al., 2022; Baldan et al., 2024). Moreover, anthropogenic infrastructure, such as urban settlements, bridges and roads exert a surplus load on the subsurface causing localized compaction (Neussner, 2019; Dörr et al., 2021).

The VMD socio-economic activities are highly dependent on water resources, as it is one of Southeast Asia's most productive areas in terms of agricultural and aquacultural food production (Van et al., 2023; Thong et al., 2010; Nguyen et al., 2019). Groundwater resources are extracted at up to half a million licensed and especially non-licensed extraction wells (Danh and Khai, 2015). With increasing trends of surface water salinization and pollution as well as more pronounced droughts, groundwater remains a water resource of major relevance in the VMD (Pham et al., 2023), which is unlikely to be replaced by other water resources in the near future. Therefore, a continuous decline in groundwater heads is anticipated, resulting in further expected land subsidence (Minderhoud et al., 2020).

Due to the low and flat topography, the hydraulic gradients in the rivers are low, enabling upstream propagation of ocean tides, resulting in tidal fluctuations of inland river water levels and salinity (Eslami et al., 2019). In an attempt to control such sea water intrusion and minimize its impact on the tributary channels, sluice gates were constructed in the southern VMD (Di Giusto et al., 2021; Hoanh et al., 2009; Nguyen, 2020), operated on seasonal or tidal scale. Fig. 1 illustrates the southern VMD with its rivers and channel infrastructure, the location of sluice gates in Ca Mau Province and the overall low topography of the VMD.

The VMD's hydrogeological units have been classified into seven aquifers and seven aquitards (Fig. 2). The top Holocene aquitard Q₂ is likely to prevent significant groundwater recharge by infiltration into the Holocene aquifer qh, particularly in the southern VMD, where it has

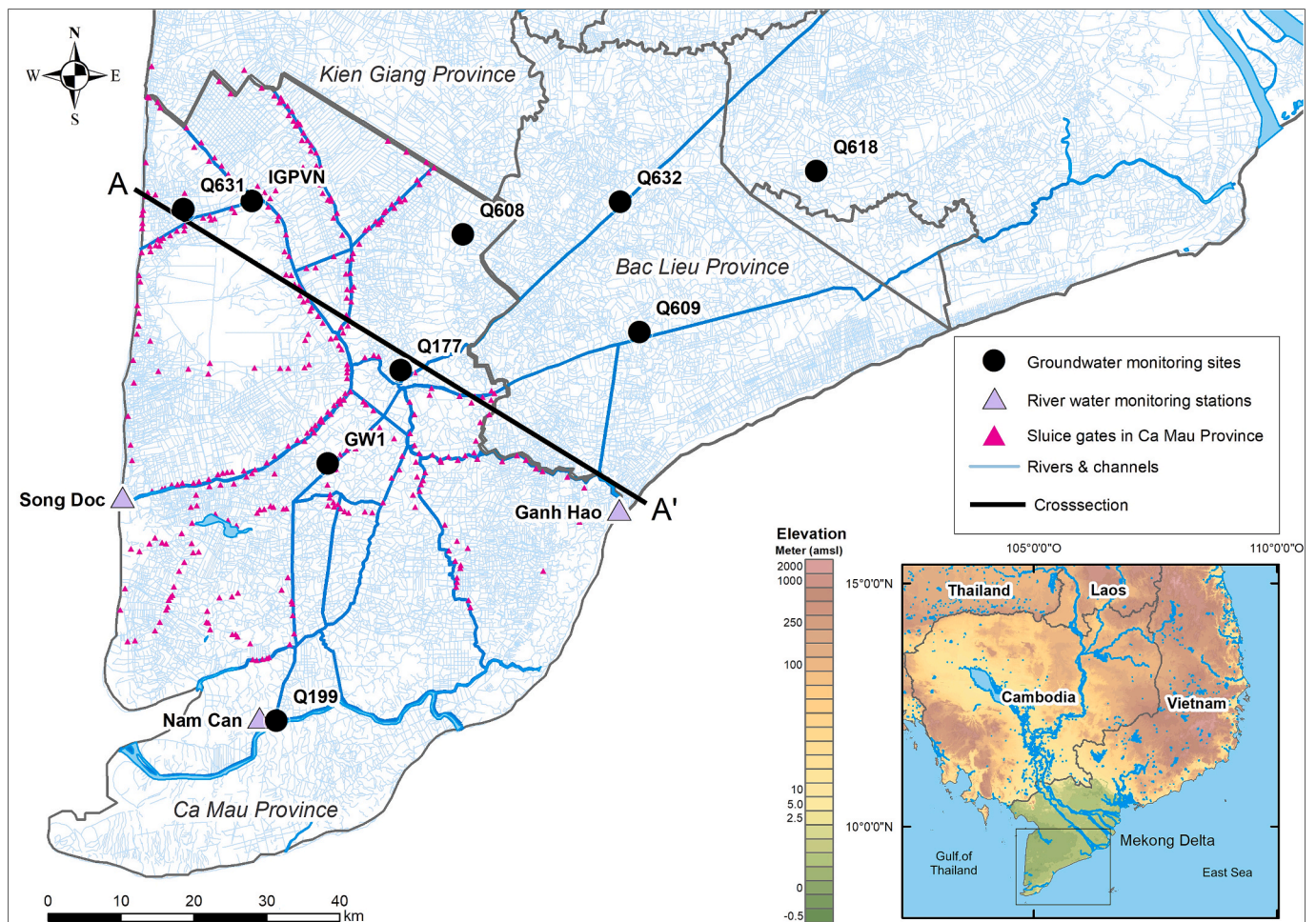


Fig. 1. Study area of the southern VMD, including the rivers and channels (bold and narrow blue lines), the location of the evaluated multi-depth groundwater and river water monitoring sites, and sluice gates in Ca Mau Province. Elevation data in the reference map are based on GTOPO30 (EROS, 2017) and locally for the VMD based on Minderhoud et al. (2019). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a thickness of up to >20 m (Anderson, 1978; Pham et al., 2019; Bauer et al., 2022). At some locations, the qh aquifer is unconfined and hence capable of receiving groundwater recharge, for example, where sand dunes are present in the coastal provinces of Ben Tre, Tra Vinh and Soc Trang (Wagner et al., 2012). Early studies identified artesian conditions prior to significant anthropogenic groundwater extraction (Anderson, 1978), while ongoing groundwater monitoring in the last decade reveals depleting groundwater heads with rates of $0.01\text{--}0.55\text{ m a}^{-1}$ in the different aquifers (Duy et al., 2021). The upper, middle and lower Pleistocene aquifers qp_3 , qp_{2-3} and qp_1 as well as the middle and lower Pliocene aquifers n_2^2 and n_2^1 and the upper Miocene aquifer n_1^3 are characterized by confined conditions. Fig. 2b illustrates a hydrogeological cross-section through the southern VMD, modified after Hoan et al. (2022). The introduced color code for the seven aquifers will be used henceforth in this study. The location of the cross-section line is marked in Fig. 1. In Fig. 2a, a detailed granulometry profile and the corresponding aquifer categorization of the IGPVN-monitoring site (location see Fig. 1) based on Pechstein et al. (2018) is presented. It shall be noted that the displayed granulometry of the Mesozoic basement (MZ) represents the crushed material rather than the undisturbed sediments. At that monitoring site, the aquifers n_2^2 and n_1^3 are not developed, and the development of the aquifers qh and qp_3 is not clearly distinguishable (Pechstein et al., 2018), indicated by the dashed blue section in the aquifer characterization in Fig. 2a.

2.2. Groundwater and surface water monitoring

The Vietnamese National Groundwater Monitoring Network (NGMN) provides a comprehensive dataset of groundwater head observations (i.e., as measured using well water levels) since the 1990s at numerous multi-depth monitoring sites in the VMD. Initially, these observations entailed manual measurements of groundwater heads on a daily to monthly basis. Since 2011, the NGMN has successively been enhanced by the installation of automated non-vented (i.e., absolute) pressure transducers (PTs) measuring groundwater heads at hourly resolution. The data obtained from the non-vented PTs is compensated for barometric pressure data recorded at each monitoring site by subtraction of the measured barometric pressure from the recorded absolute pressure (sum of water column and barometric loading) (NAWAPI, 2018).

The monitoring sites IGPVN and GW1 have been established by international research projects (IGPVN: Improvement of Groundwater Protection in Vietnam, Federal Institute for Geosciences and Natural Resources (BGR); GW1: ViWaT Engineering, Karlsruhe Institute of Technology (KIT)) complementing the NGMN-wells. At GW1, vented PTs were installed, at IGPVN non-vented PTs were replaced by vented PTs in 2021. Vented PTs are groundwater level sensors which are equipped with a venting tube that connects the submerged PT to the atmosphere, thus enabling a measurement of groundwater heads compensated for atmospheric pressure variations. Further clarification of the term barometric compensation as well as on measurement

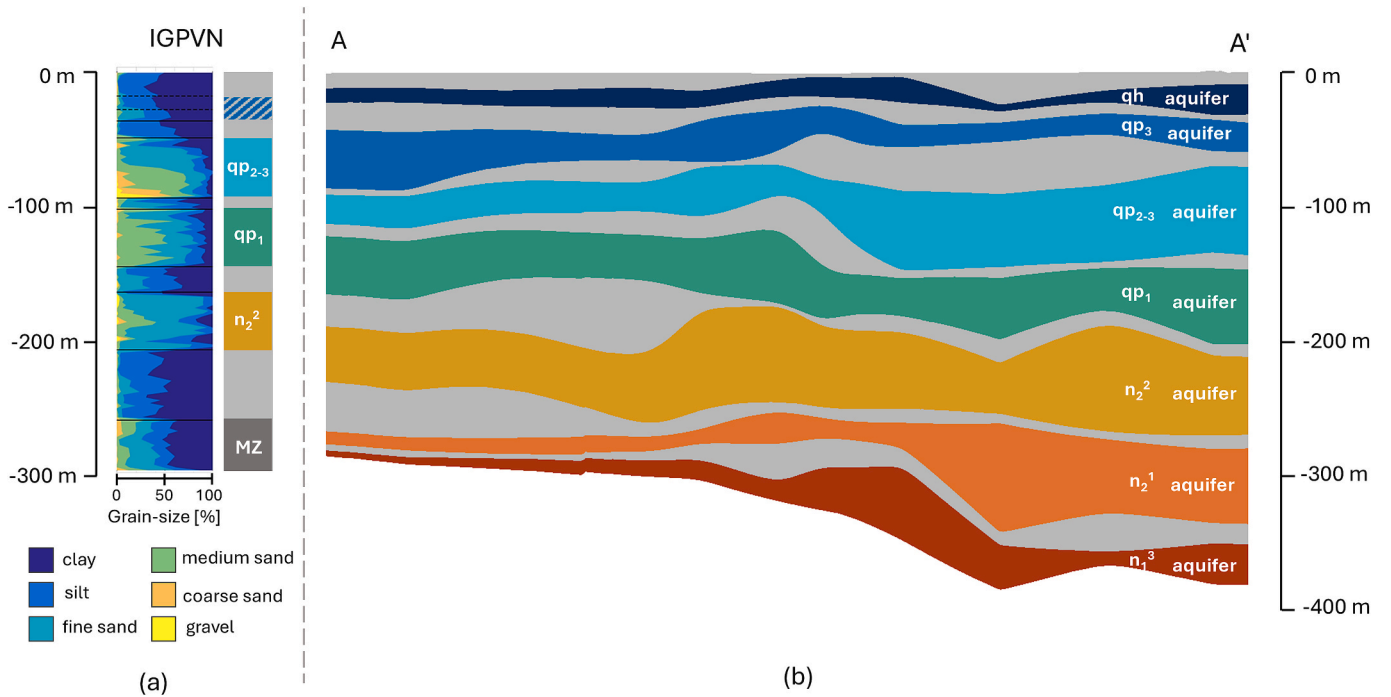


Fig. 2. Granulometry profile and aquifer-aquitard classification at the IGPVN monitoring site (Pechstein et al., 2018) (a) and hydrogeological cross section through the multi-layered aquifer-aquitard system of the southern VMD (Hoan et al., 2022) (b). The locations of the cross-section line and the IGPVN-monitoring site are marked in Fig. 1.

principles of vented and non-vented PTs is provided by Rau et al. (2019).

The IGPVN site comprises a total number of five observation wells, three of which are screened in the n_2^2 aquifer. For the observation wells IGPVN 1.3 (qp2-3), IGPVN 1.2 (qp1) and IGPVN 1 (n2^2) data is available from 2016 until 2024, with one major gap of 13 months and several minor gaps. In n_2^2 aquifer two more observation wells IGPVN 1.1 and IGPVN 1.4 recorded groundwater heads from 2016 to 2020 with non-vented PTs. For an assessment of atmospheric loading at IGPVN, two different sources of barometric pressure data are available: (i) hourly barometric pressure records from the IGPVN site, which were also used for barometric compensation before 2021, when non-vented PTs were installed and (ii) hourly barometric pressure data from a meteorological station in Ca Mau City, situated in a distance of 30 km.

In the southern VMD, river water levels are recorded at three gauging stations: (i) Song Doc, located at the estuary of the Ong Doc river into the Gulf of Thailand in approximately 2 km distance to the coast, (ii) Ganh Hao, located at the estuary of the Ganh Hao river into East Sea in approximately 1 km distance to the coast and (iii) Nam Can, located in Nam Can Town in the Cửa Lớn river, a connecting river between the Gulf of Thailand and the East Sea.

In this study, groundwater head data of 35 NGMN wells from seven stations covering six different aquifers are used, as well as of five wells at IGPVN and three wells at GW1. Additionally, records of groundwater extraction rates from a municipal water supply well (G22) in Ca Mau City between December 2023 and January 2024 were provided by the Vietnamese National Center for Water Resources Planning and Investigation (NAWAPI). The location of the groundwater and river water monitoring stations used in this study are illustrated in Fig. 1.

3. Methods

3.1. Frequency analysis

To evaluate the response of groundwater heads to Earth tides, atmospheric tides, ocean tides or river tides, the underlying frequency patterns in the respective time series are analyzed by two independent

methods: (i) the Fast Fourier Transform (FFT) and (ii) the harmonic least-squares (HALS) estimation. In FFT analyses, a given time series is decomposed into a linear sum of sinusoidal functions (Acworth et al., 2016), so that the Fourier transform $\mathcal{F}$ of the input signal $s(t)$ reads as

$$\hat{s}(f_k) = \mathcal{F}\{s(t_n)\} = \sum_{n=0}^{N-1} s(t_n) e^{-\frac{2\pi i k n}{N}} \quad (1)$$

where N is the number of observations, k is the frequency index, i is the imaginary unit, n the time index and

$$f_k = k f_s / N \quad (2)$$

with f_s as the sampling rate of the dataset. An alternative approach for the extraction of harmonic components is the application of a harmonic least squares (HALS) estimation (Agnew, 2007):

$$\min_{a_c, b_c} \sum_{n=1}^N \left[y_n(t_n) - \sum_{c=1}^C [a_c \cos(2\pi f_c t_n) + b_c \sin(2\pi f_c t_n)] \right]^2 \quad (3)$$

where N is the number of observations, t_n the time, and $y_n(t_n)$ the corresponding observation value, C is the total number of investigated harmonic components c , f_c is the frequency and a_c and b_c are the fitting coefficients.

Both methods yield in complex numbers, which can be decomposed into values of amplitude and phase for the considered frequency. The utilization of complex numbers $\hat{z}$ proves advantageous in the context of PSC analyses, as they encompass information on both the amplitude z and the phase shift ϕ . With the Eq. (4 [1-3]) any of the three values can be calculated from the other two:

$$\hat{z} = z \cdot e^{i\phi}; \quad \phi = \arg \hat{z}; \quad z = \text{abs}(\hat{z}) \quad (4 [1-3])$$

The two methods vary in the requirement of input data quality, as FFT requires continuous data whereas HALS is capable of handling gaps (Schweizer et al., 2021). While FFT yields in amplitude spectra at a fine and constant frequency discretization f_k , HALS takes only predefined frequencies into consideration. Consequently, significant variations

between calculated FFT and HALS amplitudes may suggest that for the HALS analysis, not all relevant frequencies were considered. In this study, for any performed frequency analysis, both methods were applied for validation purposes. HALS outperforms FFT in terms of accuracy in amplitude and phase estimation and therefore is preferable to FFT in PSC (Schweizer et al., 2021). Thus, the amplitudes and phases obtained from HALS were used for the PSC-parameter estimations in this study. For the HALS analyses in this study, the ten most commonly investigated frequencies in groundwater analysis as listed in Table 1 were considered. In tidal analysis, frequencies with near-diurnal periodicity are commonly denoted in cycles per day (cpd).

For the FFT analyses, gaps were filled with an autoregression algorithm (fillgaps, MATLAB, 2023), which takes the frequency patterns within the datasets into consideration. To minimize the impact of interpolation on FFT results, subsets of the complete datasets with few or no gaps were selected. The subset durations vary between 0.4 and 5.1 years with an average of 3.1 years. After the selection of groundwater sub-datasets mostly minor gaps of a few hours, e.g. as caused by bi-annual groundwater sampling campaigns, remained and required interpolation. A summary of the subset employed for the frequency analyses and a visualization of the respective time series is provided in the Supplementary information. At all wells >99 % of the data utilized in the FFT analyses is original data with <1 % of interpolated values.

The analyzed river water levels were measured at irregular intervals, on average approximately 6 times per day, requiring an interpolation of a greater fraction of the dataset to obtain a dataset of hourly resolution and thus a more careful comparison of FFT and HALS based amplitudes in the frequency analyses.

3.2. Calculation of Earth and ocean tide strains

Volumetric Earth tide strains, denoted in nanostrain (nstr), were calculated at hourly resolution using PyGTide (Rau et al., 2022b), a Python wrapper for ETERNA PREDICT 3.4 (Wenzel, 1996). Ocean tides may affect tidal signals in inland groundwater heads by two independent processes: (i) by ocean tide loading on the solid Earth (Agnew, 2012), further denoted as OT_{SE} , and (ii) by ocean tide loading on the aquifer's water (Jacob, 1950; van der Kamp, 1972), further denoted as OT_{GW} . OT_{SE} causes strain waves, which propagate from the ocean coast towards the inland by the geologic media, while OT_{GW} is a pressure wave that propagates from the ocean coast towards the inland by the liquid phase (pore water) only. The volumetric strains due to OT_{SE} are calculated with the Fortran-based software package SPOTL (Agnew, 2012) at hourly resolution. For an aquifer, which extends below the seabed, the amplitude damping of OT_{GW} in a coastal aquifer can be calculated with Eq. (5) (van der Kamp, 1972):

$$A_{gw}(x) = \frac{1}{2} A_{sw} \gamma e^{-\sqrt{\frac{\pi S_s}{K t_0}} x} \quad (5)$$

where A_{gw} (m) and A_{sw} (m) are the amplitudes in the groundwater and

Table 1

Summary of the ten most relevant frequencies in groundwater analysis after Merritt (2004), McMillan et al. (2019) and Rau et al. (2020).

Darwin name	Frequency (cpd)	Earth Tides	Atmospheric Tides	Ocean and River Tides
Q ₁	0.893244	Yes	—	Yes
O ₁	0.929536	Yes	—	Yes
M ₁	0.966446	Yes	—	Yes
P ₁	0.997262	Yes	Yes	Yes
S ₁	1.000000	—	Yes	—
K ₁	1.002738	Yes	Yes	Yes
N ₂	1.895982	Yes	—	Yes
M ₂	1.932274	Yes	—	Yes
S ₂	2.000000	Yes	Yes	Yes
K ₂	2.005476	Yes	Yes	Yes

seawater respectively, x (m) is the distance to the shoreline, γ (—) is the uniaxial loading efficiency, t_0 is the tidal period (s), equal to the inverse of the frequency f_c , S_s (m⁻¹) and K (m s⁻¹) are the specific storage and the hydraulic conductivity of the considered aquifer. Given that the Gulf of Thailand is relatively shallow with an average depth of 45 m, and a maximum depth of 83 m (Aungsakul et al., 2007; Siripong, 1985), it can be reasonably assumed that the investigated aquifers with depths of 101–142 m and 161–202 m respectively at IGPVN extend below the seabed, allowing the application of Eq. (5) for the IGPVN monitoring site.

For the evaluation of the groundwater response to the total volumetric strain caused by OT_{SE} and Earth tides, the two strain time series can be added up to a single time series prior to the conducted frequency analysis. Alternatively, if the well water level response to Earth and ocean tide strains shall be disentangled, the two time series can be considered separately. In accordance with the harmonic addition theorem (Arfken and Weber, 2005), the amplitudes and phases obtained from the merged time series of Earth tides and OT_{SE} (denoted as the complex number $\hat{z}_{f_c}^{\{ET+OT_{SE}\}}$) equals the sum of the separately calculated amplitudes and phases (each denoted as the complex numbers $\hat{z}_{f_c}^{ET}$ and $\hat{z}_{f_c}^{OT_{SE}}$):

$$\hat{z}_{f_c}^{\{ET+OT_{SE}\}} = \hat{z}_{f_c}^{ET} + \hat{z}_{f_c}^{OT_{SE}} \quad (6)$$

It shall be noted here that, depending on the phase shift, amplitudes of Earth tides and OT_{SE} could either add up or counteract each other by causing constructive or destructive interference of the sinusoidal signals.

3.3. Disentanglement of Earth, ocean and atmospheric tides

For the determination of the barometric efficiency BE in the frequency domain, the response of groundwater heads to atmospheric tides at S_2 is evaluated. Given that S_2 is present in Earth, ocean and atmospheric tides (Table 1), the S_2 signal in the measured groundwater observation data $\hat{z}_{S_2}^{GW}$ must be disentangled into its Earth and ocean tide component $\hat{z}_{S_2}^{GW-\{ET+OT_{SE}\}}$ and its atmospheric component $\hat{z}_{S_2}^{GW-AT}$. Eq. (7) is an adaptation of the formulation by Rau et al. (2020) under additional consideration of ocean tide strains:

$$\hat{z}_{S_2}^{GW-AT} = \hat{z}_{S_2}^{GW} - \hat{z}_{S_2}^{GW-\{ET+OT_{SE}\}} = \hat{z}_{S_2}^{GW} - \frac{\hat{z}_{M_2}^{GW}}{\hat{z}_{M_2}^{\{ET+OT_{SE}\}}} \hat{z}_{S_2}^{\{ET+OT_{SE}\}} \quad (7)$$

The hat denotation indicates complex numbers. After the disentanglement of Earth, ocean and atmospheric tide signals, the barometric efficiency based on the S_2 response of groundwater heads to atmospheric tides $BE_{S_2}^{AT}$ can be calculated after Rau et al. (2020) with Eq. (8) as:

$$BE_{S_2}^{AT} = \frac{1}{A_{S_2}^r} \text{abs} \left[\frac{\hat{z}_{S_2}^{GW-AT}}{\hat{z}_{S_2}^{AT}} \right] \quad (8)$$

with the amplitude response $A_{S_2}^r$ between well water levels and the actual aquifer pore pressure. $A_{S_2}^r$ is a function of well and aquifer parameters and can be calculated by using the python package *Hydro-GeoSines* (HGS, 2023).

3.4. Calculation of formation compressibility and specific storage

In unconsolidated systems like the sedimentary aquifers of the southern VMD, grain compressibility can commonly be neglected as it is much smaller than bulk compressibility (Rau et al., 2022a), so the uniaxial loading efficiency γ (—) and the barometric efficiency BE (—) can be expressed with Eq. (9) when undrained conditions are considered for the hydraulic head oscillation at subdiel frequencies (1–2 cpd) (Acworth et al., 2016; Jacob, 1940; van der Kamp and Gale, 1983):

$$BE = 1 - \gamma = 1 - \frac{\alpha}{\theta \cdot \beta + \alpha} \quad (9)$$

α as the formation compressibility (Pa^{-1}), β as the water compressibility ($4.59 \cdot 10^{-10} \text{ Pa}^{-1}$ at 20°C for water) and θ (–) as the aquifer porosity. Consequently, once BE and θ have been defined, the compressibility α can be calculated. By considering α as the drained compressibility, the specific storage S_s can be calculated with Eq. (10) (Cooper, 1966; Acworth et al., 2016):

$$S_s = \rho_w g (\theta \cdot \beta + \alpha) \quad (10)$$

ρ_w as the water density (kg m^{-3}) and g as the gravity constant (m s^{-2}) and the assumption of incompressible grains.

Forced by harmonic drivers like Earth or atmospheric tides, a flow between the aquifer and well is induced, that can be used to derive subsurface parameters including the specific storage S_s (Rojstaczer, 1988; Bredehoeft, 1967; Hsieh et al., 1987). Analytic solutions for such groundwater flow problems have been derived for confined conditions (Hsieh et al., 1987) and semi-confined conditions (Rojstaczer, 1988) as a function of well and aquifer parameters, which can be calculated with the python package *HydroGeoSines* (HGS, 2023). The sign of M_2 phase shift $\Delta\phi_{M_2}$ (°) between Earth tides and groundwater heads bares information about the flow condition in the absence of borehole skin effects (Valois et al., 2022). For example, a positive M_2 phase shift is indicative of vertical flow as given in the presence of vertical drainage from an overlying aquitard. Conversely, a negative M_2 phase shift could indicate horizontal flow in and out of the well, suggesting fully or semi-confined conditions (Rojstaczer, 1988; Rau et al., 2020; Roeloffs et al., 1989; Xue et al., 2016; Valois et al., 2022). This differentiation, derived from considerations of Earth tides as single drivers for subsurface strains, is equally applicable regardless of the total volumetric strain's origin, i.e., the sum of Earth tide strains and OT_{SE} .

The compaction η (m) of a single confined aquifer can be calculated as the product of the aquifer thickness b (m), the compressibility α (Pa^{-1}), and the change in the effective intergranular stress $\Delta\sigma_z$ (Pa) (Gambolati and Teatini, 2021) to:

$$\eta = b \cdot \alpha \cdot \Delta\sigma_z \quad (11)$$

where $\Delta\sigma_z$ can be calculated from the piezometric decline of water level in the confined aquifer Δz (m) to:

$$\Delta\sigma_z = \rho_w \cdot g \cdot \Delta z \quad (12)$$

3.5. Identification of dominant drivers

For assessing the dominant drivers for the tidal signals in groundwater heads, the S_2 and M_2 amplitude values as well as the ratio of S_2 and M_2 amplitudes are considered. Given that the S_2 amplitude in atmospheric tides is commonly below 15 mm (Ray and Ponte, 2003) and the diurnal M_2 and S_2 amplitudes in groundwater responses to Earth tides are commonly in a range of maximum 10–20 mm (Bredehoeft, 1967), S_2 and M_2 amplitudes significantly beyond these ranges indicate the presence of additional drivers. In the presence of dominant ocean or river tide loading, the S_2 and M_2 amplitudes in groundwater heads are expected to exceed the aforementioned ranges and occur in a ratio close to that of the driver's amplitudes (Patton et al., 2021). If the groundwater heads are characterized by high S_2 and low M_2 amplitudes, ocean or river tides are unlikely to be the dominant drivers, indicating that other drivers are at play.

3.6. Summary of workflow and applied methods

The presented study utilizes time series of observed groundwater heads, computed subsurface strains due to Earth tides and ocean tide loading on the solid Earth (OT_{SE}), observed barometric pressure, inland river water levels, ocean water levels (derived from estuary river water

level observations) as well as groundwater extraction rates and pumping well water level dynamics, for comprehensive frequency analyses. The identified amplitude characteristics of groundwater observation wells are discussed as evidence for the presence of loading signals in groundwater head timeseries. The ratio of M_2 and S_2 amplitudes are used to identify groundwater head timeseries where ocean tides, river tides or groundwater extraction dominate the groundwater amplitude spectra. After a site-specific assessment of potential further forcings, the S_2 signal in groundwater is disentangled into its barometric-, Earth tide- and OT_{SE} -components at a selected groundwater monitoring site. Based on that, the elastic specific storage is derived and discussed as a proxy for elastic compaction, water storage and land rebound potential in the context of land subsidence mitigation measures. Fig. 3 presents a flow chart of the study's methodological approach.

4. Results

4.1. Tidal signals in groundwater and surface water levels

A regional frequency analysis of groundwater heads reveals the presence of distinct amplitudes at characteristic frequencies like S_2 and M_2 with varying intensity. Fig. 4 summarizes the FFT amplitude spectra annotated with HALS amplitudes of the regional frequency analysis, calculated with Eqs. (1)–(3). The analysis shows a good agreement between the HALS-based and FFT-based calculated S_2 and M_2 amplitudes. Note that individual tidal components surrounding 1.00 cpd are not attributed to a specific frequency (e.g., S_1 , P_1 and K_1) as they are too close to each other (Table 1) and a differentiation between these frequencies is not considered in this work.

The frequency analyses of recorded river water levels from Ganh Hao (Fig. 5a), Nam Can (Fig. 5b) and Song Doc (Fig. 5c) reveal distinct tidal signals at all three gauging stations with unique amplitude distributions. At Ganh Hao, the tidal regime is characterized by dominant semi-diurnal frequencies with an M_2 amplitude of 925 mm and a K_1 amplitude of 649 mm (Fig. 5a-III). In contrast, at Song Doc, the amplitude at the diurnal frequency K_1 is most pronounced with 226 mm, while the amplitude at the semi-diurnal frequency M_2 is with 111 mm lower (Fig. 5c-III). At Nam Can, the tidal regime is characterized by M_2 amplitudes of 603 mm and K_1 amplitudes of 455 mm (Fig. 5b-III).

Due to the superposition of two different ocean tide regimes from the East Sea and the Gulf of Thailand, Nam Can is characterized by a distinct and unique amplitude distribution which noticeably differs from Ganh Hao and Song Doc. For all three datasets, the HALS-based amplitudes (considering only the irregularly measured raw data) and the FFT-based amplitude spectra (considering the hourly interpolated data) show a good agreement, suggesting that the interpolation of gaps (Fig. 5a-II–c-II) represent the actual river water level dynamics well.

4.2. Characterizing the drivers of tidal signals in groundwater heads

In a preliminary assessment of the dominant drivers of the tidal signals in groundwater heads, the M_2 and S_2 amplitudes obtained from the HALS analyses are summarized in Fig. 6. This preliminary assessment indicates that the M_2 and S_2 amplitudes of the majority of wells are below 10 mm and thus comply with the range commonly found within impact of Earth tides of approximately maximum 10–20 mm (Bredehoeft, 1967) and atmospheric tides of approximately 15 mm (Ray and Ponte, 2003). However, the potential influence of river or ocean tides, as well as potentially periodic groundwater extraction patterns, cannot be excluded for those locations without a site-specific assessment of the local conditions. In contrast, the M_2 and S_2 amplitudes at the observation wells at the monitoring site Q199, as well as at two observation wells at the monitoring site Q177 and one monitoring well at IGPVN exceed the typical ranges of amplitude responses for Earth and atmospheric tides (Bredehoeft, 1967; Ray and Ponte, 2003), indicating the presence of additional tidal forcings.

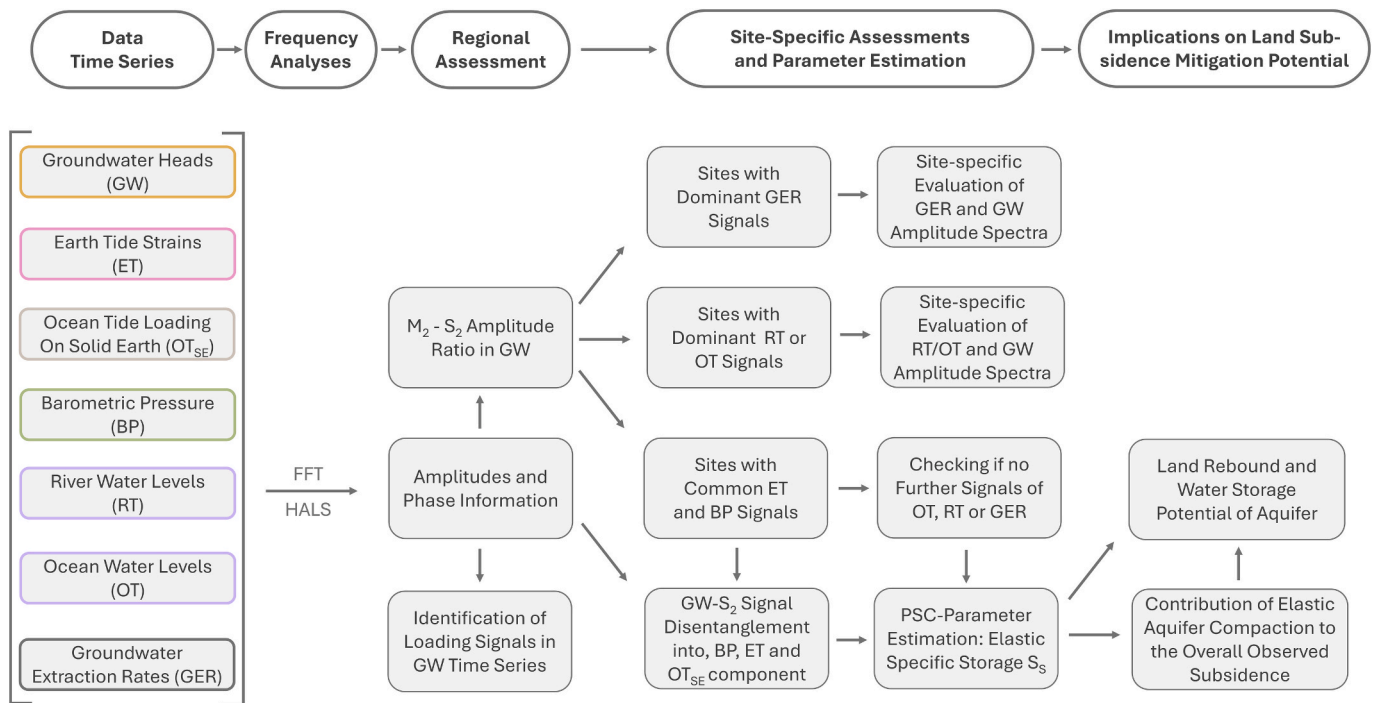


Fig. 3. Overview of the datasets and the workflow that was applied to evaluate and disentangle tidal loading signals and reveal geomechanical properties of the coastal groundwater system in the southern VMD.

At the monitoring sites Q177 and IGPVN some observation wells exhibit uncharacteristically high S_2 amplitudes, while the M_2 amplitudes do not exceed the typical response to Earth tides, indicating that an additional forcing without a M_2 frequency is at play. For those wells, a detailed assessment of the observed groundwater heads in the time domains reveals that the water level fluctuations are induced by periodic groundwater extraction patterns. Q177 is located in 475 m distance to a municipal water supply well (G22) screened in n_2^2 aquifer, which operates at scheduled intervals. Fig. 7d illustrates the evident correlation of groundwater head variations at Q177 in the n_2^2 aquifer and the groundwater extraction patterns from G22 (also from n_2^2 aquifer), characterized by a recovery of groundwater heads in the night, when the operation of the water supply wells is paused. It shall be noted here that the apparent lead of groundwater drawdown and recovery of 3 h compared to the extraction rates in Fig. 7d is considered to be due to a time offset in one of the two recorded datasets.

Fig. 7e visualizes the recorded groundwater heads in the pumping well G22 for the available four-weeks interval between December 2023 and January 2024 showing a drawdown of 4.0 m when the pumping well is operated. The FFT-amplitude spectra of the groundwater heads in the pumping well G22 and in the observation well at Q177 are visualized in Fig. 7f, showing a similar frequency response of both wells, characterized by amplitude peaks at harmonics of S_1 at multiples of 1.00 cpd.

Fig. 7b shows that for the observation well at Q177 in n_2^2 aquifer, in February and May 2018, the overall groundwater fluctuation magnitude drops from approximately 0.6 m–0.2 m. A similar temporal variation can be observed in qp_1 aquifer at Q177 (Fig. 7c), where between January and May 2022 the overall groundwater fluctuation magnitude is temporarily low and shows a sudden increase after May 2022. This incontinous magnitude in the well water level fluctuations at Q177 in qp_1 and n_2^2 indicate the presence of anthropogenic influence on the well water level fluctuations.

Similarly, the periodic groundwater head variations in the observation well IGPVN 1.2 (qp_1) can be considered to be induced by periodic groundwater extraction patterns of a local water supply well, which is located in 820 m distance, screened in qp_1 aquifer with a licensed pumping rate of $275 \text{ m}^3 \text{ d}^{-1}$ (Pechstein et al., 2018). Pechstein et al.

(2018) had concluded too, that groundwater extraction patterns are the drivers for the strong water level fluctuation in IGPVN 1.2, substantiated by an evaluation of water level variations during a short power blackout, when the water supply well's operation paused off schedule. The close-up visualization of IGPVN 1.2 (qp_1) in Fig. 10f-II underlines that the fluctuations of groundwater heads are caused by non-natural drivers, showing an irregular temporal variation which cannot be attributed to natural processes like Earth and atmospheric tide forcings.

The preliminary assessment of potential drivers (Fig. 6) suggests that ocean or river tide loading are dominant at Q199, given that both, M_2 and S_2 amplitudes exceed the range of common groundwater response to Earth or atmospheric tides. A site-specific analysis reveals that the monitoring site Q199 in Nam Can town is located in less than 100 m distance to the Cửa Lớn river (Fig. 8c). A comparison of the amplitude spectra of groundwater and river water levels (Fig. 8a and b) shows a clear correlation with an average ratio of 1:0.16 between water level amplitudes in the river and in the observation well (Fig. 8d).

4.3. Disentanglement of well water level responses to harmonic forcings

In a first step, the presence of OT_{GW} is assessed with Eq. (5) for the monitoring site IGPVN, considering the site's distance to the coast of $x = 15 \text{ km}$, as well as a hydraulic conductivity and specific storage of $1.1 \cdot 10^{-4} \text{ m s}^{-1}$ and $6.3 \cdot 10^{-6}$ respectively for the n_2^2 aquifer (Pechstein et al., 2018). A loading efficiency of $\gamma = 1$ is assumed, to calculate the maximum of expectable OT_{GW} under consideration of the aforementioned parameters. The ocean tide amplitudes (Fig. 9a) were derived from the amplitude spectrum at Song Doc (Fig. 5c-III), representing a good proxy for the ocean tides in the Gulf of Thailand due to its close vicinity to the coast and its good agreement with general tidal characterization of the Gulf of Thailand (Aungsakul et al., 2007; Cui et al., 2019).

Fig. 9b shows the damping of the three strongest ocean tide amplitudes at M_2 , K_1 and O_1 frequency, yielding in insignificant OT_{GW} amplitudes ($<0.01 \text{ mm}$) at 6.4 km inland and thus being negligible at IGPVN, located 15 km inland. On the contrary, OT_{SE} is not negligible at IGPVN with a volumetric strain amplitude of 2.0 nstr at M_2 (Fig. 10b-III

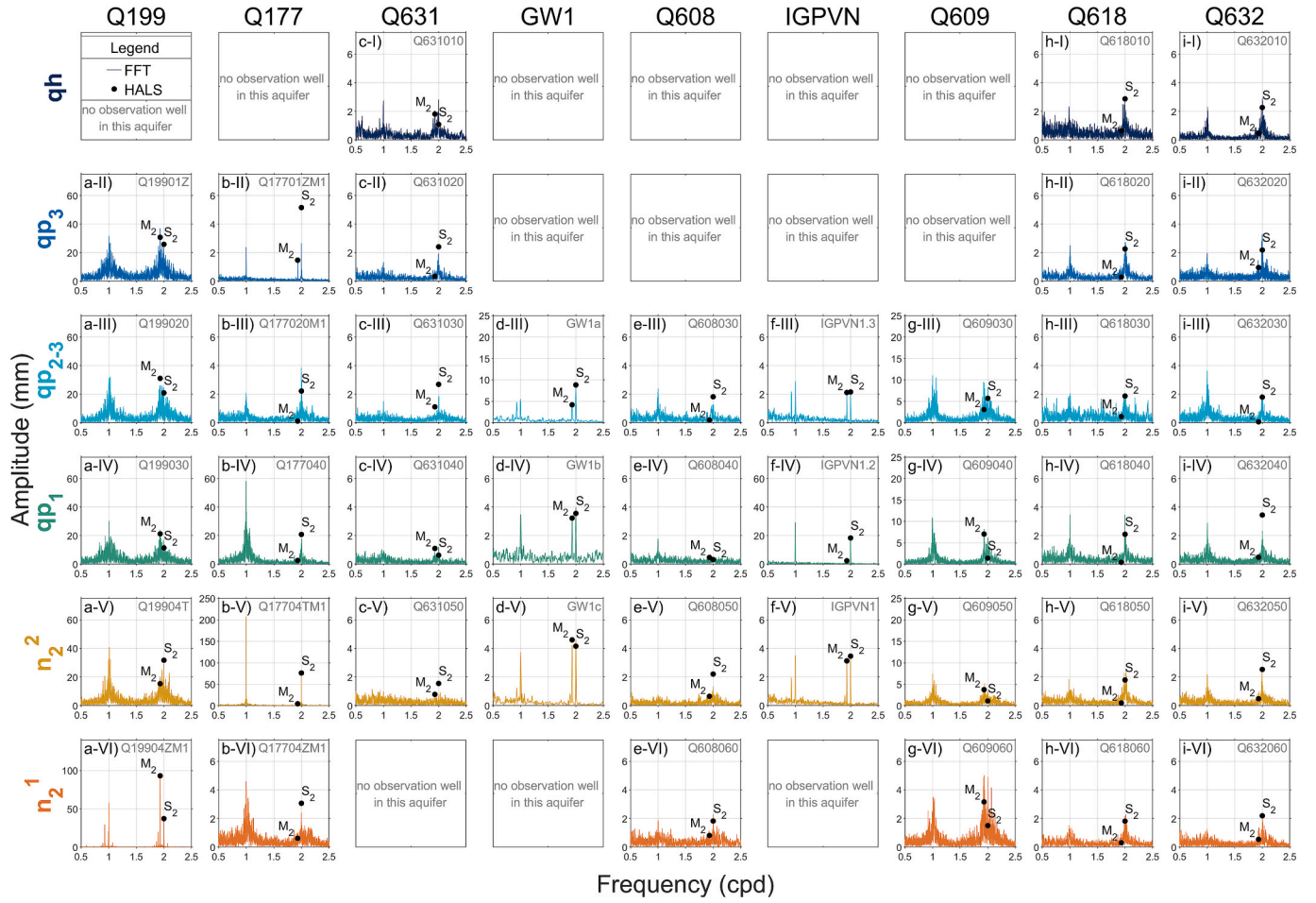


Fig. 4. Frequency analysis of 41 well water level time series in the southern VMD with FFT amplitude spectra (lines) and HALS amplitudes (calculated for the 10 frequencies listed in Table 1, displayed for M_2 and S_2 frequency as dots). The location of the nine multi-depth monitoring sites is shown in Fig. 1. It should be noted that the visualization encompasses distinct y-axis categories, namely 7.5 mm, 25 mm, 75 mm, 125 mm and 250 mm.

and b-IV). For IGPVN, no water level data of rivers or channels in the vicinity is available. Given that the site is located at the border of the freshwater area of U-Minh and the nearby channels are protected from saltwater intrusion and tidal propagation by sluice gates (Fig. 1), river tides are considered as negligible drivers for groundwater heads at IGPVN in this study.

All analyzed data are presented in Fig. 10a-I–i-I, comprising volumetric Earth tide strains (Fig. 10a-I), volumetric strains due to OT_{SE} (Fig. 10b-I), barometric pressure (Fig. 10d-I) and groundwater heads in five observation wells, screened in three aquifers (Fig. 10e-I–i-I). A close-up visualization of the data for a 12-day period in Fig. 10a-II–i-II illustrates the periodic character of each dataset. From a comparison of the measured groundwater heads in the three aquifers (Fig. 10e-II–i-II) no significant effect of the periodic groundwater extraction from qp_1 can be inferred in the adjacent aquifers. Fig. 10a-III–i-III and a-IV–g-IV illustrate the amplitude spectra for 2018 (with non-vented PTs) and 2023 (with vented PTs), both periods are marked in grey in Fig. 10a-I–i-I.

The calculated M_2 amplitudes and phases of the individual volumetric strains due to Earth tides and OT_{SE} as well as their sum are visualized in Fig. 11. The additional consideration of OT_{SE} yields in an increase of the total volumetric strain amplitude at M_2 from 17.0 nstr to 18.6 nstr and a phase shift of 3.6° compared to a consideration of Earth tide strains only.

4.4. Estimation of specific storage and compressibility

For the calculation of the barometric efficiency BE , atmospheric tides

were disentangled from Earth and ocean tides with Eq. (7) for the monitoring site IGPVN. $A_{S_2}^r$ was calculated to $A_{S_2}^r > 0.99$ for all assessed well water level time series, indicating an insignificant difference between well water levels and pore pressure heads in the surrounding aquifer. The calculated barometric efficiency for the non-vented and vented dataset of observation wells yields in consistent results with $BE = 0.19 \pm 0.02$ in n_2^2 aquifer. Calculation results for the observation well in qp_{2-3} vary between $BE = 0.12$ and $BE = 0.19$ for the assessed periods of 2018 (non-vented) and 2023 (vented).

In 2023, the phase shift between $BE_{S_2}^{AT}$ in qp_{2-3} aquifer and the atmospheric driver is with 17° (Fig. 12b-II) significantly greater than the respective phase shift in all four assessed observation wells in 2018 (Fig. 12b-I). For the observation well in qp_1 , $BE_{S_2}^{AT}$ was not calculated, given that the S_2 amplitude in groundwater heads is distorted significantly by anthropogenic groundwater extraction patterns (Fig. 7). The calculated barometric efficiency $BE_{S_2}^{AT}$ is summarized in Table 2, alongside with the M_2 amplitude response to Earth tide strains and OT_{SE} (denoted as A_{M_2}) and the respective phase shift $\Delta\phi_{M_2}$. In Fig. 12 the results are visualized as polar plots.

The M_2 amplitude responses to volumetric strains reveal a variation of 6 % ($\Delta = 0.006$ mm/nstr) at IGPVN 1.3 (qp_{2-3}), 13 % ($\Delta = 0.014$ mm/nstr) at IGPVN 1.2 (qp_1) and 3 % ($\Delta = 0.004$ mm/nstr) at IGPVN 1 (n_2^2) between the vented and non-vented periods, 2018 and 2023. For the calculated BE , the variation between the vented and non-vented dataset is 7 % ($\Delta = 0.014$ mm/mm) at IGPVN 1. Given the uncharacteristically high S_2 phase shift of 17° (Fig. 12b-II), the calculated BE at IGPVN 1.3 is

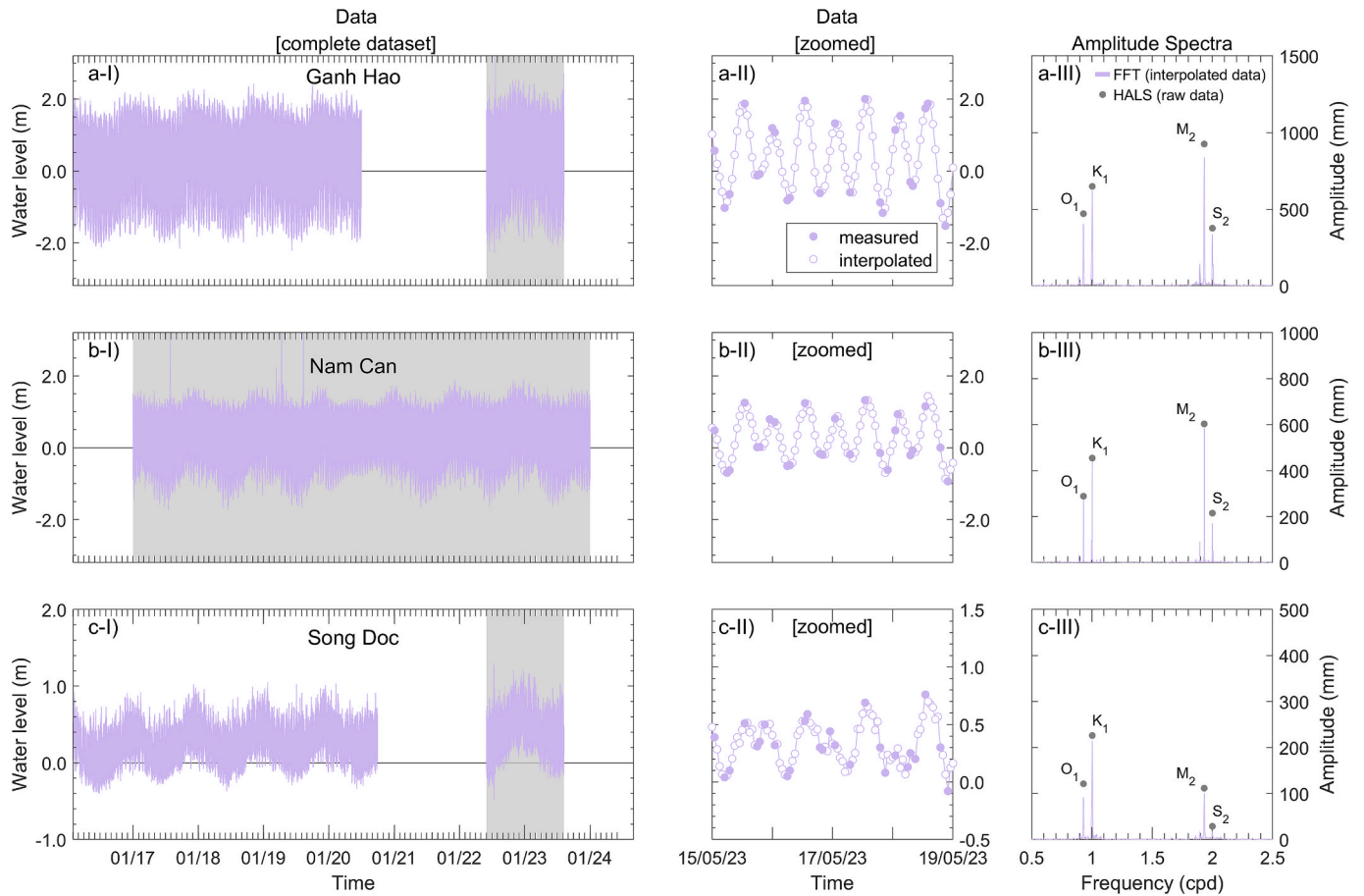


Fig. 5. Frequency analysis of river water levels at Ganh Hao (a), Nam Can (b) and Song Doc (c), including a visualization of the measured river water levels between 2016 and 2024 (I), a close-up visualization of a 4-day period (II), FFT amplitude spectra (lines), and HALS amplitudes (calculated for the 10 frequencies listed in Table 1, displayed for O_1 , K_1 , M_2 and S_2 frequency as dots) (III). The time periods used for the frequency analyses are highlighted in grey in (I) and were chosen according to the gaps and measurement frequencies in the datasets.

considered to be afflicted by the periodic groundwater extraction patterns in qp_1 and therefore not representative for a comparison. The calculation results indicate a positive M_2 phase shift of 0.9° for IGPVN 1.2 in qp_1 for 2023 (vented) while it was negative in 2018 (non-vented) (Fig. 12a-I and a-II).

The calculated M_2 phase shift between groundwater heads and volumetric strains due to Earth tides and OT_{SE} is negative in $qp_{2,3}$ and n_2^2 aquifer, indicating horizontal flow between well and aquifer to be dominant. For such flow conditions, the analytical solution of Hsieh et al. (1987) can be applied to calculate the specific storage S_s from well water level responses to volumetric strains without a requirement of a priori information on porosity. This method was applied as implemented in *HydroGeoSines* (HGS, 2023).

At IGPVN, the porosity in $qp_{2,3}$ and n_2^2 aquifer was determined to $\theta = 0.33$ for both aquifers based on grain size analysis in previous studies (Pechstein et al., 2018). The availability of porosity data allows an alternative calculation of α and S_s based on BE with Eqs. (9) and (10). The calculation results for S_s after Hsieh et al. (1987) are summarized in Table 3 alongside the calculation results of S_s based on BE with Eqs. (9) and (10). The difference in the S_s estimates of these two passive methods is small (Table 3). More importantly, the results of both passive methods ($5.9\text{--}7.8 \cdot 10^{-6} \text{ m}^{-1}$) comply well with S_s estimates from a pumping test conducted independently in the n_2^2 aquifer ($6.3 \cdot 10^{-6} \text{ m}^{-1}$, refer to Pechstein et al., 2018). While no hydraulic test was available for the $qp_{2,3}$ aquifer, the results comply well with regional aquifer parametrization of the study area (DWRPIS, 2010; Pechstein et al., 2018).

From the results in Table 3, the elastic compressibility can be

calculated with Eq. (10) as $\alpha = 6.4\text{--}7.5 \cdot 10^{-10} \text{ Pa}^{-1}$ in $qp_{2,3}$ and $\alpha = 4.5\text{--}6.4 \cdot 10^{-10} \text{ Pa}^{-1}$ in n_2^2 aquifer. With thicknesses of $b = 41 \text{ m}$ of each aquifer (Pechstein et al., 2018), an elastic compaction (rebound) η of $0.18\text{--}0.30 \text{ mm}$ per depletion (recovery) of hydraulic head $\Delta z = 1 \text{ m}$ can be derived for the two considered aquifers from Eqs. (11) and (12).

5. Discussion

5.1. Identification of tidal signals and loading imprints

As shown in the regional frequency analysis presented in Figs. 4 and 6, the groundwater heads in all assessed observation wells in the southern VMD respond to natural forcings, i.e. at M_2 and S_2 frequencies. In the study area, these tidal signals can be attributed to ubiquitous signals of atmospheric loading and Earth tide strains as well as site-specific conditions, such as river tides (Fig. 8), ocean tides (Fig. 11) and periodic groundwater extraction patterns (Fig. 7). The identification of harmonic signals in groundwater heads at S_2 and M_2 frequencies provides compelling evidence that the assessed aquifers in the southern VMD respond to external loading. This finding is not limited to the frequency domain but is evident in the time domain as well, providing a scientific framework for the conclusions of Hoang and Steinel (2021) who attribute temporarily rising groundwater heads at IGPVN during the rainy season to loading effects rather than to groundwater recharge by the means of water volume fluxes into the aquifers. However, to evaluate this specific hypothesis, further studies on seasonal surface loading dynamics are necessary.

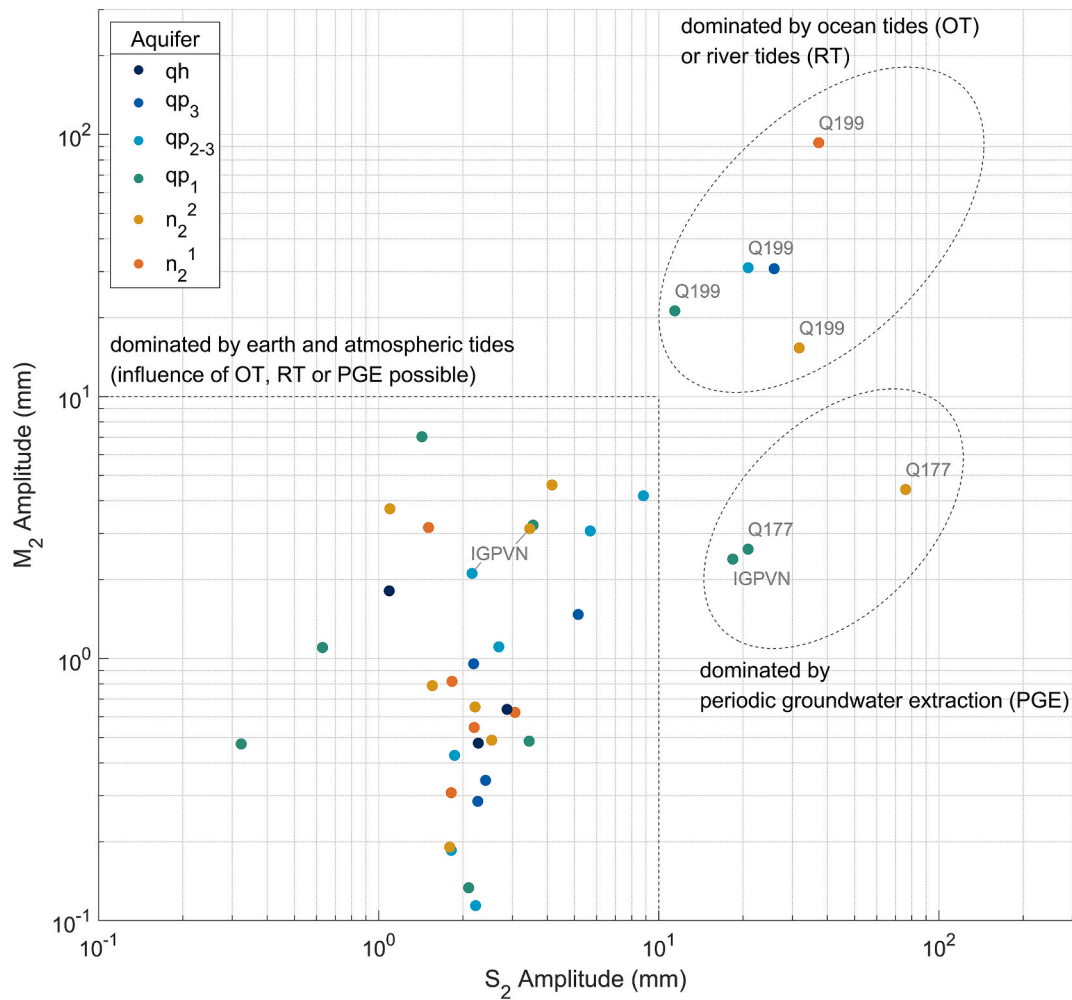


Fig. 6. Preliminary assessment of potential drivers of tidal signals in groundwater heads by a comparison of value and ratio of S_2 and M_2 amplitudes from HALS frequency analyses of 41 observation wells in six different aquifers in the southern VMD.

While the presence of loading signal imprints in groundwater heads is a common feature for confined aquifers (Bredehoeft, 1967), to the authors' best knowledge they have not yet been comprehensively described in the southern VMD. Therefore, the presented study establishes a valuable basis for further research on hydro-geomechanically coupled process dynamics in the study area. By this, the study promotes integrated considerations of hydrogeological and geomechanical problems, of which the observed land subsidence due to groundwater depletion itself is the most prominent example in the study area. In addition, the findings provide a novel perspective on previous studies in the VMD (Duy et al., 2021), which found correlations between ground and surface water levels, without exploring the nature and process dynamics causing the identified correlation.

The southern VMD is a unique study area for PSC-applications in the context of land subsidence due to its complex network of tidally influenced surface water bodies, extensive groundwater extraction and the presence of two distinct ocean tide regimes (Fig. 5). In addition, due to extensive and accelerating land subsidence rates in the low-lying delta, there is an urgent need for hydro-geomechanical subsurface characterization to develop mitigation strategies. If the multiple superposing drivers are carefully disentangled as proposed in this study, the southern VMD and other deltaic groundwater systems bare a high potential to utilize the various tidal forcings for hydro-geomechanical parameter estimations.

5.2. Revelation of multiple influences on groundwater heads

The analyses show that amplitude spectra of groundwater heads can be affected by periodic groundwater extraction patterns (Fig. 7). Demand-oriented operation of municipal water supply wells at scheduled intervals are non-sinusoidal but can leak into FFT-amplitude spectra (Fig. 7f, lines in Fig. 4b-V) at harmonics, i.e., multiples of S_1 and S_2 , as well as into HALS-based amplitude characterizations, e.g. at S_2 (dot in Fig. 4b-V). Given that these frequencies are commonly used in PSC, this novel finding highlights the need for careful site-specific analysis prior to PSC applications in densely populated regions with high freshwater demands, such as coastal plains and deltaic lowlands. In the VMD, where up to half a million licensed and unlicensed wells extract groundwater with significant spatiotemporal variability (Danh and Khai, 2015), the potential influence of groundwater extraction patterns on tidal groundwater heads must be carefully considered. Recent applications of time-domain PSC methods have anticipated the effects of groundwater extraction on tidal constituents in groundwater heads (Haehnel et al., 2024). However, to the best of the authors' knowledge, the impact of groundwater extraction patterns on PSC has not yet been demonstrated using actual observational data.

The presented novel approach illustrates that integrating OT_{SE} into PSC enhances the application of PSC in coastal groundwater systems and deltaic lowlands. Here, the consideration of OT_{SE} results in a 10 % increase of volumetric strain from 17.0 nstr to 18.6 nstr and a M_2 phase shift of 3.6° compared to the consideration of only Earth tide strains at

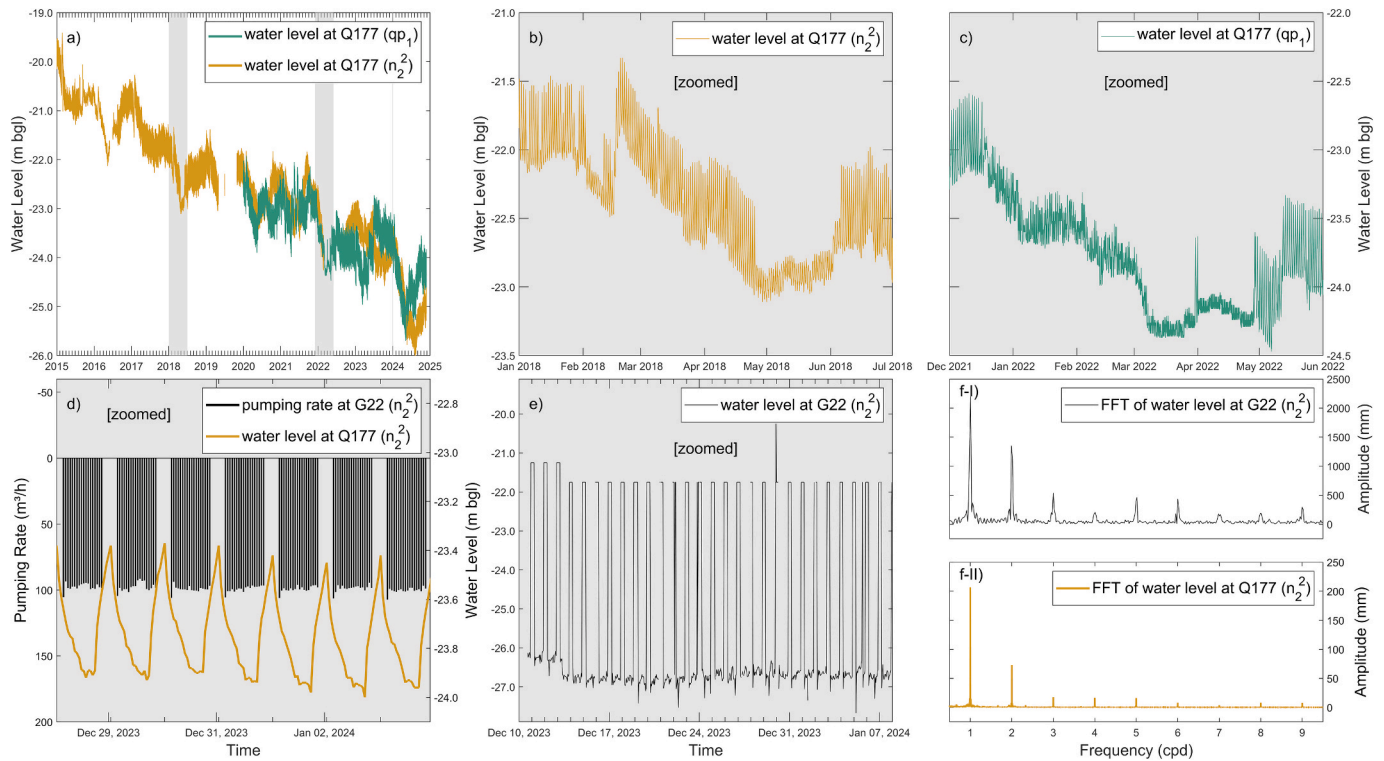


Fig. 7. Groundwater heads in qp_1 and n_2^2 aquifers from 2015 to 2024 at monitoring station Q177 (a), close-up visualization for January to July 2018 in n_2^2 (b) and for December 2021 to May 2022 in qp_1 (c), pumping rates of the water supply well G22 in n_2^2 and groundwater head variations at Q177 in n_2^2 (d), water level dynamics of the pumping well G22 (e) and FFT-amplitude spectra of groundwater heads at G22 (I) and Q177 (II) in n_2^2 aquifer (f).

IGPVN in 15 km distance to the coast (Fig. 11). When OT_{SE} is considered, the phase shift between vented groundwater head records and volumetric strains was determined to be positive in qp_1 aquifer in 2023 (0.9° , Table 2). Given that positive phase shifts are associated with vertical flow in confined systems without borehole skin effects (Valois et al., 2022), this may indicate the presence of aquitard drainage, which is a key process in land subsidence caused by groundwater depletion (Gambolati and Teatini, 2021).

Groundwater pumping for municipal water supply in qp_1 at a distance of 820 m from the observation well could lead to drainage from the adjacent aquitards into the pumped aquifer qp_1 providing a realistic scenario at the investigated study site. The identification of vertical flow using PSC complies with results obtained from a conventional pumping test, characterizing the intermittent aquitard between qp_1 and n_2^2 as leaky at IGPVN (Pechstein et al., 2018).

The study illustrates that careful disentanglement of multiple drivers of tidal signals in groundwater heads is required in regions with multiple tidal forcings. The harmonic forcings of tidally influenced rivers in close vicinity to wells can significantly exceed Earth and atmospheric tidal forcings (Fig. 6), leading to imprints in aquifers at depths exceeding 300 m (Fig. 8). Fig. 8d shows that the groundwater head response at the two major diurnal frequencies K_1 and O_1 is weaker (shifted to the left from the dashed line) compared to responses to the semi-diurnal frequencies M_2 and S_2 , which is in line with the known frequency dependency of amplitude damping (Valois et al., 2022). In such settings, where harmonic forcings act on the surface and propagate downwards into the subsurface sediments, a vertically differentiated evaluation of the aquitard hydraulic diffusivity would be possible using an assessment of phase and amplitude difference in the adjacent aquifers (Boldt-Leppin and Hendry, 2003; Larroque et al., 2013).

The aquitard hydraulic diffusivity is equivalent to the consolidation coefficient c_v , a term more commonly used in geomechanical research, describing the delayed compaction response of an aquitard (Gambolati and Teatini, 2021) and is relevant and useful in the context of land

subsidence analysis. However, unlike the tidal signals in n_2^1 aquifer (Fig. 4a-VI), the amplitude spectra from the aquifers qp_3 , qp_{2-3} , qp_1 and n_2^2 (Fig. 4a-II–a-V) are characterized by a much less precise frequency representation of the river's tidal constituents (Fig. 8a). The cause for the blurred frequency representation (Fig. 4a-II–a-V) needs to be further evaluated before the aquitard hydraulic diffusivity can be assessed using amplitude damping and phase shift. This should include a careful consideration of potential timing errors due to clock drift (Rau et al., 2019).

The novel integration of ocean tide loading on the solid Earth in quantitative PSC parameter estimations enhances the application of such passive methods in near-coastal settings such as deltaic aquifer systems.

5.3. Implications for land subsidence mitigation potential

Given the elastic nature of the tidal forcings at play (Bredehoeft, 1967) it is not possible to quantify inelastic parameters using currently available PSC methods. The differentiation between elastic and inelastic stress regimes as well as the transition between these two end-member conditions is of great importance in land subsidence analyses because (i) unlike elastic deformations inelastic deformations are irreversible (Riley, 1969), and (ii) inelastic deformations can be up to 10–100 times greater than elastic deformation for common aquitard sediments (Riley, 1969; Pavelko, 2004). However, benchmark studies on land subsidence due to groundwater depletion in the VMD (Minderhoud et al., 2017) employ lower ratios between inelastic and elastic compressibility of 5:1 for clay aquitards and 3:1 for sandy aquifers, referring to geotechnical studies in the VMD (Toan and Nu, 2013; Thoang and Giao, 2015). This parameterization indicates that one third of the inelastic aquifer compaction would be reversible, thereby emphasizing the importance of investigating elastic aquifer parameters. This is substantiated by estimations of the overconsolidation ratio OCR to approximately 1.6 (Minderhoud et al., 2017) based on a calibrated subsidence model and

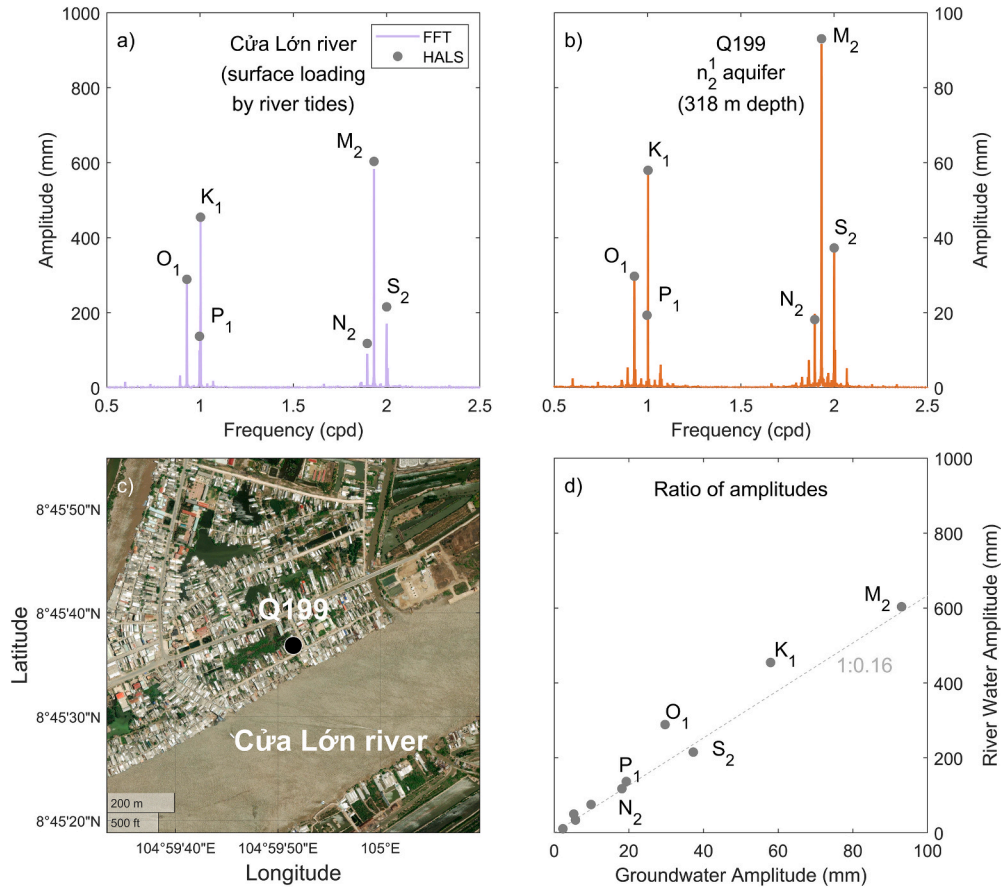


Fig. 8. FFT amplitude spectra (lines) and HALS amplitudes (calculated for the 10 frequencies listed in Table 1, displayed for O₁, K₁, P₁, N₂, M₂ and S₂ frequency as dots) of water levels of the CỬA LỚN river in Nam Can (a) and of groundwater heads in n₂¹ aquifer at monitoring site Q199 (b), satellite image (Esri, 2024) illustrating the location of the groundwater monitoring site and its close distance to the CỬA LỚN river (c), ratio of the HALS amplitudes in groundwater and river water levels of the CỬA LỚN river and n₂¹ aquifer at Q199 (d).

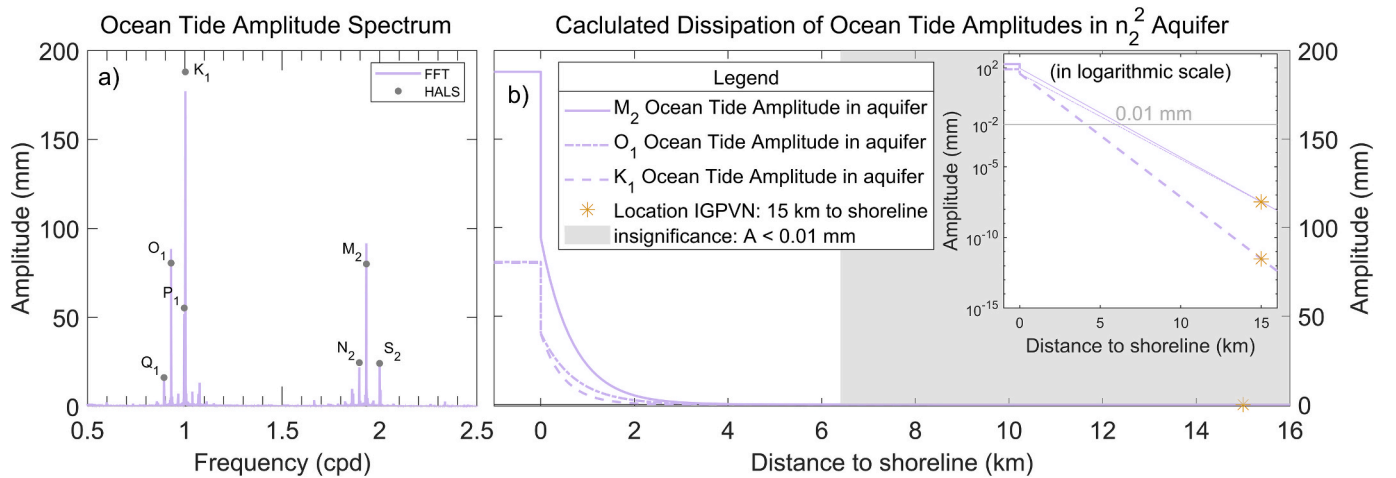


Fig. 9. FFT amplitude spectrum (lines) and HALS amplitudes (calculated for the 10 frequencies listed in Table 1, displayed for Q₁, O₁, K₁, P₁, N₂, M₂ and S₂ frequency as dots) of ocean tides in the Gulf of Thailand, derived from the amplitude spectrum of river water levels at Song Doc (a), calculated amplitude damping of M₂, O₁ and K₁ frequency due to OT_{GW} from the coast towards the inland (b).

the consideration of various geotechnical analyses (Hoang et al., 2016; Thoang and Giao, 2015). Given that $OCR > 1$ is indicative for sediments which have historically experienced stress beyond the current stress, this implies the presence of elastic deformation regimes (Hoffmann et al., 2003).

In the presented study, the elastic specific storage was derived at a

selected monitoring site in the southern VMD for qp₂₋₃ and n₂² aquifer by two independent PSC methods, i.e., (i) well water level responses to S₂ atmospheric tides ($BE_{S_2}^{AT}$), and (ii) well water level responses to M₂ Earth and ocean tide strains. Both methods deliver consistent results with values between $5.9 \cdot 10^{-6}$ and $8.8 \cdot 10^{-6}$ (m⁻¹) (Table 3). For the n₂² aquifer, the S₃ estimates from passive methods are verified by

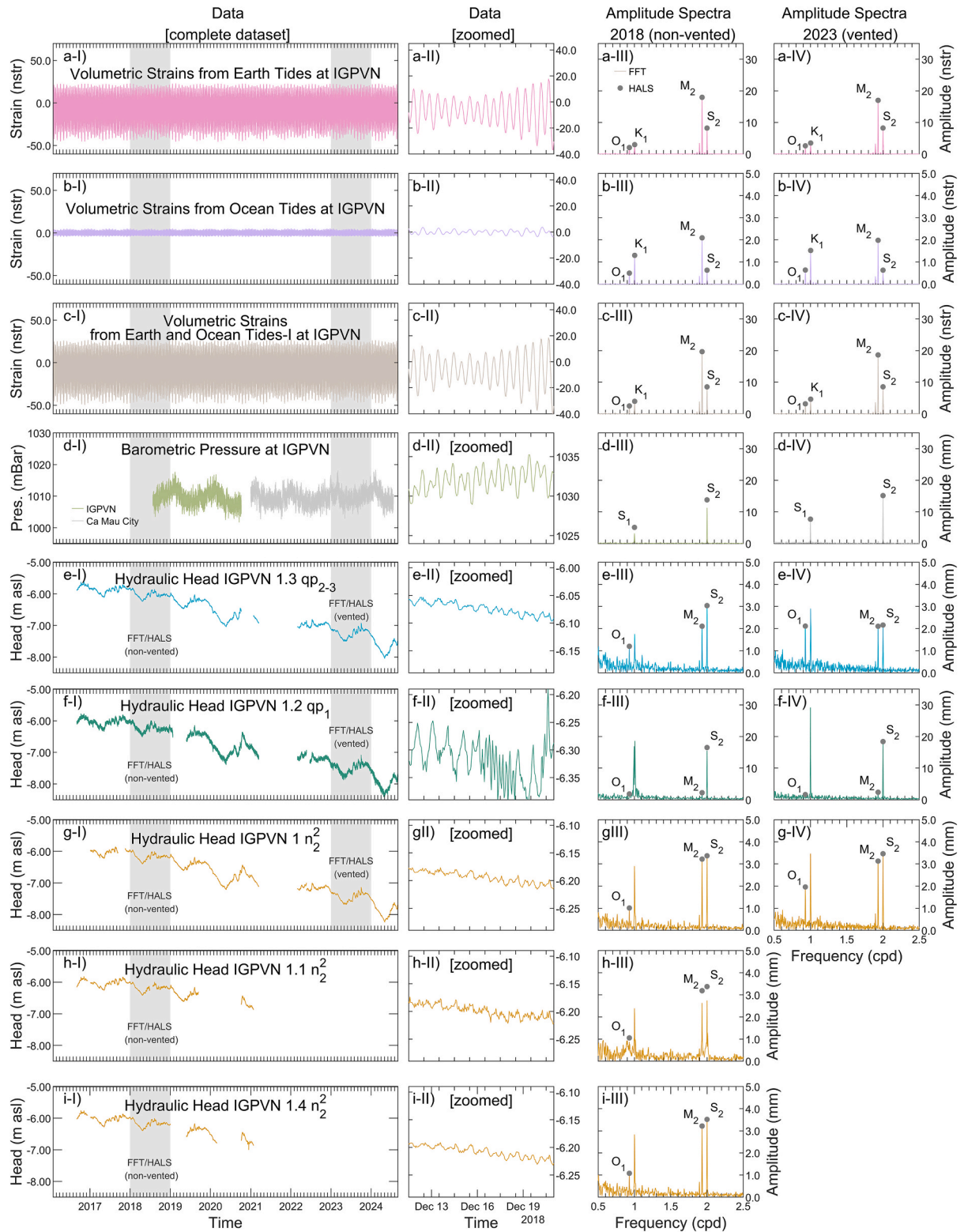


Fig. 10. Employed data (I and II) for the frequency analysis at IGPVN and the resulting FFT amplitude spectrum (lines) and HALS amplitudes (calculated for the 10 frequencies listed in Table 1, displayed for O_1 , K_1 , S_1 , M_2 and S_2 frequency as dots) for 2018 (III) and 2023 (IV), for volumetric Earth tide strains (a) ocean tide strains (b), the sum of Earth and ocean tide strains (c), barometric pressure (d), groundwater heads in the aquifers qp_{2-3} (e), qp_1 (f) and n_2^2 (g–i).

independently conducted pumping test results of $6.3 \cdot 10^{-6} \text{ m}^{-1}$ (Pechstein et al., 2018). The derived parameter values are at the lower end of common parameter ranges for aquifers (Domenico and Mifflin, 1965; Rau et al., 2018) and therefore indicate a minimum elastic groundwater storage capacity of the two investigated aquifers. On a

regional scale, previous studies derived average parameter values for the storage coefficient S in the n_2^2 aquifer of $1.07 \cdot 10^{-4}$ (–) and an average aquifer thickness of 47.6 m (DWRPIS, 2010; Pechstein et al., 2018). From this, an average specific storage S_s of $2.3 \cdot 10^{-6} \text{ m}^{-1}$ can be derived, confirming the order of magnitude of the S_s parameter range

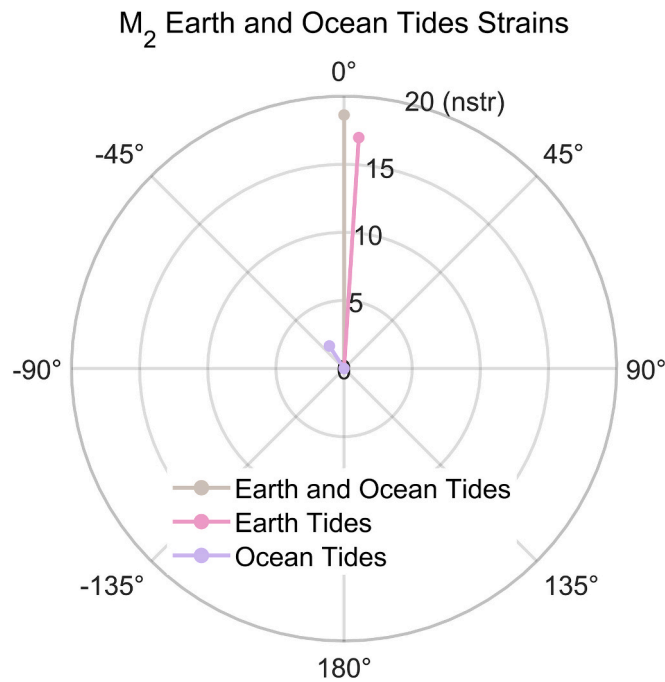


Fig. 11. Polar plot showing M_2 amplitude and phase of volumetric strains due to Earth tides $\hat{z}_{M_2}^{ET}$ and due to OT_{SE} $\hat{z}_{M_2}^{OT_{SE}}$ as well as their sum $\hat{z}_{S_2}^{(ET+OT_{SE})}$ at IGPVN, the phase is referenced to the phase of $\hat{z}_{S_2}^{(ET+OT_{SE})}$.

between $5.9 \cdot 10^{-6}$ and $7.8 \cdot 10^{-6} \text{ m}^{-1}$ derived in this study by various passive methods.

The introduction of PSC methods for the estimation of the elastic specific storage is particularly beneficial for the study area, given that the degree of accuracy for S_s -estimates is often below that for transmissivity in pumping tests (Kruseman et al., 1994), particularly in single-well pumping tests. Although the NGMN multi-depth groundwater monitoring sites provide a valuable depth-differentiated dataset in the study area, at most sites each aquifer is only monitored by a single well. In contrast to single-well pumping tests, the deployment of multiple observation wells in one aquifer enhances the reliability of pumping test results (Kruseman et al., 1994), making the parameters derived from pumping test in n_2^2 aquifer at IGPVN a valuable reference for comparison with PSC derived parameters. The good agreement between PSC-based and pumping test-based S_s calculations in n_2^2 at IGPVN demonstrates the usefulness of applying PSC to derive S_s estimations in the southern VMD and other deltaic groundwater bodies.

With the available information of aquifer porosity and thickness, the elastic compaction (and rebound) for $qp_{2.3}$ and n_2^2 aquifer at IGPVN were estimated with $\alpha = 4.5\text{--}6.4 \cdot 10^{-10} \text{ Pa}^{-1}$ to 0.18–0.30 mm per meter decline (and recovery) of water level in the confined aquifer. However, observed land subsidence rates are of several mm a^{-1} (Dörr et al., 2024) for a measured groundwater depletion rate of 0.25 m a^{-1} (Hoang and Steinel, 2021). This indicates that the elastic aquifer compaction derived for these two aquifers does not contribute significantly to the observed land subsidence rates. This finding does by no means legitimize a risk-free continuation of groundwater extraction in $qp_{2.3}$ and n_2^2 aquifer, especially given that a significant part of compaction can be expected to occur in the adjacent aquitards rather than the aquifer (Gambolati and Teatini, 2021).

Governmental circulars and decrees (Circular No. 42/2015/TT-BTNMT, Decree 53/2024/ND-CP, Circular 03/2024/ TT-BTNMT) consider MAR as a potential mitigation measure for land subsidence in the VMD. In general, the injection of water into confined aquifers may prove an efficacious land subsidence mitigation measure in two ways, namely (i) seasonal storage of surplus water resources (Seidl et al., 2024)

and (ii) repressurizing of groundwater heads (Gambolati and Teatini, 2021). A seasonal storage of surplus freshwater would reduce the annual net groundwater withdrawal and consequently also the depletion of groundwater heads and associated land subsidence. With large volumes of fresh surface water from the Mekong River and high precipitation rates during the monsoon season, significant freshwater quantities are available in the VMD on an annual basis. However, without sufficient storage capacities in the flat topography, this freshwater cannot be retained for the dry season, leading to substitution sourced from groundwater (Wagner et al., 2012).

Given that truly confined aquifers may only receive surplus water by a deformation of the matrix skeleton or the pore water (Bouwer, 2002), a process inherently contained in the definition of the specific storage S_s (Jacob, 1940), the low estimated specific storage of $<9 \cdot 10^{-6} \text{ m}^{-1}$ suggests that the considered aquifers are unsuitable for a seasonal freshwater storage based on pressurized water injection.

In addition to the reduction of net annual groundwater withdrawal, MAR can counteract land subsidence by repressurizing targeted confined aquifers (Gambolati and Teatini, 2021) with hydraulic impact zones exceeding the extent of storage zones (Dillon et al., 2009). Based on the estimations of elastic compressibility, the land rebound capability of the two investigated aquifer sediments due to a recovery of groundwater heads is in a range of $<3 \text{ mm}$ for a 10 m groundwater head increase and therefore insignificant. This emphasizes the urgency to minimize further groundwater depletion to prevent further inelastic land subsidence.

To evaluate the overall rebound capability in the southern VMD, it is essential to characterize shallow aquifer and aquitard sediments. This is particularly important because younger and shallow sediments are generally less consolidated, as indicated by the region's sedimentation history (Zoccarato et al., 2018).

While the presented study focuses on the estimation of elastic aquifer parameters, further research on PSC-based determination of aquitard parameters would be valuable for subsidence-related applications. While recent studies developed analytical solutions to derive the aquitard compressibility from groundwater responses to Earth tides (Valois et al., 2024), the solution's non-uniqueness challenges the estimation of reliable parameter values. Moreover, further investigations that aim to differentiate between elastic and inelastic contributions to land subsidence from groundwater depletion in the southern VMD are required, such as depth-differentiated multi-extensometer compaction monitoring (Dörr et al., 2023).

Given that approximately 25 % of the world's population lives on deltaic lowlands (Tamura et al., 2012) and approximately two billion inhabitants live in areas exposed to potential subsidence (Davydzenka et al., 2024), the presented approach has the potential to be applied in many highly populated coastal plains and deltaic lowlands all around the globe to inform more sustainable groundwater management.

6. Conclusions

The study proves that PSC-methods are valuable tools in the assessment of an aquifer's land subsidence mitigation potential. Imprints of tidal signals in groundwater heads (i.e., as measured using well water levels) carry valuable information about elastic geomechanical subsurface properties and process dynamics and can therefore be used to gain insights of significant relevance for the assessment of land subsidence mitigation potential. The specific storage S_s is a key parameter for an aquifer's land subsidence mitigation potential, as it incorporates the aquifer's elastic deformation characteristics. Therefore, S_s estimates provide relevant information on two key concepts in land subsidence mitigation strategies, (i) an aquifer's land rebound potential and (ii) its capability to temporarily receive and store surplus water resources. Due to the complex interplay of multiple tidal forcings, the application of previously available PSC-based parameter estimation methods for S_s was limited in coastal groundwater and subsiding deltaic aquifer systems.

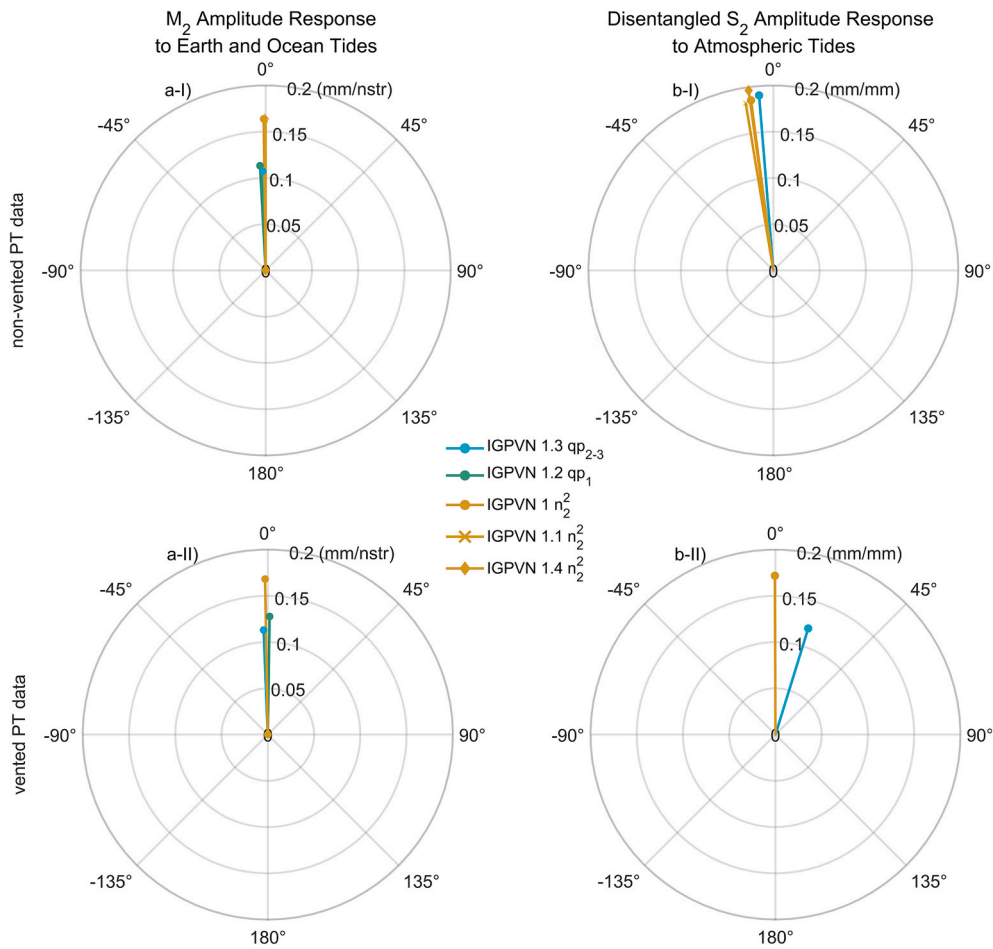


Fig. 12. Polar plots showing amplitude responses to M_2 volumetric strains due to Earth tides and OT_{SE} (a) amplitude response to S_2 atmospheric tides at IGPVN site based on groundwater observation data with non-vented PTs from 2018 (I) and with vented PTs from 2023 (II). It shall be noted that in a-I and b-I, the values for IGPVN 1.1, IGPVN 1.4 and IGPVN 1 are plotted but differ little to insignificantly from each other.

Table 2

Barometric efficiency based on S_2 responses to atmospheric tides $BE_{S_2}^{AT}$ as well as M_2 amplitude response A_{M_2} and phase shift $\Delta\phi_{M_2}$ for wells at the IGPVN site with disentangled Earth and ocean tide influence (calculated values without consideration of ocean tides are additionally displayed in brackets).

	PT	IGPVN 1.3 [qp ₂₋₃]	IGPVN 1.2 [qp ₁]	IGPVN 1 [n ₂ ²]	IGPVN 1.1 [n ₂ ²]	IGPVN 1.4 [n ₂ ²]
$BE_{S_2}^{AT}$	Non-vented	0.19 (0.19)	–	0.19 (0.18)	0.18 (0.18)	0.20 (0.19)
	vented	0.12 (0.12)	–	0.17 (0.17)		
$\Delta\phi_{M_2}$	Non-vented	–1.7 (–5.3)	–3.1 (–6.7)	–0.8 (–4.4)	–0.1 (–3.7)	–0.3 (–4.0)
	vented	–2.3 (–5.9)	+0.9 (–2.8)	–1.0 (–4.6)		
A_{M_2}	Non-vented	0.11 (0.12)	0.11 (0.12)	0.16 (0.18)	0.16 (0.18)	0.16 (0.18)
	vented	0.11 (0.12)	0.13 (0.14)	0.17 (0.18)		

This study demonstrates how to quantitatively disentangle tidal signals in groundwater heads in deltaic aquifer systems, revealing enhanced understanding of subsurface processes and properties in Vietnam's southern Mekong Delta, where loading signals in groundwater heads have not been adequately analyzed before. The findings

Table 3

Specific storage at IGPVN derived from PSC and pumping test data.

	BE	θ	S_s (m ^{–1}) Earth Tide (Hsieh et al., 1987)	S_s (m ^{–1}) Atmospheric Tides Eqs. (9) and (10)	S_s (m ^{–1}) Pumping Tests (Pechstein et al., 2018)
IGPVN 1.3 [qp ₂₋₃]	0.19	0.33	$8.8 \cdot 10^{-6}$	$7.8 \cdot 10^{-6}$	–
IGPVN 1 [n ₂ ²]	0.19	0.33	$5.9 \cdot 10^{-6}$	$7.8 \cdot 10^{-6}$	$6.3 \cdot 10^{-6}$

underscore that further groundwater depletion must be avoided in the Mekong Delta to prevent further irreversible sediment compaction and subsidence. The study emphasizes that PSC-parameter estimations require a careful analysis of local conditions, including groundwater pumping activities, which may corrupt quantitative assessments by leaking into amplitude spectra. Overall, the presented integration of ocean tide loading on the solid Earth enables PSC-parameter estimations in coastal hydrogeological environments.

The presented study is limited to the quantification of elastic aquifer properties. Further research is required to quantify inelastic aquitard compressibility which contributes considerably to the overall observed land subsidence. This could involve the development of new analytical solutions to derive the aquitard compressibility from groundwater responses to cyclic forces.

The methods derived and applied in this study are not limited to the study area of the southern VMD but can be utilized to investigate subsurface hydraulic and geomechanical properties as well as groundwater extraction-related land subsidence in any coastal plain and deltaic lowland. Therefore, this study contributes to inform more sustainable groundwater management in many stressed hydrogeological environments all around the globe.

Overall, this study demonstrates that PSC is a powerful yet underutilized low-cost technique, that may prove particularly valuable for the estimation of hydraulic and geomechanical subsurface properties as well as the evaluation of mitigation strategies in deltas subject to land subsidence due to groundwater depletion.

CRediT authorship contribution statement

Felix Dörr: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jonas Bauer:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Gabriel C. Rau:** Writing – review & editing, Validation, Methodology, Conceptualization. **Remi Valois:** Writing – review & editing, Software, Conceptualization. **Tran Viet Hoan:** Writing – review & editing, Investigation, Data curation. **Van Cam Pham:** Writing – review & editing. **Le Thi Mai Van:** Writing – review & editing, Project administration, Data curation. **Anke Steinel:** Writing – review & editing, Data curation, Conceptualization. **Franz Nestmann:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Stefan Norra:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was conducted in the frame of the project “ViWaT – Vietnam Water Technologies” funded by the German Federal Ministry of Education and Research (funding reference: 02WCL1474A). Felix Dörr thanks the Hector Fellow Academy for support. We gratefully thank the Vietnamese Ministry of Science and Technology (MOST), the National Center for Water Resources Planning and Investigation (NAWAPI) and the Department of Natural Resources and Environment Ca Mau (DONRE Ca Mau) as well as the Federal Institute for Geosciences and Natural Resources (BGR) who kindly shared the data used in this study. We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology, Germany.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2025.133844>.

Data availability

The well water level data from the sites GW1 and IGPVN (from 2016 to May 2023), as well as the calculated Earth and ocean tide strains for IGPVN and the barometric pressure data used in this study are available at a Zenodo repository: <https://doi.org/10.5281/zenodo.14671298>. The river water level data, the well water level data from IGPVN after May 2023 as well as the well water level data from the national groundwater monitoring wells are available on request at NAWAPI.

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**The recharge illusion: How seasonal surface loading
can hide continuing groundwater resource declines
in confined deltaic aquifers**

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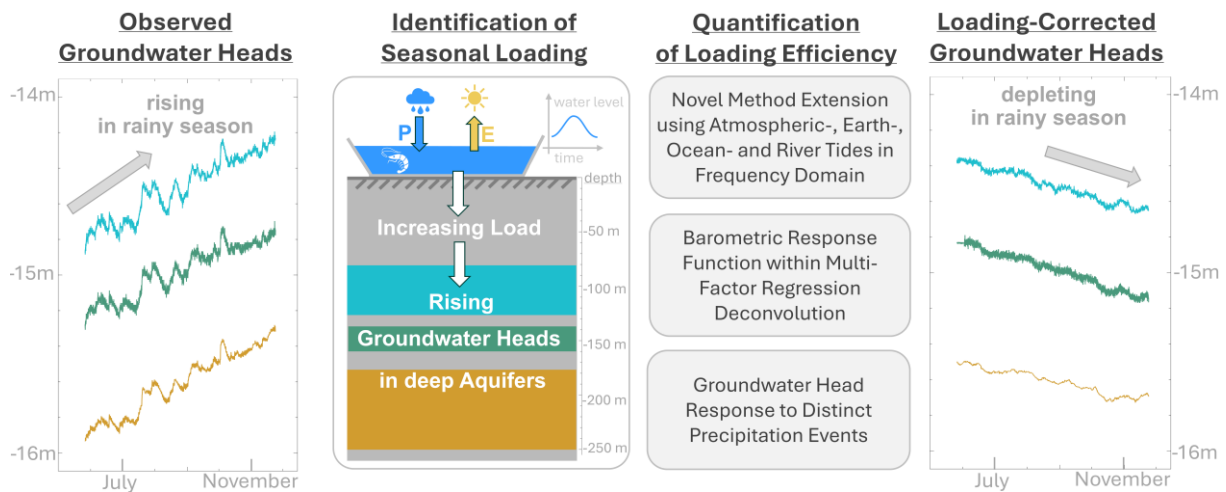
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Abstract

Reliable estimates of groundwater recharge are critical for managing water resources and preventing groundwater depletion. However, groundwater recharge estimates can be distorted when loading signals are mistakenly interpreted as signs of groundwater recharge. This study introduces a novel extension to existing frequency-domain methods to quantify loading imprints in groundwater measurements by disentangling superposing signals from Earth, atmospheric, ocean, and river tides, using the K_1 tidal constituent to remove the river tide influence. This approach enables the application of frequency-domain methods for calculating the loading efficiency in deltaic groundwater systems, where superposing multiple forcings govern tidal constituents in groundwater heads. Using multi-factor regression deconvolution analysis, surface loading signals are removed from groundwater head time series. Applying this method to groundwater head data from the southern Vietnamese Mekong Delta strongly suggests that the observed seasonal rise in groundwater heads does not reflect recharge. Instead, the apparent upward trend in uncorrected data is attributed to mechanical surface loading from seasonal surface water accumulation linked to expanding aquaculture. The loading-corrected time series show a consistent decline during both dry and rainy seasons, aligning with observed annual depletion rates. This indicates a deficiency of net effective groundwater recharge throughout the year, reflecting unsustainable groundwater exploitation practices. The methods and findings of this study offer a scientific framework for the analysis of multiple superimposed surface loading processes in deltaic aquifer systems, thereby enhancing groundwater recharge assessments in such hydrogeological environments.

Graphical abstract



Key Words

Loading Efficiency; Mekong Delta; Barometric Efficiency; Passive Subsurface
Characterization; Groundwater Head Dynamics

Highlights

- Novel method extension uses ocean and river tides in passive aquifer parametrization
- Observed groundwater heads in the VMD rise due to seasonal surface water loading
- Loading-corrected groundwater heads reveal ongoing depletion during rainy season
- Surface loading must be considered in deltaic groundwater recharge assessments

1 Introduction

Global groundwater resources are under increasing stress, and the widespread acceleration of depletion trends underscores the urgent need for effective measures to address ongoing

declines (Jasechko et al., 2024). Coastal areas are particularly vulnerable to the impact of groundwater overexploitation, as groundwater depletion promotes seawater intrusion and thus further accelerates the loss of available underground freshwater resources (Konikow and Kendy, 2005). Moreover, in many deltaic lowlands, the depletion of groundwater heads causes notable land subsidence due to the compaction of subsurface sediments (Herrera-García et al., 2021; Davydenka et al., 2024). The Asian mega-deltas like the Ganges-Brahmaputra Delta, the Yangtze Delta and the Mekong Delta are prominent examples for such subsiding deltas (Syvitski et al., 2009). The southern Vietnamese Mekong Delta (VMD) is subject to land subsidence dynamics with rates locally exceeding 0.03 m a^{-1} (Erban et al., 2014; Minderhoud et al., 2017; Dörr et al., 2024). Given its average elevation of only about 80 cm above mean sea level in 2018 (Minderhoud et al., 2019), such pronounced subsidence represents an existential threat to the VMD.

While advancing salinization and increasing pollution often restrain the use of surface water resources in the southern VMD (Bauer et al. 2025; Binh et al. 2025), groundwater remains to serve as a crucial water resource for the region's water dependent socio-economic activities (Hoan et al., 2022, Pham et al., 2023). The overexploitation of groundwater causes an ongoing depletion of the hydraulic heads in the multilayered aquifer-aquitard system with rates of 0.01 to 0.55 m a^{-1} across its seven aquifers (Duy et al., 2021) and sustainable water resource management remains an unsolved challenge.

To prevent further groundwater depletion and associated land subsidence, the determination of sustainable groundwater extraction rates is essential and therefore accurate and reliable groundwater recharge assessments become ever more relevant for the southern VMD and other subsiding deltas.

Despite long-lasting and multidisciplinary research efforts (Anderson, 1978; Pham et al., 2019; Duy et al., 2021; Bauer et al., 2022), groundwater recharge processes in the VMD remain uncertain at the present time. In some coastal provinces of the VMD, the topmost Holocene aquifer (qh) is unconfined and hence generally capable of receiving groundwater recharge (Wagner et al., 2012). However, in most parts of the southern VMD it is overlain by the Holocene aquitard (Q_2). With thicknesses of up to >20 m (Anderson, 1978; Pham et al., 2019, Figure 1b) this aquitard constrains significant groundwater recharge by percolation of rain- or surface water resources where present. For the deeper Pliocene, Pleistocene and Miocene aquifers, the intermediate aquitards restrict substantial vertical flow from the qh aquifer to deeper aquifers for which no recharge areas have been identified in the VMD (Pechstein et al., 2018). A potential hydraulic interconnection between the deep aquifers in the southern VMD and outcropping Cambodian alluvial strata remains uncertain and a pending transboundary challenge of essential importance to the VMD's water security (Lee et al., 2018). This is underpinned by recent hydrogeochemical and isotopic analyses across the multilayered aquifer system, suggesting that most groundwater was recharged into the Upper Pleistocene aquifer qp_{2-3} during the last glacial episode when seawater levels were low (Pham et al. 2019, Bauer et al. 2022, Osenbrück et al., 2025). However, these studies on the other hand indicate that local vertical flow or leakage processes through the aquitards may be present (Bauer et al. 2022, Osenbrück et al., 2025).

Hydrodynamic studies (e.g. Duy et al., 2021) investigated seasonal fluctuations in groundwater levels and their correlation with river water levels, suggesting that the deeper aquifers might receive recharge from upstream areas of the VMD. More recently, Van et al. (2023) applied the water-table fluctuation method (Healy and Cook, 2002) in the southern VMD, a method

originally derived for unconfined conditions, to estimate groundwater recharge based on observed seasonally rising groundwater heads and precipitation data.

However, in confined aquifers, groundwater head fluctuations are not solely caused by water mass fluxes, i.e. extraction and recharge, but also by mechanical load acting on the aquifer's confining unit, like for example variations in soil moisture or water levels of surface water bodies (van der Kamp and Maathuis, 1991). Such loading signals bear the potential of being misinterpreted as groundwater recharge, given that they cause an increase of water levels in observation wells (van der Kamp and Schmidt, 2017).

Over the past decade, hydrogeological studies in other subsiding delta systems, such as the Bengal Basin (e.g. Burgess et al., 2017), have identified and investigated loading effects in groundwater observation data. These studies highlight both the importance of accounting for such effects and the limitations of traditional analyses that ignore them, particularly in Southeast Asian mega-deltas. Dörr et al. (2025) uncovered the presence of loading signals in groundwater head time series in the southern VMD, paving the way to assess the contribution of loading signals to apparent seasonally rising groundwater levels in the southern VMD.

The objective of the present study is to identify and quantify the impact of mechanical loading processes due to the accumulation of surface water on seasonally rising groundwater heads in the southern VMD. To achieve this, this study introduces a novel extension to previous frequency-domain methods (Acworth et al., 2016; Rau et al., 2020), which utilize the S_2 frequency (2.00 cycles per day) for the calculation of the loading efficiency γ (-), using K_1 signals for the removal of river tide influence on groundwater head amplitudes. The novel approach expands the applicability of such methods to deltaic groundwater systems, where superposing multiple tidal forcings govern tidal constituents in groundwater heads. While previous methods were only applicable in the absence of river and ocean tide loading (Acworth et al.,

127 2016; Rau et al., 2020), the present method extends the recent inclusion of ocean tide loading
128 (Dörr et al., 2025) by integrating river tide effects and thus, for the first time, enables a
129 quantitative disentanglement of Earth-, atmospheric-, ocean-, and river tide components in
130 groundwater heads.

131 Evaluating the influence of loading signals on groundwater heads by using the novel extension
132 to existing methods developed in this study enhances the understanding of groundwater
133 response to surface water loading in the study area and supports more accurate groundwater
134 recharge assessments. The insights gained from the case of the VMD are transferable to other
135 delta systems in Southeast Asia and beyond.

2 Materials and Methods

2.1 Hydrometeorological data

To assess the potential contribution of loading effects on rising groundwater heads in the southern VMD, this study utilizes hydrometeorological data from the monitoring site GW1 (Figure 1) in Ca Mau Province in the southern VMD, located in an area dominated by inland aquaculture (Figure 1a; Vu et al., 2022; Van Binh et al., 2025) and an extensive multi-channel system (Le et al., 2023; Figure 1c). The monitoring site GW1 was established by the ViWaT Engineering research project by the Karlsruhe Institute of Technology (KIT), the Vietnamese

National Center for Water Resources Planning and Investigation (NAWAPI) and the Department of Natural Resources and Environment Ca Mau (DONRE Ca Mau).

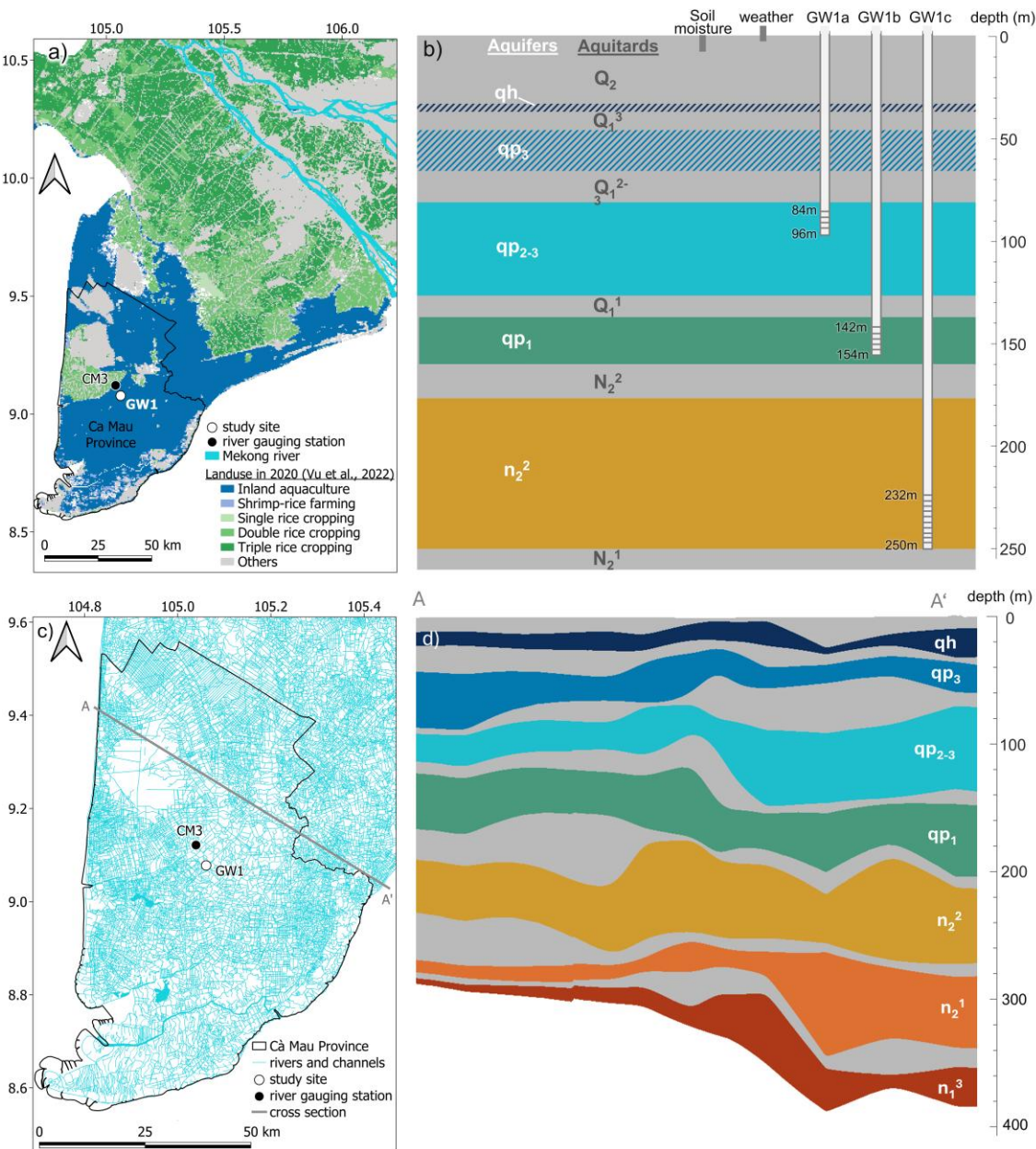


Figure 1 Study area and location of the CM3 river station and the GW1 hydrometeorological monitoring site in the southern VMD as well as land use map from 2020 (Vu et al., 2022) (a), aquifer-aquitard categorization and screen depths of observation wells at GW1 (b), rivers and channels in the southern VMD (c) and hydrogeological cross section through the multi-layered aquifer-aquitard system of the southern VMD (modified after Hoan et al., 2022) (d). Note that the depth and height of soil moisture and weather sensors in (b) are not scaled.

At GW1, the top Holocene aquitard Q_2 has a thickness of approx. 32.5 m (Figure 1b). Like at other study sites in the southern VMD (Pechstein et al., 2018), the development of the aquifers qh and qp₃ is not clearly distinguishable at GW1, indicated by the dashed blue

sections in the aquifer characterization in Figure 1b. The introduced color code for the aquifers will be used throughout this study.

The following data from GW1 is utilized for the assessment of loading signals in groundwater heads: (i) hourly to 3-hourly groundwater heads obtained using vented pressure transducers (PTs) in three observation wells (GW1a, GW1b, GW1c) screened in the upper-middle Pleistocene aquifer (qp_{2-3}), lower Pleistocene aquifer (qp_1) and middle Pliocene aquifer (n_2^2), respectively (Figure 2); (ii) 15-minutely observations of the soil's volumetric water content (-) in nine depths between 0.05 and 1.00 m (Figure 3); (iii) minutely observations from a meteorological station comprising data on air temperature, precipitation, relative humidity, solar radiation, barometric pressure and wind speed (Figure 4).

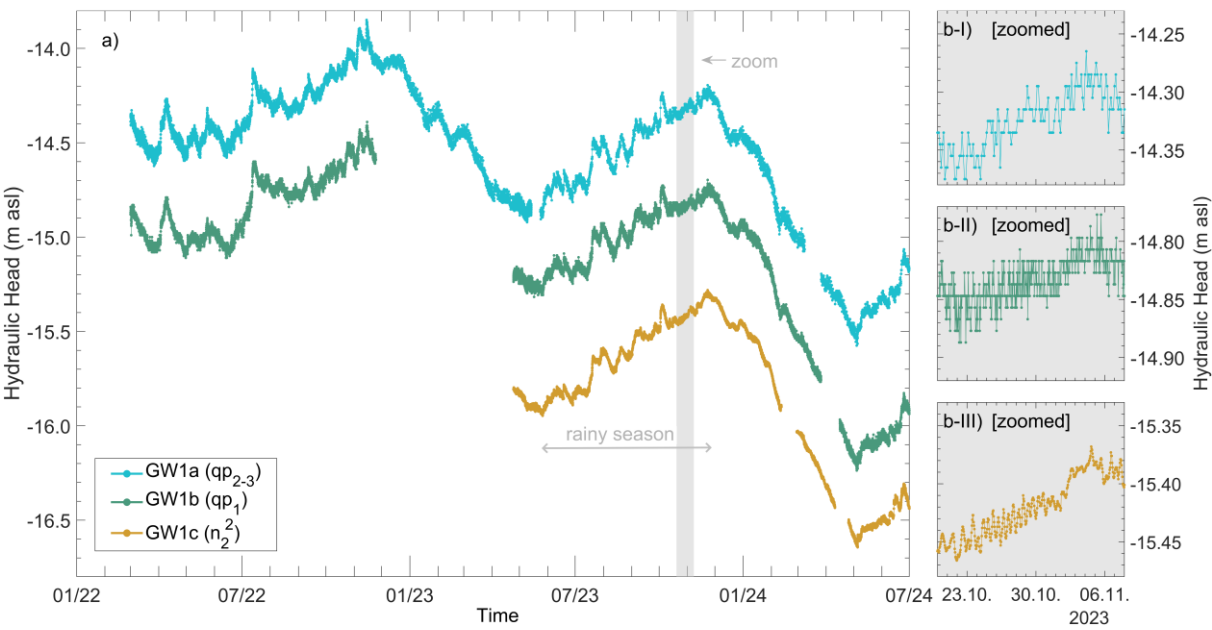


Figure 2 Hydraulic head observation data of three observation wells at GW1 screened in the upper-middle Pleistocene aquifer (qp_{2-3}), lower Pleistocene aquifer (qp_1) and middle Pliocene aquifer (n_2^2) from January 2022 to July 2024 (a) and a 20-day zoom-in visualization between October and November 2023 (b)

The observed hydraulic heads in the confined aquifers qp_{2-3} , qp_1 and n_2^2 (Figure 2a) show exhibit dynamics, with rising heads between end of May and end of November 2023 (rainy season, see Figure 4d) and declining heads between end of November 2023 and early May 2024 (dry season, see Figure 4d).

Figure 2bI-III illustrates the different resolutions of the PTs of approx. ± 10 -15 mm for GW1a and GW1b and approx. ± 2 -5 mm for GW1c. The temporal resolution varies between 1 hour (GW1b and GW1c, Figure 2b-II and b-III) and 3 hours (GW1a, Figure 2b-I). The precipitation sensor has a measurement range of 0-400 mm/h and an accuracy of $\pm 5\%$ of measurement in the range between 0 to 50 mm/h. Figure 3 illustrates the soil water content observations at GW1, showing notable variation between the dry and rainy season in depths up to 30 cm (Figure 3a-c), while below 60 cm a nearly constant volumetric water content is observed (Figure 3g-i). The sensor was calibrated by a soil specific calibration using laboratory water content analyses of soil samples from each observation depth (Ledieu et al., 1986).

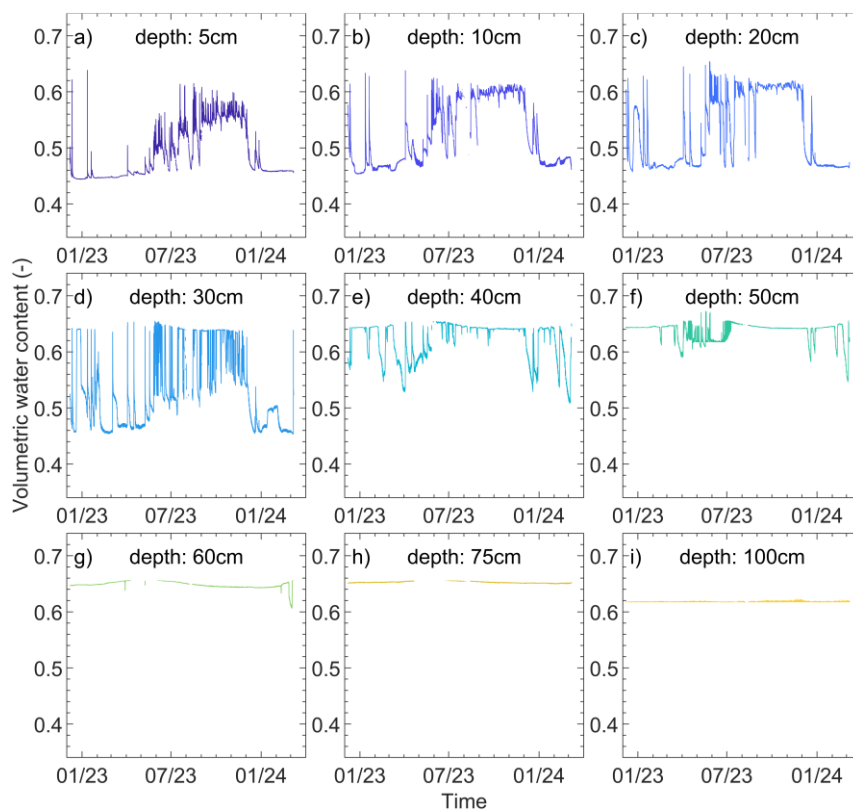


Figure 3: Observation of soil volumetric water content at GW1 in different depths between 5 cm and 100 cm

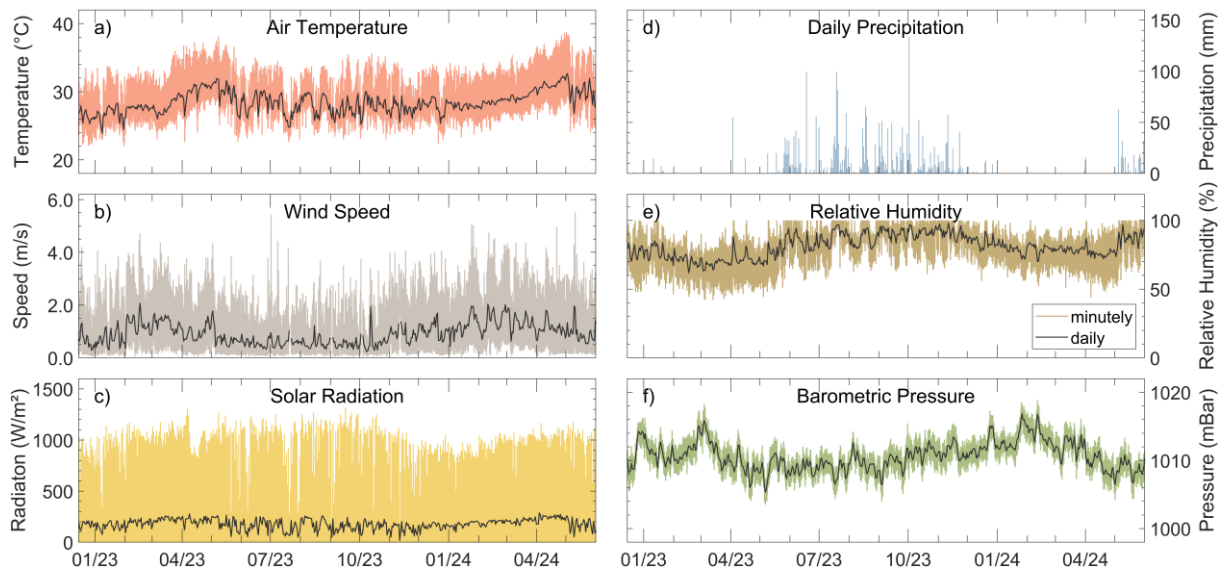


Figure 4 Measurement data of the meteorological monitoring station at GW1 (colored lines) and daily averages (black lines)

In 5 km distance to GW1 (Figure 1a), surface water levels are measured at the CM3-Rach Cui station at hourly resolution (Figure 5). The surface water levels are characterized by seasonal variations with rising water levels between July and November as well as by variations on tidal scale. These seasonal and sub-diel water level dynamics are induced by ocean tides as well as seasonal variations in the upstream feed of freshwater and comply well with the overall reported river water levels dynamics in the southern VMD (Bauer et al., 2025).

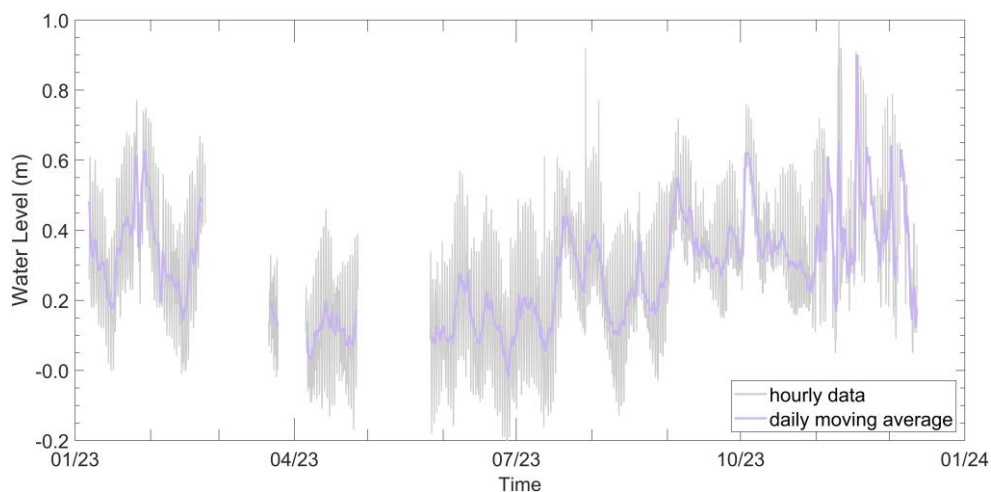


Figure 5 Hourly data on surface water levels at the gauging station CM3 Rach Cui

2.2 Water balance and land use land cover classification

For the analysis of seasonal surface loading $\Delta\sigma_L$ (mm), the water balance in the proximity of the study site GW1 is analyzed. In the presented study, the general surface water balance of accumulated precipitation P (mm), accumulated evapotranspiration E (mm) and accumulated runoff R (mm) (Eq. (1)) is considered:

$$\Delta\sigma_L = P - E - R \quad (1)$$

Given that the site exhibits 32.5 m of aquitard at the surface, no actual unconfined aquifer exists at the site (Figure 1b). Hence, there is no additional loading from unconfined shallow groundwater level changes on the assessed deep aquifers.

The responding area of an observation well to surface loading can be approximated as a circular area with a radius of at least ten times the depth of the observation well (Smith et al., 2017). For the calculations in this study, radii of ten times the depth of GW1a-c are utilized for the estimation of the observation wells' responding area, complemented by an impact assessment of potential uncertainties on the calculation results. Given that actual evapotranspiration and runoff depend on land use and land cover (LULC), in this study four types of LULC-classes are differentiated within the estimated responding surface area: (i) ponds, (ii) vegetated land (iii), sealed surfaces as well as (iv) rivers and channels. These four types of LULC-classes differ in their accumulation of precipitation, their evapotranspiration rates as well as their drainage and runoff behavior.

In this study, based on field observations, LULC-areas identified as ponds are considered as undrained water bodies, supposing that they are not continuously connected to the river and channel network and therefore accumulate precipitation and do not contribute to surface water runoff. In the traditional extensive shrimp farming system, the ponds' water management was on tidal basis, linking the ponds' water levels to water levels in rivers and

218 channels by fortnightly opening and closing of the ponds' sluice gates (Johnston et al., 2000).
 219 On the other hand, water level assessments of intensive shrimp farming ponds in the study
 220 area showed increasing pond water levels within a production cycle from initially 0.8 – 1.0 m
 221 to 1.5 – 2.0 m due to precipitation as well as the addition of supplemental water (Anh et al.,
 222 2010). Sources of used supplemental water were not specified by Anh et al. (2010) and are
 223 likely to vary according to the availability of different water resources, e.g. harvested
 224 rainwater or surface water in sufficient quality. Despite legal restrictions, a survey from Tra
 225 Vinh province suggests that also groundwater is used as supplemental water in shrimp farming
 226 (Van Tuan et al., 2024). Given that intensive shrimp farming systems account for the largest
 227 share of recent shrimp production in the VMD (Ho et al., 2025), in this study aquaculture
 228 ponds near GW1 are considered as intensive shrimp farming ponds, a presumption that
 229 matches field observation and is validated by an evaluation of pond sizes within the analysis.

230 For ponds $\Delta\sigma_L$ is equivalent to variations in the pond water level and is calculated by the
 231 difference between accumulated precipitation and evaporation. The evaporation rate for
 232 ponds E_w (mm d⁻¹) is calculated with Eq. (2), a simplified form of the Penman (1948) equation
 233 derived by Valiantzas (2006) for the application in settings with measurement data from
 234 routine meteorological stations:

$$E_w = 0.051(1-\alpha)R_s\sqrt{T+9.5}-2.4\left(\frac{R_s}{R_a}\right)^2 \quad (2)$$

$$+0.052(T+20)\left(1-\frac{RH}{100}\right)(a_U-0.38+0.54u)$$

235 with α (-) as the albedo (for open water surfaces $\alpha = 0.08$ (Allen et al., 1998)), R_s as the
 236 measured solar radiation (MJ m⁻² d⁻¹), T as the measured air temperature (°C), R_a as the
 237 calculated extraterrestrial radiation (MJ m⁻² d⁻¹) based on the FAO56 method (Allen et al.,

1998), RH (%) as the measured relative humidity, $a_U = 1$ according to the original Penman (1948) wind function, and u as the measured wind speed (m s^{-1}).

Areas identified as sealed surfaces like urban settlements do not accumulate water and temporary precipitation loading is completely converted into surface water runoff or evaporation. Therefore, areas classified as sealed surfaces are considered to be fully drained in this study.

The seasonal accumulation of water resources on vegetated land is challenging to determine precisely in the study area, given that several factors such as infiltration, plant water accumulation, inundation, irrigation practices and drainage runoff contribute to this process. On the one hand, the high clay content of the topsoil most likely prevents significant infiltration. In the present study this is assessed by a quantitative evaluation of the soil moisture loading, i.e., the variation of soil water volume, derived from the depth differentiated soil moisture observation at GW1 (Figure 3). On the other hand, plant- and canopy water accumulation as well as inundation of farmland such as rice paddies add to the overall surface load on vegetated land. Given that these contributions cannot be quantified with the data available, this study does not utilize a single value for $\Delta\sigma_L$ for vegetated land but considers a range of possible values. In this approach a share between 0 % and 50 % of the areas classified as vegetated land are considered to accumulate surface water resources, characterized by the overall water balance dynamics of precipitation and evaporation, equivalent to the loading dynamics of ponds.

For LULC-areas classified as rivers or channels, the loading is directly derived from river water level observations in the proximity of GW1 (Figure 5). For the LULC-classification, a detailed visual assessment of Google Satellite Imagery, dated to February 2024, was performed, given

that remote sensing approaches, for example as used by Vu et al. (2022), have insufficient accuracy for the required site-specific analysis.

2.3 Loading signals in the time domain

Water levels in deep groundwater observation wells in confined aquifers, such as GW1a, GW1b and GW1c respond to variations in the water balance at the surface (van der Kamp and Maathuis, 1991). When hydrometeorological processes like soil moisture variations, ponding of surface water, barometric pressure variations or snow accumulation cause a spatially extensive and uniform surface load, the coupled stress-flow equations can be simplified to a 1D problem and the general relationship between aquifer pore-pressure response and surface loading can be written for saturated, linearly elastic, porous media using van der Kamp and Gale (1983):

$$\frac{\partial u}{\partial t} = \gamma \frac{\partial \sigma_L}{\partial t} + D \frac{\partial^2 u}{\partial z^2} \quad (3)$$

where u is the pore pressure, t is time, γ is the loading efficiency, σ_L is the total stress (mechanical load) acting at the top, D is the hydraulic diffusivity, and z is elevation.

The loading efficiency γ (-) describes the partitioning of external stress that is imposed on an aquifer between the sediment matrix and the pore water (Domenico and Schwartz, 1998). The two terms on the right hand side of Eq. (3) represent the two governing key processes, namely the undrained pore-pressure response to changes in mechanical load ($\gamma \frac{\partial \sigma_L}{\partial t}$), and the vertical transient flow of groundwater due to the pore-pressure variations ($D \frac{\partial^2 u}{\partial z^2}$) (van der Kamp and Schmidt, 2017).

While variations of the total stress are instantaneously transmitted into the subsurface to depths of kilometers (Schulze et al., 2000), the transient flow is inherently subject to delay, which is characterized by the time factor T (s) as in Eq. (4) (van der Kamp and Schmidt, 2017)

$$T = \frac{b^2}{D} \quad (4)$$

where b (m) is the thickness of the confining aquitard and D ($\text{m}^2 \text{s}^{-1}$) its hydraulic diffusivity. The time factor T scales the time frame for the aquifer-aquitard interaction (van der Kamp and Schmidt, 2017). In an ideal confined aquifer, D converges to zero and the transient flow term is negligible, whereas in leaky aquifer systems a more careful assessment of the contribution of transient flow is necessary. If the duration of a loading signal is much smaller than T , the groundwater response will not be significantly affected by flow through the overlying aquitard (van der Kamp and Schmidt, 2017).

In the present study, the loading efficiency γ was utilized to remove the loading signals due to mechanical loading ($\Delta\sigma_L$) from hydraulic head measurements in three observation wells at the monitoring site GW1. For that, γ was evaluated by three independent methods: (i) the S_2 response of groundwater levels to atmospheric tides $BE_{S_2}^{AT}$; (ii) the groundwater level response to selected distinct precipitation events; (iii) the barometric response function (BRF).

The BRF is calculated using a regression deconvolution approach, where changes in groundwater pressure at a given time t are expressed as the convolution of changes in barometric pressure at times before t , in the form of instantaneous response coefficients (IRC). The cumulative sum of the IRCs is referred to as BRF (Rasmussen and Crawford, 1997).

Toll and Rasmussen (2007) enhanced this method by additionally considering Earth tide effects in the regression as an independent driver for variations of well water levels, represented by the Earth tide response function (ERF). Methods like the multi-factor

correction of groundwater levels (MUFACO) (Haehnel et al., 2024) generalize the forcings to consider more processes, e.g., ocean tide and precipitation loading, therefore allowing an individual and more flexible consideration of multiple influences.

In aquifers with near-ideally confined conditions, the BRF typically increases towards a plateau. In that case, the BRF's maximum represents the barometric efficiency BE (-) (Toll and Rasmussen, 2007). This is inherently coupled to the loading efficiency γ by Eq. (5) (van der Kamp and Gale, 1983):

$$\gamma = 1 - BE \quad (5)$$

In semi-confined aquifers, the BRF decreases with time, indicating significant contribution of vertical transient flow. Therefore, the shape of the BRF can be used to characterize the aquifer confinement status (Rasmussen and Crawford, 1997; Butler et al., 2011; Spane, 2002). Moreover, once the response function to a certain forcing or multiple forcings are derived, they can be used to remove the imprints of the respective effects in the observed groundwater heads (Rasmussen and Mote, 2007; Toll and Rasmussen, 2007).

In addition to the evaluation of the BRF, the groundwater head responses to selected distinct precipitation events are used to assess the loading efficiency in this study. Given that short and distinct precipitation events are abrupt increments in the surface loading (Bardsley and Campbell, 2000), slow processes like evaporation as well as surface and subsurface drainage processes can be neglected, Eq. (3) can be simplified and the loading efficiency γ can be calculated with the ratio of accumulated precipitation and increase in observed groundwater heads. To minimize the influence of low sensor accuracy at GW1a and GW1b (Figure 2 b-I and b-II) and to reduce the impact of tidal forcings (Earth-, ocean-, and atmospheric tides), linear trends were fitted to the groundwater head data before and after each precipitation event. The durations of these trends were selected based on the longest available precipitation-free

periods. The resulting start and end values provide a robust basis for the quantitative assessment of γ .

2.4 Multi-factor regression deconvolution

In the present study, a multi-factor regression deconvolution is applied to correct groundwater heads and to derive the BRF. This approach accounts for tidal and seasonal drivers influencing groundwater-head variations at the study site. The considered drivers include the ubiquitous drivers of (i) Earth tides and (ii) atmospheric pressure variations, as well as site-specific drivers including (iii) river water levels, (iv) ocean tide loading on the solid Earth (OT_{SE}), and (v) calculated variations in pond water levels (see section 2.2). Considering the aquaculture-dominated land use and the dense network of rivers and channels in the study area (Figure 1a and c), pond water loading and river water levels control the seasonal surface loading signals in groundwater heads. The impact of observed river tides at CM3 on groundwater heads at GW1 is assessed using a magnitude-squared coherence analysis based on measured time series of river water levels and groundwater heads at the respective sites.

Volumetric Earth tide strains are computed for the monitoring site GW1 with *PyGTide* (Rau et al., 2022), a Python wrapper for *ETERNA PREDICT 3.4* (Wenzel 1996), under consideration of longitude, latitude and elevation of GW1. The volumetric strains due to ocean tide loading on the solid Earth (OT_{SE}) are calculated with the Fortran-based software package *SPOTL* (Agnew, 2012) at hourly resolution for GW1. OT_{SE} causes strain waves, propagating from the ocean coast towards the inland by the geologic media. In another independent process (denoted as OT_{GW}), ocean tides exert a loading on the aquifer's water (Jacob, 1950; van der Kamp, 1972), causing a pressure wave that propagates from the ocean coast towards the inland by the liquid phase (pore water) only. Dörr et al. (2025) showed that in the southern VMD, groundwater tides due to OT_{GW} reach insignificance (< 0.01 mm) in 6.4 km distance in the middle Pliocene

aquifer n_2^2 . Given that the study site GW1 is in approx. 28 km distance to the coast, OT_{GW} is considered irrelevant for the tidal composition of groundwater at GW1.

Building on previous studies in the VMD, the hydraulic diffusivity D of the overlying aquitards N_2^2 , Q_1^1 and Q_1^{2-3} (see Figure 1b) can be estimated from mean values of the vertical hydraulic conductivity and the specific storage coefficient based on Minderhoud et al. (2017) to $D(Q_1^{2-3}) = 2.3 \cdot 10^{-3} \text{ m}^2 \text{ s}^{-1}$, $D(Q_1^1) = 5.1 \cdot 10^{-4} \text{ m}^2 \text{ s}^{-1}$, and $D(N_2^2) = 5.5 \cdot 10^{-4} \text{ m}^2 \text{ s}^{-1}$. With aquitard thicknesses of 16.7 m, 9.2 m and 17.8 m at GW1 (Figure 1b), the time factor T can be estimated with Eq. (4) to be approx. 1.4, 1.9 and 6.7 days, respectively. Based on these time factors, a maximum time lag of 7 days (168 hours) was selected in the multi-factor regression deconvolution, to account for potential contributions of vertical flow to the loading-groundwater response.

Within the multi-factor regression deconvolution, uncertainties are assessed in form of the response functions' standard deviations, which are derived from the covariance matrix of the IRC during the regression deconvolution (Haehnel et al., 2024).

2.5 Loading signals in the frequency domain

Complementary to the evaluation of the BRF, this study also assesses BE in the frequency domain by an evaluation of groundwater level response to atmospheric tides at S_2 frequency (2.0 cycles per day). For that, the underlying frequency patterns in the time series of Earth-, ocean-, river- and atmospheric tides, as well as groundwater heads are analyzed by two independent methods: (i) the Fast Fourier Transform (FFT); (ii) the harmonic least-squares (HALS) estimation. In this study, HALS analyses are conducted on the ten most studied frequencies in groundwater analysis, as outlined in Table 1. Prior to any performed frequency

analysis, the time series are detrended with a 3-day moving window to remove lower frequencies and improve the extraction of the relevant tidal constituents (Rau et al., 2020). Given that HALS outperforms FFT in terms of accuracy in amplitude and phase estimation (Schweizer et al., 2021), amplitudes and phases obtained from HALS are used for the assessment of BE . The additional consideration of FFT offers redundancy to the HALS-based amplitude and phase characterization and has the potential to detect amplitudes beyond those listed in Table 1.

Table 1 Summary of the ten most relevant frequencies in groundwater analysis after McMillan et al., (2019)

Darwin name	Frequency (cpd)	Earth Tides	Atmospheric Tides	Ocean/River Tides
Q_1	0.893244	Yes	-	Yes
O_1	0.929536	Yes	-	Yes
M_1	0.966446	Yes	-	Yes
P_1	0.997262	Yes	-	Yes
S_1	1.000000	-	Yes	-
K_1	1.002738	Yes	-	Yes
N_2	1.895982	Yes	-	Yes
M_2	1.932274	Yes	-	Yes
S_2	2.000000	Yes	Yes	Yes
K_2	2.005476	Yes	-	Yes

Within the HALS estimation of amplitudes and phases, a covariance matrix for the fitted coefficients can be calculated and used to derive the standard deviation (Rau et al., 2020).

2.6 Disentangling Earth and river tides for an improved estimation of barometric efficiency

The barometric efficiency (BE) based on the S_2 response of groundwater levels to atmospheric tides (denoted as $BE_{S_2}^{AT}$) is evaluated to derive the loading efficiency with Eq. (5). Given that S_2 signals are present in Earth-, atmospheric-, ocean-, and river tides (Table 1), the S_2 signal in

groundwater levels $\hat{Z}_{S_2}^{GW}$ needs to be disentangled into its individual drivers before $BE_{S_2}^{AT}$ can be calculated. The mathematical formulation of frequency disentanglement uses complex numbers (denotated by a hat) to account for phase and amplitude information of each signal. For settings without river or ocean tide loading, Rau et al. (2020) introduced a complete tidal disentanglement for S_2 signals in groundwater heads, based on M_2 signals in groundwater and Earth tide strains using:

$$\hat{Z}_{S_2}^{GW \cdot ET} = \frac{\hat{Z}_{M_2}^{GW}}{\hat{Z}_{M_2}^{ET}} \hat{Z}_{S_2}^{ET} \quad (6)$$

Recent extensions of this method included OT_{SE} strains in the analysis by a consideration of the total volumetric strain caused by OT_{SE} and Earth tides (Dörr et al., 2025). To achieve this, the two strain time series can be added up to a single time series, further denoted with the superscript $\{ET+OT_{SE}\}$, prior to the conducted frequency analysis (Dörr et al., 2025).

To enable the calculation of $BE_{S_2}^{AT}$ in deltaic groundwater systems, the present study introduces a novel extension of previous methods (Rau et al., 2020; Dörr et al., 2025), which for the first time allows a quantitative disentanglement of Earth-, atmospheric-, ocean-, and river tide components in groundwater heads. To remove the river tide contribution to the M_2 and S_2 response in groundwater heads, the K_1 signal in river tides and groundwater heads is utilized. From the ratio of K_1 signals in river tides and groundwater, the phase shift and amplitude damping of the K_1 signal are calculated, which are then assigned to the M_2 and S_2 signal of the river water levels to estimate the river tide influence on M_2 and S_2 signals in groundwater observation wells. It is noted that this is a simplified consideration assuming insignificant K_1 contribution of Earth tides to groundwater amplitudes ($\hat{Z}_{K_1}^{GW \cdot ET} = 0$) and neglecting the frequency dependency of amplitude damping and phase shifting (Valois et al.,

2022; 2024). The applicability of this simplified assumption needs to be validated in any individual application.

Similar to the M_2 -based disentanglement of Earth tides (Rau et al., 2020, Eq. (6)), the introduced K_1 -based disentanglement of river tides can be formulated with Eq. (7) and (8) for M_2 and S_2 frequencies.

$$\hat{Z}_{M_2}^{GW \cdot RT} = \frac{\hat{Z}_{K_1}^{GW}}{\hat{Z}_{K_1}^{RT}} \hat{Z}_{M_2}^{RT} \quad (7)$$

$$\hat{Z}_{S_2}^{GW \cdot RT} = \frac{\hat{Z}_{K_1}^{GW}}{\hat{Z}_{K_1}^{RT}} \hat{Z}_{S_2}^{RT} \quad (8)$$

The M_2 response of groundwater to Earth tides and OT_{SE} can then be calculated by subtracting the river tide contribution (Eq. (8)) from the M_2 signal in groundwater:

$$\hat{Z}_{M_2}^{GW \cdot \{ET+OT_{SE}\}} = \hat{Z}_{M_2}^{GW} - \hat{Z}_{M_2}^{GW \cdot RT} \quad (9)$$

417

Then, the disentanglement of Earth-, atmospheric-, ocean-, and river tide components in S_2 groundwater signals can be formulated with Eq. (10).

$$\begin{aligned} \hat{Z}_{S_2}^{GW \cdot AT} &= \hat{Z}_{S_2}^{GW} - \hat{Z}_{S_2}^{GW \cdot \{ET+OT_{SE}\}} - \hat{Z}_{S_2}^{GW \cdot RT} \\ &= \hat{Z}_{S_2}^{GW} - \frac{\hat{Z}_{M_2}^{GW \cdot \{ET+OT_{SE}\}}}{\hat{Z}_{M_2}^{\{ET+OT_{SE}\}}} \hat{Z}_{S_2}^{\{ET+OT_{SE}\}} - \frac{\hat{Z}_{K_1}^{GW}}{\hat{Z}_{K_1}^{RT}} \hat{Z}_{S_2}^{RT} \end{aligned} \quad (10)$$

420

After the disentanglement of Earth-, ocean-, river- and atmospheric tide signals, BE can be calculated based on the S_2 response of groundwater heads to atmospheric tides $BE_{S_2}^{AT}$ as:

$$BE_{S_2}^{AT} = \frac{1}{A_{S_2}^r} \text{abs} \left[\frac{\Delta_{S_2}^{GW \cdot AT}}{\Delta_{S_2}^{AT}} \right] \quad (11)$$

423 with $A_{S_2}^r$ as the amplitude response between water levels in the observation well and the
 424 actual aquifer pore pressure. $A_{S_2}^r$ is a function of well and aquifer parameters and for wells
 425 screened in confined aquifers with $K > 1 \cdot 10^{-5} \text{ m s}^{-1}$, $A_{S_2}^r$ ranges usually between 0.99 and 1.00
 426 and is therefore negligible in Eq. (11) (Rau et al., 2020).

427 2.7 Summary of applied methods and workflow

428 The deep analysis and quantification of loading imprints in groundwater heads utilizes time
 429 series of observed groundwater heads, computed Earth tide- and OT_{SE} -strains, measured
 430 barometric pressure, river water levels, and precipitation data. A novel method extension is
 431 introduced to derive the loading efficiency γ from the S_2 response of groundwater heads to
 432 atmospheric tides, using K_1 signals for the removal of river tide signals in groundwater head
 433 amplitude spectra. The results are verified using two independent established time domain
 434 methods: (i) the barometric response function (BRF) within a multi factor regression
 435 deconvolution, and (ii) the groundwater level response to distinct precipitation events. The
 436 surface loading dynamics are assessed using an analysis of precipitation-evaporation-driven
 437 accumulation of surface water resources in aquaculture ponds, river water level dynamics and
 438 a land use land cover classification. Using multi-factor regression deconvolution as well as
 439 complementary the quantification of the loading efficiency γ and the derived seasonal loading
 440 dynamics, observed groundwater heads are corrected from all loading influences. Figure 6
 441 presents a flow chart visualizing the study's methodological approach and a concise schematic
 442 illustrating the novel tidal disentanglement workflow.

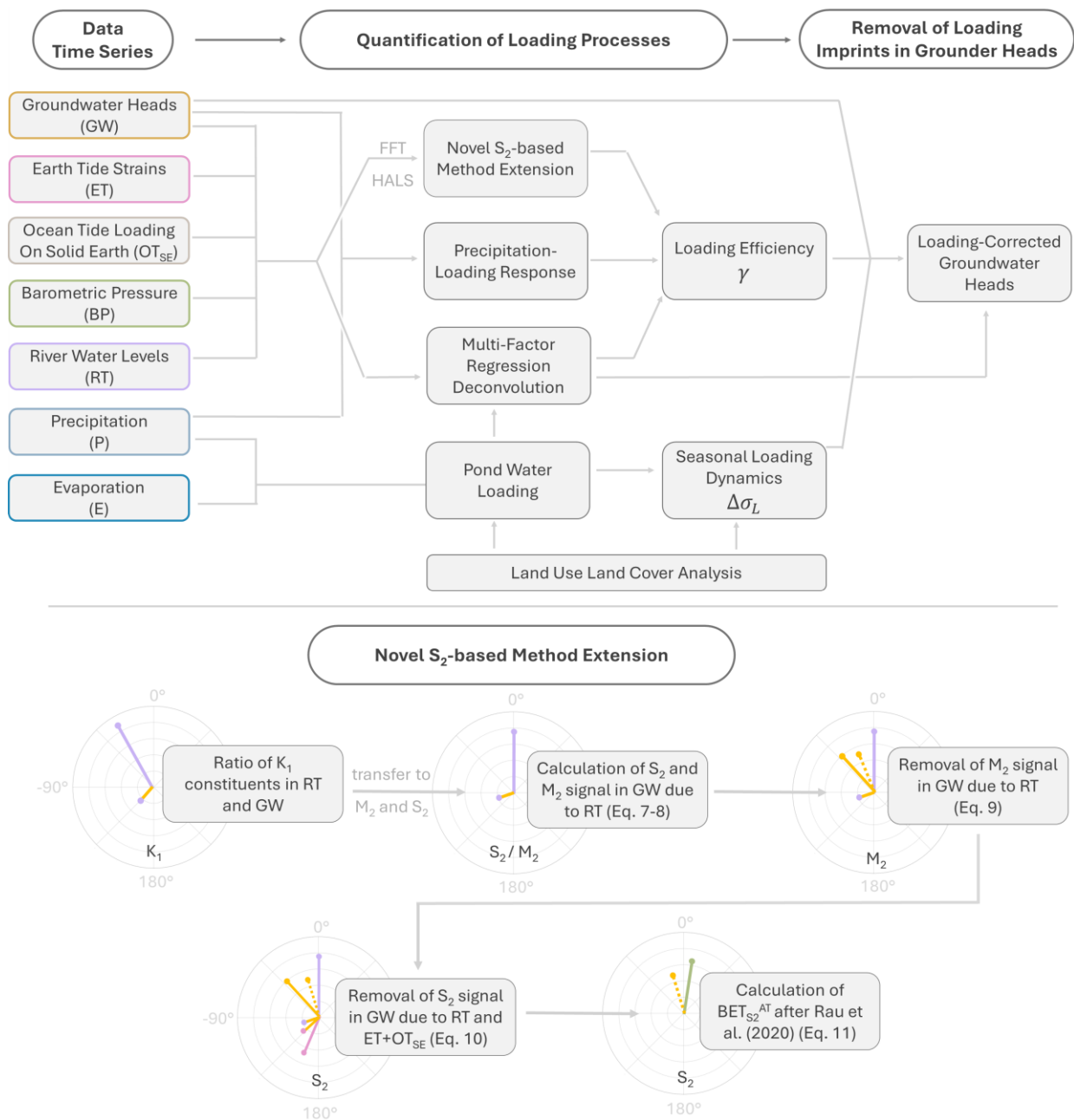


Figure 6: Overview of the workflow and methods applied in the present study.

3 Results

3.1 Seasonal surface water loading

A detailed site-specific analysis of satellite imagery agrees with the regional land use classification of Vu et al. (2022) on a local scale for GW1, identifying inland aquaculture as a dominant LULC-class in the proximity of GW1. Figure 7a shows that the majority of the land area is covered by aquaculture ponds and vegetated land, while rivers, channels and sealed surfaces have a minor contribution to the overall land cover. Most ponds are characterized by sizes of approx. 1 ha, confirming a dominant share of intensive shrimp farming ponds (Ho et al., 2025). Figure 7b visualizes the change in percentage for each LULC-class relative to the distance from GW1, showing that aquaculture ponds and vegetated land each comprise approximately 40-50%, sealed surfaces account for 6-15% and rivers and channels contribute the remaining 0-5%, depending on the distance to GW1. The responding area of each groundwater observation well, estimated using ten times the depth of their screen casing to approx. 0.9 km 1.5 km and 2.4 km for GW1a, GW1b and GW1c respectively, is illustrated through dashed vertical lines in Figure 7b. This shows that for GW1c, the share of ponds to the total responding area is greatest with 50 %, whereas for GW1a and GW1b it is closer to 45%.

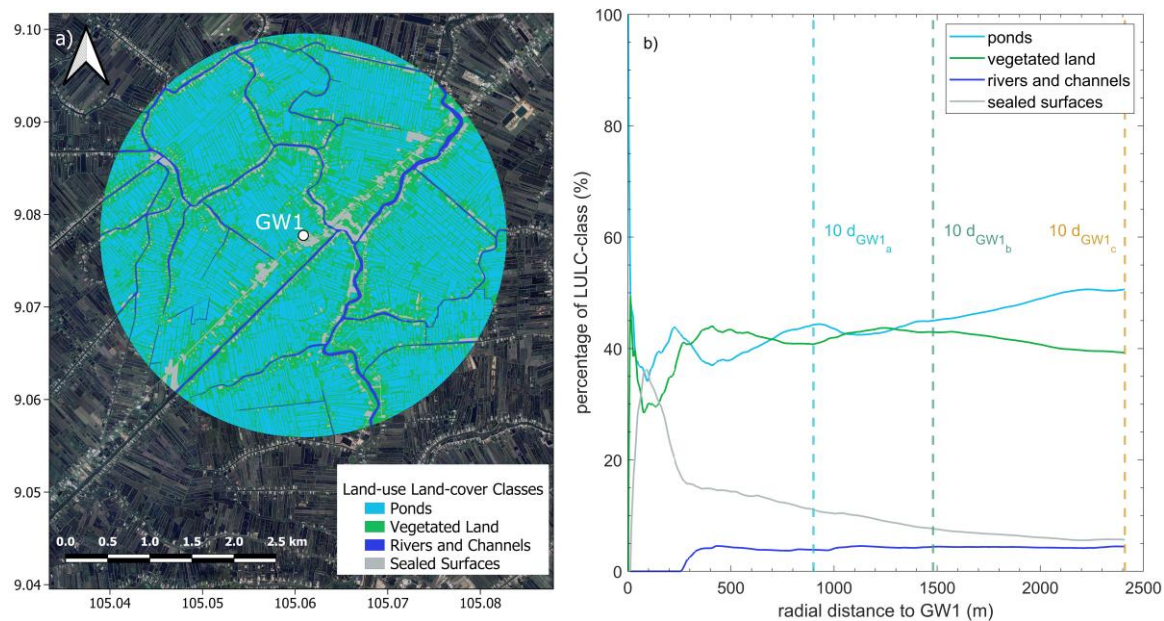


Figure 7: LULC-classification in the proximity of GW1, Imagery data: Google, © 2024 Maxar Technologies (a) and the change of each LULC-class in radial distance to GW1(b).

The loading due to aquaculture ponds is calculated by the water balance of observed accumulated precipitation (Figure 4d and Figure 8a) and the calculated evaporation for open water bodies (Eq. (2) and Figure 8a) under consideration of the observed meteorological parameters (Figure 4). Figure 8b illustrates the seasonal variation of the calculated pond loading, characterized by a decrease (unloading) between December and May, when evaporation exceeds precipitation and an increase (loading) in the remaining months, which are governed by monsoon precipitation.

The calculated soil moisture loading (Figure 8b) is characterized by seasonal variations of maximum 0.06 m and is therefore negligible compared to the calculated pond water loading. Thus, even though vegetated land covers 40-45% of the area (Figure 7b), the effect of soil moisture variations on the groundwater heads is negligible compared to pond- and river water loading effects. The comparison of the calculated pond water loading and the observed groundwater heads at GW1 (Figure 8c) reveals a pronounced similarity between the calculated loading and the groundwater head dynamics during the rainy season. Figure 8c also illustrates a correlation between river water level dynamics and groundwater head dynamics,

which is particularly well pronounced during extreme events (peaks in timeseries) as well as in February 2023 (highlighted by a gray box in Figure 8c) and less in the overall trend.

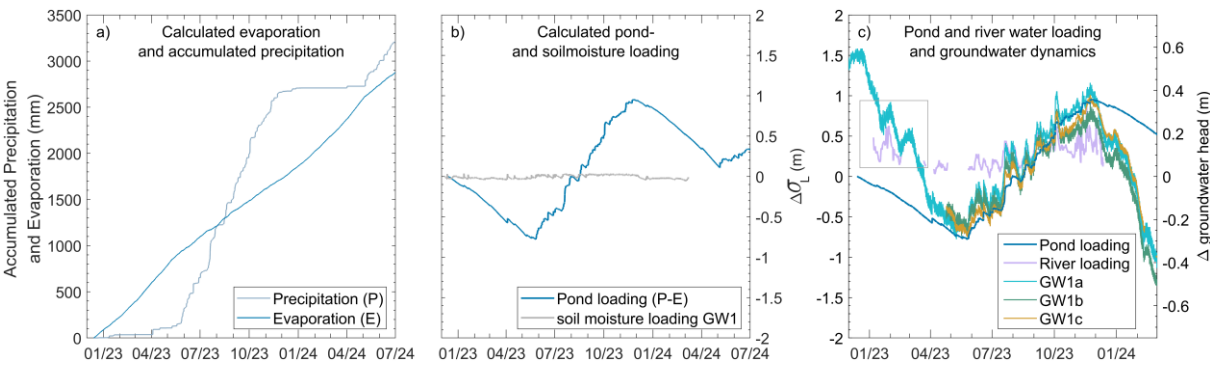


Figure 8: Accumulated precipitation and accumulated calculated evaporation at GW1 (a), derived surface loading due to variations in pond water levels and soil moisture at GW1 (b) and dynamics of pond loading, river loading and groundwater heads at GW1 (c).

3.2 Groundwater response to distinct precipitation events

The hydrometeorological monitoring station at GW1 recorded distinct precipitation events of 99.0 mm, 289.5 mm and 63.5 mm on 18.06.2023, between 14.07. and 20.07.2023 and on 05.05.2024, respectively. Figure 9 illustrates the immediate response of groundwater heads in the three observation wells GW1a, GW1b and GW1c to each of these events. Table 2 summarizes the estimated loading efficiency based on the groundwater response to the three precipitation events, calculated as the simple ratio of recorded precipitation and observed groundwater level rise.

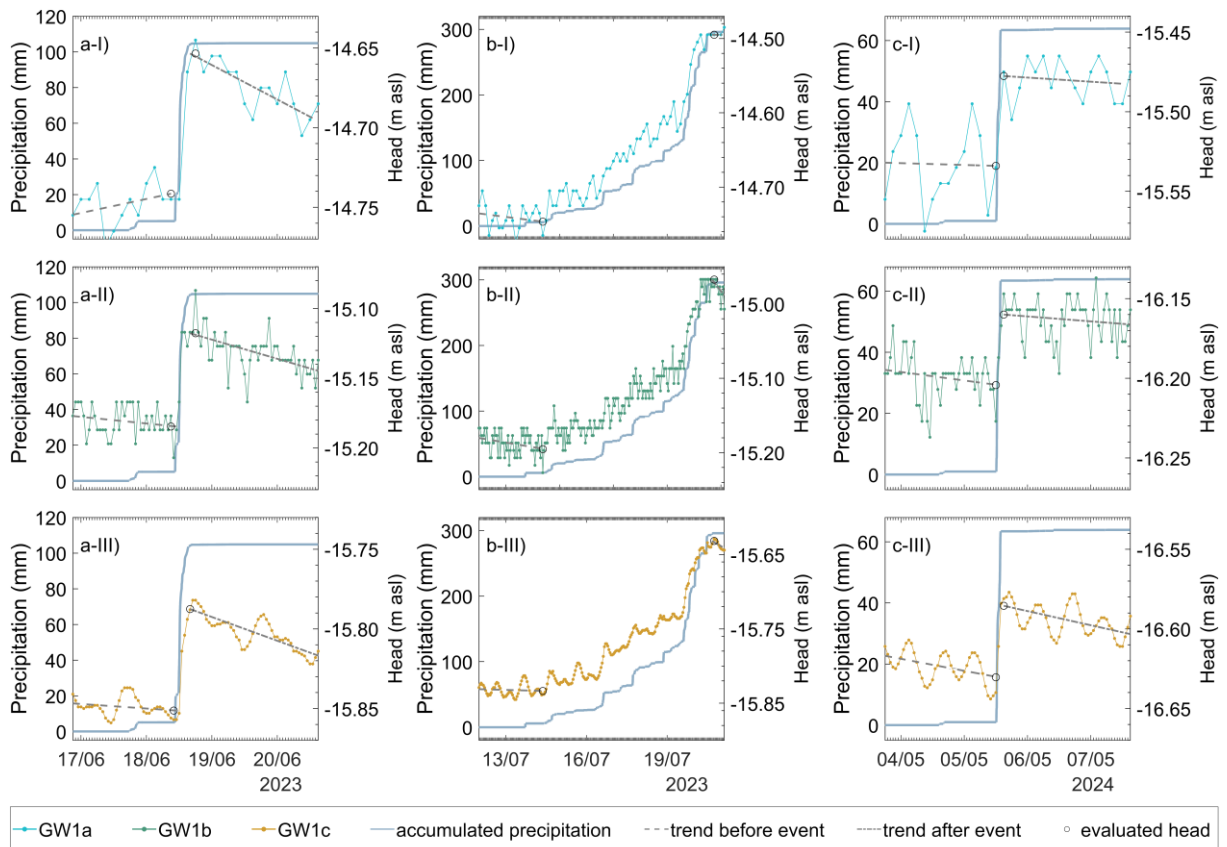


Figure 9: Hydraulic head response to three precipitation events (a to c) at GW1 site in the observation wells GW1a, qp_{2-3} (I), in GW1b, qp_1 (II) and in GW1c, n_{z^2} (III)

The assessment of groundwater head responses to three distinct precipitation events yields loading efficiency ranges of $\gamma_{GW1a}=0.87-0.90$, $\gamma_{GW1b}=0.68-0.79$ and $\gamma_{GW1c}=0.64-0.72$ with corresponding averages of 0.89, 0.72, and 0.69, respectively.

Table 2 Loading efficiency derived from hydraulic head responses to three precipitation events at GW1 in the southern VMD

	Date & Duration	GW1a	GW1b	GW1c
Precipitation (mm)	18.06.2023 [6 hours]	99.0	99.0	99.0
Groundwater response (mm)		88.0	66.9	63.8
Loading Efficiency (-)		0.889	0.676	0.644
Precipitation (mm)	14.-20.07.2023 [150 hours]	289.5	289.5	289.5
Groundwater response (mm)		251.6	228.1	202.0
Loading Efficiency (-)		0.869	0.788	0.698
Precipitation (mm)	05.05.2024 [2 hours]	63.5	63.5	63.5
Groundwater response (mm)		56.4	44.3	44.9
Loading Efficiency (-)		0.903	0.708	0.718

3.3 Loading efficiency from frequency analysis

The loading efficiency was derived in the frequency domain from $BE_{S_2}^{AT}$, i.e., the barometric efficiency based on the S_2 response of groundwater heads to atmospheric tides. $BE_{S_2}^{AT}$ was calculated with the novel method extension introduced in this study (Eq.(10)) utilizing the data presented in Figure 10 comprising volumetric Earth tide strains (Figure 10a-I), ocean tide loading on the solid Earth (Figure 10b-I), river water levels at CM3 Rach Cui (Figure 10c-I), barometric pressure (Figure 10d-I) and groundwater heads in three observation wells (Figure 10e-I to g-I). The FFT amplitude spectra annotated with HALS amplitudes (Figure 10 e-III to g-III) reveal distinct amplitudes in the groundwater heads at O_1 , K_1 , M_2 and S_2 frequency, resulting from a superposition of Earth- and ocean- tide amplitudes (Figure 10a-III and Figure 10b-III), river tide amplitudes (Figure 10c-III) and barometric amplitudes (Figure 10d-III). The sum of Earth tide- and OT_{SE} -strains are dominated by semidiurnal frequencies with a $K_1:M_2$ amplitude ratio of 0.24 while the river tides are dominated by diurnal frequencies with a $K_1:M_2$ amplitude ratio of 2.57. In the three groundwater wells the $K_1:M_2$ amplitude ratio varies between 0.95 (GW1c, 241 m depth), 1.37 (GW1b, 148 m depth) and 1.47 (GW1a, 90 m depth).

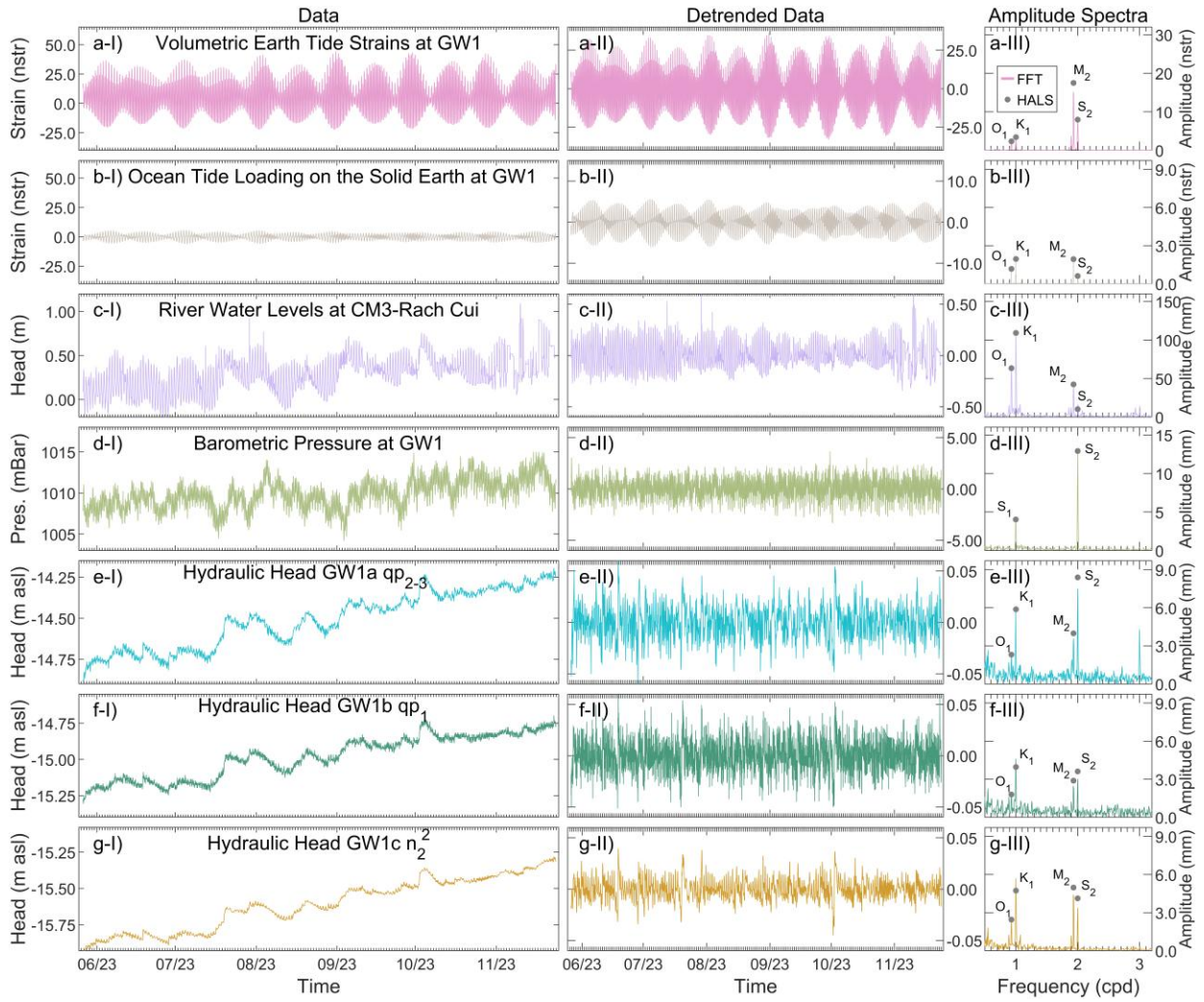


Figure 10: Employed measurement data (I, left side) and detrended data (II, middle) used for the frequency analysis at GW1 and the resulting FFT amplitude spectrum (lines) and HALS amplitudes (calculated for the 10 frequencies listed in Table 1, displayed for O_1 , K_1 , M_2 and S_2 frequency as dots) (III, right side), for computed volumetric Earth tide strains (a), computed ocean tide loading on the solid Earth (b), river water levels at CM3 Rach Cui (c), barometric pressure (d), groundwater heads in the aquifers qp_{2-3} (e), qp_1 (f) and n_2^2 (g).

The amplitude spectrum of GW1a (Figure 10e-III) shows an additional amplitude peak at 3.0 cpd, a frequency which is not present in the drivers amplitude spectra (Figure 10a-III to d-III).

Therefore, GW1 is not used for the quantification of $BE_{S_2}^{AT}$, given that such an amplitude response at 3.0 cpd is indicative for nearby groundwater extraction afflicting the observed S_2 groundwater amplitude (Dörr et al., 2025). For the calculation of the $BE_{S_2}^{AT}$, atmospheric tides were disentangled from Earth-, ocean- and river tides with Eq. (10) for GW1b and GW1c. $A_{S_2}^r$ was calculated as 0.99 for GW1b and GW1c, respectively. Table 1 Table 3 summarizes the HALS amplitudes, phases, and corresponding standard deviations at the O_1 , K_1 , M_2 and S_2 frequencies for multiple drivers, including Earth tides, OT_{SE} , river water levels, and barometric

pressure, as well as for groundwater heads at GW1a–c. The uncertainties in amplitudes and phases of the tidal constituents in the drivers and groundwater heads are generally small to moderate, with standard deviations mostly below 1% in amplitude and 1° in phase for Earth tides, OT_{SE}, and barometric pressure. Tidal constituents of the river water levels exhibit slightly higher variability, with standard deviations of <4% and <2.1° for O₁, K₁, and M₂, and up to 15% and 8.5° for S₂ amplitudes and phases, respectively. For the groundwater data, GW1a and GW1b show larger relative standard deviations compared to GW1c. At GW1c, standard deviations range between 2.5–5.0% in amplitude and 1.7–2.9° in phase, whereas GW1a and GW1b exhibit higher relative deviations of 5–19% in amplitude and 3–11° in phase.

Table 3 Calculated HALS amplitudes and phases for multiple drivers and groundwater heads at GW1 for O₁, K₁, M₂ and S₂ frequency including the calculated standard deviation (±σ)

Frequency	Drivers							
	Earth Tides		OT _{SE}		River Water Levels		Barometric Pressure	
	Amplitude ± σ (nstr)	Phase ± σ (°)	Amplitude ± σ (nstr)	Phase ± σ (°)	Amplitude ± σ (mm)	Phase ± σ (°)	Amplitude ± σ (mm)	Phase ± σ (°)
O ₁	2.34 ± 0.02	10.3 ± 0.6	1.17 ± 0.01	152.7 ± 0.2	63.45 ± 1.52	310.8 ± 1.4	-	-
K ₁	3.42 ± 0.04	103.7 ± 0.7	1.95 ± 0.01	222.6 ± 0.3	109.2 ± 2.73	38.4 ± 1.4	-	-
M ₂	17.49 ± 0.02	22.4 ± 0.1	1.94 ± 0.01	183.7 ± 0.1	42.42 ± 1.52	201.6 ± 2.1	-	-
S ₂	7.97 ± 0.02	182.2 ± 0.2	0.61 ± 0.01	323.3 ± 0.5	10.28 ± 1.52	244.9 ± 8.5	12.67 ± 0.09	256.3 ± 0.4
Frequency	Groundwater response							
	GW1a		GW1b		GW1c			
	Amplitude ± σ (mm)	Phase ± σ (°)	Amplitude ± σ (mm)	Phase ± σ (°)	Amplitude ± σ (mm)	Phase ± σ (°)		
O ₁	2.31 ± 0.44	276.2 ± 10.9	1.8 ± 0.28	273.1 ± 8.9	2.45 ± 0.12	261 ± 2.9		
K ₁	5.88 ± 0.78	359.2 ± 7.6	3.96 ± 0.5	355.6 ± 7.2	4.73 ± 0.22	356.2 ± 2.7		
M ₂	3.99 ± 0.44	169.5 ± 6.3	2.89 ± 0.28	160.1 ± 5.5	4.97 ± 0.12	180.2 ± 1.4		
S ₂	8.39 ± 0.44	92.9 ± 3	3.61 ± 0.28	40.2 ± 4.4	4.12 ± 0.12	45.1 ± 1.7		

The magnitude-squared coherence between river tides at CM3 and groundwater heads in GW1c yielded high values of 0.91, 0.93, and 0.97 for the major tidal constituents O₁, K₁, and M₂, respectively, indicating a significant influence of river tides on groundwater heads.

Figure 11 visualizes the signal disentanglement of the method extension. Note that the radial axes in the polar plots are in logarithmic scale to provide a comprehensive visualization of the

wide range of signal amplitudes. The amplitude damping and phase shift between river tides and groundwater signals at K_1 (Figure 11a) are projected to M_2 and S_2 frequency, to estimate the river tide contribution in the respective groundwater signals (squares in Figure 11b-c). The M_2 groundwater signals are displayed in Figure 11b after removal of the river contribution. Figure 11c visualizes the S_2 groundwater signals after removal of the Earth tides, OT_{SE} and river tides, i.e. the groundwater response to atmospheric tides. These values yield in a calculation of $BE_{S_2}^{AT} = 0.31$ for GW1b and $BE_{S_2}^{AT} = 0.30$ for GW1c with Eq. (11). Consequently, the loading efficiency calculates to $\gamma_{GW1b} = 0.69$ and $\gamma_{GW1c} = 0.70$ with Eq. (5), respectively. For comparison, $BE_{S_2}^{AT}$ was additionally calculated after Rau et al. (2020) without a consideration of OT_{SE} and river tides. This calculation results in $BE_{S_2}^{AT} = 0.29$ for GW1b and $BE_{S_2}^{AT} = 0.30$ for GW1c.

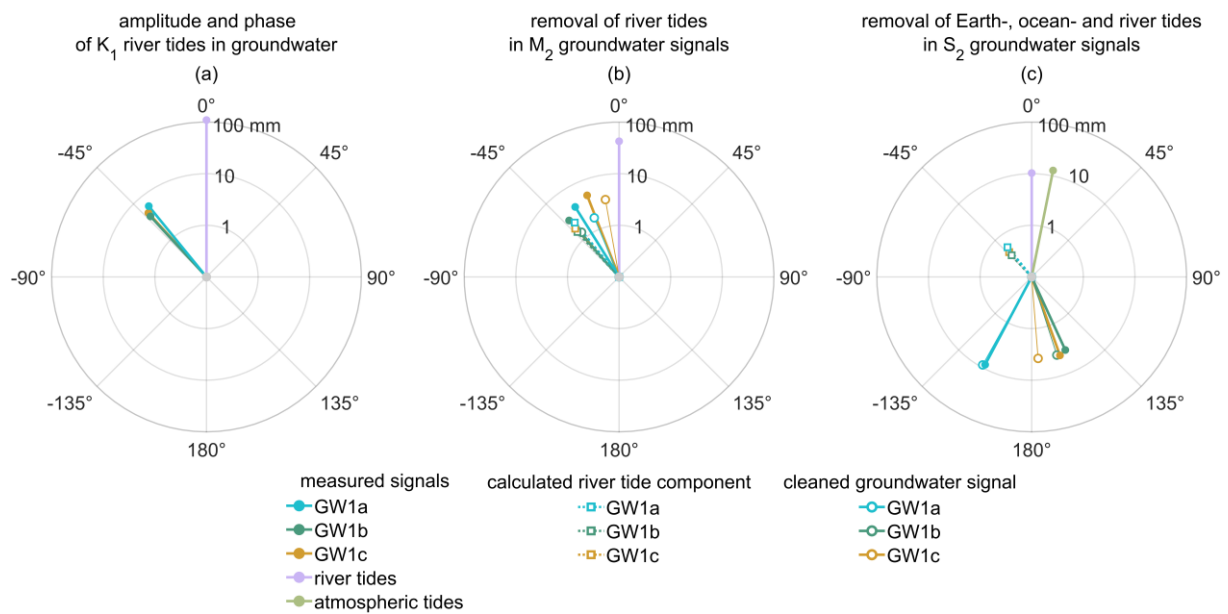


Figure 11 Results of the signal disentanglement using Eq. (7) to Eq. (10). The signals comprise of amplitude and phase of K_1 river tides in groundwater signals (a), the removal of river tides in M_2 groundwater signals (b) and the removal of Earth tides, ocean tide loading on the solid Earth, and river tides (c). Note the logarithmic scale of radial axes in the polar plots.

3.4 Multi-factor regression deconvolution

Figure 12 summarizes the response functions to atmospheric tides (Figure 12a, utilizing data from Figure 10 d-l), (ii) volumetric strains due to Earth tides and OT_{SE} (Figure 12b, utilizing the sum of timeseries in Figure 10 a-l and a-II), (iii) pond water loading (Figure 12c, utilizing data

from Figure 8b) and (iv) river water levels (Figure 12d, utilizing data from Figure 10 c-I), obtained from the multi-factor regression deconvolution for GW1a (Figure 12a-I to d-I), for GW1b (Figure 12a-II to d-II) and for GW1c (Figure 12a-III to d-III). This includes an illustration of the calculated uncertainty of each response function. Given that the response functions are the cumulative sum of the respective IRCs, uncertainties of the IRCs accumulate in the response function with increasing time lag consideration.

The response functions of GW1c are characterized by small standard deviations, whereas the multi-factor regression deconvolution yields large standard deviations for GW1a and GW1b. The regression deconvolution yields a good $R^2 = 0.89$ for GW1c. For GW1a and GW1b moderate to poor R^2 of 0.55 and 0.16 are calculated within the multi-factor regression deconvolution.

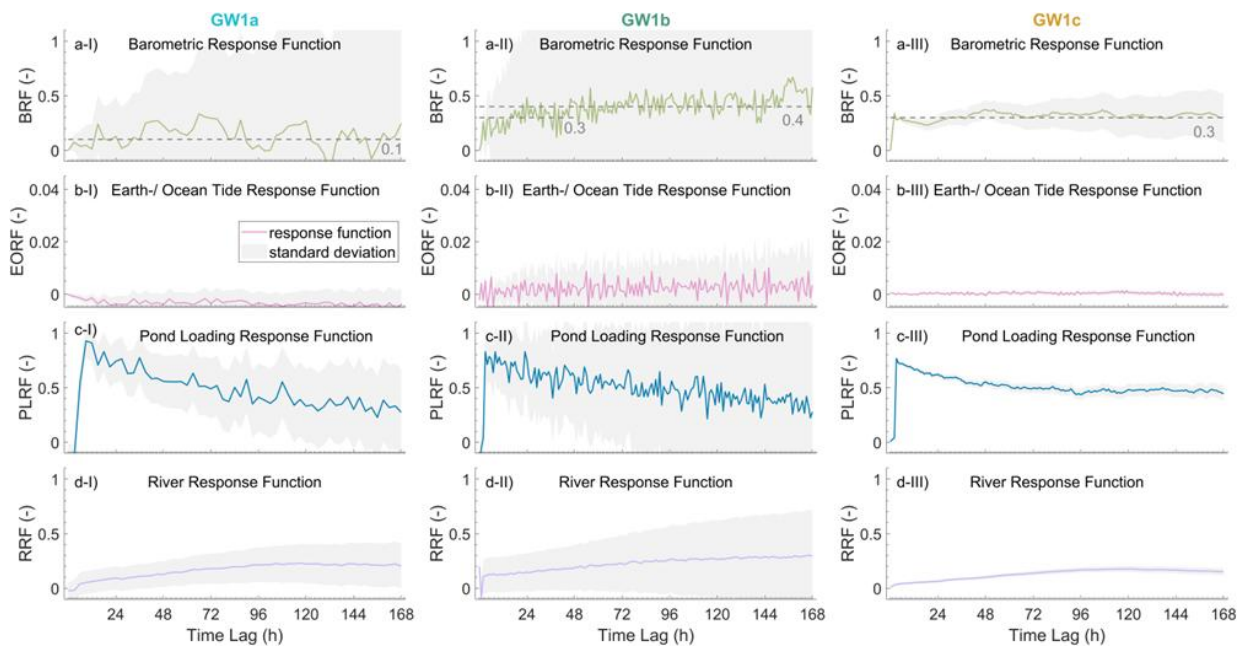


Figure 12: Response functions obtained from MUFACO for barometric loading (a) Earth tide- and OT_{SE} -strains (b) pond water loading (c) and river water loading (d) for the observation wells GW1a (I), GW1b (II) and GW1c (III) under consideration of maximum time lag of 7 days (168 hours)

For GW1c, the BRF approaches a constant value of approx. 0.3 (Figure 12a-III), from which $\gamma_{GW1c} \approx 0.7$ can be derived with Eq. (5). For GW1a, the BRF varies around an average value of approx. 0.1, suggesting $\gamma_{GW1a} \approx 0.9$ while for GW1b, the BRF approaches a value of approx.

0.3 in the first 48 hours of time lag consideration and later approx. 0.4, which would suggest $\gamma_{GW1b} \approx 0.6-0.7$. The response function to Earth tide- and OT_{SE}-strains (denoted as Earth- and ocean- tide response function EORF) of all three wells (Figure 12b) approach constant values < 0.01 .

The response function from the calculated pond water level, denoted as pond loading response function PLRF, are characterized by an initial rise followed by decreasing trends converging towards a constant value for all three observation wells. For GW1a (Figure 12c-I), the PLRF peaks at approx. 0.9 and decreases to approx. 0.3, whereas for GW1b (Figure 12c-II), the PLRF decreases from 0.8 to 0.3. The PLRF of GW1c (Figure 12c-III) is characterized by less noise and a decrease from 0.75 to approx. 0.4. The river water response functions (Figure 12d) are characterized by increasing trends, resulting in plateaus of approx. 0.22 for GW1a, 0.30 for GW1b and 0.17 for GW1c, respectively.

For comparison, the BRF was additionally derived for GW1c with MUFACO considering barometric pressure as the only driver, neglecting Earth-, ocean- and river tides as well as pond loading. This comparative analysis resulted in a distinctly different BRF, characterized by an oscillation and increase up to 0.75 and a poor R^2 of 0.37. The poor R^2 and the resulting high standard deviation in the response functions at GW1a and GW1b are attributable to accumulating uncertainties of the IRC and are a consequence of the low sensor precision of GW1a and GW1b (Figure 2b).

3.5 Estimated correction of groundwater head data

The observed groundwater head data was corrected from loading signals using the calculated response functions for barometric pressure, volumetric strains due to Earth tides and OT_{SE}, precipitation-evaporation based loading of ponds and river water levels (Figure 12). Figure 13

summarizes the obtained estimation of the corrected groundwater heads for the three observation wells at GW1, indicating depleting groundwater levels for all wells, when loading signals are removed from the observation data. For GW1a, GW1b and GW1c, the observed groundwater heads are characterized by increasing trends of 1.29 m a^{-1} , 1.10 m a^{-1} and 1.24 m a^{-1} respectively during the rainy season, whilst the corrected heads indicate depleting trends of -0.59 m a^{-1} , -0.65 m a^{-1} and -0.44 m a^{-1} respectively.

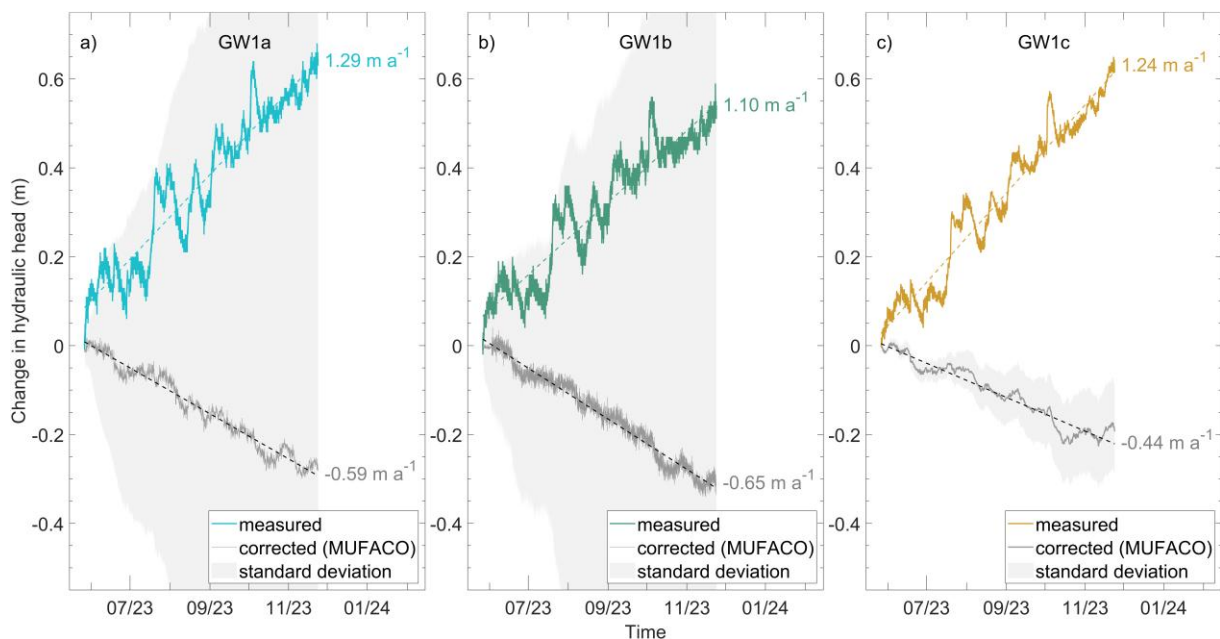


Figure 13: Corrected groundwater heads for GW1a (a) GW1b (b) and GW1c (c) based on a multi factor regression deconvolution under consideration of barometric pressure, Earth tide- and OT_{SE} -strains, pond water loading and river water levels under a maximum time lag consideration of 7 days (168 hours).

The standard deviations of the response functions (Figure 12) are projected into the standard deviation of the corrected groundwater levels (Figure 13). For GW1c (Figure 13c) the minor standard deviations in the response functions (Figure 12 a-d III) lead to a moderate standard deviation in the corrected head, encompassing corrected depletion rates ranging from -0.23 m a^{-1} to -0.66 m a^{-1} . For GW1a and GW1b, the high standard deviations of the response functions are transferred into high standard deviations for the corrected heads.

For comparison, the groundwater heads at GW1a, GW1b and GW1c were corrected based on the derived loading efficiencies γ and the area-averaged surface loading $\Delta\sigma_L$ for each of the three wells. Based on the three applied approaches to calculate the loading efficiency, $\gamma_{GW1a}=0.9$, $\gamma_{GW1b}=0.7$ and $\gamma_{GW1c}=0.7$ were utilized for the correction. Given that the accumulation of water resources on vegetated land cannot be quantified precisely with the data available, the surface loading $\Delta\sigma_L$ and therefore also the corrected groundwater heads are characterized by a value range, depending on the considered share of water accumulation on vegetated land between 0% and 50%. Figure 14 shows that for GW1a, GW1b and GW1c the corrected heads based on γ and $\Delta\sigma_L$ comply best with the deconvolution-based correction for a respective share of water accumulation on vegetated land of 25%, 46% and 36%. These shares imply that depending on the distance to GW1, 54% - 75% of the vegetated land discharge surface water out of the wells' responding area, while the remaining fraction underlies the balance of accumulated precipitation and evaporation.

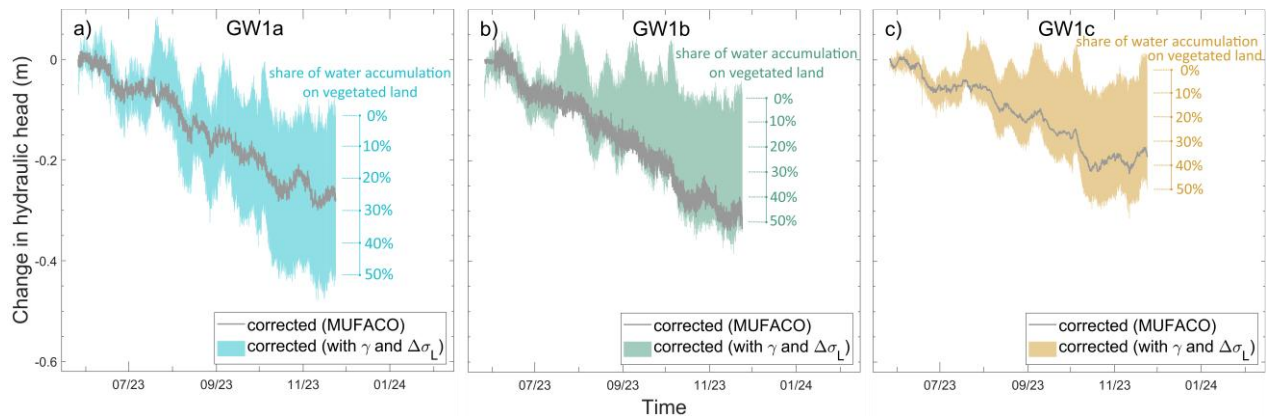


Figure 14: Corrected groundwater heads for GW1a (a) GW1b (b) and GW1c (c) based on derived loading efficiencies and seasonal surface loading dynamics. For comparison, the corrected groundwater heads based on MUFACO (Figure 13) are included in the graphs.

4 Discussion

4.1 Quantification of loading signals in deltaic groundwater systems

The loading efficiency γ is derived in the frequency domain using a novel extension of previously introduced methods to assess the S_2 response of groundwater heads to atmospheric tides. While previous frequency-domain methods were only applicable in the absence of river and ocean tide loading (Acworth et al., 2016; Rau et al., 2020), the method extension presented in this work covers a disentanglement of multiple influences, such as Earth-, OT_{SE} -, atmospheric-, and river tides in groundwater heads. The presented K_1 -based removal of river tide influences on groundwater head amplitude spectra enables the application of S_2 -based methods for the calculation of γ in deltaic groundwater systems, where superposing multiple tidal forcings govern tidal constituents in groundwater heads.

The results of this novel extension are verified using two additional independent methods: (i) the barometric response function (BRF), and (ii) the groundwater head response to distinct precipitation events. All three methods yield consistent results of $\gamma_{GW1a} \approx 0.9$, $\gamma_{GW1b} \approx 0.7$ and $\gamma_{GW1c} \approx 0.7$, confirming that the new frequency-based approach is valid.

The calculated $K_1:M_2$ amplitude ratio in groundwater heads lie within 0.95-1.47 and therefore between the $K_1:M_2$ amplitude ratios in Earth tide- and OT_{SE} -strains (0.24) and the $K_1:M_2$ ratio in river water levels (2.57). This, together with the conducted magnitude-squared coherence analysis, indicates the presence of river tide imprints in groundwater head amplitude spectra and underlines the necessity to disentangle these influences with the introduced novel approach (Eq. (7)-(10)).

668 The method's presumption of insignificant K_1 contribution from Earth tide- and OT_{SE} -strains to
 669 groundwater signals is evaluated by a multiplication of the $K_1:M_2$ amplitude ratio in Earth tide-
 670 and OT_{SE} -strains (0.24) with the M_2 amplitude in groundwater due to Earth tide- and OT_{SE} -
 671 strains (1.7 mm, 1.3 mm, 3.3 mm, see Figure 11b). This simplified consideration results in
 672 calculated amplitudes of 0.4 mm, 0.3 mm, 0.8 mm, which equals a share of 7%, 8% and 17%
 673 of Earth tide- and OT_{SE} -strain contribution to the K_1 signal in groundwater heads. While these
 674 contributions are minor compared to the river tide signals, they might not per se be
 675 considered negligible. However, given that the complementary calculation of BE without
 676 consideration of river tides and OT_{SE} based on the method of Rau et al. (2020) shows minimal
 677 variations of BE (0.00 - 0.02), inaccuracies due to simplifications within this method are
 678 negligible for the application with the given tidal composition at the study site. The
 679 uncertainties in the HALS-based estimation of tidal constituents (Table 3) are generally low,
 680 and given the consistency with loading efficiencies derived from other methods, uncertainties
 681 in the tidal constituents are considered to have a negligible effect on the calculated $BE_{S_2}^{AT}$ and
 682 γ .

683 The investigation of rainfall loading responses in deep observation wells is an established
 684 method for the assessment of loading signals in groundwater head data (Sophocleous et al.,
 685 2006; Bardsley and Campbell, 2000; Jan et al., 2007) and is suitable to verify the results of the
 686 novel approach that disentangles multiple influences. In assessments of rainfall loading
 687 responses, uncertainties may originate from limitation of the groundwater level and the
 688 accuracy of the precipitation monitoring instrument. While more intense precipitation events
 689 result in a clearer groundwater level response, there is a concomitant decrease in the accuracy
 690 of the recorded precipitation. Moreover, intense precipitation events, which typically occur in
 691 the tropical monsoon rainfall environment of Southeast Asia, commonly underly high

692 spatiotemporal variation (Mandapaka et al., 2017), highlighting the need for on-site
 693 precipitation records when evaluating groundwater head responses to precipitation loading.
 694 The minor to moderate variations in the calculated loading efficiency of ± 0.02 to ± 0.06 across
 695 three independent precipitation events (Table 2) align well with estimates of γ based on BRF
 696 and $BE_{S_2}^{AT}$. In contrast to the first and third precipitation events, which lasted approximately
 697 2 and 6 hours respectively, the second event extended over a substantially longer period of
 698 about 150 hours. Given the derived time factors and the general assessments of Smith et al.
 699 (2017), such long-duration precipitation events may allow for pore pressure dissipation
 700 through groundwater flow, whereas the shorter events can be considered instantaneous in
 701 terms of loading. Accordingly, the two short events are more appropriate for estimating the
 702 loading efficiency γ . The long-duration event yields a notably higher γ at GW1b, whereas γ
 703 values at GW1a and GW1c remain in the range of those derived from the shorter events.
 704 Overall, the results support the method's applicability in the study area, particularly for short-
 705 term precipitation events, and underline its potential for application in other deltaic aquifer
 706 systems in Southeast Asia with similar hydrometeorological and hydrogeological settings.

707 Calculating the BRF is a well-established method for the estimation of BE and γ (Furbish 1991;
 708 Rasmussen and Crawford, 1997; Turnadge et al., 2019). The present study derives the BRF
 709 within a multi-factor regression deconvolution, and not only from barometric and
 710 groundwater observations. The consideration of all relevant loading signals within MUFAO
 711 proved essential, given that a comparative analysis considering barometric pressure as the
 712 only driver suggested distinctly different values for BE and γ compared to the complete
 713 consideration with additional Earth-, ocean- and river tides as well as pond loading. To the
 714 authors' best knowledge, this study is first to consider multiple forcings, such as Earth-, ocean-

and river tides as well as seasonal surface water accumulation, when calculating BRF, BE and γ . This allows application in more settings such as deltaic aquifers.

Oscillating BRF-patterns as in BRF_{GW1a} (Figure 12a-I) are indicative for non-constant groundwater extraction influencing the regression deconvolution (Haehnel et al., 2024). Dörr et al. (2025) showed that periodic groundwater extraction can leak into amplitude spectra of observation wells at harmonics, i.e., multiples of S_1 , including S_2 and S_3 . Therefore, the presence of the S_3 amplitude peak (Figure 10d-III) and the oscillating BRF-pattern at GW1a are indicators for nearby groundwater extraction, afflicting the observed S_2 groundwater amplitude.

Overall, the results demonstrate the presence of loading signals in observed groundwater heads across the three aquifers in the southern VMD and establish a solid quantification of γ . This is supported by independent analyses in both the frequency domain (Figure 10) and the time domain, covering periods from a few hours (Figure 9a) to days (Figure 9b) and months (Figure 8c). Furthermore, the findings align with recent research (Hoang and Steinel, 2021; Dörr et al., 2025) in identifying loading signals in the southern VMD. For the first time, this study provides a quantification of the loading efficiency of γ for three vertically stacked and highly exploited aquifers in the deltaic aquifer of the southern VMD. Further applications in the study area would benefit from more multi-parameter monitoring stations comprising observations of groundwater dynamics, soil moisture and meteorological parameters, such as the here utilized study site GW1.

4.2 Seasonal loading characteristics

The dynamics of observed groundwater heads have an evident correlation with the calculated loading due to pond water level dynamics in the rainy season (May to November, Figure 8c). Based on the elaborated framework of groundwater-loading response for confined

groundwater systems (Eq. (3)), the local aquifer-aquitard stratification (Figure 1b), as well as the time scale of the groundwater-loading responses (Figure 9, Figure 12) this correlation strongly suggests, that loading effects cause the apparent seasonal rise in groundwater heads.

Directly after precipitation events, the load of the fallen rainwater exerts a spatially extensive and uniform load (Figure 9 and peaks in Figure 8c), as well as equally rising river water levels (Figure 8c). Given that the river water levels regulate the responding area's drainage dynamics, the correlation of increasing and decreasing groundwater head dynamics after intensive precipitation events (peaks in Figure 8c) with the river water level dynamics is associated to drainage and temporary loading-unloading dynamics. Therefore, the correlation of river water levels and groundwater heads is particularly well pronounced when heads peak and decrease due to distinct intensive precipitation events and the subsequent drainage (Figure 8c).

The rise in pond water levels, calculated by means of accumulated precipitation and evaporation, complies well with reported seasonally rising water levels in intensive shrimp farming ponds in the study area, as observed by Anh et al. (2010). However, in the absence of direct monitoring data on pond water levels and records of supplemental water use, a more precise characterization of water level dynamics in the aquaculture ponds is not feasible for the investigated study site. Considering legal restrictions on groundwater abstraction for aquaculture (Van Binh et al., 2025) and the declining quality of surface water, the availability of suitable water sources for supplemental use appears limited. The overall good agreement between the precipitation–evaporation-based estimates and both reported seasonal pond water level trends and the loading efficiencies derived from the PLRF and other approaches in this study supports the validity of using precipitation and evaporation as proxies for pond water levels in the study area. Future investigations would benefit from continuous

monitoring of pond water levels and quantification of supplemental water use in aquaculture systems. Given the rapid expansion of coastal aquaculture in Southeast Asia (Luo et al., 2022), precipitation accumulation in such ponds likely represents a significant surface loading process influencing groundwater head dynamics in confined deltaic aquifer systems across the region.

Whilst the accumulation of surface water induces an increase in observed groundwater levels during the rainy season (May to November in Figure 8c), declining surface water levels in the dry season, e.g. due to pond water evaporation and significantly lower river water levels due to reduced upstream discharge of the Mekong River, equally cause a decline of observed groundwater heads. However, due to the lack of longer (i.e., complete annual) datasets, the present analysis is largely restricted to evaluating loading dynamics during the rainy season, which curtails the full potential of the presented approach. Multi-year time series encompassing several seasonal loading and unloading cycles would provide a valuable basis for future investigations aiming to correct groundwater head variations for surface loading effects in the VMD. In the absence of continuous dry-season observations, unloading dynamics can only be addressed qualitatively for short subperiods in this study. For instance, the short temporary rise in observed groundwater levels at GW1 during the dry season in February 2023 shows an evident correlation with the river water level dynamics (highlighted by a square box Figure 8c). This is interpreted to be due to unloading caused by a temporary hydraulic connection of aquaculture ponds and the multi-channel system, as a result from pond flushing activities, a common practice for sludge removal between production cycles during this time (Anh et al., 2010).

A comparison of the response functions to river water levels (Figure 12d) and pond water loading (Figure 12c) shows a stronger response to the calculated loading of ponds than to the

river water levels. Together with the evaluation of pond sizes, field observations, and the elaborated interpretation of the PLRF, this supports the assumption that the majority of the aquaculture ponds within the study area are operated as intensive shrimp farming ponds and accumulate water from precipitation.

The identification of surface loading as a major contributor to rising groundwater heads in the southern VMD enables a more refined evaluation of groundwater responses to periods of extreme hydrological conditions, such as dry-season droughts or exceptionally wet rainy seasons. Within this framework, severe groundwater depletion during droughts can be attributed not only to increased water demand but also to exceptionally low surface water levels and the associated unloading effects. Similarly, rainy seasons with exceptionally high precipitation and the resulting elevated surface water levels induce a more pronounced seasonal rise in groundwater heads compared to rainy seasons with average rainfall.

4.3 Aquifer confinement status: Surface water drainage vs. aquitard leakage

The pond loading response functions obtained from the multi-factor regression deconvolution are characterized by an initial rise and a subsequent decrease with increasing time lag consideration (Figure 12c). The initial peaks represent the loading efficiency as they feature the groundwater responses to precipitation events, which exert a uniform loading within the entire responding area of the observation well at first. These peak values comply well with the loading efficiency derived from BRF, $BE_{S_2}^{AT}$ and the response to the selected distinct precipitation events. Whilst aquaculture ponds are considered to accumulate precipitation and hence the load, urban areas and parts of vegetated land drain the rainwater into the multi-channel systems, from where it is discharged from the responding area of the observation well. This causes a decrease of the overall load, which manifests as a decrease in the PLRF

curve. Understanding the decreasing trends of the PLRF curves as unloading signals due to surface water drainage, the values towards which the PLRF converges are associated with the product of the loading efficiency and the percentage of area, which accumulates water resources over the rainy season. For all PLRF curves (Figure 12c), this complies well with the derived LULC-classification considering ponds and parts of vegetated land (Figure 7b) and loading efficiencies, in particular for GW1c (Figure 12c-III), where due to a good sensor resolution, the uncertainty of the response function is minimal. This suggests that the various surface loading of individual LULC can be simplified to a uniform loading based on their share of land cover. However, unless the accumulation of water resources can be formulated precisely for all LULC-classes, the removal of loading signals based on γ and $\Delta\sigma_L$ can only provide a range of possible corrected groundwater heads (Figure 14) depending on the accuracy of $\Delta\sigma_L$ estimates for each LULC-class and the representativeness of the responding area. With regard to the latter, Figure 7b shows minor variations in the spatial distribution of LULC-class, thereby indicating that imprecise estimates on the size of the responding area would have little impact on the corrected groundwater heads.

While decreasing trends in response functions are commonly indicative for semi-confined conditions (Butler et al., 2011; Hussein et al., 2013), the obtained decreasing trends of the pond loading-response functions are attributed to surface drainage processes in the study area. A misinterpretation of the decreasing trends in response functions as an indicator for aquitard leakage or aquitard drainage would be precarious in the context of land subsidence due to aquitard compaction. Further investigations on the correlation of groundwater depletion and sediment compaction due to aquitard drainage are required, such as depth-differentiated multi-extensometer compaction monitoring (Dörr et al., 2023).

834 With the available data, an independent quantitative consideration of these drainage-induced
835 temporary loading-unloading processes is not possible beyond the presented descriptive
836 assessment. Further studies, aiming to enhance the assessment of seasonal loading signals by
837 the calculation of a uniform loading time series for the loading response areas of the
838 groundwater wells, need to consider and verify the water balance of all LULC-classes. This
839 would include a quantification of plant and canopy water accumulation as well as multi-year
840 time series encompassing measurements of pond water levels, temporary inundation levels
841 of vegetated land as well as investigations on the source and use of supplemental water in
842 aquacultural practices.

843 For barometric as well as Earth- and ocean tide loading signals, which are predominantly
844 characterized by (semi-)diurnal loading cycles, the vertical transient flow of groundwater due
845 to the pore pressure in Eq. (3) may be neglected, as the estimated time factors of 1.4 to 6.7
846 days are greater than the (semi-)diurnal loading duration (van der Kamp and Schmidt, 2017).
847 This is substantiated by the shape of the BRF and EORF curves (Figure 12a-b) which are
848 characterized by plateaus and therefore indicate confined conditions, i.e. no vertical flow from
849 an overlying aquitard due to the processes under consideration.

850 Conversely, for longer loading cycles like the seasonal pond water loading, the vertical
851 transient flow of groundwater may generate a certain flow. The time factor T describes the
852 duration in which 93 % of the consolidation and associated drainage processes are completed
853 (Shukla et al., 2009; Terzaghi, 1943). Therefore, using a time lag of 7 days (168 hours) is
854 sufficient to capture potential contributions of vertical flow to the groundwater-loading
855 response within the multi-factor regression deconvolution for the study area, where T was
856 estimated between 1.4 and 6.7 days. However, as the shape of the PLRF curve is governed by
857 drainage processes of surface water resources, which equally cause a declining trend in the

response function, the present study cannot provide evidence for or against aquitard leakage processes based on the shape of response functions.

4.4 Corrected groundwater heads and implications for groundwater recharge

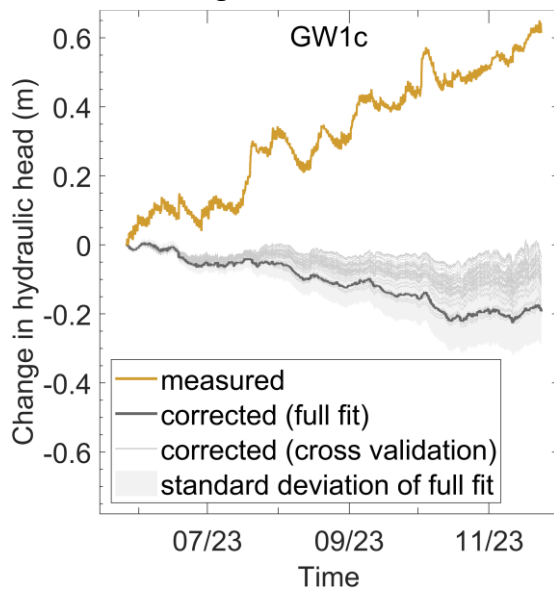
Regression deconvolution has been applied in multiple previous studies to remove diverse influences on groundwater heads, e.g., barometric pressure (Furbish 1991; Rasmussen and Crawford, 1997), Earth tides (Toll and Rasmussen, 2007), soil moisture and variations in surface water storage (van der Kamp and Maathuis, 1991), river water levels (Spane and Mackley, 2011), sea levels (Haehnel et al., 2024) or to evaluate aquifer hydraulic conductivity with atmospheric slug test (Valois et al., 2022; 2023).

The multi-factor regression deconvolution applied in this study allows an individual and more flexible consideration of multiple influences (Haehnel et al., 2024) and is therefore suitable for the assessment and removal of multiple forcings on observed groundwater levels as given in deltaic groundwater systems. To the best of the authors' knowledge, this study is the first to consider a variety of natural forcings in the correction of observed groundwater heads, including Earth, ocean and river tides, barometric pressure variations as well as surface water accumulation in anthropogenically managed environments.

In the study area, the removal of loading signals during the rainy season reveals corrected groundwater heads with downward trends, whilst the observed (uncorrected) groundwater heads show rising trends. The estimated corrected depletion rates during the rainy season of -0.59 m a^{-1} , -0.65 m a^{-1} and -0.44 m a^{-1} are below the annual average depletion rates of -0.70 m a^{-1} , -0.97 m a^{-1} and -0.73 m a^{-1} for the three assessed observation wells calculated between rainy season onsets 2023 and 2024 (Figure 2a).

881 The corrected groundwater heads derived from the multi-factor regression deconvolution are
882 subject to uncertainties. The illustrated standard deviations in the results demonstrate that
883 the measurement precision and resolution of groundwater level sensors exert a pronounced
884 influence on the magnitude of these uncertainties. At observation wells GW1a and GW1b,
885 groundwater heads were recorded with low precision (Figure 2b), resulting in equally
886 imprecise response coefficients. The uncertainties of the response coefficients accumulate in
887 the response function and ultimately manifest in the uncertainties of the corrected
888 groundwater heads. Figure 12 and Figure 13 illustrate that both response functions and
889 corrected heads exhibit substantial uncertainties at GW1a and GW1b, where sensor
890 resolution is low, whereas uncertainties are minimal to moderate at GW1c, where
891 measurements were obtained with higher precision. This pattern is also reflected in the R^2 of
892 the regression deconvolution, characterized by good R^2 of 0.89 for GW1c and moderate to
893 poor R^2 of 0.55 and 0.16 for GW1a and GW1b respectively. Despite their low R^2 values and
894 high standard deviations, the response functions and corrected heads at GW1a and GW1b are
895 considered reliable, supported by the consistency of groundwater dynamics (Figure 2a) and
896 response functions (Figure 12) with those of GW1c, as well as their overall agreement with
897 other methods applied in this study. In addition to uncertainties arising from sensor
898 resolution, uncertainties in the estimation of pond water loading, derived here from a
899 precipitation–evaporation-based approach, contribute to the overall uncertainty of the
900 corrected heads. To reduce these effects in future studies, continuous monitoring of pond
901 water levels is recommended.

902 Within a cross-validation framework, the performance of the multi-factor regression
 903 deconvolution was evaluated exemplarily for GW1c. For this purpose, a set of response
 904 functions was derived from 60 sub-datasets, each covering 120 days of the complete
 905 observation period, and subsequently applied to correct the full groundwater head time
 906 series. Figure 15 illustrates that all 60 corrected time series consistently confirm the overall



depletion trend, albeit with a less pronounced decline compared to the correction based on the full dataset. This result supports the interpretation of persistent groundwater depletion and, at the same time, emphasizes the importance of long-term records comprehensive model validation for a more accurate quantification of the depletion rate.

914 *Figure 15 Measured and corrected groundwater heads for GW1c, including 60 corrected time series derived within the cross-*
 915 *validation framework*

916 In light of the outlined uncertainties, independent validation is necessary to strengthen the
 917 presented conclusions regarding persistent groundwater depletion. Such validation could
 918 involve analyses of mass variations derived from the Gravity Recovery and Climate Experiment
 919 (GRACE) satellite mission (Tapley et al., 2004), combined with observations of pond and river
 920 water levels and detailed records of groundwater extraction rates at monthly or higher
 921 temporal resolution. Considering legal restrictions on groundwater use for large-scale rice
 922 farming and aquaculture (Van Binh et al., 2025), it is reasonable to assume that a substantial
 923 share of groundwater extraction meets seasonally independent demands, such as domestic
 924 water use. Considering the long-term annual-average groundwater depletion rates of recent
 925 years and decades together with the conceptual framework presented here, which attributes
 926 seasonally rising groundwater heads to surface loading, a persistent decline in loading-

corrected groundwater heads throughout the seasons appears realistic. Thus, the smaller yet pronounced depletion rates obtained from the corrected groundwater heads during the rainy season appear reasonable compared to the annual-average groundwater depletion rates. Depending on the underlying uncertainties, the magnitude of these depletion rates may vary, yet the overall pattern is consistently reproduced.

Overall, the evaluation of uncertainties in the corrected groundwater heads indicates that the derived depletion rates may not accurately represent the actual loading-corrected groundwater dynamics. Nevertheless, they support the overall conclusion that loading-corrected groundwater heads decline during the rainy season, whereas the measured data show a rising trend.

In addition to the loading correction by multi-factor regression deconvolution (Figure 13), groundwater heads were corrected based on the derived loading efficiency γ and the change of the area-averaged surface load $\Delta\sigma_L$ (Figure 14). Due to the uncertainty about surface water accumulation on vegetated land, groundwater heads corrected by this method are characterized by a high uncertainty. A comparison with the groundwater head correction by MUFACO suggests that 25% (GW1a), 46% (GW1b) and 36% (GW1c) of the vegetated land accumulate water resources based on the balance of precipitation and evaporation, while the remaining share of vegetated land is drained. Given that unintended flooding and inundation of agricultural farmland can be counteracted relatively effectively in the VMD by its complex multi-channel system of irrigation and drainage channels (Le et al., 2023), this is in a reasonable order of magnitude and substantiates the correction based on MUFACO.

The comparison of the two approaches for the correction of loading signals underlines that, unless a precise water balance within the loading response area of an observation well can be formulated, a correction of groundwater heads by multi-factor regression deconvolution is

preferable to a correction based on calculated values for γ and derived surface loading timeseries.

Overall, the evaluation of loading-corrected groundwater heads indicates that groundwater recharge, if present, is insufficient to compensate for extractions in the assessed aquifers. This aligns with the local and regional thicknesses of the Holocene Q₂ aquitard of approx. 20-30 m (Figure 1b; Anderson, 1978; Pham et al., 2019; Bauer et al., 2022), through which percolation of surface water is considered unlikely at the timescale considered in this study. By the multi-factor regression deconvolution, any significant rise in observed heads was attributed to local loading processes on the ground surface. The loading-corrected time series therefore contain no indication for possible recharge at potential aquifer outcrops, which have been shown to propagate as pressure signals through confined aquifers (Armstrong & Narayan, 1998).

In previous studies (Duy et al., 2021), a relationship between groundwater and river water levels in the VMD was identified using time series analysis. However, as the authors acknowledge themselves, the applied black-box correlation is incapable of exploring the causes for the observed relationship. Therefore, considering the present results, the postulation of possible groundwater recharge to shallow and deep aquifers during the flood season should be reconsidered. The present analysis shows that the observed groundwater dynamics can be consistently explained by mechanical loading responses rather than by actual infiltration and recharge. Data-driven approaches can provide valuable insights into process dynamics, but their interpretation must remain embedded within a consistent physical framework. In the context of this study, that framework is the groundwater response to mechanical surface loading. When recharge is postulated, as in Duy et al. (2021), its plausibility should be evaluated in light of the actual hydraulic gradients and transmissivities controlling recharge flow processes.

975 Furthermore, the applicability of the water-table-fluctuation method must be carefully
976 reconsidered wherever the investigated aquifer is confined or not developed, such as at the
977 monitoring sites Q177 and Q199 in the southern VMD analyzed by Van et al. (2023). The
978 water-table-fluctuation method attributes rising groundwater heads to groundwater
979 recharge. While this approach is feasible for unconfined aquifers, its application in confined
980 settings is inappropriate and can lead to a misinterpretation of loading-induced head increases
981 as recharge. Under such conditions, the observed rise in groundwater heads in the southern
982 VMD most likely reflects hydro-geomechanical responses to surface loading rather than actual
983 infiltration or recharge.

984 Overall, this study challenges previous interpretations by Duy et al. (2021) and Van et al.
985 (2023), which attributed groundwater responses to precipitation and river water levels as
986 indicators of recharge without appropriately accounting for surface loading effects.

987 This study highlights the importance of identifying and removing loading signals from
988 groundwater head data for strongly confined aquifers in aquaculture-dominated deltaic
989 systems to achieve an accurate understanding of water resource dynamics. It emphasizes that
990 reliable groundwater recharge assessments in such environments must account for these
991 loading effects. By doing so, the findings provide valuable guidance for efforts to determine
992 sustainable groundwater extraction rates and preventing further depletion. Future research
993 could combine the presented data-driven approach with physically based methods to further
994 assess potential groundwater recharge and verify both local and regional water balances. In
995 particular, obtaining reliable groundwater extraction data for use in comprehensive water
996 balance analyses, together with a delta-wide hydro-geomechanically coupled groundwater
997 model that accounts for surface loading, would provide a sound framework for more holistic
998 recharge assessments. Such integrative approaches would enable a more detailed

understanding of the spatial and temporal variability of actual recharge processes and surface loading, as well as the associated groundwater head dynamics, thereby supporting the validation of recharge estimates derived from the groundwater-loading analysis presented in this study.

By showing that groundwater recharge, if present at all, is insufficient to compensate for the current exploitation, the present study highlights the necessity for developing alternative freshwater resource strategies as essential concepts for the region's sustainable development.

5 Conclusion

Observed rising trends in groundwater heads within confined aquifers may not necessarily indicate groundwater recharge, as these trends can also be attributed to mechanical loading at the surface. A comprehensive analysis of loading signals in groundwater heads in the southern VMD between 2023 and 2024 strongly suggests that the seasonal rise in groundwater heads is primarily due to the accumulation of surface water in aquaculture ponds during the rainy season. By removing these loading signals from groundwater observation data, the trend reverses, showing declining groundwater heads. This implies that not only in dry but also in rainy season, groundwater recharge, if present, is incapable of compensating for the groundwater exploitation in the study area. Independent validation, for example using GRACE-based mass balances, is essential to substantiate the conclusions on persistent groundwater depletion.

The influence of temporary flooding and inundation on surface loading processes in deltas has been a persistent phenomenon over the course of geological history. However, the recent

rapid expansion of aquaculture ponds has introduced a new infrastructure capable of holding substantial surface water volumes. This shift in land use and land cover is a common feature in many deltaic and coastal zones across Southeast Asia, highlighting the broader relevance of this study beyond the southern VMD. Future research would greatly benefit from monitoring data on pond water level dynamics, solid quantification of hydraulic properties, water balances and other factors contributing to seasonal surface loading to improve the correction of groundwater heads in confined aquifers beneath.

Data-driven approaches to groundwater recharge assessment must be firmly grounded in a consistent physical framework. Purely statistical correlations between surface and groundwater levels may lead to misinterpretations of recharge processes. The preconditions for applying easy-to-use methods, such as the water table fluctuation method, must be carefully evaluated, as these methods are not suitable for confined aquifer systems. Within the framework of groundwater-loading response in confined aquifers, the analysis of groundwater head responses to distinct precipitation events represents a straightforward and effective diagnostic indicator of loading effects. A sound quantification of surface and, where present, unconfined aquifer water balances provide an essential foundation for the (multi-)seasonal correction of groundwater head time series for loading signals. Combined with a robust definition of loading efficiency, or integrated within a multi-factor regression deconvolution, these water balances constitute key input parameters for isolating and removing loading signals from groundwater head time series on (multi-)seasonal time scales. Furthermore, the reliability of such deconvolution-based corrections strongly depends on the availability of long-term observation records and should be systematically tested, for example through cross-validation, to ensure robust and transferable conclusions.

The method of calculating an aquifer's loading efficiency from the groundwater head responses to atmospheric tides at the S_2 frequency has seen significant development over the past decade. Unlike earlier approaches limited to areas without river and ocean tidal influences, the current method incorporates these additional tidal drivers into the analysis, representing a novel advancement. This advancement enables the calculation of loading efficiency using S_2 -based methods in deltaic groundwater systems elsewhere, where multiple tidal forcings influence the tidal constituents in groundwater heads.

These findings provide valuable insights for groundwater recharge assessments and play a critical role in shaping sustainable water resource management strategies in the southern Mekong Delta and other confined deltaic aquifers. By evaluating loading signals within groundwater time series, this study advances a more holistic understanding of groundwater dynamics - especially the coupling between hydrological and geomechanical processes - in confined deltaic aquifer systems.

CRediT authorship contribution statement

Felix Dörr: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Visualization

Jonas Bauer: Formal analysis, Investigation, Visualization, Writing – review and editing

Gabriel Rau: Conceptualization, Methodology, Validation, Writing – review and editing

Elias Lewi: Methodology, Writing – review and editing

Hoan Viet Tran: Data curation, Investigation, Writing – review and editing

Remi Valois: Software, Writing – review and editing

Le Thi Mai Van: Data curation, Project administration, Writing – review and editing

Anke Steinel: Conceptualization, Writing – review and editing

Franz Nestmann: Funding acquisition, Project administration, Resources, Supervision, Writing – review and editing

Stefan Norra: Funding acquisition, Project administration, Resources, Supervision, Writing – review and editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this study are available at a Zenodo repository:

<https://doi.org/10.5281/zenodo.17279956>

Acronyms and Abbreviations

BE: Barometric Efficiency

BRF: Barometric Response Function

ERF: Earth Tide Response Function

1083 EORF: Earth- and Ocean Tide Response Function
1084 FFT: Fast Fourier Transform
1085 GRACE: Gravity Recovery and Climate Experiment
1086 HALS: Harmonic Least Squares
1087 IRC: Instantaneous Response Coefficient
1088 LULC: Land-Use Land-Cover
1089 MUFACO: Multi-Factor Correction of Groundwater Levels
1090 OT_{GW} : Ocean Tide Loading on the Aquifer's Water
1091 OT_{SE} : Ocean Tide Loading on the Solid Earth
1092 PLRF: Pond Loading Response Function
1093 PT: Pressure Transducer
1094 RRF: River Response Function
1095 VMD: Vietnamese Mekong Delta
1096

1097 Acknowledgements

1098 This research was conducted in the frame of the project “ViWaT – Vietnam Water
1099 Technologies” funded by the German Federal Ministry of Education and Research (funding
1100 reference: 02WCL1474A). Felix Dörr thanks the Hector Fellow Academy for support. We
1101 gratefully thank the Vietnamese Ministry of Science and Technology (MOST), the National
1102 Center for Water Resources Planning and Investigation (NAWAPI) and the Department of
1103 Natural Resources and Environment Ca Mau (DONRE Ca Mau) as well as the Federal Institute
1104 for Geosciences and Natural Resources (BGR) for the good cooperation and providing data.
1105 We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology,
1106 Germany. We acknowledge the developers of the software tools PyGTide, HydroGeoSines,

and Groundwater.app for making their applications and methods publicly available, which supported parts of the data analysis in this study.

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Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

Groundwater Use Habits and Environmental Awareness in Ca Mau Province, Vietnam: Implications for Sustainable Water Resource Management

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ARTICLE INFO

Keywords:

groundwater extraction
groundwater use habits
environmental awareness
Ca Mau

ABSTRACT

The Vietnamese Mekong Delta including Ca Mau province (CMP) is seriously affected by land subsidence. Groundwater over-extraction is considered to be a major driver for this process. To address the reduction of groundwater (GW) extraction as a potential counter measure for further subsidence, this study focuses on understanding the importance of GW in people's life and water using habits as well as their awareness with current environmental problems in Ca Mau. Therefore, GW sampling campaigns and surveys were conducted in all 9 districts of Ca Mau province in 2019 and 2020. The analyzed water samples showed a connection with information from questionnaires and created a general picture of water using habits. GW plays an important role in people's lives, it is used for washing, cooking, drinking and other activities. People use GW for different purposes depending on their perception of water quality. For important and direct health related purposes, such as cooking or drinking, people prepare to treat water more carefully or choose another alternative water resource. The analytical approach to evaluation results based on viewpoints from general to detail helped to dig deeper into people's stories to explain research results with their behavior in each situation. When people are dependent on GW and have no option to use alternative water resources, the importance level of GW in their life increases and their awareness of GW over-extraction becomes less. If people have another water source to use such as tap water (TW), habits of using GW change. This opens up the idea that a potential alternative water will reduce the dependence of people on GW and protect GW from over-exploitation. Besides, people in Ca Mau do not have much awareness of land subsidence or the reason leading to environmental problems. Therefore, raising the awareness of people by well-design education campaigns should be strongly considered.

1. Introduction

Vietnam is one of the most threatened area with the effect of sea level rise (Hens et al., 2018) as well as climate change related to the intensity of natural disasters (MONRE, 2016; Oxfarm, 2008). The Vietnamese Mekong Delta, including Ca Mau province (CMP), is located at the Lower Mekong River and forms the very southern edge of Vietnam. The Mekong Delta has an extremely low mean elevation above sea level (around 0.8 m) (Minderhoud et al., 2019, 2017). In addition, the Mekong Delta is facing a great number of environmental challenges and sustainability problems during the twenty first century due to the

decrease of sediment supply from its catchment due to upstream dams, saltwater intrusion from the sea, sea level rise and flooding as well as significant land subsidence (Allison et al., 2017; Tran et al., 2021). Human activities and climate change have impacts on saltwater intrusion into GW systems in Mekong Delta (Han et al., 2021). The Mekong delta has to deal with salinity intrusion in the dry season and flooding during the rainy season. For example, in the dry season of 2015/2016, eight provinces in the Mekong delta have announced an emergency situation due to drought and salinization (Bäumle, 2017). In recent years, due to rapid social-economic development and an increase in population, the increasing demand of freshwater led to an increased exploitation of

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<https://doi.org/10.1016/j.envc.2023.100742>

Received 10 March 2023; Received in revised form 21 June 2023; Accepted 21 June 2023

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GW without any planning, what causes serious problems in the Mekong Delta in general and Ca Mau Peninsula in particular (Friedrich et al., 2008; Van, 2019). Therefore, water security in the region is seriously endangered due to a decrease in freshwater quantity and quality, mainly caused by salinization, pollution and over-extraction (Ha et al., 2018). GW over-exploitation leading to an average decline of hydraulic heads of around 30 cm per year, potentially plays an important role in ongoing land subsidence (Erban et al., 2014). Land subsidence in Mekong Delta is leading to the unsustainability of area (Gustafson et al., 2018; Di Giusto et al., 2021).

The Vietnamese Mekong Delta has a transition in agriculture from mono-culture (rice farm) to multi production like shrimp-rice to be more sustainable (Nguyen et al., 2021). CMP, is the shrimp basket of Vietnam with a high demand of GW for farming. The export of these goods is of uttermost importance for Vietnam's economy. However, Ca Mau's groundwater resources are intensively affected by saltwater intrusion and a decrease of hydraulic heads resulting in a lack of freshwater for estimated 95,600 households (UN, 2020). Thus, this region urgently needs the identification, development and implementation of adapted relief measures to save it from complete inundation by the sea (Minderhoud et al., 2020). Bauer et al., 2022 described the challenges of the Mekong Delta as "a progressive loss of land and freshwater". One major counter measure to mitigate land subsidence might be to stop or significantly reduce GW extraction from deep, confined aquifers and switching to alternative water resources, such as surface water from the rivers and channels, rainwater, pumped water from the Mekong River, or desalinization of sea water. However, before even starting with one of these measures, it has to be investigated how people would react on such intensive intervention into their daily life. Many previous studies have shown that sustainable adaptation is only successful if the local people fully accept it. People intend to increase their adaptation when they are aware of the risk of climate change to many aspects of their life (Luu et al., 2019).

People in CMP are diverse in terms of living standards as well as access to water resources. To start reducing the use of GW, it is necessary to understand the importance of GW in people's life. Research needs to reflect people's opinions and their assessment of the water they are using. People's perception of GW quality and surrounding factors might influence their usage habits. Some factors affecting the acceptance of water source are public awareness about water supply, distribution, treatment as well as income and other personal factors (Baumann, 1983). Another case study in Bengaluru, India evaluated the factors impacting the acceptance of recycled water. One of the noticeable results was that 89% of the people using surface water were not aware of waste water treatment concepts or water reuse at all (Ravishankar et al., 2018). Another research in Vietnam also indicated that people's choice of water source depend on availability, quality of the water sources and financial situation of the household (Danh and Khai, 2015). In CMP, a recent study showed that people are not fully aware of the danger of submersion by the sea (Di Giusto et al., 2021). In addition, to our best knowledge, facing many problems of water use, there are still no studies on people's perception on water usage habits, with both quantitative and qualitative aspects in Ca Mau. On the one side, quantitative research is a research approach, which evaluates the relationship between variables by numeric data collection and analysis (data can be expressed in numbers or scores). On the other side, qualitative research is a research approach, which concentrates on discovering individual's experiences with phenomena by narrative or text data collection and analysis (data can be expressed in words and images) (Clark et al 2016). The combination of these two approaches creates enhanced methods that can show a more comprehensive view of people's opinion in Ca Mau from a personal perspective as well as statistical analysis (Creswell, 2017). Therefore, in this study a comprehensive GW quality assessment combined with a survey in CMP was conducted. This study emphasizes on the relationship between water quality and people's water use habits with the quantitative approach. At the same time, the open-end questions and group discus-

sion from the qualitative approach open up explanations to the problem, explaining why people in CMP are overusing GW and evaluates their possible alternative options.

2. Methodology

2.1. Study area

The study area in this research focus in Ca Mau province (CMP). Ca Mau is the southernmost province in Vietnam, surrounded by sea in three directions. CMP includes 9 districts (Ca Mau, U Minh, Tran Van Thoi, Dam Doi, Thoi Binh, Cai Nuoc, Phu Tan, Nam Can, Ngoc Hien). This area contains high density of river and canals, it is flat and low area, average elevation is around 0.5 to 1.5 m above sea level. (Pechstein et al., 2018). Ca Mau is located in the monsoonal zone, it has a tropical monsoon climate with two main seasons (rainy and dry seasons). The rainy season is usually from May to November and the dry season is from November to May.

The population of CMP is around 1.2 million people with 603,250 males and 589,150 females in 306,999 households. Sex ratio in Ca Mau is around 102.39 male/100 female. According to Ca Mau Statistic Office in 2021, main labor force is in rural area with 535,892 people with 80.01%, labor force in urban area accounts for 19.99% with 133,881 people. The occupation of people in CMP includes high level professionals, mid-level professionals, clerks, personals services, protective workers, sales workers, skilled agricultural, forestry and fishery workers, craft and related trade workers, machine operators, unskilled occupations and others. The most popular occupations are workers related to agricultural, forestry and fishery sector with 214,153 workers accounting 32.63% and unskilled workers with 254,550 workers accounting 38.78%. The key activities in the development of economy sector is agriculture, especially aquaculture (with a total area of 297,200 ha). GW extraction in Ca Mau is mainly used for agriculture, aquaculture and domestic use in rural area, from mostly small to medium sized wells with pumping rates $>200 \text{ m}^3/\text{day}$. However, the number of GW extraction wells is approximately 175,710 wells including only 248 centralized wells and 452 licensed extraction wells (Pechstein et al., 2018). It means most wells are illegally extracting GW without any exact estimation of extraction rates.

2.2. Questionnaires

2.2.1. Data collection

The data set was collected on the basis of questionnaires and group discussions with households in CMP. Questionnaires were collected by face-to-face interviews between the authors, an instructor from the local government and a household member. Field trips were implemented by visiting nine districts in CMP to collect data. The first survey was carried out in March 2019 with 87 questionnaires and water samples collected in all nine districts. The second survey took place in December 2019 and January 2020 with 57 questionnaires and water samples focusing on the northern part of CMP. Based on the experiences from the first field trip on March 2019, questionnaires were collected together with groundwater samples at the same location. Groundwater samples were taken systematically to cover all regions in CMP (Fig. 1a, 1b). Following the approach by Ravishankar et al (2018), the authors of this study are aware that some aspects of this study might not be representative for a commune, district or CMP as a whole. However, as this is the first study in the area, it is important to qualitatively focus on basic factors and reasons impacting groundwater extraction as well as the connection between people's story and the respective water quality. In total, 144 questionnaires and 144 GW samples were collected (Fig. 1a). At first, a survey was conducted to get the results and lead to the following up questions in discussion for better understanding of initial finding from quantitative research (Clark et al, 2016). The questionnaire was designed with 28 questions in the first version and was extended by 35

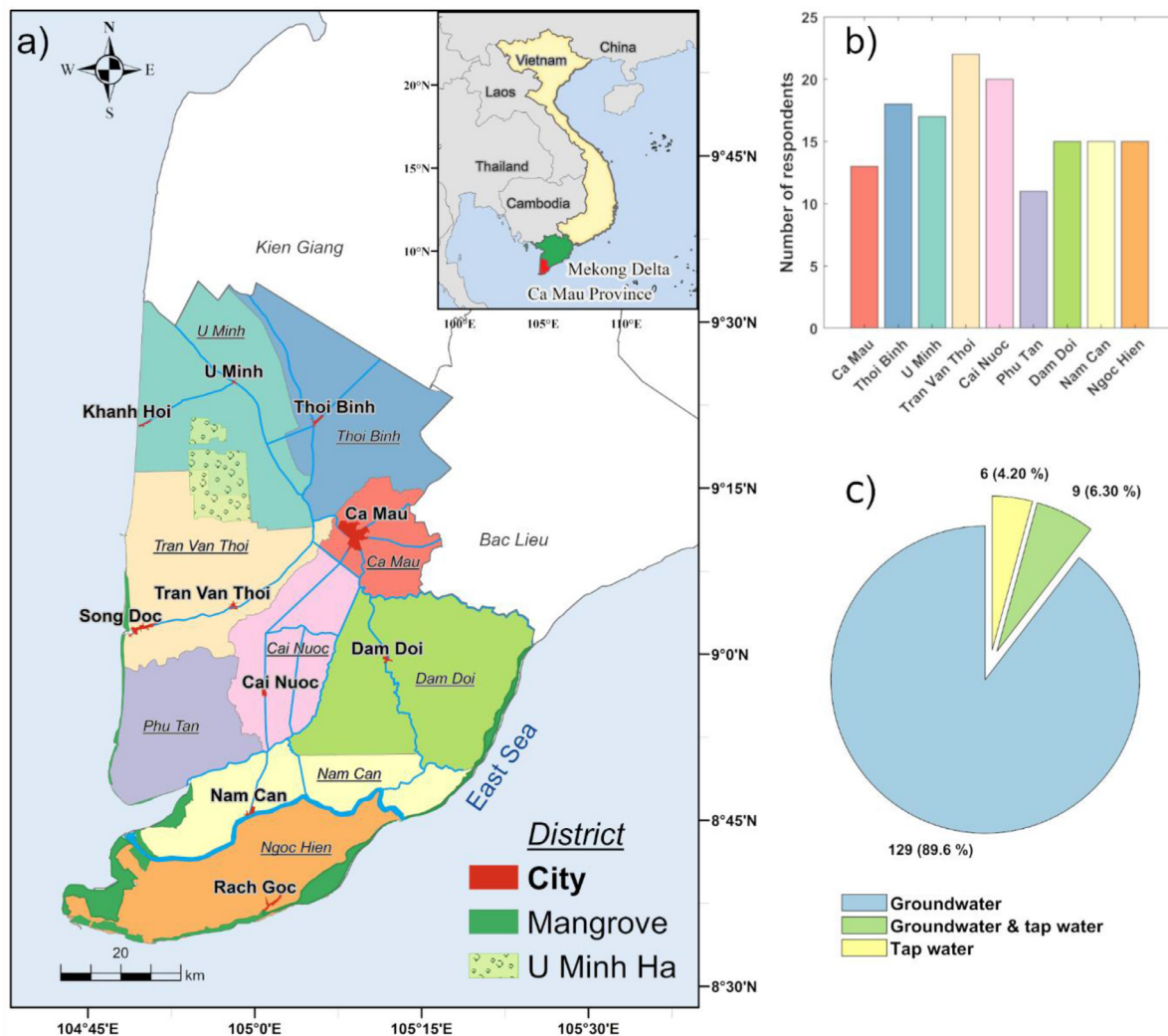


Fig. 1. a. Questionnaire locations in Ca Mau, b. Distribution of respondents in the nine districts of Ca Mau, c. Percentage of households in different groups (GW users and TW users).

questions in the second version after the evaluation of the results of the first survey. The second version focuses more on people's assessment of GW quality and their awareness of negative environmental impacts, such as salinization and land subsidence. All questions were explained and discussed with households directly. The questionnaire system is designed and divided into four main parts with easy to understand contents to match the perceptions of the respondents in CMP. The first part covers basic information surrounding the respondents, such as living conditions. The second part explores information about groundwater extraction and water use habits. The third part describes the potential of alternative water sources and the last part is about people's perceptions and awareness of overexploitation and land subsidence in CMP. The level of awareness of the people is divided by level from 1 to 4, with 1 being the lowest level, meaning that people totally have no knowledge of this issue. Level 2 means that people heard about this issue somewhere but they do not understand it clearly. Level 3 means that people know about the problem and have a basic understanding of the causes. Level 4 is the highest level when the people capture the whole picture, understand the issue and relevant information.

After completing a questionnaire, in the following group discussion part, respondents had a deeper discussion with the interviewer to explain their answers and stories.

2.2.2. Data analysis

To evaluate the outcomes of the questionnaires, well established quantitative and qualitative approaches are applied. The quantitative approach covers statistical evaluation of the questions related to numbers such as amount of water use or number of people using the well etc. Similarly, the qualitative approach consists of a hermeneutical evaluation of questions related to words and text, such as the favorite water source or GW using purpose etc.

The selection of locations was based on the general idea to get a complete overview about the different living conditions and water resources around the whole province rather than a statistical overview based on the distribution of population. Distribution of questionnaires in Ca Mau province is shown in Fig. 1b. Information gained from data collection was expressed with the points of view from general view into detailed explanation.

According to observations and interviews, beside groundwater, there are three other types of water sources used in CMP, including rain water, tap water, and bottled water (from private water supplier). Tap water (TW) is not available for the whole province. TW is obtained from GW, which is treated at a drinking water plant and distributed usually to nearby households in the same ward or commune. Until now, fresh water management and distribution are not effective. GW is the major

water source which is used mainly for domestic purposes (Ha et al., 2015). The number of households that possess the ability to use TW is not as high as compared to households using GW. In this study, although the main research subject are households using groundwater (GW users) and GW samples, tap water households (TW users) are also approached and interviewed to collect further information. For this reason, the respondents (144 questionnaires in total) were divided into two groups. Group 1 includes all households that only have GW as the main source of water called GW users, and group 2 includes households that own a GW well but also have direct access to tap water, or use TW only, called TW users. Results from 2 groups of respondents were selected, analyzed and compared to understand the difference of their thought and behaviors between 2 groups. The distribution of questionnaires in two groups is not the same (Fig. 1c). GW users accounts for 89.6% questionnaires, the percentage of people who use only TW and TW together with GW are 4.20% and 6.20%, respectively. Important reason for this extra subject is that people who get experience in using TW have more diversity in perception and they can evaluate water sources and their consumption habits in a wider view. This study focused on the group of GW users and the number of TW users is used for comparison. The number of TW users is small and do not have the meaning to be a representative for the whole group.

2.3. Water quality

GW samples were collected in parallel to the questionnaires and were analyzed in the frame of the previous study by Bauer et al. (2022), emphasizing on GW evolution and geochemistry. However, only major ions and parameters were considered in this study. The sampling methods are described in Bauer et al. (2022) in detail. Briefly, GW samples were collected from households, small businesses and water supply stations with the aim to cover the whole province. Sampling points were selected based on their spatial relevance, general access as well as permission situation. The number of samples is more than the number of questionnaires. GW was collected after 15 minutes of pumping to ensure that the sample originate from the aquifer and not the stagnant water which was standing in the well casing prior to pumping. GW was taken and measured some parameters on site, or brought back into laboratory for further analysis, as described in Section 2.3.2. To prepare for analysis, 25 mL of GW sample was filtered through a 0.45 µm cellulose-acetate filter (Satorius Stedim Biotech GmbH). 50 µL of high purity nitric acid was added to the filtered sample to prevent the precipitation of cation (APHA AWWA, 2005) and 50 µL of sodium azide was added to inhibit microbiological processes to ensure a correct anion analysis (Vanderford et al., 2011). Physiochemical parameters including temperature, pH, electrical conductivity (EC), Oxygen and redox were determined on site by using a multi parameter portable meter (WTW Multi 3630 IDS). Total alkalinity was also measured on site with a titration kit (Merck KGaA, Germany). Besides, samples after filtration and acid/sodium azide addition were transported to Germany and analyzed with IC (X-Series 2, Thermo Fisher) for anions and ICP-MS (Dionex, ICS-1000; Trennsäule IonPac As14 Suppressor ERS 500) for cations at the Karlsruhe Institute of Technology in the laboratories of Institute of Applied Geosciences.

After analysis, the samples of GW were compared with the people's subjective assessment of the water quality from the questionnaires. In addition, the concentration of ions, are compared with the National Technical Regulation on Domestic Water Quality QCVN 01-1/2018 BYT to know whether the water quality meets the usage standards or not. The dashed red line represents the QCVN standards and shows clearly that some parameters of samples are over the permissible standards for domestic water (Fig. 5). If the dashed red line does not appear in the figure, it means all values of each parameter meet QCVN standards. All necessary parameters were analyzed and a comparison was carried out between the group of people using GW for non-drinking and drinking purpose. One more aspect to be discussed is samples where

GW is chosen as the best water resource. Not all parameters from the list of Vietnamese standard QCVN 01-1: 2018/BYT are considered. This study focuses on some selected parameters, which are most important to evaluate domestic water quality and are easy for people to realize if they occur in harmful concentration. The parameters include pH, EC, NH_4^+ , Cr, As, Cd, Sb, Pb, Al^{3+} , Mn^{2+} , Zn, B, Fe, Ba, Na^+ , Ca^{2+} , Cl^- , SO_4^{2-} . pH is the basic parameter, which can affect to value of other parameters. Heavy metals such as cadmium, lead and chromium dissolve more easily in highly acid water (DeZuane, 1997). Besides, iron and manganese are not serious substances, which cause health problems, but can cause bitter taste in drinking water even at very low concentration. When water containing higher amounts of Fe^{2+} and Mn^{2+} are exposed to air, these ion can oxidize and precipitate and the water can turn to be turbid (APHA AWWA, 2005). Zinc is not harmful at small concentration, but it can cause strange taste in drinking water with concentration of above 4 mg/L. Zinc at concentrations between 3–5 mg/L in water can cause the greasy film when boiling (WHO, 2018). Besides, using lead pipes increases lead concentration in drinking water and after long term, it could affect children mental health. Arsenic also causes a risk to health after long term exposure (WHO, 2018). Ammonia (NH_4^+) concentration can be over the taste threshold at 35 mg/l (WHO, 2018).

3. Results and discussion

3.1. General information of respondents

In this study, households' information of GW use issues along with perceptions of GW over-exploitation are used for the analysis. Percentage of males and females among the respondents was a ratio of 2 males: 1 female. The average household size is 5.5 people per household. According to the Ca Mau Statistic Office, the population in rural area is much higher than in urban area (920948 with 77.2% in comparison with 271452 people, around 22.8%). In this study, respondents are also focused on rural area with around 91.0% and 9.00% respondents in urban area. Most respondents who used groundwater lived in rural area. In urban area, tap water is supplied to the households from water supplier station.

The interviewed households have a variety of occupations, from growing rice, farming shrimp to doing small business to working as employees of a company or officer in government.

The majority of respondents are farmers (rice or shrimp farming) with 68.1%. There are also small self-employed households including restaurants, bars, selling bottled water with 16.7%. People working in companies and government organization known as officers, accounted for 10.4% of interviewees, and finally 4.86% of interviewees were workers. In Ca Mau population, percentage of these occupations are 32.6%, 8.50%, 2.93% and 8.87% respectively (according to Ca Mau Statistic Office, 2021)

The household's income is difficult to estimate because most interviewees do not have a stable monthly income but their income is determined by the success of the crop or shrimp harvest. Usually, people in Ca Mau have more than one source of income. One person can be an employee but also a small seller or a farmer. According to Ca Mau Statistic Office, average monthly income per capita in urban and rural region in 2018 is 2,985,900 VND/pp/month (around 129.6 USD/pp/month). This income is including wage or salary (798,300 VND) (around 34.7 USD /pp/month), income from agriculture, forestry and fishery (self-employment) (1,015,200 VND) (around 44.1 USD), income from non - agriculture activities (813,400 VND) (approximately 35.4 USD) and others (359,100 VND) (around 15.6 USD). This data fits to the authors' impressions in CMP.

Respondents are mainly normal households where GW is used only for domestic purposes. Besides, there were some other types of households. Some households own their business which require much water such as bike washing, restaurant, shrimp farming. Others are private

Table 1
Purpose of using groundwater in Ca Mau province (N=144 questionnaires).

Purpose of groundwater use	Percentage of respondents using groundwater for this purpose
Washing	97.0%
Cooking	65.7%
Drinking	25.4%
Others (gardening, doing business...)	23.9%

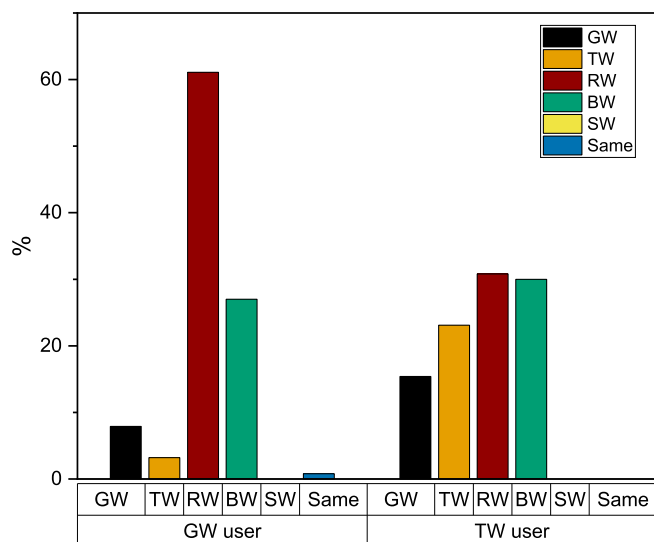


Fig. 2. Best water source in household's opinion.

water suppliers who sell water bottles or owners/managers of water station.

3.2. Current state of using water resource

Groundwater is popular and plays an important role in people's lives in CMP. To understand if people would accept stopping GW usage, it is necessary to understand the importance and specific role of GW in their daily life under social and economic aspects.

According to the results of 144 questionnaires, GW is used for many purposes in CMP, which are listed in Table 1. Households consume GW to wash clothes, dishes, cook or even drink directly. However, washing clothes and dishes consume the highest amount of GW.

Two groups of GW users and TW users have different opinions for certain aspects. For each group, their experience with TW differs, leading to their perception of several different assessments regarding water quality or convenience of use. People have sensory assessments of each water source they use, in terms of water volume, water quality, and as a consequence which water source is the best. Opinions of respondents about the best water source are shown in Fig. 2.

Among GW users, rainwater (RW) is rated as the best quality with 61.1% agreement of households and according to the respondents: "Rainwater is sweet and delicious, is usually boiled to drink tea. Rain water is only used for the main drinking and cooking purpose. Although the water quality is good, the amount of rain water is not enough for another purpose." Their opinions about rain water is based on long-time experiences of using it. According to Đoàn Thu Hà and Hồ (2014), rain water in the Mekong Delta is also considered as high quality water source and it meets Vietnamese standards for almost all parameters.

However, contamination of fecal parameters are due to the condition of rain water storage and treatment (Wilbers et al., 2013). Second is bottled water (BW) with 27.0%. In fact, BW comes from groundwater but it is treated in private filtration systems and sold to people. People have confidence in the water quality after treatment with the filtration system and think that BW is of good quality.

In addition, the TW users group believes that RW, BW and TW are the top three with the best water quality, with 30.8%, 30.0% and 23.1% respectively. Even though they have access to TW, they still believe that RW has a better quality in taste. Some interviewees said that TW is sometimes still affected by pipes, strange color changes and its taste is worse than that of RW. Not so many respondents think all water sources have the same quality and no one chose surface water (SW) as the best water source. SW in Ca Mau Peninsula is widely contaminated with organic matters, nutrients, total suspended solids, and microorganisms (Giao, 2022).

On the other hand, both target groups believe that in general GW quality is not really good, with only 7.90% for GW users and 15.4% for TW users voted for GW as the best water resource. The perception of households about groundwater is nearly compatible with the water quality due to the characteristics of some parameters in terms of color, smell and taste (mentioned in Section 3.3). In addition, the role of GW in the life of the household with access to TW has decreased. The importance level of GW in people's life from the results of the survey is shown in Fig. 3.

The question posed to residents is how important GW is in their lives. The answer is divided from level 1 (not important) to level 4 (extremely important, irreplaceable). For the GW users group, none of the people choose level 1, up to 30.3% and 66.4% of the respondents choose the importance level of GW to be level 3 and 4. For the TW users, the importance of GW in people's life is less important, with 22.2% at level 3 and 55.6% at level 4 (Fig. 3). It can be seen that when the group of people is able to use TW, the importance of GW decreases.

Moreover, the use of GW for drinking purposes is a matter of great concern. GW users can be further divided into two subgroups: (i) a group of people who use GW for the purpose of drinking and (ii) a group of people how use GW for non-drinking purposes. If people use GW for the purpose of drinking, people tend to pay more attention to water quality and they usually use some pre-treatment to make water safer for drinking (Fig. 4).

The results show that only 4.2% did not use any pre-treatment before drinking GW, which might be concerning for their health. However, 25% of the subgroup did use a settling process to remove suspended particles before drinking, while 20.8% used both settling and boiling methods to ensure safe water. The majority of the respondents, 50%, relied on filtration systems to remove impurities before drinking GW. Normally, people use mini filtration systems at home. The price of a mini system is in range of 6.000.000 VND (around 260 USD) and they have to change the filter every 3-6 months with a price of around 90.000 VND/filter (around 3.90 USD). These findings highlight the importance of promoting safe water practices to ensure the health and wellbeing of the population, particularly for those who do not currently use any pre-treatment methods (Fig. 4).

The importance of GW in people's lives is affected by their intention in using GW as well as whether they have other water sources such as TW to use. Besides using GW, people also have access to other water sources such as RW, SW, BW or TW for different purposes. The self-assessment question of best quality water opens up potential alternatives to replace GW as main water source. Fig. 2 shows that RW is preferred by people and rated as the best quality water source for both GW users and TW user groups. RW is also a popular drinking water source in the Mekong Delta with positive characteristics of color, taste and smell (G. J. Wilbers et al., 2013b). However, the quantity of RW is not enough for people's demand during the dry season when they only can collect and store rain water in few and rather small containers (Li et al., 2016).

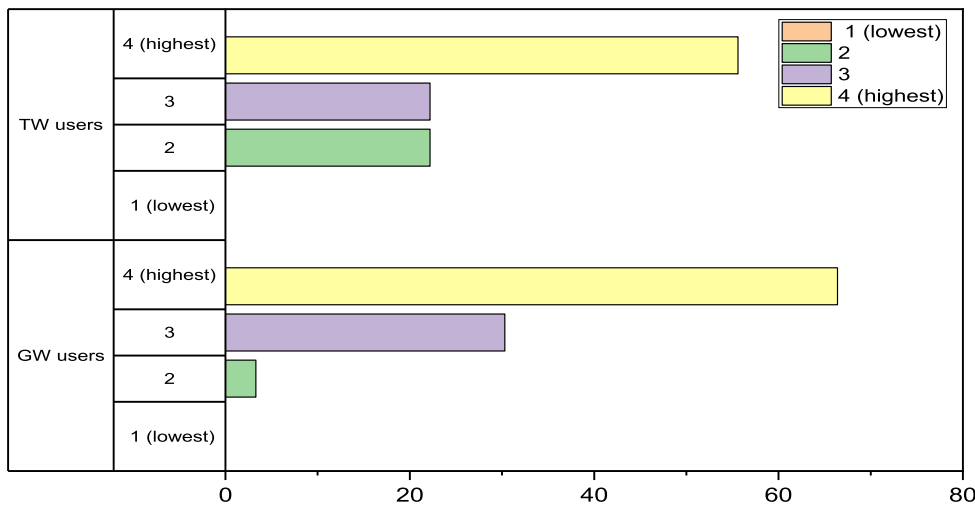


Fig. 3. Importance level of groundwater in 2 groups of households.

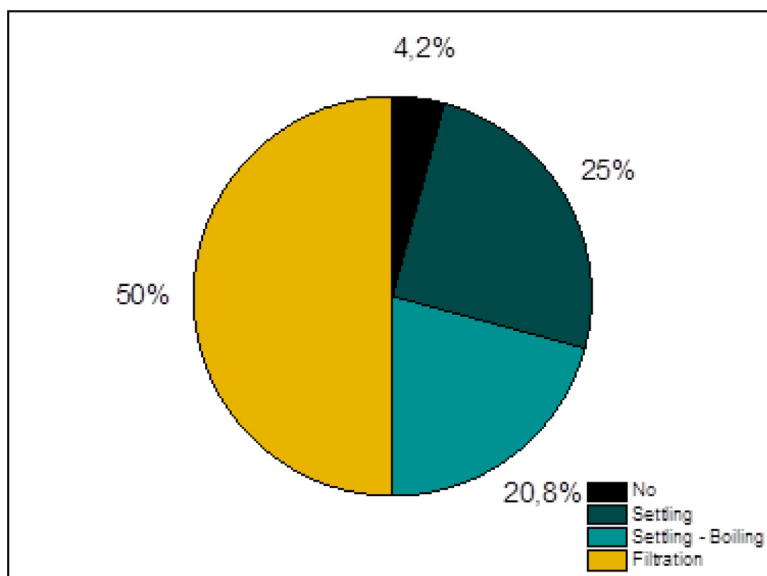


Fig. 4. Treatment practices for groundwater before using for the purpose of drinking.

3.3. Groundwater quality at the locations where GW is used for the purpose of non-drinking and drinking

Since the scientific assessment of water quality through proper measuring equipment is not an option for most of the people in CMP, their decisions and actions in using water depend on their individual gustatory and olfactory senses. According to feedback from residents through interviews, when people perceive strange water quality in regard to taste, color or odor, they will not use GW for drinking. According to the findings of Bauer et al. (2022), the analysis of water samples regarding EC, reveals that certain GW does not meet the necessary standards for direct consumption as drinking water. The graphical representation in Fig. 5 presents a comparative analysis of water quality parameters (as discussed in Chapter 2.3) in areas where GW is used for drinking purposes (blue boxplot) and areas where GW is not utilized for drinking (red boxplot). In general, values where GW is used for non-drinking purpose have a wider range and there are more outliers in the plot. The depth of the GW extraction wells also has to be considered to know which aquifer households use for each purpose. The median depth of 120m for both groups correspond to the upper-middle Pleistocene aquifer qp2-3, which is the common aquifer on a household wells in Ca Mau, accounting for 63.37% amount of exploitation based on the estimation of GW model (Hoan et al., 2022). However, non-drinking purpose wells have few ex-

ceptions with deeper wells. This indicates that the depth is not extremely important, this also agrees with Bauer et al., 2022 who identified that water chemistry is more a regional feature rather than a vertical one.

On the one hand, the results state that most samples for non - drinking purpose (red boxplot) show that EC and pH parameters met the regulatory limits. However, many water samples in the study area show concentrations of NH_4^+ , B, Fe^{2+} , Ba^{2+} , Na^+ , Cl^- , SO_4^{2-} exceeding the threshold value for drinking water in Vietnam (Fig. 5). Due to the noticeable strange taste, color or general appearance of these samples, households evaluated their quality poorly, and thus, did not choose them as a source of drinking water. Non-drinking water have higher pH, also correlated with EC. There are some dependent variables of high EC, mostly Cl^- , pH, SO_4^{2-} , Na^+ , Ca^{2+} and B. It is interesting that NH_4^+ is higher in the group of samples with higher EC. This could probably support the assumption that presumably contaminated saline GW from the shallow aquifer is leaking into deeper aquifers (Bauer et al., 2022).

Regarding the “easy-to-detect” water quality parameters above, GW samples utilized for drinking purposes (blue boxplot) are comparatively superior to the water quality of samples not used for drinking purposes, as depicted in Fig. 5. However, further investigation into the questionnaires is necessary to explain this result, as there are some exceptions that require deeper analysis.

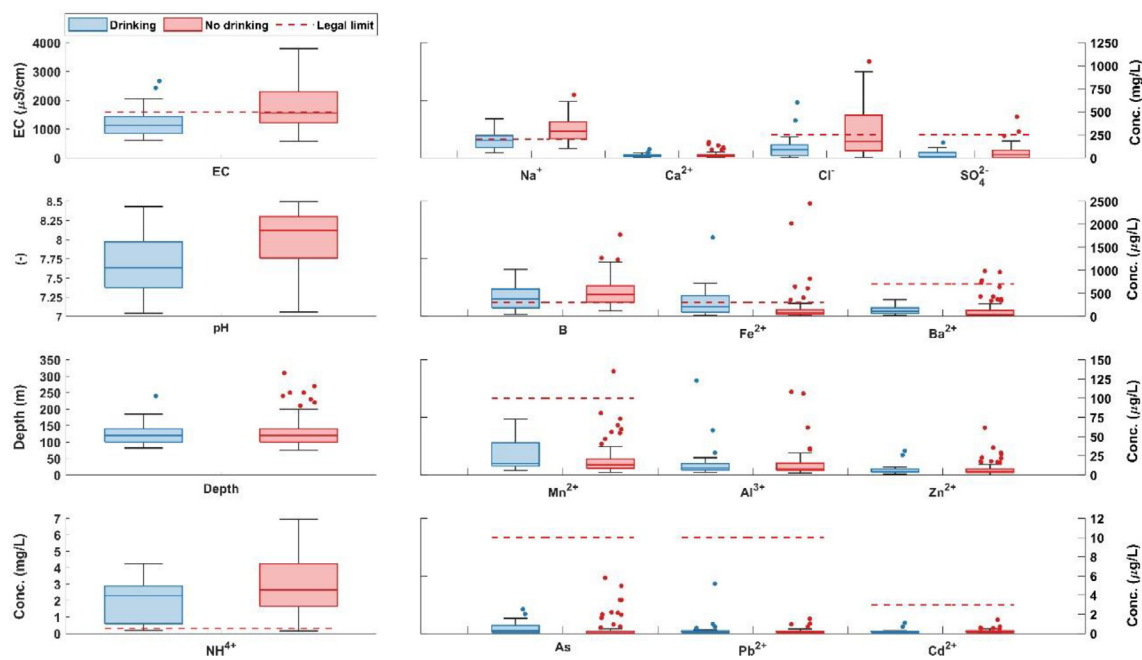


Fig. 5. Groundwater quality at the locations where GW used for the purpose of non – drinking (red boxplot) and drinking (blue boxplot).

For samples with iron (Fe) concentration exceeding the standards (>0.30 mg/L) that people use for the purposes of drinking, people also have different ways of treating GW before consumption as drinking water source. Seven of them use treatment methods before consumption. Of those two households use sedimentation, three use sedimentation with filtration and boiling, and two use a mini filtration system. Two households do not use pre-treatment and rely on other sources like RW and BW for drinking, using GW only as a backup in emergencies.

In the case of samples with Boron (B) levels exceeding the permissible limit (>0.30 mg/L), 15 samples were found to exceed the limit. Among these, two samples were consumed without any pre-treatment, five samples were settled, two were boiled, five were filtered, and one sample was obtained from a water treatment plant. Unlike iron, Boron is a substance that has minimal impact on taste and is challenging to detect for the households by themselves.

For Sodium concentration, there are twelve households exceeding the standard (>200 mg/L). At the same time all twelve households have Boron concentration exceeding the standard, too. Of these twelve samples, one is from a water plant. Two households do not use any measure before using the GW because these households use mainly RW and BW as their primary drinking source, GW is an additional option for them in case of emergency. The other four households are using sedimentation and they also use additional sources for drinking, like RW and BW. Two households boil water, three households treat water with filtration systems and they do not use any other water sources. When households use treatment for GW, it could be assumed that they intend to increase the water quality before they use it for drinking water source.

Similarly, in a household with Chloride concentrations exceeding the standard (>250 mg/L) (concentration of Sodium, Boron also exceeds the standard), there are two locations. One household has a professional water treatment system, filtration and UV disinfection to treat water after extraction and distribute water as a supplier of potable water. Another household uses only a small amount of GW for drinking; they also use BW (filtered water) and RW instead.

Households using GW for both, cooking and drinking purposes, often have high water quality, with chemical parameters in the range of permissible limits. Biological parameters can be discussed further in future studies. For those households that use GW for drinking purposes but do not have good enough water in terms of quality, when digging into the

discussion, it could be realized that they only use very little amount of GW for this purpose. In addition, they also have a different amount of water from rain or bottled water as main sources, or they will treat GW with different treatment before use, depending on their ability (Table 2). It is suggested by previous studies that people in CMP should treat GW before drinking (Ha et al., 2022). However, treatment for GW has to be appropriate with current water quality.

People have a certain perception of GW quality leading to their different usage behavior. Therefore, people's perceptions as well as their stories need to be discussed more to find out about what factors can affect their water use habit, perhaps convenience and applicability of water sources, available alternative water sources and economic conditions.

3.4. GW quality of households where GW is perceived as best water resource

Through their perceptions, people identify some uncertainties in the quality of the water they use. It can be said that the perceptions of the people and their responses are important factors in determining water quality as well as the role of GW in people's life and the status of GW extraction.

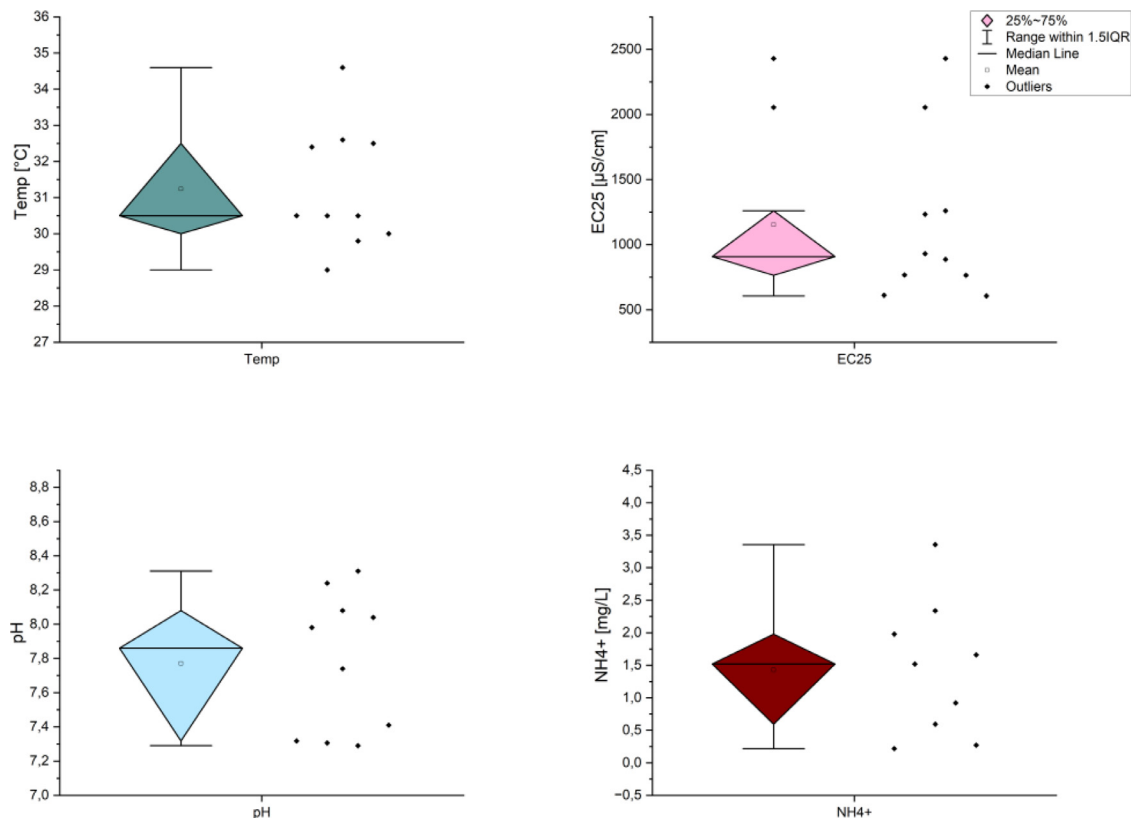
Figs. 6 and 7 shows that most samples, which are perceived to have the best water quality, adapt with QCVN standards. There are not so many samples to parameters over the thresholds. For each situation there will be a reasonable explanation in Table 2.

For households whose water samples exceed the QCVN standard for Boron, the first sample is from a restaurant. Assuming that the quality of all types of water is same, they use a large amount of GW daily for restaurant business (400 – 500L/day). GW use brings financial benefits to the household at a very low cost, therefore GW is still the best water source in their situation. The remaining three out of five samples from households are using GW as the main source of water for drinking. They believe in the quality of their current water source because two households use a mini-filtration system for private households and one household is a supplier of potable (bottled) water with a professional treatment system. The fifth household uses a sedimentation method. This household still uses GW and RW in combination because of the low cost although TW is available. When RW runs out in the dry season,

Table 2

Reasons why households still appreciate GW although some parameters of GW samples do not meet the standard.

Group	Reasons	Extend explanation for the reasons
GW as drinking water source	Use of basic water treatment before utilization (settling, boiling, filtering via cloth) before drinking	The traditional practices of water treatment brings a sense of assurance regarding the quality of the treated water, thus rise a level of confidence of household when they use GW for drinking.
	Use of mini filtration system at home before drinking	People trust in the water treatment quality of modern filtration devices as advertised.
	Use of professional water treatment system (for private water supplier) before drinking	GW sample is an input of professional water treatment of private water supplier. They treat GW then distribute water bottles to households nearby.
	Use of professional water treatment system (for water station) before drinking	GW sample is an input of professional water treatment plan which is designed for specific GW to guarantee the output can be delivered to people and used for all purposes.
	Use of rain water or tap water mainly, GW is only used in case of emergency	GW is only used with a small amount if people is lack of other water sources (TW, RW). GW is not the first priority water source in these cases.
GW as the best water source	Do business with high amount of water utilization (restaurant, shrimp farm)	People use a considerable amount of water for their business operations. GW has the lowest cost and meets their business water usage demands.
	Use of professional water treatment system (for private water supplier)	GW is an essential input for professional water treatment by private water suppliers. It directly relates to their economic benefit and becomes a significant source of their income.

**Fig. 6.** Groundwater quality at the point of GW as best water source (in people opinion) (Temperature, EC25, pH, NH₄⁺).

the main water source could be GW. The last household does not use GW for drinking purposes, GW is used as the main source of water, not only for washing and cooking purposes, but also in shrimp farming. Each month, the household uses much electricity to pump underground water up and the electricity bill to pump groundwater reach to 9.000.000 -10.000.000 VND/month (391 USD to 434.8 USD). GW is used for work that generates a large income for the family, so it is appreciated for its quantity and quality.

Only two samples have chlorine content exceeding the standards. Both use GW as main water source and apply modern filtration systems

before use. One uses a mini-filtration system for the household and one uses a large filtration system for bottled water production and distribution. This also explains the simple reason that although the original water quality is not good to reach the standards, GW is mainly used and still is be the best water source.

Depending on the different cases, people always have their own reasons to choose which water source they consider to be the best, even though the water quality does not meet the standards of domestic water. The quality of GW and RW is highly appreciated, but RW has a great limitation in terms of inadequate water storage volume, so it is still used

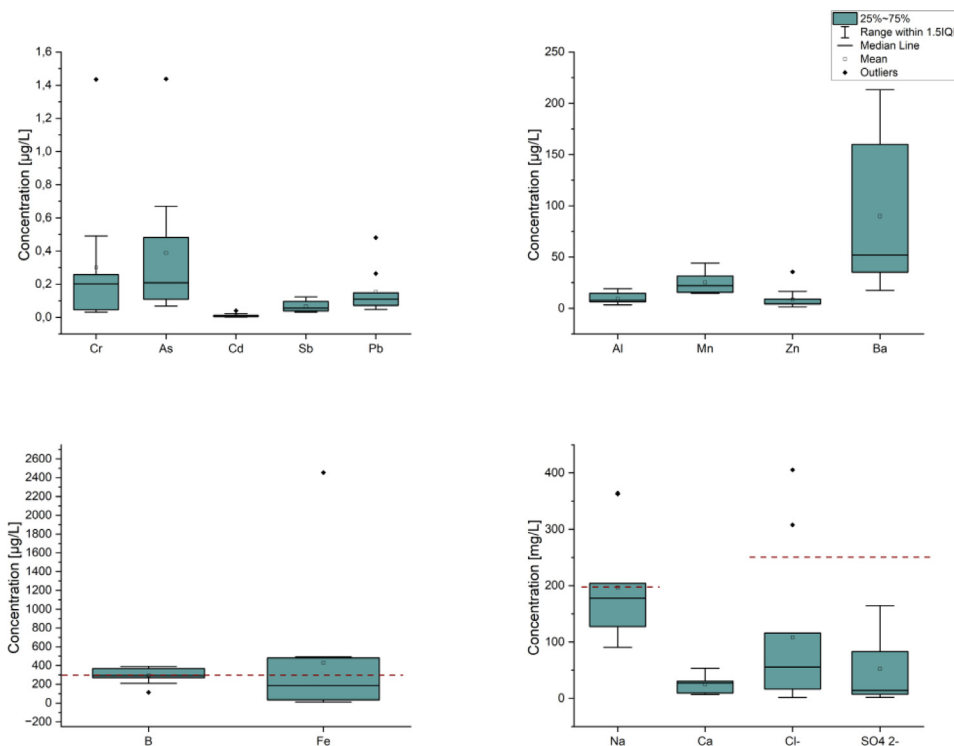


Fig. 7. Groundwater quality at the point of GW as best water source (in people opinion) (other parameters).

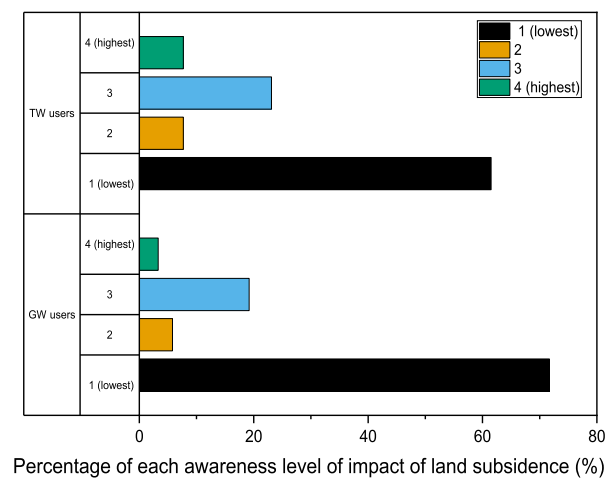
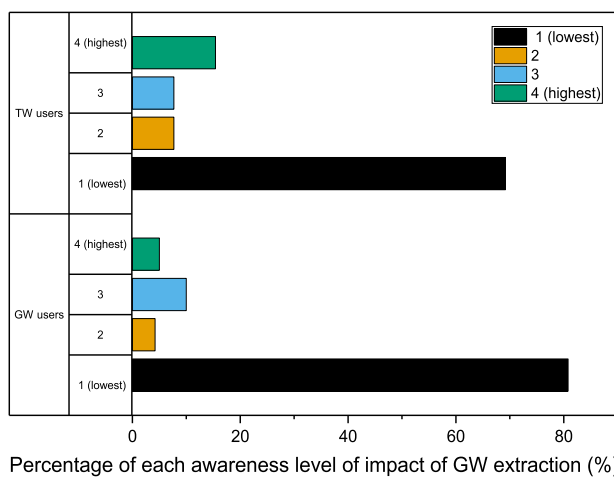


Fig. 8 & 9. Awareness level of people with impact of GW extraction and land subsidence state.

only in the rainy season, in general GW is preferred in comparison with rain water. Seemingly unlimited availability is a strong positive aspect of using GW in people's opinion.

3.5. Evaluation of people awareness about the impact of groundwater extraction on land subsidence

Changing people's living habits is not simple. The priority of this study is to understand people's thoughts and perceptions of their issues. The next question in the questionnaire sheds further light on people's awareness of land subsidence impact and the effects of excessive GW extraction. Most of the people have low or extremely low awareness of these two problems as shown in Figs. 8 and 9.

In the two questions on the awareness issue, the number of households is also divided into two groups as in the previous part: GW users and TW users. According to the results collected, 80.8% of GW users had the lowest level (level 1) of awareness of the impact of GW extrac-

tion, 69.2% for the TW users group. With the highest level of awareness about the impact of GW extraction, the GW users group only has 5.00% of the households at this level, while TW users group has 15.4%.

Similar to the question of people's perception of land subsidence in Ca Mau, the level of awareness among GW users on this issue from level 1 to level 4 was 71.7%, 5.8%, 19.2% and 3.30% respectively. As for the TW users, the level of awareness of the people is higher with the rate from low to high of 61.5%, 7.70%, 23.1% and 7.70%.

In general, respondents in this study mainly are not aware of the impact of GW extraction as well as land subsidence in Ca Mau. The level of awareness of people about these issues is extremely low and needs to be promoted. In addition, the importance of GW to people's life is extremely high (Fig. 3), which could lead to a low level of awareness.

The opinions about the importance of GW and people's awareness of excessive GW extraction as well as land subsidence show an inverse relationship. The more people depend on groundwater use, the harder it is to pay attention to the issues surrounding excessive groundwater extrac-

tion. Similar to the farmers in the Red River Delta, people do not have the intention to adapt to climate change when they do not realize any threat to their life and health (Luu et al., 2019). Currently, GW plays an important role in people's lives, while their awareness of overexploitation and land subsidence in Ca Mau is limited, it leads to the lack of attention to climate change issues. According to Eslami et al. (2021) inadequate understanding of environmental systems and processes in the Mekong Delta results in misinterpretation of socio-environmental aspects, ineffective policymaking, and an uninformed public opinion. The latter aspect is important, as only a well educated and informed society may accept change in their daily life.

It can be seen that the TW users and GW users object groups have quite different answers, although the number of TW users' questionnaires is still small compared to GW users. For the next study, it is necessary to expand the number of TW users and focus on making a case study in an area that contains both two subjects for deeper comparison.

The proposed alternative water sources should also be analyzed and applied to each condition, considering the advantages and disadvantages of this water source for each area to get the most accurate results. RW is mentioned frequently in the answers of households as potential alternative water resources. Research on how to overcome the disadvantages of RW subtraction is also very interesting when RW has gained the interest of the people using it.

4. Conclusion

This study has created a general picture of the Ca Mau household's GW using habits. The research approach of evaluating ground water quality parameters and then going into detail about each response of the people has shown more closely and explained the analysis results as well as the connection between the survey and sample analysis data.

The study shows the opinions of households concerning GW use habits based on questionnaires that are reasonably collected according to the spatial and social condition distribution. These results do not claim to be statistically representative for the whole CMP population, however, it is a crucial first step in the evaluation of GW use habits in CMP. GW plays an important role in people's life, it is used for washing, cooking and other activities (restaurant business, shrimp farming, bottled water business, etc.). Depending on the people's perception of different GW qualities, they use GW for different purposes. People estimated the water quality through their perception without knowing the water quality though professional analysis techniques. For important and direct health-related purposes such as cooking and drinking, people have to prepare and treat GW as well as provide alternative water sources to GW if they feel that the water quality is inadequate. As people become more dependent on groundwater (GW users), their awareness of the potential impacts of GW extraction becomes less, and the importance of GW in their lives increases. Besides, people do not have much awareness about land subsidence processes in Ca Mau in general and especially about the potential, that GW extraction can be a major factor for land subsidence. If people have more options to use water, such as TW users, habits of use or dependence on GW as well as their perception of the harmful effects of groundwater extraction change. This opens a research direction to find potential alternative water besides tap water to meet the needs of the people - as a solution to reduce the current excessive exploitation of GW.

Author contributions

Van Cam Pham: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft, Visualization. **Jonas Bauer:** Investigation, Writing - Review & Editing, Visualization. **Nicolas Börsig:** Investigation, Writing - Review & Editing, Project administration. **Johannes Ho:** Investigation, Review & Editing. **Long Vu Huu:** Investigation & Review. **Hoan Tran Viet:** Review & Editing. **Felix Dörr:** Re-

view & Editing. **Stefan Norra:** Writing - Review & Editing, Supervision, Project administration, Funding acquisition

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

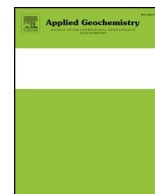
Acknowledgment

This research was carried out as a part of the project ViWaT- Engineering, funded by the German Federal Ministry of Education and Research (BMBF) under grant No. 02WCL1474A. We sincerely thank the Vietnamese National Center for Water Resources Planning and Investigation and the Department of Natural Resources and Environment Ca Mau (DONRE Ca Mau) for their kindly support. We would like to thank the laboratory staffs of the Institute of Applied Geosciences at KIT, Karlsruhe and all project partners working together in this project. I would like to express a special thanks to the financial support of Graduate Funding from the German States (Landesgraduiertenförderung). Finally, we acknowledge support from the KIT-Publication Fund of the Karlsruhe Institute of Technology.

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Indications that weathering of evaporite minerals affects groundwater salinity and As mobilization in aquifers of the northwestern Hetao Basin, China

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ARTICLE INFO

Editorial handling by Prof. M. Kersten

Keywords:

Salinization
Sulphate minerals
pH decrease
Ca²⁺ release
Sulphide
As mobilization

ABSTRACT

Elevated arsenic (As) concentration and salinity (TDS > 1000 mg/L) seriously affect the groundwater quality in the Hetao Basin, China, however, the origin of groundwater salinity and its influence for As mobilization has not been widely studied. In this study, the influence of evaporite minerals weathering on groundwater salinity and As mobilization were investigated by lithological and mineralogical analysis of sediments from two boreholes in combination with groundwater hydrogeochemical characteristics analysis in the northwestern Hetao Basin. Results from a water-leaching method suggest that Na and Ca related sulphates dominate the evaporite minerals in sediment samples. Groundwater salinization mainly results from evaporation and Na⁺/Ca²⁺ cation exchange followed by sulphate and silicate minerals weathering. Saturated indices for calcite, dolomite and unsaturated indices for gypsum as well as negative correlation between pH and SO₄²⁻ suggest that groundwater chemistry does not reach equilibrium with continual carbonates precipitation by an excessive Ca supply from Ca related sulphates weathering. The groundwater pH decrease and Ca²⁺ release during weathering of Ca related sulphates can retard As desorption from Fe (oxyhydr)oxides and clay minerals. Furthermore, pyrite minerals were also found in the sediments induced by high sulphide flux and it can cause As sequestration. However, modeling results suggest the occurrence of thio-As species in the study area, which can potentially enhance the As mobilization. This study contributes to the ongoing research into As mobilization in the groundwater of lacustrine basins.

1. Introduction

Co-occurrence of groundwater salinization (with total dissolved solids (TDS) > 1000 mg/L) and As contamination (> 10 µg/L) has been widely found in the aquifers of Argentina, the tidal delta plain of southwest Bangladesh and many basins in the north of China (Guo and Wang, 2005; Nicolli et al., 2012; Rodríguez-Lado et al., 2013; Xie et al., 2013; Ayers et al., 2016; Li et al., 2016). Reductive dissolution of As-containing Fe (oxyhydr)oxides and/or competitive As desorption are considered critical mechanisms causing groundwater As enrichment (Nordstrom, 2002; Ahmed et al., 2004; Guo et al., 2013a). Possible reasons for groundwater salinization include: saline intrusion, historic marine transgression, evaporite minerals weathering and excessive evaporation of surface water and shallow groundwater (Apple and

Postma, 2005; MacDonald et al., 2016). Since elevated salinity and As concentration are both influenced by groundwater hydrochemical evolution processes, their connection should be highlighted, however, few studies have addressed those two issues until now. Elevated groundwater redox components, especially SO₄²⁻, which increases during the groundwater salinization processes, can influence the As partitioning process between sediments and groundwater by formation of secondary minerals in the aquifer sediments (Lowery et al., 2007; Buschmann and Berg, 2009; Kao et al., 2011; Guo et al., 2016; Smith et al., 2017), whereas some elevated concentrations of ions such as HCO₃⁻ and Ca²⁺ can influence the As desorption/adsorption from clay minerals and Fe (oxyhydr)oxides (Brahman et al., 2013; Fakhreddine et al., 2015). Therefore, clarifying the saline source and connection with As contamination is essential for understanding the As

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<https://doi.org/10.1016/j.apgeochem.2019.104416>

Received 12 April 2019; Received in revised form 27 August 2019; Accepted 30 August 2019

Available online 30 August 2019

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mobilization process as well as safe groundwater exploration.

Groundwater salinization processes in the semi-arid to arid inland basins of the Yellow River catchment have recently attracted increased attention, these include the Hetao Basin, the Datong Basin and the Huhhot Basin (Smedley et al., 2003; Deng et al., 2009; Xie et al., 2012; Li et al., 2016; Jia et al., 2017). Groundwater with TDS > 1000 mg/L approximately accounts for 91% of total groundwater samples ($n = 634$) in the Hetao Basin (Gao et al., 2014). Deng et al. (2009) suggested that evaporation caused the elevated salinity, whereas Jia et al. (2017) proposed that evaporite dissolution might contribute to groundwater salinization. However, there is no comprehensive study to show the influence of evaporites dissolution on the groundwater salinization process. In general, three processes can contribute solutes to groundwater, these include: evaporite dissolution, carbonate dissolution and silicates weathering (MacKenzie and Garrels 1971). The most distinctive geologic feature of the Hetao Basin is the lacustrine deposit, which is known to contain evaporite minerals (Eugster, 1980; Smoot and Lowenstein, 1991). Evaporite minerals can drive salinization since chlorides and sulphates are more dissolvable than carbonates and both show higher weathering rates than silicates (MacKenzie and Garrels 1971), whereas weathering of rock-forming aluminosilicates in the typical clastic sediments of Hetao Basin contribute to an enrichment of different cations in groundwater (Wang et al., 2009). During the late Pleistocene epoch, the shrinking of a paleolake might have accumulated evaporites in the sediments of the Hetao Basin, though it is presently unclear as to which specific evaporite minerals (Jia et al., 2016). In this study, the distribution of evaporite minerals in depth profiles were investigated using a water-extraction method. Afterwards, the groundwater salinization process is analyzed with emphasis on the influence of evaporite mineral dissolution.

Historically, research into the groundwater hydrochemistry of the Hetao Basin has focused far more on As contamination than salinization (Gao, 1999; Guo et al., 2008; Deng et al., 2009; Rodríguez-Lado et al., 2013). Microbial reduction of Fe (oxyhydr)oxides releasing As into groundwater is thought to be the most important mechanism for As mobilization (Guo et al., 2008, 2013a; Li et al., 2014), though fewer studies have been conducted into the influence of desorption-adsorption processes, which can be largely affected by divalent cations (Ca^{2+} , Mg^{2+}) and competing anions (HCO_3^- , OH^- , SiO_4^{4-}) (Smedley and Kinniburgh, 2002; Wang et al., 2009; Fakhreddine et al., 2015). Evaporites accumulated in Pleistocene epoch can significantly influence As mobilization/immobilization in the aquifer of Hetao Basin. Firstly, evaporite minerals are thought to be an important sink for trace elements such as As, B and F (Thiede and Cameron, 1978; Tabelin et al., 2017). For example, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and calcite (CaCO_3) can incorporate As into their structures (Winkel et al., 2013; Zhang et al., 2015). Secondly, dissolution of evaporites can largely influence the groundwater pH and alkalinity conditions, which are key parameters for As desorption from Fe (oxyhydr)oxides and clay minerals (Plummer et al., 1990; Nordstrom, 2002; Podgorski et al., 2017). Furthermore, sulphide formation resulting from sulphate reduction can influence As partitioning between groundwater and sediments as described above (Kirk et al., 2004; Planer-Friedrich et al., 2018). This study focus on the influence of evaporite minerals weathering on As mobilization.

Based on the assumption that evaporites weathering will contribute to the elevated groundwater salinity and influence As mobilization processes, the objectives of this study are: 1) to clarify the distribution of evaporite minerals in the study area and their influence on groundwater hydrochemical composition; and 2) to evaluate the effects of the evaporites weathering on As mobilization.

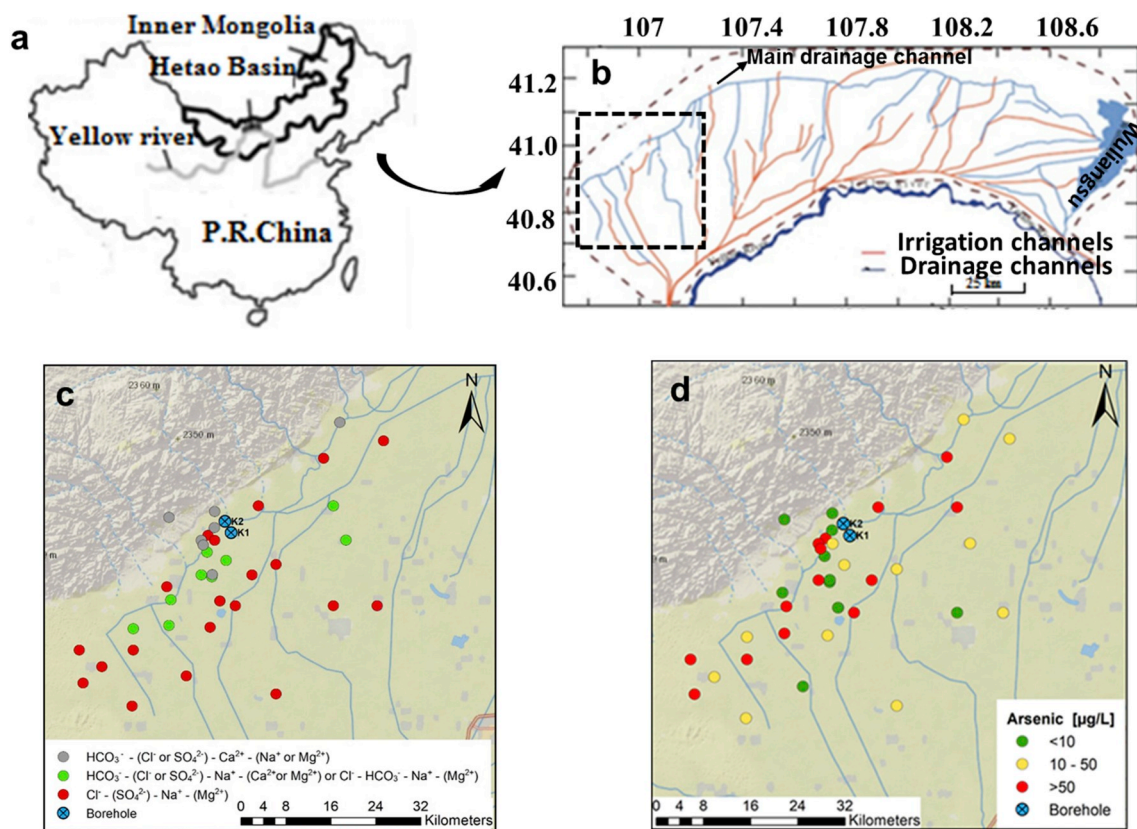


Fig. 1. Description for study area: a) geography position of the Hetao Basin, b) landscape of the Hetao Basin with labeled study area, the graph is modified from Jia et al. (2014), c) Google map of study area with groundwater samples, labeled groundwater chemistry types and boreholes area, d) Google map of study area with groundwater samples, labeled groundwater As concentration range and borehole area. Part of groundwater data is cited from Guo et al. (2011) with detailed information showed in Table S1.

2. Overview of the study area

The research area (Fig. 1) is located in the Hangjinhouqi, the northwest part of the Hetao Basin, near the paleolake sedimentation center. It is also one of most serious As contamination area in the Hetao Basin (Deng et al., 2011).

The Hetao Basin (13,000 km²) is located in the middle of Inner Mongolia (Fig. 1). It is a Cenozoic rift basin bordered by the Langshan Mountains in the north and the Kubuqi desert towards the south, stretching from Ulan Buh desert in the west to Wuliangsu Lake in the east. The Yellow River flows through from west to east along the southern margin of the basin, which is around 60 km away from the Lang Mountains. The Hetao Basin has typical semi-arid to arid continental climate. Precipitation mainly falls between June to September with an average monthly value of 200 mm and evaporation varies from 2000 to 2500 mm per year.

The Langshan Mountains, located in the north of the Hetao Basin, are mainly composed of Archen-Mesoproterozoic metamorphic rocks including gneiss, schist, phyllite, slate, and late Paleozoic igneous rocks mainly granite and diorite (Liu et al., 2016). In the early late Pleistocene epoch (~120 ka), alluvial-lacustrine sediments were developed while the Yellow River gradually migrated from the pediments of the Langshan Mountains to the south of the basin (Jia et al., 2016). Paleolakes gradually dried out after further 50 ka (Yang et al., 2018).

In the study area, the groundwater table ranges from ~1 m to 10 m (Guo et al., 2012). For irrigation and drinking, groundwater is mainly supplied from the Holocene-late Pleistocene fluvial/alluvial-lacustrine aquifer at up to 100 m depth. In general, the study area consists of an unconfined aquifer and a semi-confined aquifer separated by a clay layer at ~40 m depth (Inner Mongolia Institute of Hydrogeology, 1982; Jia et al., 2014).

3. Methods

3.1. Groundwater sampling and analysis

Thirty-seven groundwater samples from hand-pumped tube wells at depths < 100 m and one rain water sample were collected (7 samples were collected in 2017 and 30 groundwater and rain water samples are cited from Guo et al. (2011)). Detailed measurement information for published data was shown in Guo et al. (2011). Groundwater samples from October of 2017 were collected by the CUGB (China University of Geoscience (Beijing)) group and the KIT (Karlsruhe Institute of Technology) group. The sampling followed the same procedure as in Guo et al. (2011) except that groundwater was run through solid phase extraction (SPE) (Meng et al., 2001) and measured by HG-FIAAS (Hydride Generation Flow Injection Atomic Absorption Spectroscopy) with a PerkinElmer Analyst 200 coupled with a FIMS-400 Hydride Generation System and Auto sampler. Detection limit of FIAAS is around 0.1 µg/L. The groundwater samples were analyzed within one month after sampling. All groundwater sampling area and chemistry types used for hydrochemistry process analysis are shown in Fig. 1. Detailed results show in Table S1.

3.2. Multi-level well installations

Two multilevel wells (K1 and K2) were drilled by the CUGB group using circulatory drilling method in October 2015. K2 is located in the transition area, north of K1 with a distance of around 2 km, while K1 is located in the flat plain (Fig. 1). After cores were brought to the surface, they were sectioned into 10 cm lengths, capped, and placed into N₂ purged bags according to lithology and color variations observed by eye. Sub-samples of the sediments were transported to the KIT group.

The multi-level samplers were installed by CUGB group in October of 2015. Each well has 7 sampling levels placed at depths ranging from 15 to 80 m. Groundwater samples were collected from each depth of K1

and K2 and hydrochemical characteristics were analyzed by the CUGB group according to the method mentioned above.

3.3. Sediments characterization

Geochemical and mineralogical analysis of the sediments samples was performed at AGW (Institute of Applied Geoscience) of KIT in 2017. Samples were freeze-dried and homogenized by manual grinding. Mineralogy of the core samples was determined by X-ray diffraction (XRD) (Kristalloflex D500, Siemens, Germany) at 40 kV and 25 mA. Cu Kα₁-radiation was used at angles between 2° and 80°. Major minerals were identified using calibrated spectra by the software EVA program (Bruker) using the database of PDF 2002. Afterwards, the spectra were semi-quantified using known mineral compositions (Snyder and Bish, 1989; Norra et al., 2005).

Trace element composition in the sediments were determined by means of Energy Dispersive X-ray Spectrometry (EDX; Epsilon 5, PANanalytical). Results were regularly checked and corrected by standard material (SOIL-5, n = 4; GXR-6, n = 4; GXR-2, n = 4; SL-1 n = 4) with a precision better than 5%. Major elements (K, Na, Si, Ca, Mg, Fe, Mn) were analyzed by Wavelength Dispersive X-ray Spectrometry (WDX; S4 Explorer, Bruker AXS) with glass beads. The measurement accuracy (within 5%) was regularly checked by standard material AGV-1 (USGS).

Total sulphur (TS) and carbon (TC) content in the sediments were measured by Carbon-Sulphur-Analyzer (CS-2000, Leybold Heraeus, Germany) and total organic carbon (TOC) was measured after inorganic carbon removal by repeated addition of 20% HCl (Suprapure, Merck) at 60 °C. Detection limits for C and S are both 0.1 mg/kg. The measurement accuracy (± 0.5%) was controlled by reference material Cast Iron 92400–3100 (%C 4.20 ± 0.03 and %S 0.023 ± 0.001, USGS) and Steel 92400–3050 (%C 0.147 ± 0.002 and %S 0.027 ± 0.001, USGS).

3.4. Soluble salts in the sediments

The chemical composition of soluble salts were determined by a water-extraction method slightly modified from Tabelin et al. (2014) and analyzed at AGW of KIT. Four grams of each sediment sample was added into 20 mL of Milli-Q water. The extraction was performed in centrifuge tubes with mixing speed 300 r/min for 24 h. Afterwards, samples were centrifuged for 30 min at 4000 rpm and the pH and electrical conductivity (EC) were measured in the supernatant solution using pH and EC meters (WTW). The alkalinity was measured using a titration method with bromocresol green-methyl red indicator (Merck). Samples for cation and As concentration analysis were filtrated using 0.45 µm filters (cellulose acetate) and preserved by adding 1% 6 M HNO₃ (Superpure, Merck). Cations (Ca²⁺, Mg²⁺, Na⁺, K⁺) were measured by ICP-OES (Varian 715 ES), while anions (SO₄²⁻, Cl⁻) were analyzed using Ion Chromatography (Dionex, ICS-1000). The measurement accuracy (± 2%) was controlled by River Water reference (RW-LGC6020). Arsenic concentrations from extracted samples were analyzed with HG-FIAS.

3.5. Geochemical modeling and statistical analysis

Saturation indices (SI) for dolomite (CaMg(CO₃)₂), calcite (CaCO₃) and gypsum (CaSO₄·2H₂O) as well as As species calculation were modelled using PHREEQC with Wateq4f database, which was updated for As species according to Helz and Tossell (2008). The modeling temperature was assumed to be 10 °C according to the groundwater temperature ranging from 5.5 °C to 15.6 °C in the Hetao Basin (Li et al., 2013). The pH value, element concentration as well as As species (As (III) and As(V)) are known from measurement results. Statistical analysis for water as well as sediments data was done using IBM SPSS statistics.

Table 1

Semi-quantitative mineral abundance of sediments with different lithology from K1 and K2 borehole (except peat layers). Detailed information for single sample can be found in Table S2.

Mineral	Sand (wt %) (n = 22)	Silt (wt %) (n = 14)	Clay/silty clay (wt %) (n = 14)
Quartz	52 ± 4	39 ± 5	31 ± 3
Plagioclase	26 ± 2	30 ± 5	28 ± 8
K-feldspar	14 ± 3	12 ± 5	13 ± 8
Calcite	3 ± 1	8 ± 3	11 ± 6
Mica	4 ± 1	7 ± 2	12 ± 6
Dolomite	< 1	< 1	1
Chlorite/Kaolinite	< 1	2 ± 1	4 ± 3

4. Results

4.1. Sediments lithology and bulk chemical composition

Sediments from both K1 and K2 boreholes are dominated by fine sand and silt (Fig. S1). Quartz and feldspar (plagioclase and K-feldspar) are major minerals in the sediments (> 70%), while carbonates (calcite, dolomite), mica and clay minerals are minor phases (Table 1). The TIC content in the sediments ranges from ~0.6% to 1.5%, while the CaO and MgO content ranges from ~3.2% to ~7.1% and ~1.0%–~2.8%, respectively. Positive correlations between CaO and total inorganic carbon (TIC) ($R^2 = 0.97$) and between MgO and total inorganic carbon (TIC) ($R^2 = 0.83$) indicate that Ca^{2+} and Mg^{2+} mostly exist as carbonates (Fig. S2). Evaporite mineral content is below the detection limit of the XRD characterization except trace amounts of gypsum together with pyrite detected in a peat layer at a depth of 28.4 m in K2 (Table S2).

The average sulphur content in the sediments is 480 mg/kg for clayed or silt samples and 230 mg/kg for sandy samples (Table 2). However, no observable correlation between TS and TOC (0.045%–0.597%) combined with the low content of sulphides or polysulphides (evidenced by S K-edge XAS measurement; unpublished data) suggest that sulphur (S) mainly exists in form of sulphates in the sediments.

Arsenic content in the solid phases (except peat layers) ranges from 5 mg/kg to 41 mg/kg (Table 2) with an average content of 14 mg/kg. It is related with Fe content ($R^2 = 0.87$) (Fig. S3) rather than the TOC content, indicating that As mainly bonds/adsorbs into Fe related (oxyhydro)oxides and Fe-containing clay minerals in the sediments. Peat sediments (sediments with high content of organic matter) have higher As content up to 328 mg/kg at a depth of 28.4 m.

4.2. Soluble salts in sediments

Higher content of soluble salts ($\text{EC} > 1000 \mu\text{S}/\text{cm}^3$) was found in the near-surface sediments (< 4 m) compared to deeper sediments and mostly originate from sulphates and chlorides (Fig. 2). The lowest EC

value was observed at a depth around 6 m ($98 \mu\text{S}/\text{cm}^3$) in K1, suggesting that the accumulative soluble salts in deeper sediments are rarely sourced from top sediments. EC of Milli-Q water extracts for clayed/silty clayed samples (average $330 \mu\text{S}/\text{cm}^3$) is slightly higher than that in silty/sandy samples ($200 \mu\text{S}/\text{cm}^3$). Moreover, sandy/silty samples from K1 have higher EC values ($228 \mu\text{S}/\text{cm}^3$) than that of sandy/silty samples from K2 ($174 \mu\text{S}/\text{cm}^3$) (Fig. 2). The pH values of sediments vertically vary from 8.0 to 9.8 (Fig. 2). Such alkaline pH values are characteristic for saline or saline-sodic sediments and soils in arid and semi-arid regions as well as many fresh lakes (Inoue et al., 1998).

Water-extractable SO_4^{2-} content in sediments (at depth > 4 m) ranges from 56 to 555 mg/kg with an average value of 177 mg/kg, more than 5 times higher than the soluble Cl^- (from 8 to 92 mg/kg with an average value of 33 mg/kg). In both K1 and K2, the sediments at depth between ~10 m and ~40 m have higher soluble SO_4^{2-} content than sediments in the lower parts (Fig. 2). Average equivalent abundances of water-soluble cations of K1 sediments decrease in the order: Na^+ (56%) > Ca^{2+} (28%) > Mg^{2+} (14%) > K^+ (2%). Linear regression analysis shows that $[\text{SO}_4^{2-}]$ positively correlates with $[\text{Na}^+ + \text{Ca}^{2+}]$ ($R^2 = 0.55$) (Fig. 3a), it hints to the potential occurrence of glauberite ($\text{Na}_2\text{Ca}(\text{SO}_4)_2$) in K1. In the borehole K2, average Ca^{2+} equivalent abundance of total cations (60%) is higher than that of the Na^+ (26%) followed by Mg^{2+} (11%) and K^+ (3%). Positive correlations between soluble SO_4^{2-} and Ca^{2+} contents of K2 sediments ($R^2 = 0.50$) with the molar ratio of $\text{SO}_4^{2-}/\text{Ca}^{2+}$ close to 1 (Fig. 3a) indicates that SO_4^{2-} mainly exists as Ca-sulphates (gypsum or anhydrite (CaSO_4)). The sulphates dissolution system is buffered by carbonates dissolution, which is indicated by correlations between $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ and $[\text{HCO}_3^-]$ ($R^2 = 0.37$), $[\text{Ca}^{2+}]$ and pH ($R^2 = 0.65$) (Fig. 3b, c). Peat sediments leach out higher amount of SO_4^{2-} and Ca^{2+} with contents up to 5240 mg/kg and 1770 mg/kg at a depth of 28.4 m in K2, which is consistent with the gypsum/anhydrite detected by XRD.

4.3. Water-soluble As in the sediments

Water-soluble As is generally low in sediments from both K1 and K2. Arsenic concentration in the extraction solution (except peat layers) generally ranges from 0.3 $\mu\text{g}/\text{L}$ to 7.4 $\mu\text{g}/\text{L}$ with an average value of 2.5 $\mu\text{g}/\text{L}$ (average 13 $\mu\text{g}/\text{kg}$ in sediments), which only accounts for less than 0.1% of total As content in the sediments (average 14 mg/kg) (Fig. 2). An exception is that the As concentration in extraction solution is 23 $\mu\text{g}/\text{L}$ (115 $\mu\text{g}/\text{kg}$) at a depth of 11.5 m of K1 aquifer sand, more than 10 times higher than average value. Noticeably, arsenic release in the sand samples depends on the sediments pH conditions ($R^2 = 0.74$) (Fig. 3d).

4.4. Groundwater chemistry

All groundwater samples show a neutral or weakly alkaline condition with pH values ranging from 7.1 to 8.9. The detailed groundwater hydro-chemical characteristics analysis is shown in Guo et al. (2011).

Table 2

Major and trace elements composition from sediments depth profiles of K1 and K2 (except peat layers). Detailed information for single sample can be found in Table S3.

Lithology	Number	SiO_2 (wt %)	Na_2O (wt %)	CaO (wt %)	MgO (wt %)	K_2O (wt %)	Al_2O_3 (wt %)	MnO (wt %)	Fe_2O_3 (wt %)
clay/silty clay	14	53.9 ± 6.4	1.4 ± 0.4	7.1 ± 1.8	2.8 ± 0.5	3.0 ± 0.3	14.3 ± 1.5	0.09 ± 0.02	5.6 ± 1.0
silt	14	62.0 ± 6.5	1.7 ± 0.2	6.6 ± 1.4	2.2 ± 0.7	2.3 ± 0.3	11.4 ± 1.5	0.07 ± 0.02	4.1 ± 1.0
sand	22	77.0 ± 3.1	1.8 ± 0.1	3.2 ± 0.7	1.0 ± 0.2	2.1 ± 0.2	8.8 ± 0.6	0.04 ± 0.01	3.2 ± 0.7
Lithology	Number	TOC (wt %)	TIC (wt %)	TS (wt %)	As (mg/kg)	Sr (mg/kg)	Ba (mg/kg)	Rb (mg/kg)	
clay/silty clay	14	0.402 ± 0.198	1.537 ± 0.463	0.048 ± 0.017	21 ± 8	263 ± 56	513 ± 85	146 ± 17	
silt	14	0.229 ± 0.147	1.401 ± 0.398	0.048 ± 0.025	14 ± 5	241 ± 65	456 ± 45	105 ± 17	
sand	22	0.058 ± 0.011	0.578 ± 0.175	0.023 ± 0.005	7 ± 2	176 ± 9	450 ± 37	83 ± 9	

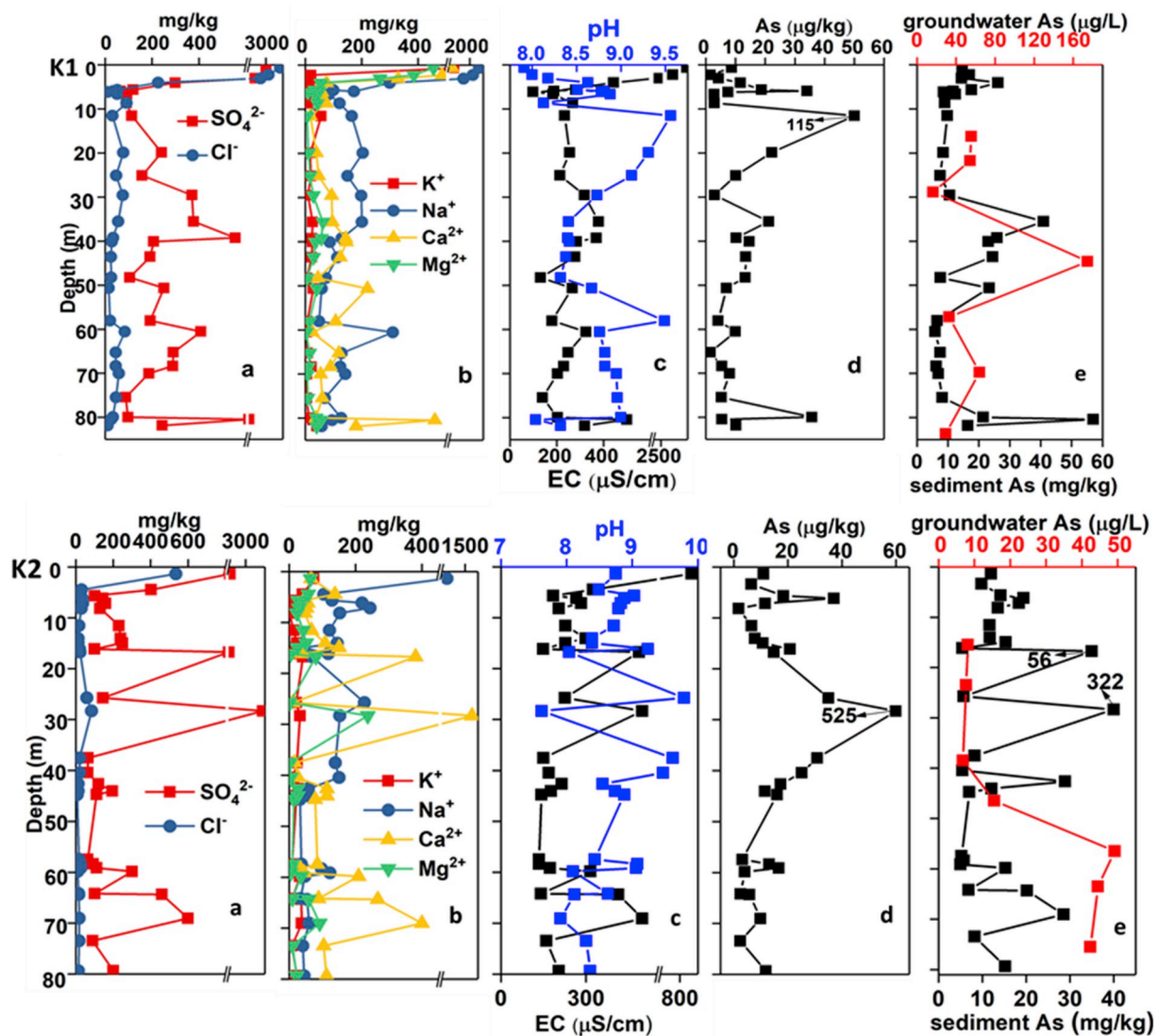


Fig. 2. Depth profiles of soluble salts from the sediments of K1 and K2. (a) content of soluble anions in the sediments: SO_4^{2-} and Cl^- , (b) content of soluble cations in the sediments: K^+ , Na^+ , Ca^{2+} , Mg^{2+} , (c) pH and electrical conductivity (EC) values in the sediments extraction solution, (d) soluble As content in the sediments, (e) arsenic content in the sediments as well as As concentration in the groundwater. The measurement values are provided in Table S4.

Isotopic compositions ($\delta^2\text{D}$ and $\delta^{18}\text{O}$) show that groundwater is of meteoric origin (Guo et al., 2011). Samples collected from alluvial fans and transition area have HCO_3^- or SO_4^{2-} as main the anions, and Ca^{2+} or Na^+ as the main cations (Fig. 1). In the flat plain, most groundwater samples are of the HCO_3^- - Na^+ type or Cl^- - Na^+ type, the latter near the main drainage channel (Fig. 1). More than 70% of analyzed groundwater samples are saline groundwater with TDS values (from 420 to 6730 mg/L) higher than 1000 mg/L. The depths profiles of TDS show that most saline groundwater occurs in the unconfined aquifer with depths between 10 m and 30 m (Fig. S4). SO_4^{2-} concentration ranges from near < 0.1 mg/L to 1260 mg/L, accounting for 18% of total anions in average.

Arsenic concentrations range from < 1 $\mu\text{g/L}$ to 666 $\mu\text{g/L}$ with an average concentration of 142 $\mu\text{g/L}$ in the study area (Guo et al., 2011). High TDS groundwater (84%) occurs concurrently with As concentrations above 10 $\mu\text{g/L}$, even though no direct correlation between TDS and As is observed. Arsenic concentrations in investigated groundwater samples are negatively correlated with SO_4^{2-} and Ca^{2+} concentration as well as ORP values (reducing conditions), while it is positively correlated with pH values (Table 3).

5. Discussion

5.1. Origin of groundwater chemical composition

Mineralogical analysis combined with mass-balance calculation yields important information on groundwater chemical composition for groundwater chemical composition (Mukherjee et al., 2009; Wang et al., 2009; Xie et al., 2013). Plots of $[\text{Mg}^{2+}/\text{Na}^+]$ vs $[\text{Ca}^{2+}/\text{Na}^+]$ and $[\text{HCO}_3^-/\text{Na}^+]$ vs $[\text{Ca}^{2+}/\text{Na}^+]$ in groundwater are presented in Fig. 4a and b along the mixing line with silicate, evaporite and carbonate minerals as end-members obtained from Gaillardet et al. (1997, 1999). Results show that groundwater chemistry evolution is mainly controlled by incongruent silicate and evaporite minerals weathering. Molar ratio of $[\text{Na}^+ + \text{K}^+]$ to total cations (varying from 0.34 to 0.97 with an average value of 0.72) is much higher than $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ (varying from 0.03 to 0.66 with an average value of 0.28) (Fig. 4c). Combined with lithological analysis, Na^+ and K^+ in the groundwater primarily provided from incongruent dissolution of feldspar and mica. In addition, sulphate minerals accumulated in soils or sediments might recharge Na^+ into groundwater (Jalali, 2007; Li et al., 2016), however, halite (NaCl) in sediment profiles is rare and limited leaching from

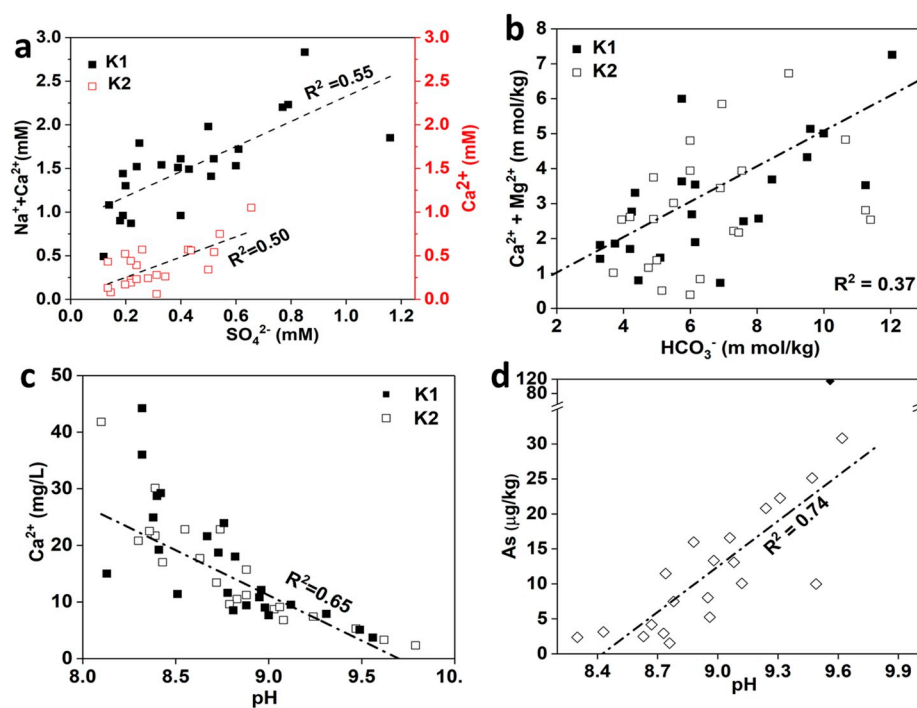


Fig. 3. Regression liner analysis of soluble salts in the sediments samples at depth > 4 m (except peat layers). (a) correlation between soluble SO_4^{2-} concentration and Na^+ as well as Ca^{2+} concentration in the extraction solution, (b) correlation between soluble HCO_3^- concentration and Mg^{2+} as well as Ca^{2+} concentration in the extraction solution, (c) relationship between sediments pH and soluble Ca^{2+} , (d) regression liner analysis to show As leaching in the sand samples depending the sediments pH. The filled square symbol stands for one outlier samples with high leached As content ($115 \mu\text{g/kg}$) at depth 11.5 m of K1 borehole.

Table 3

Pearson's correlation matrices for geochemical parameters showing marked correlations at a significant level $p < 0.01$. Part of groundwater data was cited from Guo et al. (2011).

	pH	ORP	EC	NH_4^+	Cl^-	SO_4^{2-}	HCO_3^-	K^+	Na^+	Mg^{2+}	Ca^{2+}	As(III)	As _T	Fe(II)	Fe _T	DOC	H ₂ S
pH	1																
ORP (mV)		1															
EC ($\mu\text{S}/\text{cm}^3$)			1														
NH_4^+ (mg/L)				1													
Cl^- (mg/L)			0.95		1												
SO_4^{2-} (mg/L)	-0.64	0.51	0.66		0.54	1											
HCO_3^- (mg/L)			0.73		0.65	0.50	1										
K^+ (mg/L)			0.63		0.64			1									
Na^+ (mg/L)			0.94		0.93	0.55	0.82	0.47	1								
Mg^{2+} (mg/L)	-0.49		0.82		0.77	0.71	0.48	0.73	0.64	1							
Ca^{2+} (mg/L)	-0.76					0.53				0.54	1						
As(III) ($\mu\text{g/L}$)	0.58	-0.68				-0.53					-0.48	1					
As _T ($\mu\text{g/L}$)	0.61	-0.68				-0.58					-0.47	0.97	1				
Fe(II) (mg/L)														1			
Fe _T (mg/L)		-0.54											0.51	0.43	0.78	1	
DOC (mg/L)																1	
H ₂ S ($\mu\text{g/L}$)		-0.51				-0.44							0.48				1

surface soil, shown by the TDS values in the soluble salts profile.

The effects of cation exchange are evaluated by an equivalent plot of corrected bivalent Ca^{2+} and Mg^{2+} versus corrected Na^+ (Fig. 4d). Groundwater samples from the study area form a slope near -1.0 , indicating that $\text{Na}^+/\text{Ca}^{2+}$ cation exchange is an important process for groundwater chemistry evolution (Mukherjee et al., 2009). Besides $\text{Na}^+/\text{Ca}^{2+}$ exchange, the positive correlation between $[\text{Cl}^-]$ and TDS ($R^2 = 0.89$) shows that strong evaporation probably occurs in the study area (Fig. 4e). However, there is no correlation between $\delta^{18}\text{O}$ and Cl^- concentration (Fig. 4f), which might be due to the fact that non-direct evaporation processes such as plant transpiration are contributing to the Cl^- enrichment, while the isotope compositions remain unchanged (Zimmermann et al., 1967). The deuterium excess further indicated that non-direct evaporation contributes to the groundwater salinity (Jia et al., 2017).

Compared with other high As alluvial systems in south and south-east Asia, SO_4^{2-} concentration in groundwater of the Hetao Basin is

relatively high (Berg et al., 2007; Guo et al., 2016). Molar ratio of SO_4^{2-} to Cl^- is up to 1.11, while the average $\text{SO}_4^{2-}/\text{Cl}^-$ ratio in the precipitation is 0.72. Lithological and soluble salt analysis reveals that SO_4^{2-} concentration can partly be attributed to the Na- and Ca-related sulphates which are among main evaporite minerals found in the sediments.

5.2. Contribution of evaporite minerals weathering to groundwater chemistry

Evaporite minerals found in the sediments are mainly Na and Ca related sulphates occurring as gypsum or anhydrite and most likely as glauberite. The weathering of Ca-sulphates can induce the groundwater dedolomitization process (Bischoff et al., 1994; Atekwana and Seeger, 2015), the total mass transfer of the dedolomitization process is given by the reaction (Apple and Postma, 2005):

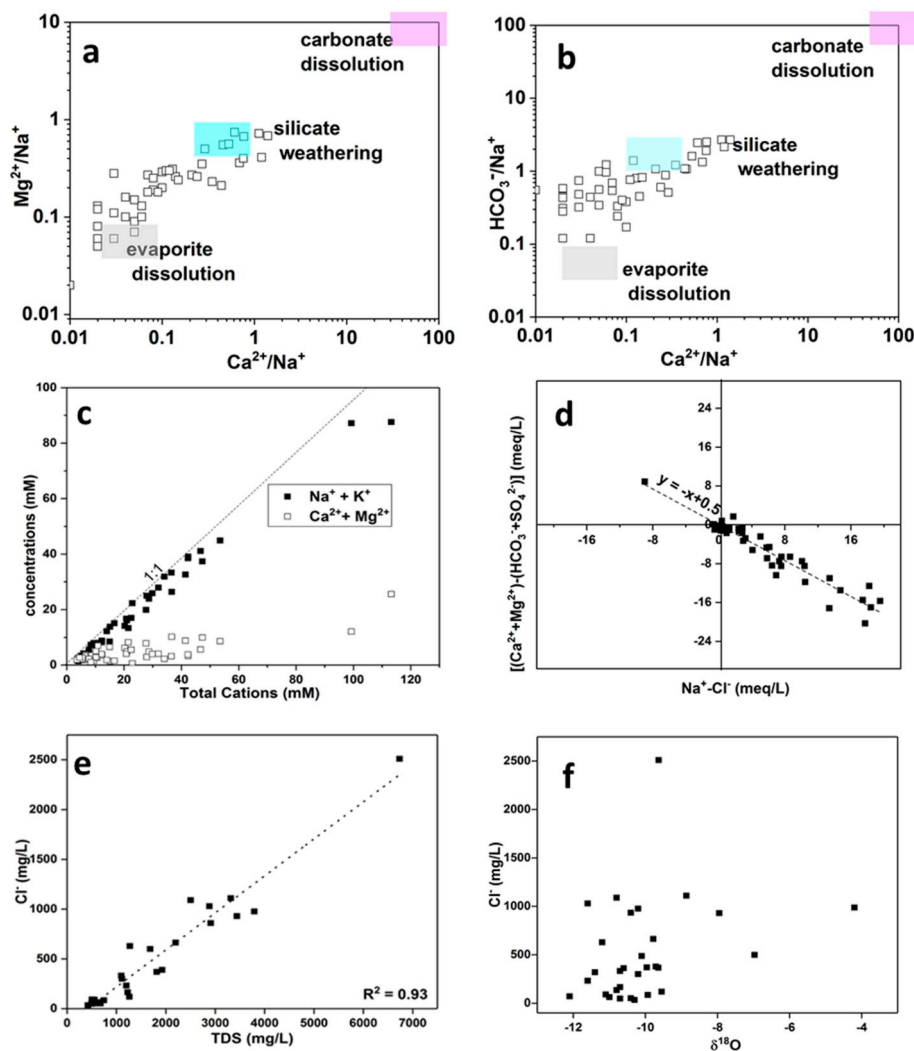
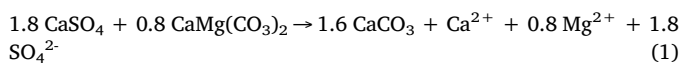


Fig. 4. Bivariate plots of ion analysis in groundwater. (a), Na-normalized Mg^{2+} ($\mu M/\mu M$) versus Ca^{2+} (μM), (b), Na-normalized ($\mu M/\mu M$) and HCO_3^- versus Ca^{2+} (μM), (c), molar ratio of Ca^{2+} and Mg^{2+} as well as Na^+ and K^+ versus total cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) in groundwater samples (d), Ca^{2+} and Mg^{2+} less HCO_3^- and SO_4^{2-} against Na^+ less Cl^- to indicate cation exchange (e), concentration of Cl^- versus TDS, (f), concentration of Cl^- versus $\delta^{18}O$. The weathering end members of silicates, carbonate and evaporites are cited from Gaillardet et al. (1997, 1999). Part of groundwater data is cited from Guo et al. (2011).



The theoretical molar ratios of $[Ca^{2+}]/[SO_4^{2-}]$ and $[Mg^{2+}]/[SO_4^{2-}]$ are 1:1.8 and 0.8:1.8, respectively. All groundwater samples in the study area are undersaturated with respect to gypsum, indicating the potential of Ca sulphates dissolution (Fig. 5). The Ca^{2+} and Mg^{2+} concentrations of groundwater simultaneously increase with increasing SO_4^{2-} concentration (Table 3). However, molar ratios of Mg^{2+} or Ca^{2+} to SO_4^{2-} are not strictly along the theoretical ratio line (Fig. 6a). The saturation index shows most groundwater samples are supersaturated with dolomite and saturated with calcite, this possibly suggests that the dedolomitization process may not further influence the hydrochemical conditions. Co-increased Ca^{2+} and Mg^{2+} concentrations with SO_4^{2-} concentration can be related to carbonate precipitation inhibitors, which are related to the Mg disturbance for the calcite crystal growth (Berner, 1975). Hydrogen (H^+) release resulting from precipitation of carbonates driven by gypsum can induce pH decrease (Back et al., 1983; Hanshaw and Hallet, 1978). The negative relationship between pH and SO_4^{2-} and between pH and Ca^{2+} further indicates that the carbonate precipitation is driven by gypsum (or anhydrite) or glauberite dissolution still actively happens in the research area (Fig. 6b and

Table 3.

For evaluating the influence of soluble sulphates for groundwater salinity, soluble SO_4^{2-} is converted to groundwater SO_4^{2-} concentration based on the assumption that aquifer porosity is 0.2 and mass density of sediments is 2.65 g/cm^3 , which are typical values for sediments (Francis and Brinkley, 1976) (Fig. 7a). Higher concentrations of both solid-phase and liquid phase SO_4^{2-} are observed at K1 borehole compared to the K2 borehole, this supports the hypothesis that groundwater SO_4^{2-} originates from the sediments. In general, groundwater SO_4^{2-} concentration is related to the water-soluble fractions of the SO_4^{2-} within sediments at the similar depth from both K1 and K2 borehole ($R^2 = 0.67$) (Fig. 7b), which also supports the hypothesis that part of SO_4^{2-} in the groundwater originates from evaporite minerals. Seasonal variation of groundwater SO_4^{2-} concentrations was monitored in the study area and found that most wells showed increasing trends from 2006 to 2010 (Guo et al., 2013b), confirming that sulphate minerals are still contributing SO_4^{2-} to the groundwater and weathering rate of sulphate minerals would be faster than the SO_4^{2-} reduction rate in general.

5.3. Potential effect of soluble evaporite minerals on As mobilization

More than 80% of high TDS groundwater is contaminated with As

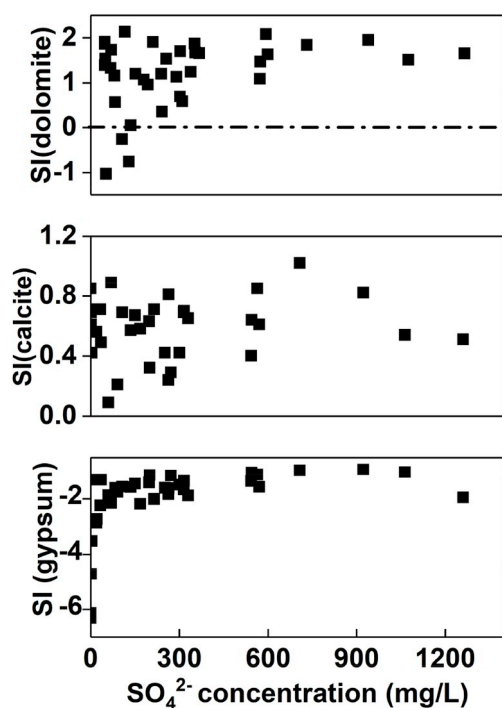


Fig. 5. Comparison of calcite (CaCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$), and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) saturation indices as a function of SO_4^{2-} concentration. Part of groundwater data was cited from Guo et al. (2011).

(> 10 $\mu\text{g/L}$). Evaporation can cause enrichment of elements, therefore possibly causing typical elevated As concentrations which is known to occur in groundwater in semi-arid to arid regions (Deverel and Millard, 1988; Nickson et al., 2005; Karroum et al., 2017). However, there is no significant correlation between the concentrations of major ions (except for SO_4^{2-} and Ca^{2+} and Mg^{2+}) and As concentrations (Table 3), indicating that As immobilization/mobilization in the groundwater is mainly influenced by factors other than evaporations.

Water-soluble As only accounts for a minor percentage of the total As content in sediments and is independent of soluble salts, while it is related to the pH conditions in the leaching solution. In the Hetao Basin, arsenic is mainly incorporated into/adsorbed onto Fe containing minerals including Fe (oxyhydr)oxides and clay minerals. The adsorption abilities of those minerals are significantly influenced by solute pH conditions. With elevated solute pH, As species especially HAsO_4^{2-} , can be desorbed from iron oxides or clay mineral surfaces to the solution

(Schwertmann and Cornell, 1992; Dixit and Hering, 2003; Bhattacharyya and Gupta, 2008). The pH-dependent As concentration in the leaching solution suggests that the As release from the sediments matrix could be influenced by the groundwater pH conditions in the Hetao Basin. The spatial patterns in groundwater hydrochemistry show that pH decreases with the continual carbonate precipitation, which is driven by Ca related sulphates dissolution. On one hand, the decreased pH can retard As desorption from (oxyhydr)oxides and clay minerals. Furthermore, the divalent cation- Ca^{2+} can increase the positive surface charge of clay minerals (Fakhreddine et al., 2015), the adsorption potential of clay minerals for As will increase. The positive correlation between groundwater pH and As concentration, as well as the negative correlation between Ca^{2+} concentration and As concentration reinforces this hypothesis. The pH-dependent As release has already been evidenced in the La Pampa Basin of Argentina (Smedley et al., 2005). Furthermore, previous studies suggest that As could be incorporated into the crystal structures of precipitating carbonates, but mostly with $\text{pH} > 9$ (Goldberg and Glaubig, 1988; Fakhreddine et al., 2015), it would have minor influence for weakly alkaline pH conditions of groundwater in the Hetao Basin.

Redox cycles of sulphur and iron in the groundwater can promote sulphides formation, and therefore influencing the As mobilization in the groundwater. In the Hetao Basin, arsenic concentration generally increases with the increasing sulphide concentration under relatively low sulphide flux (< 50 $\mu\text{g/L}$) (Table 3 and Fig. 8a). This could be related to that As release from sediments increases with stronger groundwater reducing conditions, which occurs simultaneously with SO_4^{2-} reduction. In addition, the modeling results show that sulphide can form thio-As species, especially with As(V) (HAsO_4^{2-}) in the groundwater. In comparison with As(V) or As(III) species, thio-As species are much more stable in the groundwater, which can potentially increase the As mobilization in the aquifer (Sø et al., 2018) (Fig. 8b). This is consistent with previous suggestions that sulphide could stabilize As by formation of thio-As species under a subsurface alkaline environment (Stucker et al., 2014; Mladenov et al., 2014). Furthermore, Fe (oxyhydr)oxides can be thermodynamically reduced by sulphide (Poulton et al., 2004; Sun et al., 2016). However, it is unexpected with such high amount of reactive Fe in the sediment matrix under low sulphide flux, reaction of sulphide with Fe^{2+} from microbial reduction of Fe (oxyhydr)oxides inhibits the reaction between H_2S and Fe (oxyhydr)oxides. However, some samples with high sulphide concentrations ($\geq 50 \mu\text{g/L}$) have relatively lower As concentration was found in Hetao basin (Fig. 8a). This possibly suggests that As could incorporate into pyrite, which is confirmed in the peat sample with high content of As at depth 28.4 m of K2, and pyrite together with gypsum are being characterized (Table S2). The reactive organic carbon leached from detrital

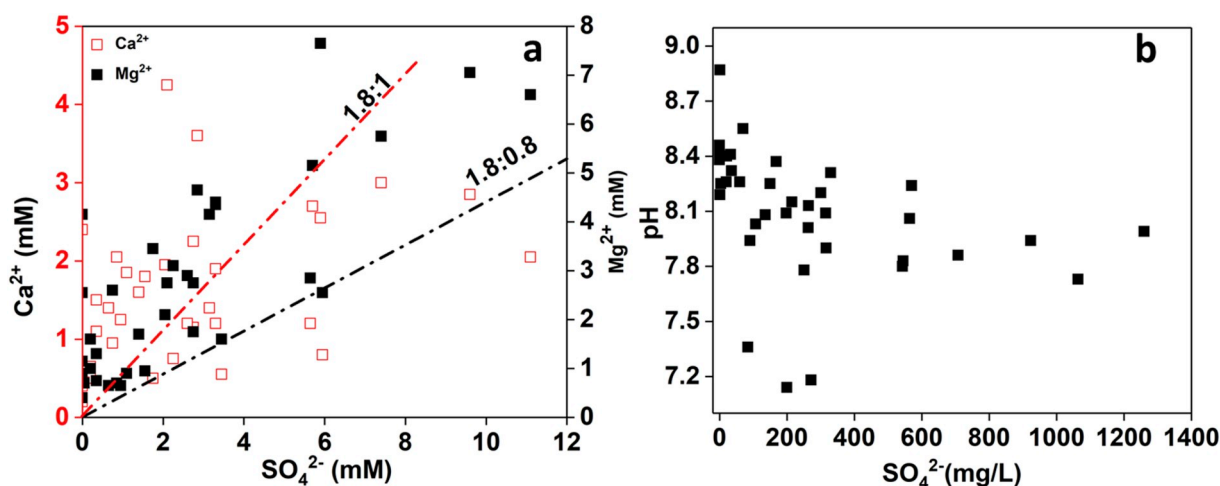


Fig. 6. Bivariate plots of Ca^{2+} and Mg^{2+} versus SO_4^{2-} (a) and pH versus SO_4^{2-} , (b) part of the groundwater data was cited from Guo et al. (2011).

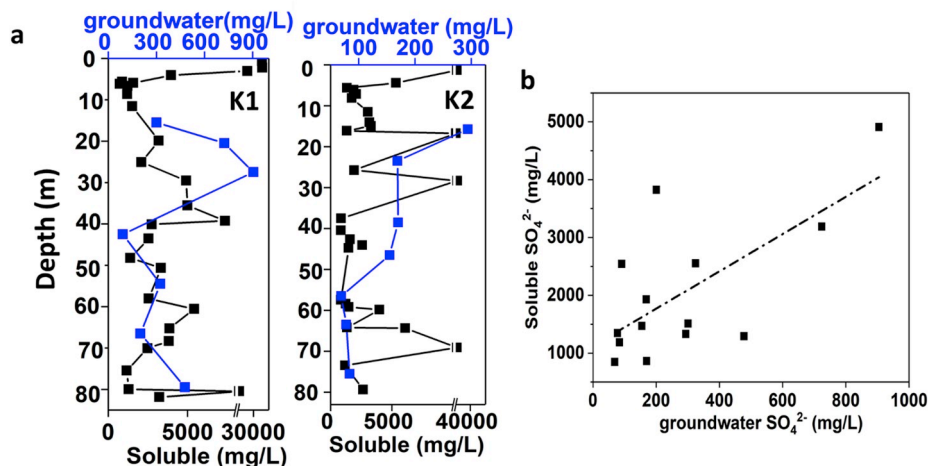


Fig. 7. Depth profile of sediments soluble SO_4^{2-} and groundwater SO_4^{2-} (a) and correlation (b) (soluble SO_4^{2-} in sediments is converted into groundwater SO_4^{2-} concentration basing on assumption that aquifer porosity is 0.2 and mass density of sediments is 2.65 g/cm^3).

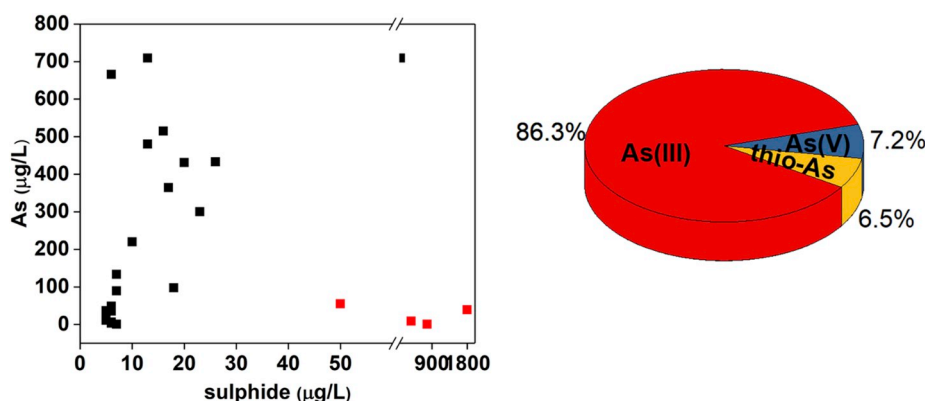


Fig. 8. Influence of sulphide concentration for As mobilization: (a) bivariate plots of As versus sulphide, the red filled squares show groundwater samples with higher sulphide concentration and relatively low As concentration ($< 100 \mu\text{g/L}$), (b) example of modeling results for As species (As concentration: $515 \mu\text{g/L}$, sulphide concentration: $16 \mu\text{g/L}$). Thio-As species stands for As-sulphide complex, As content for respective species was calculated if the concentration is higher than $1 \mu\text{g/L}$. Part of the groundwater data is cited from Guo et al. (2011). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

peat layers or recharged from surface provides enough electrons for SO_4^{2-} and Fe^{3+} reduction (Guo et al., 2019), and therefore promoted formation of arsenianpyrite/arsenopyrite in the aquifer. Similarly, the significant role of pyrite for As sequestration has already been evidenced in the Mekong River Delta and Bangladesh (Lowery et al., 2007; Stuckey et al., 2015).

6. Conclusions

In the study area, more than 70% of groundwater shows salinization properties with $\text{TDS} > 1000 \text{ mg/L}$. In combination with lithological analysis, major ion ratios show that the groundwater salinization is mainly caused by evaporation and $\text{Na}^+/\text{Ca}^{2+}$ cation exchange followed by silicate and evaporite minerals weathering.

Water-extraction experiments show that evaporites mainly include sulphates. Whereas evaporite mineral dissolution only releases less than 0.1% of total As in sediments, it can influence As concentration via groundwater salinization processes. Saturation indices of gypsum, calcite and dolomite and negative correlation between pH and SO_4^{2-} suggest that groundwater chemistry does not achieve equilibrium with carbonate precipitation and Ca sulphates weathering. The pH decrease and Ca^{2+} release induced by Ca sulphates weathering can retard As desorption from the Fe (oxyhydr)oxides and clay minerals. Furthermore, arsenic can be incorporated into the structure of pyrites which forms following by SO_4^{2-} reduction, which is evidenced by XRD characterization in peat (organic carbon-rich) layers. However, modeling results suggest that trace sulphide may form thio-As species with HASO_4^{2-} , which would be much more stable in comparison with H_3AsO_3

and HASO_4^{2-} species in the groundwater. Further research should be attempted to model the quantification effects of sulphates dissolution on groundwater salinization and As mobilization process in the Hetao Basin.

Acknowledgement

The study was financially supported by the National Natural Science Foundation of China (grant Nos. 41825017, 41702272 and 41672225). We express the special thanks to Graduate School for PhD students of KIT-center Climate and Environment (GRACE) at Karlsruhe Institute of Technology for the field trip funding to go to Hetao Basin. We are grateful for the help for analytical supports from our colleagues B. Oetzel (XRD, XRF and CSA) and G. Preuss (ICP-OES and FIAS), C. Moessner (IC) and XRD spectra analysis support from G. Ott. We also appreciate the help from CUGB group during the field trip to the Hetao Basin. We are grateful for the language update from M.S. O. Moore and Dr. S. Islam in University of Manchester. We especially give thanks to the editor and reviewers for giving valuable suggestions and comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apgeochem.2019.104416>.

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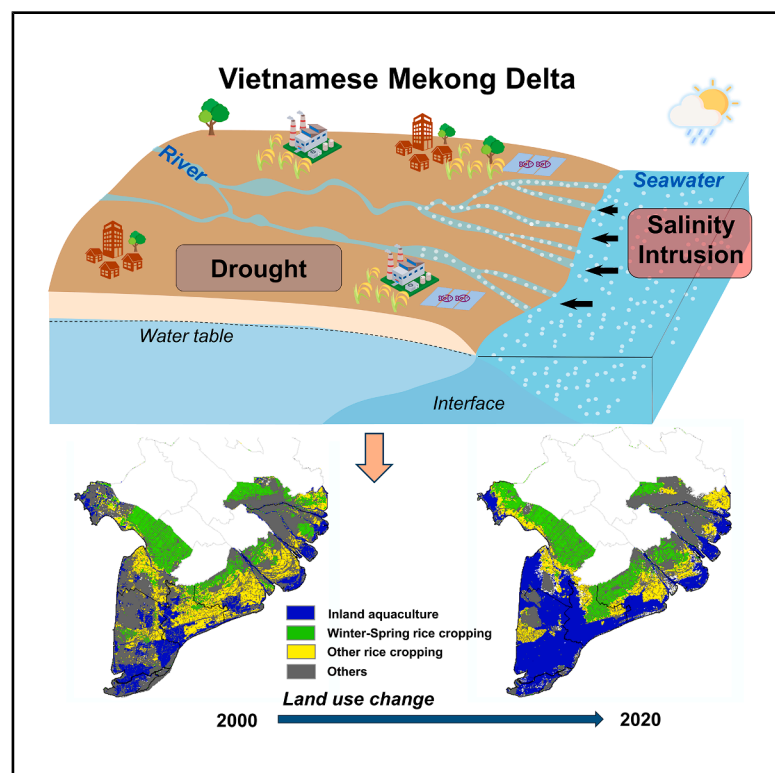
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Land use change in the Vietnamese Mekong Delta: Long-term impacts of drought and salinity intrusion using satellite and monitoring data

Graphical abstract



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In brief

Earth-surface processes; Remote sensing; Agricultural land

Highlights

- Salinity intrusion and drought reduce rice yields in VMD's coastal provinces
- Satellite data reveal shifting land use patterns linked to extreme dry seasons
- Adaptive cropping and water strategies are vital for delta agricultural resilience



Article

Land use change in the Vietnamese Mekong Delta: Long-term impacts of drought and salinity intrusion using satellite and monitoring data

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SUMMARY

Drought and salinity intrusion (DSI) increasingly threaten agriculture and aquaculture in coastal regions. Focusing on the Vietnamese Mekong Delta (VMD), we examined how DSI from 2000 to 2020 influences rice cropping, aquaculture area, and rice yield across seven coastal provinces. *In-situ* discharge and salinity monitoring, combined with satellite-derived land use data and yield validation, revealed the highest DSI impacts during the 2010–2011, 2015–2016, and 2019–2020 dry seasons. Local governments employed strategies such as drought-tolerant rice, improved irrigation, and revised cropping schedules to mitigate losses, yet further investments remain vital. Our findings provide evidence-based insights for managing DSI and strengthening agricultural resilience in the VMD and other vulnerable deltas worldwide.

INTRODUCTION

Drought and saline intrusion (DSI) have increasingly affected aquaculture and agricultural production in many river deltas worldwide, home to over half a billion people.^{1,2} These phenomena and processes have adversely undermined the livelihoods and sustainability of millions of coastal inhabitants, especially those based on agriculture and aquaculture. A drought is defined as a period when an area or region experiences below-normal values of precipitation (meteorological drought), streamflow (hydrological drought), or soil water content (agricultural drought).³ SI refers to the upstream movement of saline water from the sea into freshwater zones⁴ and becomes more extreme in drought years.⁵ Recent intensification of SI has degraded crucial ecosystem services worth trillions of dollars globally that provide fertile alluvial soils, sustaining biological diversity, and aquatic habitat for flora, fauna, and fisheries in many deltas worldwide.¹

DSI has caused direct impacts on various economic sectors in different regions worldwide. Five of the direct consequences are: (1) crop yield reduction in Bangladesh's coastal agriculture,^{6,7} (2) agricultural lands and aquaculture production in the Tagus Estuary of Portugal,⁸ (3) significant loss of land, livestock, freshwater fish, agricultural yield reduction (~30%), and migration of tens of thousands of inhabitants in the Indus and Ganges deltas,⁹ (4) challenged livelihoods of thousands of farmers by blocking

agriculture development in the Yellow River Delta,^{10,11} and (5) mangrove habitat shift and significantly high tree mortality in some parts of the Orinori and Mississippi rivers.^{2,12} Besides the direct consequences, SI has far-reaching socio-environmental impacts, as it can cause severe drinking water scarcity, threaten food security, and create health problems.¹³ These examples highlight that socio-environmental consequences caused by SI are crucial at multiple scales. Intensifying SI at the global scale has recently become a crucial sustainability challenge of humankind designated by the United Nations' Sustainable Development Goals in terms of zero hunger, good health and well-being, and clean water and sanitation.¹⁴ These studies also predicted that the increasing climate change-driven DSI may accelerate agricultural yield losses, thus threatening the livelihoods, food security, and income generation of many coastal inhabitants worldwide.

The Vietnamese Mekong Delta (VMD) is among the most affected regions in Southeast Asia by DSI.¹⁴ Spatiotemporal agricultural production patterns and aquaculture have been severely affected by DSI across the delta, especially in the coastal provinces.¹⁵ In recent dry seasons, the VMD has experienced two strong DSI events in 2015–2016 and 2019–2020,⁵ and just recently in 2024, with the full extent of the impacts still unknown. During the 2015–2016 dry period, the DSI damaged a total agricultural area of 210,000 hectares (or ha) in almost all



provinces in the VMD, whereas 250,000 households encountered freshwater shortages.¹⁶ Subsequently, in the 2019–2020 dry season 10 out of 13 provinces experienced increased SI, resulting in a notable water shortage to 96,000 households (430,000 people) and harm to 58,000 ha of rice, 6,650 ha of fruit trees, 1,241 ha of vegetables, and 8,715 ha of aquaculture.¹⁷ DSI is becoming more severe yearly, putting high pressure on local governments to seek adaptation strategies and alternative farming systems. At the grassroots level, many farmers have tried to adapt to the shocks and stressors entailed by DSI, i.e., land use transformation and learning new techniques, but their livelihoods remain insecure.¹⁸ This insecurity is largely due to a lack of scientifically grounded guidance from authorities on adaptive measures. Instead, farmers have predominantly relied on their own experiences and observations to make land use decisions. As a result, in some regions, the newly transformed land may not be suitable due to the impacts of DSI.

In the VMD, most previous studies have assessed the magnitude and impacts of either drought^{19–22} or SI^{23–25} on different fields. Some studies highlighted the intensification of SI under extreme drought events⁵ and riverbed incision due to river damming and sand mining.²⁶ Tran et al. [2019] correlated soil salinity with drought intensity in Ben Tre Province, and they found that drought intensified salinity in rice-cultivated and natural cropland areas, but an opposite trend was detected in aquaculture areas.²⁷ However, a comprehensive assessment of the spatio-temporal correlation between DSI and land use change in the VMD's coastal area still needs further exploration. To date, Smaijl et al. [2015] was the most comprehensive research in assessing SI dynamics in the entire VMD under the combined impacts of climate change and human activities with an emphasis on the impact of the future projected SI on agriculture production, from which combined soft and hard measures were proposed.²⁵ However, SI dynamics were assessed merely using numerical modeling that was calibrated and validated using data before 2012, which is relatively outdated due to the region's fast-changing conditions. Moreover, their study did not consider SI in drought events which may exacerbate SI impacts.¹⁵ Because of that, recent severe DSI events, e.g., in 2015–2016 and 2019–2020, should be investigated to understand their effects on land use changes and crop yields in the coastal provinces. A comprehensive study similar to Smaijl et al. [2015]²⁵ for recent DSI for the entire VMD's coastal provinces using long-term monitored data is of an urgent need to understand the dynamics, the causes, and the consequences of the past DSI events, from which better solutions can be proposed for implementation in the future.

Several studies have examined the impacts of drought and SI individually on different aspects of agricultural land use change across the VMD^{28–32}; however, none of these studies has explicitly examined the long-term relationship between DSI events and land use changes or their specific impacts on crop area and yields in the VMD. The coastal delta's land use management strategies have evolved in response to DSI, which has been exacerbated by climate change and environmental pressures.^{24,31} Cultivated land is shrinking, while soil quality and crop yields have decreased over the years due to increased DSI in many coastal regions.^{29,30} Pests also overgrow and increase their ability to cause disease, leading to a higher risk of

disease transmission to animals, affecting crops and livestock.¹⁷ While the river experiences lower water levels in the dry season,²³ coastal economic activities and fishing and aquaculture activities are seriously affected by the high-saline concentration water fluxes from the sea.³³ During the drought, people relied on fresh groundwater resources for domestic use, and this over-extraction has further worsened land subsidence and groundwater salinization.³⁴ Overall, the previous findings overlooked the impacts of the DSI on the long-term land use changes in coastal provinces. Evaluating the impacts of these changes, particularly on crop area and yields, remains essential for understanding this complex relationship.

The present study aims to address two knowledge gaps. First, we examine hydrological drought and salinity intrusion (DSI) patterns—using discharge, salinity, and satellite-based land use data—to understand long-term trends and their impact on Winter-Spring rice cropping in coastal provinces in terms of area and yield. Second, we evaluate how land use transformations mitigate the negative effects of DSI, particularly during extreme events (e.g., 2016 and 2020), and recommend sustainable strategies for different coastal regions. We aim to answer two key research questions: (1) How did DSI affect Winter-Spring rice crop area and yield from 2000 to 2020 in each study province? and (2) To what extent has DSI been extreme over the years in terms of intrusion boundary and intensity to agricultural activities? Our study contributes novel insights into hydrological DSI analysis and land use transformation strategies, offering evidence-based solutions that not only enhance agricultural and aquaculture resilience in the VMD but also serve as a blueprint for similarly vulnerable deltas and DSI-affected farming regions worldwide.

RESULTS

Drought and salinity intrusion in the last two decades

Drought years were identified using SSI-6 from 2000 to 2020 (Figure 1) and compared with the literature (Table 1). Six drought events were identified with two consecutive droughts occurring in 2003–2004 and 2004–2005. The most severe drought in magnitude was in 2019–2020 ($-1.5 < \text{SSI-6} < -1.93$), followed by the drought in 2015–2016 ($-1.67 < \text{SSI-6} < -1.85$). However, the 2015–2016 drought caused the strongest impacts on socio-economics in the VMD.¹⁵ During 2000–2020, the interval between two droughts ranged from one to five years, with an average of three years. This is alarming because the interval was up to eight years (1992 and 1998) before 2000.

Figure 2 shows that salinity concentrations at almost all analyzed stations have increasing trends, in which the trends in some stations are statistically significant of either 5% or 10% significance levels. At stations in the East Vietnam Sea, Binh Dai experienced the most increased maximum (0.15 g/L/yr) and minimum (0.4 g/L/yr with $p < 0.05$) salinity concentrations during 2000–2020. On the other hand, Tra Kha and Ganh Hao did not have a clear trend in both maximum and minimum salinity concentrations. At stations in the Gulf of Thailand, the highest increase in salinity is at Xeo Ro, with a rate of 0.35 and 0.19 g/L/yr in the maximum and minimum salinity concentrations (both have $p < 0.1$), respectively. In general, maximum salinity concentration increased in the Gulf of Thailand (i.e., at Xeo Ro) more than in the

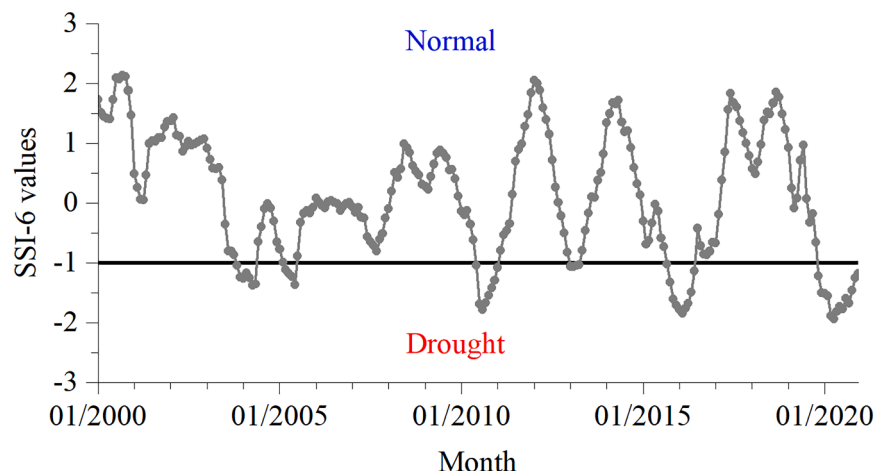


Figure 1. Monthly SSI-6 values at the Tan Chau station

rice cropping and other crops were practiced mainly in Kien Giang, Soc Trang, and Tra Vinh provinces, while the areas in Ca Mau and Bac Lieu were cultivated mainly with aquaculture. On the other hand, orchard gardens were located mainly in Tien Giang province.

Effects of drought and salinity on Winter-Spring rice area and yield

Analyzing long-term trends during 2000–2020, we found that the Winter-Spring rice area increased in Kien Giang

East Vietnamese Sea; however, the reverse relation is true for minimum salinity concentration.

In drought years, e.g., 2004–2005, 2012–2013, 2015–2016, and 2019–2020, salinity concentrations were significantly higher than in normal years. Maximum salinity concentrations in 2016 were higher than the long-term (2000–2020) average by 3.9%, 31.1%, 17.0%, 16.6%, and 49.8% at Binh Dai, An Thuan, Tra Kha, Song Doc, and Xeo Ro, respectively. In 2020, maximum salinity concentrations were even higher, increasing by 11.7%, 31.2%, 87.5%, 26.4%, and 38.2% at Binh Dai, An Thuan, Tra Kha, Song Doc, and Xeo Ro, respectively, compared to the long-term average. The increasing rates in the minimum salinity concentrations were even greater than those in the maximum values, for instance, by 58.8%, 110.3%, 87.5%, 22.0%, and 138.6% in 2020 compared to the long-term average. At Ganh Hao, however, the maximum salinity concentrations in 2016 and 2020 were slightly lower than the long-term average by –4.0% and –1.5%, respectively. The dynamics of salinity in the area are complex, and additional research is necessary to grasp all contributing factors, both natural and anthropogenic.

Dynamics of the Winter-Spring rice area and yield

Figure 3 presents the high agreement between MODIS satellite products and statistical data on total rice planted and aquaculture areas in seven provinces. The figure shows that the MODIS satellite can accurately detect areas of rice and aquaculture in the studied province, although it slightly underestimated the aquaculture area in Kien Giang Province. In general, with correlations of determination R^2 of 0.97 and 0.95 for rice and aquaculture, respectively, applying satellite products in land use pattern detection is considered reliable.

The dynamics of the Winter-Spring rice cropping area were investigated from 2000 to 2020 in the coastal areas, as shown in Figure 4 for a temporal scale of five years, and Figure S1 in the Supplementary for the temporal scale of one year. Four classes of land use types were examined, including (1) inland aquaculture (blue), (2) Winter-Spring rice cropping (green), (3) other rice cropping (yellow), and (4) other land use pattern, i.e., forest, orchards, and built-up areas (gray). Land use patterns exhibit varying changes across provinces. Specifically, Winter-Spring

($p < 0.001$), Tra Vinh ($p = 0.0002$), Bac Lieu ($p = 0.0001$), and Soc Trang ($p < 0.001$), but decreased in Ben Tre ($p < 0.001$) and Tien Giang ($p < 0.001$) (Figure 5A). The increasing rate was highest in Kien Giang, at 3,382 ha/yr, followed by Soc Trang, at 1,451 ha/yr. Tien Giang experienced the greatest decreasing rate, at –1,330 ha/yr, while Ben Tre decreased by –595 ha/yr. On the other hand, the Winter-Spring rice yield has statistically increased in five out of seven coastal provinces. For Ben Tre ($p > 0.05$) and Ca Mau, limited data are available for trend testing, but a similar trend can be inferred (Figure 5B). Bac Lieu increased the most in regard to Winter-Spring rice yield (by 19 quintals/ha/yr, $p < 0.001$), followed by Kien Giang (by 12 quintals/ha/yr, $p < 0.001$) and Soc Trang (by 11 quintals/ha/yr, $p < 0.001$). Ben Tre insignificantly increased by 1 quintal/ha/yr ($p > 0.05$).

As seen in Figure 5A, the Winter-Spring rice cropping area between 2000 and 2020 only changed slightly in the seven coastal provinces of the VMD. Kien Giang (green color) had the largest area for rice cropping, increasing steadily from 230,000 ha in 2000 to 260,000 ha in 2003. Afterward, this area decreased to 250,000 ha in the drought years 2004 and 2005, then increased steadily to 300,000 ha in 2016 and slightly declined to 280,000 ha in 2020. The area of the Winter-Spring rice cropping in Soc Trang province (red color) was relatively stable from 2000 to 2014 with approximately 140,000 ha, but then increased significantly in 2015, remaining unchanged until 2020 at 200,000 ha. The rice cropping area in Tien Giang shows a reduction from 100,000 ha in 2000 to 50,000 ha in 2020. The areas of rice practiced in Tra Vinh, Ben Tre, Ca Mau, and Bac Lieu were limited, varying from only 20 ha to 50,000 ha.

The Winter-Spring rice cropping area in Ben Tre decreased substantially during the 2016 and 2020 drought years. Although the rice cropping area in Ben Tre is generally smaller compared to other provinces, it experienced a sharp decline in 2016, reducing to just 1/74 of the average area recorded between 2000 and 2015. In 2020, this area further declined, shrinking to only 1/440 of that average. In the other coastal provinces of the VMD, the Winter-Spring rice cropping area did not decrease significantly during the historically severe drought years of 2016 and 2020.

Table 1. Drought years in the VMD using SSI-6

Year	This study		Apel et al. ²⁹	Loc et al. ⁵	Nguyen et al. ²³
	SSI-6	Severity			
2000–2001	Normal				
2001–2002	Normal				
2002–2003	Normal				
2003–2004	Drought	Moderate	Drought		
2004–2005	Drought	Moderate	Drought	Drought	Drought
2005–2006	Normal				
2006–2007	Normal				
2007–2008	Normal				
2008–2009	Normal				
2009–2010	Normal				
2010–2011	Drought	Severe	Drought	Drought	Drought
2011–2012	Normal				
2012–2013	Drought	Moderate	Drought		
2013–2014	Normal				
2014–2015	Normal				
2015–2016	Drought	Severe	Drought	Drought	Drought
2016–2017	Normal				
2017–2018	Normal				
2018–2019	Normal				
2019–2020	Drought	Severe		Drought	Drought

The influence of droughts on rice yield is presented in Figure 5B. Rice yield in the seven provinces varies from 40–55 to 60–65 quintals/ha from 2000 to 2020. Within six drought events over the last two decades (Table 1), the droughts in 2015–2016 and 2019–2020 were considered extreme.^{5,18} As a result, rice yield was affected in 2016 and 2020, as illustrated in Figure 5B. Particularly, rice yield in Ben Tre and Tra Vinh provinces was impacted seriously in 2016, with a reduction of 23.6 quintals/ha (reduced by 45%) and 14 quintals/ha (reduced by 26%), respectively, in comparison with the mean values in previous years (2000–2015). Similarly, rice yield in 2020 dropped by 14 quintals/ha (reduced by 27%) in Ben Tre and 19 quintals/ha (reduced by 35%) in Tra Vinh compared with the 2000–2015 average.

Figure 6 shows pairwise relationships between maximum salinity concentration and the Winter-Spring rice area and yield in six coastal provinces (Ca Mau was excluded because of a lack of data on rice cultivation in some years). In Ben Tre, an increase in salinity caused a significant reduction in the rice cropping area ($p = 0.04$, Figure 6A) and rice yield ($p = 0.04$, Figure 6G). If salinity concentration increased by 1.0 g/L, the rice area and yield in Ben Tre would decrease by 864 ha and 0.9 quintal/ha, respectively. The Winter-Spring rice crop in Ben Tre was significantly affected by DSI, likely due to the province's long-standing poor soil quality and groundwater conditions. In Tien Giang, salinity was negatively correlated with the rice area (Figure 6E), but positively correlated with rice yield (Figure 6K) indicating that yield increased even as salinity rose ($p = 0.06$) (Figure 6K). This can be explained by the fact that local farmers in Tien Giang, following warnings and guidance from local authorities, have not cultivated the Winter-Spring rice crop during years of high

salinity, particularly in drought years. As a result, the areas not affected by salinity have been able to maintain productive rice yields even during the DSI years.

Differently, an increase in salinity tended to increase the rice area ($p = 0.08$, Figure 6B) and yield in Kien Giang ($p = 0.13$, Figure 6H). Farmers in this province may cultivate rice-shrimp farming and salinity-tolerant rice varieties³⁵ which, therefore, were not affected by salinity intrusion (SI). Additionally, farmers may have gained more valuable experience after the 2015–2016 event, enhancing the resilience of their farming activities to DSI. In Tra Vinh, the rice yield would significantly decrease if salinity increased ($p = 0.04$, Figure 6L), although the rice area did not show a statistical relation with salinity increase ($p > 0.05$, Figure 6F). Similar to Ben Tre, farmers in Tra Vinh would need support from local authorities to mitigate the impacts of salinity on rice cultivation. Regarding the remaining provinces, increases in salinity potentially reduced the rice area but it is not statistically significant.

DISCUSSION

Reflections on the impacts of droughts and salinity intrusion (DSI) on land use change

We identified six drought events which are consistent with the findings of Apel et al. [2020], Loc et al., [2021b], and Nguyen et al. [2023].^{5,22,28} However, the 2015–2016 drought caused the strongest impacts on socioeconomics in the VMD¹⁵ because of good early warning in 2020, lessons learned from the 2015–2016 event, and well-prepared strategies.^{5,15,28} During 2000–2020, the interval between two droughts ranged from

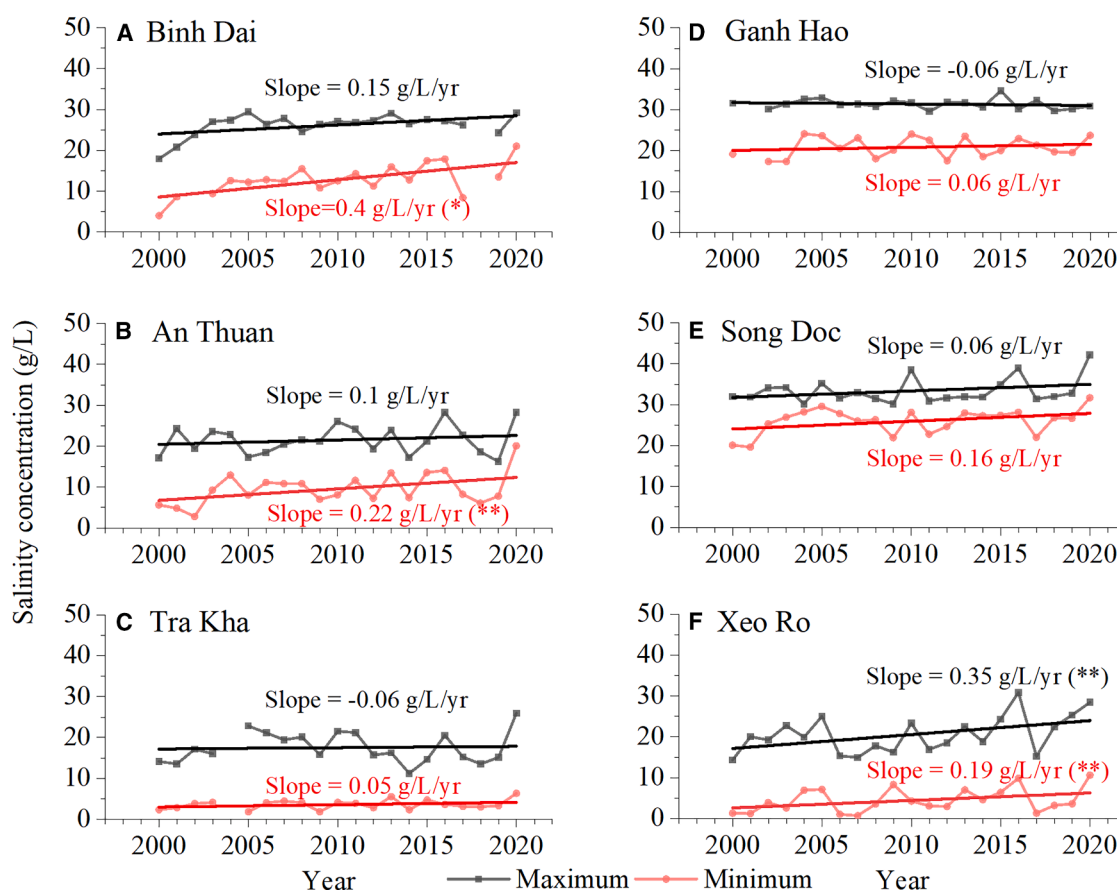


Figure 2. Max-min salinity (Feb–Apr) at six stations, with Sen's slope trends and significance at 95% (*) and 90% () confidence levels by Mann–Kendall test**

Trends of maximum and minimum salinity concentrations (from February to April) at Binh Dai (A), An Thuan (B), Tra Kha (C), Ganh Hao (D), Song Doc (E), and Xeo Ro (F) Stations from 2000 to 2020. Slope values are from Sen's slope method, while the symbols (*) and (**) mean values are statistically significant at 95% and 90% confidence levels, respectively, by Mann–Kendall tests.

one to five years, with an average of three years. This is alarming because the interval was up to eight years (1992 and 1998) before 2000, as Loc et al. [2021b]⁵ indicated that there would be more frequent drought events in the upcoming decades. This phenomenon may also be controlled by stronger El-Niño events in recent years. El-Niño Southern Oscillation (ENSO) prediction is highly complex and contains significant uncertainties.^{36,37} However, there are hints that anthropogenic forcing might be responsible for changes in ENSO patterns, potentially promoting ENSO variability and extremes.³⁸ Furthermore, recent studies assume that the influence of ENSO has increased significantly in the post-dam era since 2010 in the VMD,³⁹ which might contribute to the severity of the most recent drought events. In addition, according to a 40-year analysis from 1977 to 2010, average temperatures in Vietnam, particularly in the southern part, are rising at a rate more than twice the global average. Therefore, evaporation could become a growing concern for freshwater resources, particularly for open systems like rice farming or aquaculture, and especially during the dry season, further contributing to drought scenarios.⁴⁰

Salinity concentrations at almost all analyzed stations show increasing trends, except at Tra Kha and Ganh Hao where no clear trend was observed in either maximum or minimum salinity levels. This may be due to large sluice gates protecting the land behind Ganh Hao, allowing seawater to remain surrounding this station area during the dry season, which may explain why an increasing trend in SI was not observable. This means that sluice gate management complicates spatiotemporal SI patterns. Despite these trends, land use patterns in the coastal area remained relatively stable over the past two decades. This result fits previous studies by Nguyen et al. [2021b]³³ and Tran et al. [2017]⁴¹ regarding agricultural transformation and aquaculture bonds in the coastal provinces.

Provincial policies on rice and aquaculture developments

This study has uncovered different magnitudes of effects of DSI on rice yields and areas across coastal provinces over the past two decades, with notable peaks observed during the dry seasons of 2005, 2016, and 2020. In practice, provincial governments have implemented various strategies to mitigate the impacts on

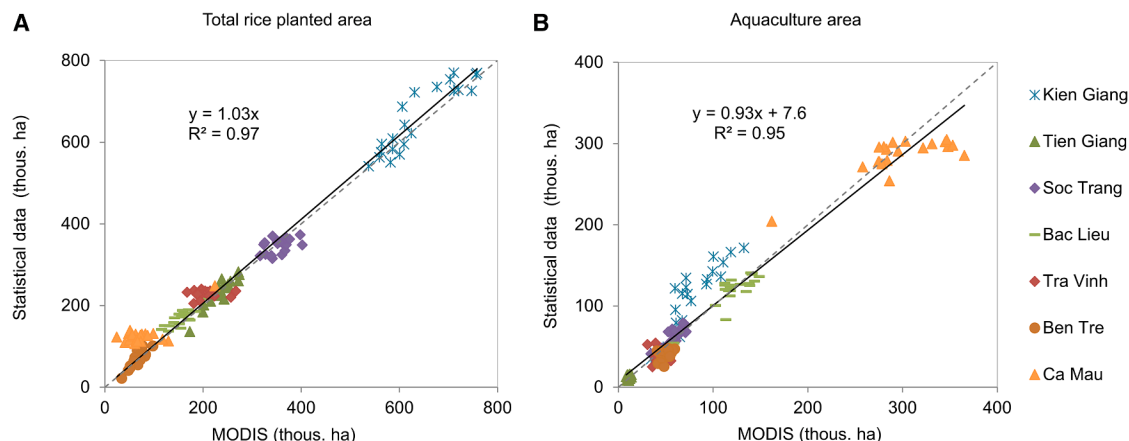


Figure 3. Accuracy of satellite land use data compared with statistical data at the provincial level

rice-based crops and aquaculture developments.^{35,42} One key measure involves the advancement of drought and salt-tolerant rice varieties and crop rescheduling following forecasting,³⁵ as well as the adoption of water-saving irrigation techniques and water management strategies,^{43,44} particularly after the severe damage in 2016. By encouraging the cultivation of resilient rice-based varieties that can withstand saline conditions and require less water, these provinces aim to safeguard rice yield and integrated crops against the adverse effects of the DSI. We emphasize the importance of continuous innovation in crop selection and water management, the introduction of stricter regulations managed by local authorities for specific locations with scalable solutions over time, and enhanced stakeholder collaboration through annual evaluation programs—all essential for ensuring the sustainability and resilience of agricultural practices in the face of climate-related challenges.

Additionally, investment in infrastructure for water management, such as the construction of sluice gates and embankments, helps regulate freshwater flow and minimize salinity levels in rice-growing areas, thereby preserving crop yields but only for the locations protected for freshwater cultivation.³² These infrastructures are, however, costly, especially for developing countries such as Vietnam in terms of investment, operation, and maintenance⁴⁵; hence, nature-based solutions, such as actively promoting freshwater storage reservoirs and rainwater harvesting systems, would be seriously considered to upscale for the long-term sustainability of the delta.^{46,47} Diversifying agricultural activities is a key strategy for enhancing resilience against rising DSI, alongside efforts to reduce freshwater demands.³⁰ The government could introduce pilot projects in salinity-affected areas to demonstrate the success of these diversified models and build farmer confidence. By broadening income sources and reducing dependence on freshwater, such measures help sustain agriculture and aquaculture amid fluctuating salinity levels. Given agriculture and aquaculture's vital role in most coastal communities in the VMD, developing saline-tolerant species and integrating rice farming with aquaculture should be considered as top priorities for adapting to environmental changes projected to worsen due to climate change and human activities in the future.^{32,48}

To address freshwater scarcity sustainably, stricter regulation and monitoring of deep groundwater extraction are essential. While large-scale rice farming and aquaculture are prohibited from using groundwater, unregulated private wells persist due to limited farmer awareness, underscoring the need for comprehensive oversight and education programs.⁴⁹ The overexploitation might in the long term exacerbate land subsidence and, thus, further promote SI. Overall, strategies, despite directly relying on the effort of farmers, could not be successful without the orientation and leadership of multiple-scale governments, enterprises, and scientists to enhance investment in research and technology transfer initiatives which enable farmers to access knowledge and resources for sustainable aquaculture practices tailored to the challenges posed by the DSI across the coastal provinces and beyond the VMD.

Limitations of the study

It is essential to express certain limitations in this research. First, an indirect relationship between SI and agricultural yield in the VMD was detected as our research primarily focuses on the relationship between rice yield and DSI, which may not fully capture the broader spectrum of agricultural activities affected by these drivers. Second, the complexity of the delta's ecosystem suggests that other variables, such as soil types and water management techniques, could influence the observed outcomes.⁵⁰ Third, although satellite sensors are able to provide daily images for processing land use products, the publishing of statistical data is typically delayed until a year later.^{51,52} This impedes the examination of the relationship between the effect of salinity and drought on rice yield in real time, e.g., the current drought year observed in 2024 cannot be assessed; hence, future studies could develop predictive models for the DSI index. Fourth, we analyzed long-term SI by examining salinity during the peak months from February to April, which is in the later phases of the Winter-Spring rice crop. This ensures the consistent availability of salinity data at all analyzed stations. However, if comprehensive data become available, analyzing the full spectrum of salinity concentration throughout the Winter-Spring rice season (December to April), along with mapping the spatiotemporal extent of DSI for the entire region, may provide more insightful results.

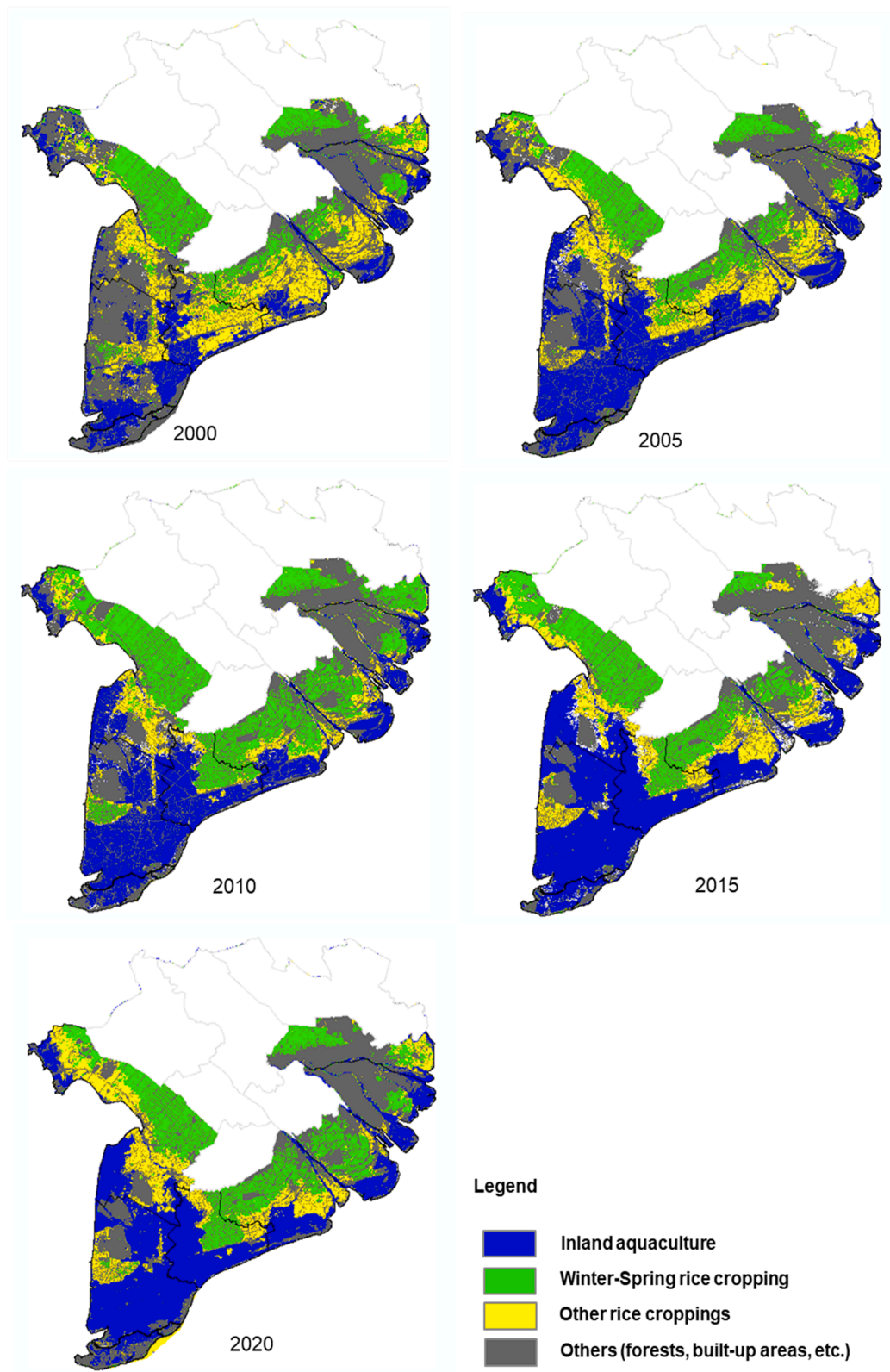


Figure 4. Dynamics of Winter-Spring rice cropping area in the coastal provinces

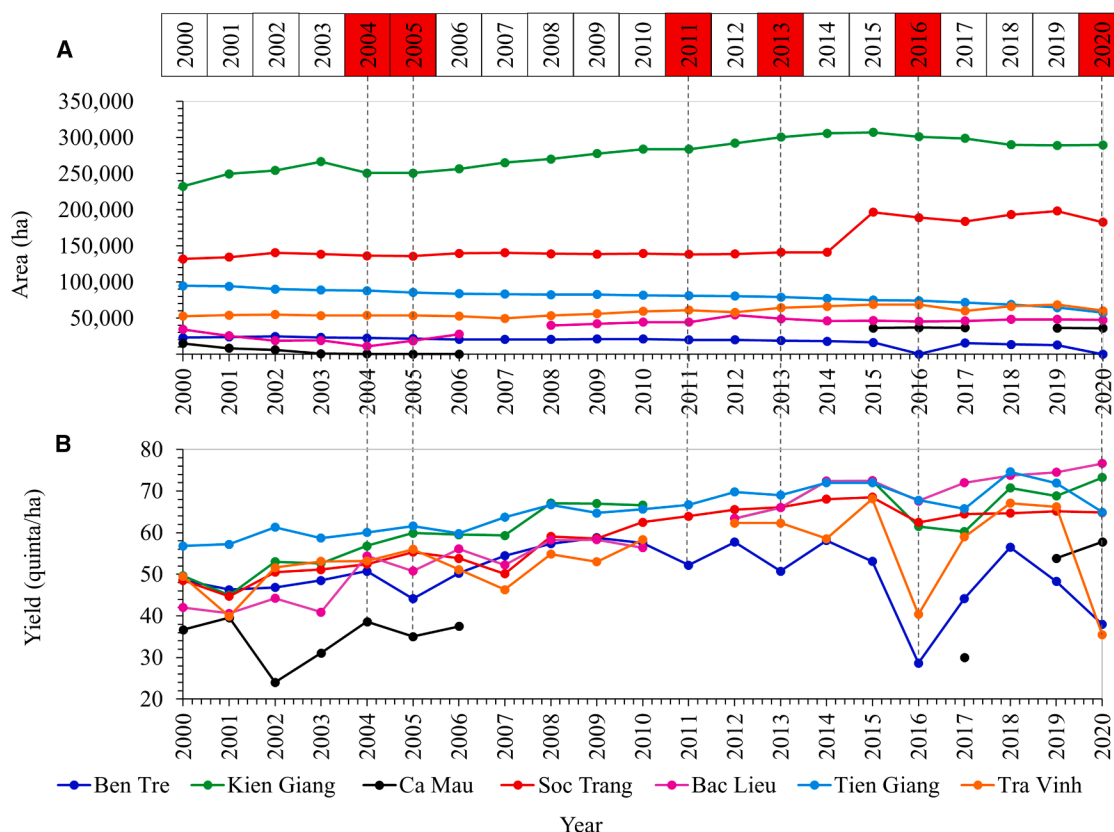


Figure 5. Trends in Winter-Spring rice area and yield from 2000–2020

Dynamics of Winter-Spring rice cropping area (A) and yield (B) from 2000 to 2020 in relation to droughts. The year (x axis) represents the later year to reflect the growing season of the Winter-Spring crop; for instance, “2020” stands for 2019–2020.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and information should be directed to Dung Duc Tran, dungtranducvn@yahoo.com.

Materials availability

No new unique materials, data or reagents were generated in this study.

Data and code availability

- Data: the data reported in this paper are available within the main text or supplemental information and will be shared by the [lead contact](#) upon reasonable request.
- Code: this paper does not report original code.
- Other items: Any additional information required to reanalyze the data reported in this paper will be shared by the [lead contact](#) upon reasonable request.

ACKNOWLEDGMENTS

This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 105.08-2023.40. We offer our special thanks to Ms. Nguyen Ngoc Hoa (the Southern Regional Hydrometeorological Center), Mr. Vu Quang Trung (Hydraulic Engineering Construction 2 Company), and the Vietnamese National Hydro-meteorological Data Centre for kindly providing salinity and hydrological data to conduct this research. The authors appreciate Prof. Kantoush’s Laboratory at DPRI of Kyoto University for providing the salinity data through the JASTIP project.

This research is also funded by Vietnam National University Ho Chi Minh City (VNU-HCM) under grant number TX2025-24-01.

AUTHOR CONTRIBUTIONS

D.V.B., D.D.T.: Conceptualization, methodology, data curation, formal analysis, software, visualization, writing – original draft, and writing – review and editing. V.H.T.D., J.B., E.P., H.H.L.: Writing – review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests. Dr. Park is a Guest Editor on the Special Issue titled “Salinization of soils in agriculture: Threats, monitoring, and mitigation” and he was not involved in the peer-review process of this paper.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- **KEY RESOURCES TABLE**
- **METHOD DETAILS**
 - Study area
 - Data collection
- **QUANTIFICATION AND STATISTICAL ANALYSIS**
 - Drought classification analysis
 - Salinity intrusion analysis
 - Land use detection of Winter-Spring cropping area

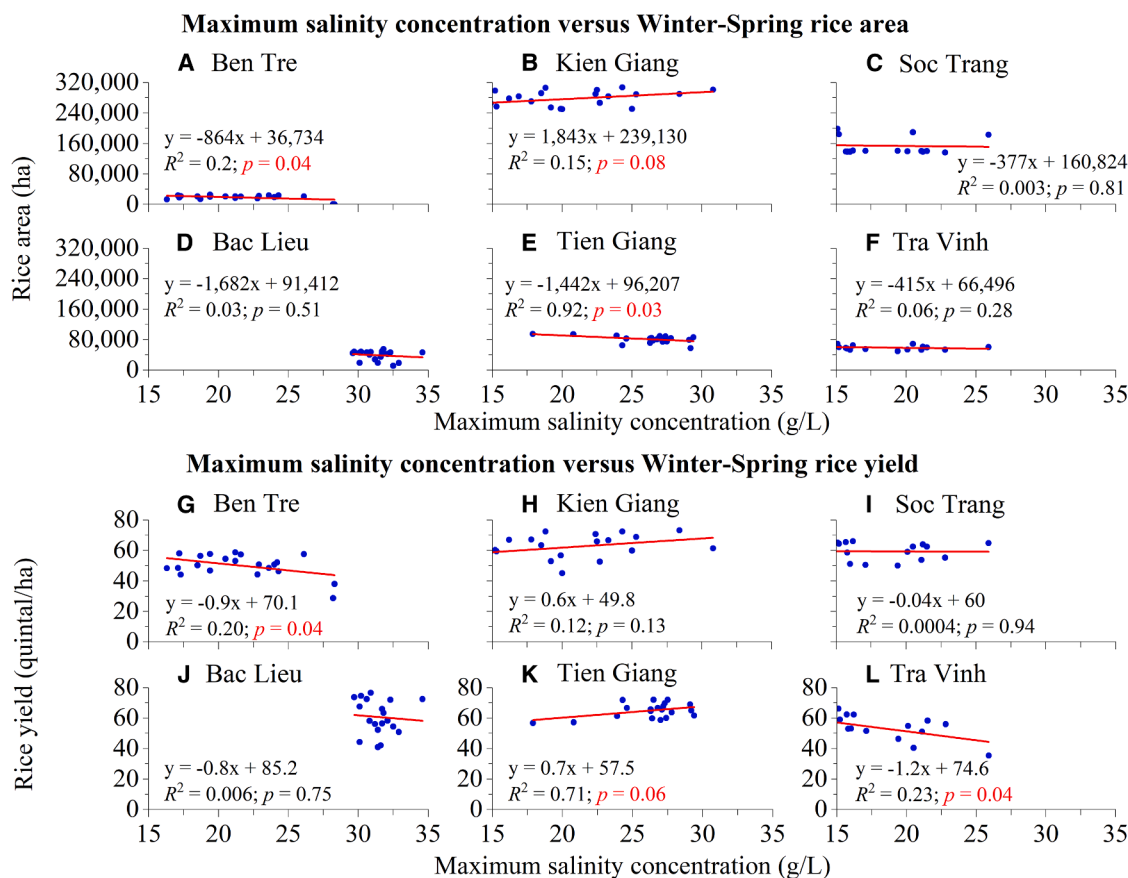


Figure 6. Relationship between station-based maximum salinity concentration and the Winter-Spring rice area and yield in the coastal provinces. The null hypothesis (no trend) is rejected when $-1.96 < Z < 1.96$ ($p < 0.05$ at the 5% significance level) and $-2.576 < Z < 2.576$ ($p < 0.01$ at the 1% significance level).

- Linking salinity impacts to rice farming alternative and management solutions

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.isci.2025.112723>.

Received: June 1, 2024

Revised: January 20, 2025

Accepted: May 19, 2025

Published: May 22, 2025

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
ArcGIS Desktop	ESRI	https://desktop.arcgis.com https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources
Python	OSI-approved open source	https://github.com/python

METHOD DETAILS

Study area

The VMD is located at the end of the Mekong River Basin, where the Tien and Hau Rivers flow across the delta plain (Figure S4). The study area (green colour) includes seven coastal provinces of the VMD, i.e., Kien Giang, Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, Ben Tre, and Tien Giang. In this region, land use types are mainly rice (accounting for 40%–60%), fish/shrimp farming (10–20 %), and other land use systems (32–42%), see Figures S1–S3. While the upper areas of the VMD are facing challenges due to flooding,^{53,54} riverbank erosion,^{55,56} and sand mining,⁵⁷ the coastal areas are severely impacted by coastal erosion,^{58,59} land subsidence due to over-exploitation of groundwater,⁶⁰ and especially by salinity intrusion and droughts.^{5,61}

Salinity intrusion is an annual event in the coastal provinces of the VMD, lasting about six months from January to June, peaking in February–April, affecting 1.7 million ha.⁴² However, it can appear earlier with higher magnitude and longer intrusion length in severe drought years.^{15,23} The two extreme droughts in 2016 and 2020 are marked by extensive saltwater intrusion (contour lines in Figure S4) into the inland of the VMD. Although the former was recorded as the most severe drought and SI over the past 90 years, four years later, the latter surpassed the former, with a deeper SI length of approximately 10 km.¹⁵

Data collection

Discharge and salinity concentration data

Tan Chau (on the Tien River) and Chau Doc (on the Hau River) (Figure S4) are the two gauges that monitor the river discharge at the entrance of the VMD close to the Vietnam–Cambodia border. The flow regimes of these two stations largely reflect hydrological processes in the VMD. The Tien River transports approximately 80% of the total water entering the VMD from the Mekong River.³⁸ Therefore, while drought events cover larger areas, the drought conditions at the Tan Chau station provide a reliable representation of the overall drought status in the VMD. The daily discharge dataset at Tan Chau was collected from 1980 to 2020 from the Vietnamese National Hydro-meteorological Data Centre (VNHDC) to determine the drought status. Daily discharge values stretch continuously from 1996 to 2020 with some missing values from 1980 to 1995. The missing discharges were reconstructed using distinct discharge–water level rating curves for the rising (April to September) and falling (October to March) phases fitted by polynomial regression with the least squares optimization scheme. Details of data treatment and processing were available in Binh et al. [2020, 2021].^{23,26}

Daily maximum salinity concentrations at six monitoring stations, namely Binh Dai, An Thuan, Tra Kha, Ganh Hao, Song Doc, and Xeo Ro, from February to April (the peaking DSI period) during 2000–2020 in both the Gulf of Thailand and the East Vietnam Sea (Figure S4) are incorporated in the analysis. Salinity concentrations were measured every two hours per day, from which the daily maximum and minimum values were obtained. We pre-processed the collected raw data for which outliers were checked and removed using the *Statsmodels* library in Python. Salinity concentration data were provided by the VNHDC, the Southern Regional Hydrometeorological Center, and the Japan–ASEAN Science, Technology and Innovation Platform (JASTIP) project. These three months of salinity concentrations are assessed because they are the main factor affecting the productivity of the Winter–Spring rice crop in the VMD’s coastal provinces (from December to April) – the most important crop in a year. Moreover, the February–April salinity data are consistently available during 2000–2020. The stations were selected because they met the following three criteria. First, they are evenly distributed in the study area. Second, the distance from the selected stations to the river mouths is relatively similar, ranging from four to seven km, to facilitate the comparison. Third, they have long-term data from 2000 to 2020, meeting the requirement for statistical tests and being consistent with other datasets used. Therefore, the chosen monitoring locations can be considered representative of the seven coastal provinces of the VMD.

Satellite land use maps

Land use/land cover maps in the VMD from satellite products were collected from 2000 to 2020.^{51,62} The MODIS land use maps were processed for land use detection by applying three important indices, i.e., Enhanced Vegetation Index (EVI), Land Surface Water

Index (LSWI), and Difference Value between EVI and LSWI (DVEL). Within the scope of this study, we only presented the EVI index to show the characteristics of rice and aquacultures based on MODIS time-series images, the EVI index is expressed as:

$$EVI = 2.5 \frac{NIR - RED}{NIR + 6RED - 7.5BLUE + 1} \quad (\text{Equation 1})$$

where RED is the red band (sur_refl_b01), NIR is the near-infrared band (sur_refl_b02), SIWR is the short-wave infrared band (sur_refl_b06), and BLUE is the blue band (sur_refl_b03) of the MODIS surface reflectance.^{52,63}

Land use maps are used to examine the spatiotemporal dynamics of cropping patterns and areas in the coastal provinces within the last two decades (Figures S1 and S2 in the Supplementary). Afterward, we focused on the Winter-Spring rice crop, normally cultivated from the beginning of December to the end of April.

Statistical data

Statistical data on rice crop and aquaculture areas were collected online from the General Statistical Office for the period of 2000–2020 to evaluate the accuracy of land use data from remote sensing products. Besides, the data on rice yield of the Winter-Spring rice crop were additionally collected from statistical yearbooks in seven coastal provinces, i.e., Kien Giang, Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, Ben Tre, and Tien Giang to evaluate the rice yields and rice area within the dry seasons.

QUANTIFICATION AND STATISTICAL ANALYSIS

Figure S5 shows the flowchart of the research methodology. First, we collected, processed, and treated the data for the daily discharge, daily salinity concentrations, monthly land use maps from the MODIS satellite, and the Winter-Spring rice crop area and yield. Second, we identified and classified hydrological drought using the monthly-averaged discharge at the Tan Chau station. Third, we analyzed long-term trends of the maximum salinity concentration at six salinity stations in the studied coastal provinces. Fourth, we analyzed long-term spatiotemporal changes in the annual land use during the Winter-Spring crop in the dry season extracted from MODIS satellite imagery. Fifth, we linked extreme salinity intrusion events with hydrological droughts. Sixth, we assessed the effect of DSI, especially in extreme years, on land use changes in terms of the extent and yield of rice. Finally, our results were discussed in the context of DSI mitigation measures, in particular after the 2016 extreme event, and recommend suitable land uses along with corresponding management solutions.

Drought classification analysis

There are typically four categories of drought, including meteorological, hydrological, agricultural, and socioeconomic droughts.³ Land use management in the VMD is directly linked with hydrological drought because agriculture in the delta is irrigated using water directly from the Mekong River system. The standardized streamflow index (SSI) was used to determine whether a year can be classified as a drought year. SSI was calculated using monthly discharge data at Tan Chau, which was averaged from the daily discharge. Although drought was assessed from 2000 to 2020, we calculated SSI from 1980 to 2020 so that there is long-term data for statistical analysis. Past drought events identified by SSI were cross-validated with the literature and recorded information from the statistical yearbook.

SSI was calculated from the monthly discharge data using Log-logistic distribution.⁶⁴ SSI, first introduced by Modarres [2007],⁶⁵ is principally similar to the standardized precipitation index (SPI). SSI calculation was performed using the following equation:

$$SSI = \Phi^{-1}(F(T(Q_i))) \quad (\text{Equation 2})$$

where: Q_i is the observed monthly discharge; $T(Q_i)$ is the transformed discharge data (using a logarithmic transformation to normalize the distribution); and $F(T(Q_i))$ is the cumulative distribution function (CDF) of the transformed streamflow data. Φ^{-1} is the inverse standard normal distribution function, which converts the CDF value into a standardized SSI.

The drought status was evaluated using SSI-6 (6-month average) following the finding from Nguyen et al. [2023].²² We first categorized the monthly SSI-6 into normal ($SSI-6 > -1.0$) or drought ($SSI-6 \leq -1.0$), and then classified the severity of the drought into moderate ($-1.49 < SSI-6 < -1.0$), severe ($-1.99 < SSI-6 < -1.5$), and extreme ($SSI-6 < -2.0$) by adopting the drought classification of Modarres [2007].⁶⁵ The drought years detected by the SSI-6 were cross-checked with the literature^{5,22,28}

Salinity intrusion analysis

Daily maximum salinity concentrations from February to April were processed to derive annual maximum, mean, and minimum salinity concentrations. Then, the trend and rate of change were estimated using the Mann-Kendall test^{66,67} and the slope method of Sen,⁶⁸ respectively. These methods were previously used to assess long-term changes in flow regimes in the Mekong River.²³

In the Mann-Kendall test, statistic S for a given time series $\{x_i; i = 1, 2, \dots, n\}$ is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (\text{Equation 3})$$

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if } x_j > x_i \\ 0 & \text{if } x_j = x_i \\ -1 & \text{if } x_j < x_i \end{cases} \quad (\text{Equation 4})$$

The variance of S is computed as:

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (\text{Equation 5})$$

When the sample size $n > 10$, the standard normal test statistic Z is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (\text{Equation 6})$$

where x_i and x_j are the data values in time series i and j ($j > i$), respectively; n is the number of data (observations); $\text{sgn}(x_j - x_i)$ is the sign function; $\text{Var}(S)$ is the variance of statistic S ; m is the number of tie groups; t_i is the number of ties of extent i . Positive Z indicates an increasing trend, while negative Z indicates a decreasing trend. The null hypothesis (no trend) is rejected when $-1.96 < Z < 1.96$ ($p < 0.05$ at the 5% significance level) and $-2.576 < Z < 2.576$ ($p < 0.01$ at the 1% significance level).

The rate of change is estimated using the slope method of Sen using a non-parametric procedure. The estimates of the slope of N pairs of data are calculated as:

$$Q_i = \left(\frac{x_j - x_k}{j - k} \right) \text{ for } i = 1, \dots, N \quad (\text{Equation 7})$$

where x_j and x_k are data values at times j and k ($j > k$). The N values of Q_i are ranked from the smallest to the largest and the median of the slope, that is the Sen's slope estimator, is estimated as:

$$Q_{\text{med}} = \begin{cases} Q_{[(N+1)/2]} & \text{if } N \text{ is odd} \\ \frac{Q_{[N/2]} + Q_{[(N+2)/2]}}{2} & \text{if } N \text{ is even} \end{cases} \quad (\text{Equation 8})$$

The sign of Q_{med} reflects the time series trend, and its values reveal the slope of the trend.

Land use detection of Winter-Spring cropping area

In this research, we analyzed the land use patterns for the coastal areas in the dry season from December to the end of April to detect the Winter-Spring rice cropping areas to investigate the effect of drought and salinity on rice yield during the dry season. The land use maps were derived from MODIS satellite products based on the algorithms by Sakamoto et al. [2009].⁵² Figure S6 illustrates an example of the time series of EVl variations for typical land use types in three years of 2018–2020, i.e., the rice cropping area in Kien Giang Province (a), the shrimp farming in Ca Mau Province (b), and other types of land use patterns in Tien Giang Province (c). It can be seen that the EVl time series in Figure S6A varies significantly around 0.4 (from -0.15 to 0.8) with clear peaks. Here, the Winter-Spring cropping was selected as the first peak in a year (red boxes). The EVl time series in Figure S6B shows a minor change from 0 to 0.2 for the shrimp farming area, while Figure S6C displays a variation of the EVl time series from 0.4 to 0.7 without any trend at the other land use pattern.

Linking salinity impacts to rice farming alternative and management solutions

The Winter-Spring rice area and yield were pairwise correlated with maximum salinity concentration to understand how salinity influences rice farming. Using simple linear regression, we identified the rate of impact through the slope of the regression line. By comparing spatial similarities and differences among the analyzed provinces, we evaluated the suitability of existing land use patterns and current rice-farming policies in each region. We then proposed adaptive farming alternatives and policy implications on management solutions to ensure the sustainability of rice-based agriculture.



OPEN ACCESS

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SPECIALTY SECTION

This article was submitted to
Environmental Informatics and Remote
Sensing,
a section of the journal
Frontiers in Environmental Science

RECEIVED 28 June 2022

ACCEPTED 13 September 2022

PUBLISHED 11 October 2022

CITATION

Qian J, Liu H, Qian L, Bauer J, Xue X,
Yu G, He Q, Zhou Q, Bi Y and Norra S
(2022), Water quality monitoring and
assessment based on cruise monitoring,
remote sensing, and deep learning: A
case study of Qingcaosha Reservoir.
Front. Environ. Sci. 10:979133.
doi: 10.3389/fenvs.2022.979133

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Water quality monitoring and assessment based on cruise monitoring, remote sensing, and deep learning: A case study of Qingcaosha Reservoir

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Accurate monitoring and assessment of the environmental state, as a prerequisite for improved action, is valuable and necessary because of the growing number of environmental problems that have harmful effects on natural systems and human society. This study developed an integrated novel framework containing three modules remote sensing technology (RST), cruise monitoring technology (CMT), and deep learning to achieve a robust performance for environmental monitoring and the subsequent assessment. The deep neural network (DNN), a type of deep learning, can adapt and take advantage of the big data platform effectively provided by RST and CMT to obtain more accurate and improved monitoring results. It was proved by our case study in the Qingcaosha Reservoir (QCSR) that DNN showed a more robust performance ($R^2 = 0.89$ for pH, $R^2 = 0.77$ for DO, $R^2 = 0.86$ for conductivity, and $R^2 = 0.95$ for backscattered particles) compared to the traditional machine learning, including multiple linear regression, support vector regression, and random forest regression. Based on the monitoring results, the water quality assessment of QCSR was achieved by applying a deep learning algorithm called improved deep embedding clustering. Deep clustering analysis enables the scientific delineation of joint control regions and determines the characteristic factors of each area. This study presents the high value of the framework with a core of big data mining for environmental monitoring and follow-up assessment in a manner of high frequency, multidimensionality, and deep hierarchy.

KEYWORDS

deep learning, environmental big data mining, cruise monitoring, remote sensing, water quality, monitoring, assessment

1 Introduction

A growing population and climate change along with land use changes are increasing pollutant loads into freshwater ecosystems, making clean water an increasingly critical issue worldwide Sagan et al. (2020). As one of the indispensable foundations of clean water management, developing an economical, accurate, and practical water quality monitoring and assessing system has become unavoidable to scientists, policymakers, and environmental resource managers.

The traditional and widely applied water quality monitoring is point-based, placing a fixed site of varying density and dispersion in the area to measure the water quality within a given time series. However, limited research resources such as staff, time, equipment, money, and accessibility become a challenge. Thus, the spatial interpolation method was conducted to estimate water quality by limited monitoring points Li and Heap (2014). This method required a massive decentralized monitoring point across the study area, which is also subjected to limited research resources Lee et al. (2012).

With the significant development of sensors, cruise monitoring technology (CMT) has proven to be more effective for extracting environment-related parameters compared to point-based monitoring Holbach et al. (2014). It relies on a multisensor probe to record the water quality data as well as consecutive geographic information along the cruise route. Although CMT makes progress in monitoring compared to the point-based method because it can collect a large amount of *in situ* measurement data in a certain period of time, a route design is still necessary since the geographic information is a key parameter to spatial interpolation modeling.

In recent years, remote sensing technology (RST) has developed rapidly and played a significant role in the data collection and analysis of different Earth resources Feyisa et al. (2014). The data collected by RST are area-based since RST can scan the objective area directly. The status of water quality in a broader space is obtained according to an inversion model established using the *in situ* monitoring data (i.e., water quality parameters) and corresponding RST image data Yuan et al. (2020). According to the interaction with light, water-quality parameters can be categorized into optical parameters (i.e., chlorophyll-a and turbidity) and nonoptical parameters (i.e., dissolved oxygen); it should be noted that most of the studies have focused on optical parameters, and the detection accuracy for nonoptical parameters is not high Hassan et al. (2021). Specific internal correlations between spectral information and nonoptical parameters are very complex and challenging to find due to the absence of direct optical properties Niu et al. (2021). Therefore, data-driven machine learning has become an indispensable tool for finding this complex correlation Zhong et al. (2021) Sagan et al. (2020). In earlier studies, linear approaches such as multiple linear regression (MLR), partial least squares (PLSs), and genetic algorithms

(GAs) were popular Ortiz-Casas and Peña-Martinez (1989); Stork and Autrey (2005); Zhan et al. (2003). Although linear models showed some degree of accuracy and feasibility, the nonlinear relationship between the *in situ* measured data and RST data makes the linear models less reliable in interpreting information from RST Chang et al. (2015). With the development of machine learning, several nonlinear approaches such as support vector regression (SVR), random forest regression (RFR), and gradient boosting decision tree (GBDT) have been developed and applied by many scientists to capture complex statistical relationships between RST and measured water quality parameters in recent years Kim et al. (2014); Forkuor et al. (2017); Abdel-Rahman et al. (2013). With the advances in algorithm development and computing power, the drawbacks of traditional machine learning become apparent, while deep learning, with its powerful big data processing capabilities, is receiving more attention. In our framework, deep neural networks (DNNs), one type of deep learning, were selected as a tool to approximate the complex nonlinear relationship between measured water quality parameters and RST observations through multilayer perception Marçais and de Dreuzy (2017).

It is important to note that the performance of deep learning methods is particularly dependent on a large number of training samples, which is difficult to obtain in real-world scenarios Sagan et al. (2020). The CMT mentioned earlier can significantly increase the speed of acquiring training samples, thus providing a sufficient database for deep learning RST inversion model building. On the other hand, RST, to a certain degree, liberates CMT from dependence on route design since geographic information is not involved in the inversion modeling.

As an important part of the water monitoring project, a representative and reliable assessment of water quality is necessary because of the spatial and temporal variability of water parameters Simeonov et al. (2003). The conventional methods for assessing the quality of water bodies are the single-factor assessment method, water quality grading method, and comprehensive pollution index method. These methods play an active role in the assessment process of water quality. However, the single-factor assessment method does not fully describe the overall water quality when there are multiple impairments. The water quality grading method ignores the influence of extreme contributing factors (maximum and minimum pollutant parameter values), making it difficult to assess the overall water quality conditions between sites when extreme conditions occur. The calculation result of the comprehensive pollution index method is a relative value and cannot indicate the specific water quality classification Ji et al. (2016). In particular, when faced with the huge and complex matrix of water quality attributes formed by the establishment of a big data platform like this study, making a meaningful water quality assessment is often difficult Singh et al. (2005). A cluster

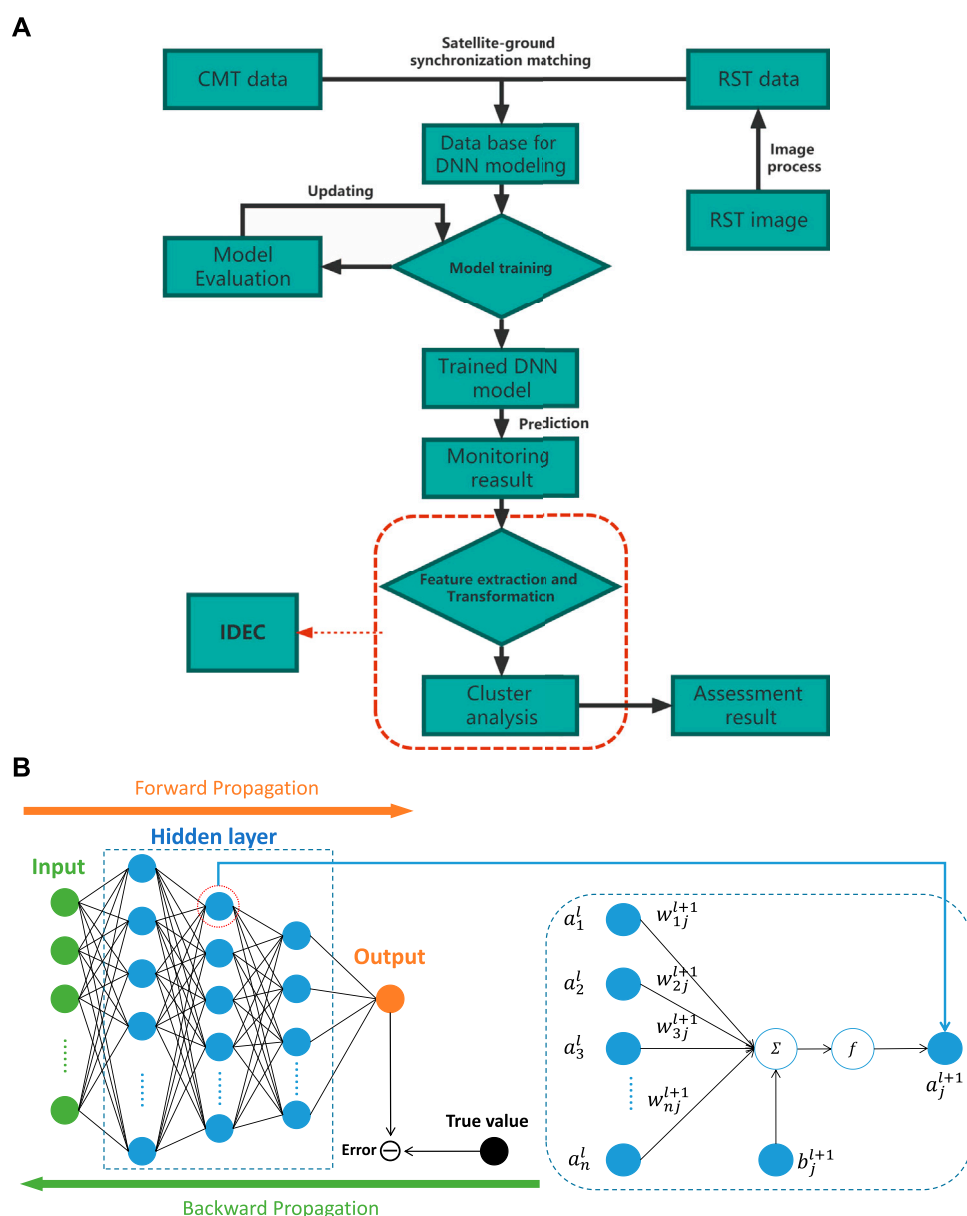
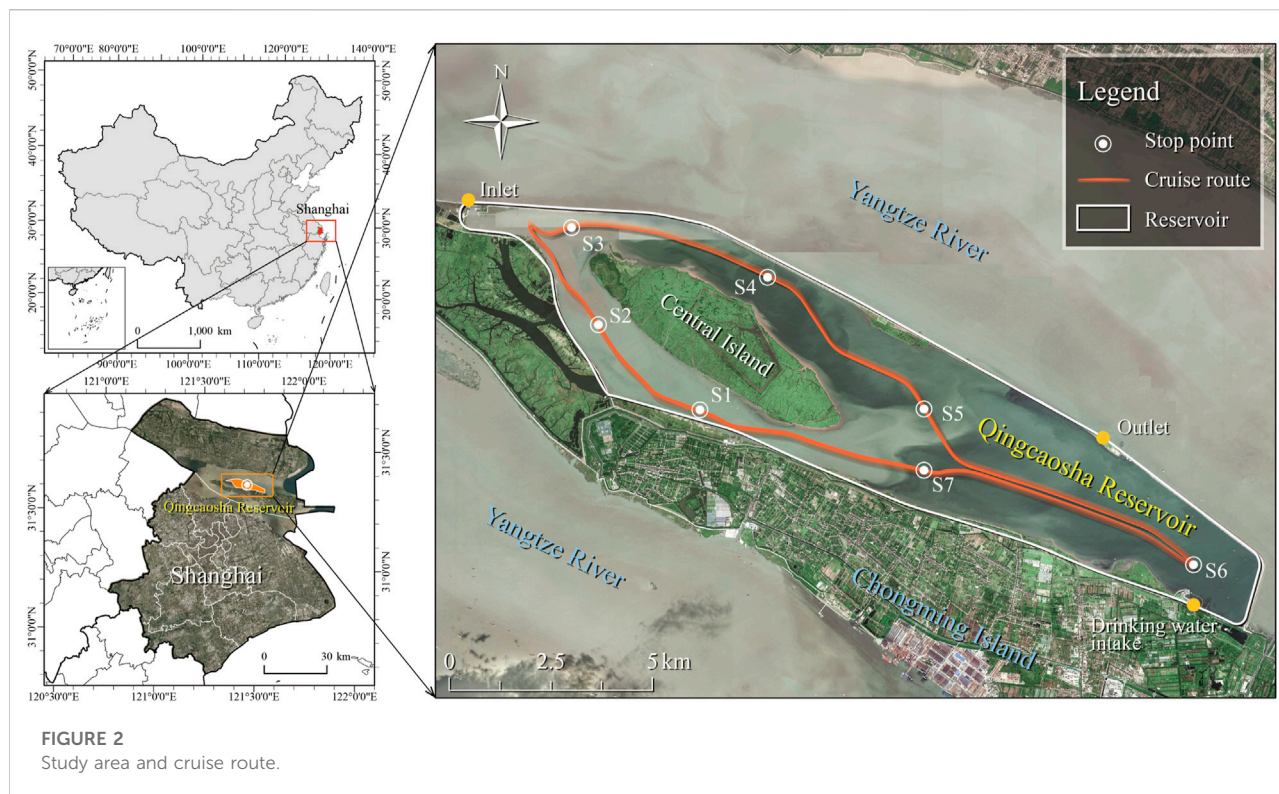


FIGURE 1
Schematic illustration of (A) the novel framework and (B) the architecture of DNN.

analysis can be applied to interpret these complex data matrices to help understand the water quality and ecological status of the studied systems, identifying the possible resources and finding rapid solutions to pollution problems by grouping the data so that similar elements are assigned to the same group and different elements are assigned to different ones (Vo-Van et al. (2020); Simeonov et al. (2003)). Additionally, considering that deep clustering is more effective at analyzing big data than traditional clustering methods (Guo et al. (2017), such as K-means and C-means, an advanced deep learning clustering

algorithm, improved deep embedded clustering (IDEA), was used for the water quality assessment in this study.

The aim of this study is to develop a novel framework with a core of big data mining, integrating (1) CMT data from multisensor monitoring systems, 2) RST information from the satellites, and 3) deep learning for rapid and effective overall water quality evaluation and the follow-up assessment of the environmental situation. This novel framework was applied in the Qingcaosha Reservoir (QCSR), located in Shanghai, to prove its reasonability and reliability.



2 Materials and methods

To achieve a robust performance in water quality monitoring and assessment, the framework integrates the following three modularized parts: RST, CMT, and deep learning. The DNN model is responsible for efficient water quality monitoring on a big data platform created by CMT and RST, while the IDEC model is used for further assessment based on the previous monitoring results (Figure 1A). A sampling activity in QCSR (Supplementary Figure S1) was implemented to validate the performance of the framework. QCSR is one of the largest tidal reservoirs around the world. It is located in the middle of the Yangtze River Estuary (31.42–31.49N, 121.55–121.71E), and is the new largest drinking water supply for about 12 million Shanghai residents Liu et al. (2016a) since 2010 (Figure 2). The reservoir is long and narrow with a surface area of approximately 70 km² and an average depth of 2.7 m Liu et al. (2016b).

2.1 Remote sensing module

Sentinel-2 is an Earth observation satellite designed to systematically deliver optical imagery at high spatial resolution (10, 20, and 60m) over land and waters Drusch et al. (2012) (Supplementary Table S2). Due to its relatively high resolution and free accessibility, Sentinel-2 is widely used in environmental

research. Its multi-spectral instrument (MSI) acquires 13 spectral bands from 440 nm to 2,200 nm. The image of Sentinel-2 on 19 January 2020 (the same day as the CMT *in situ* measurement) was downloaded from the official website of the U.S. Geological Survey (<https://earthexplorer.usgs.gov/>). The level-1C data product was selected in this study and this series of data has been radiometrically and geometrically corrected (including orthorectification).

RST image is processed in order of radiometric calibration, atmospheric correction, RST image fusion, and research area clipping to finish the conversion from images to spectral values (Figure 1A). One conventional atmospheric correction algorithm, Fast Line-of-Sight Atmospheric Analysis of Hypercubes (FLAASH) was set as an atmospheric correction algorithm in this study Buma and Lee (2020). The specific RST parameters set, including ground elevation, atmospheric model, aerosol retrieval, and water retrieval, were found in the files alongside their respective multispectral images. The RST images (not including bands 1, 9, and 10) were resampled to 10 m by the Gram-Schmidt pan sharpening method (Supplementary Material), one of the most widely used high-quality methods for RST image fusion Zhang et al. (2019). All of the RST data processing could be conducted using the packaged functions in ENVI®. The RST data were processed by Z-score normalization (Supplementary Material) before being input to the models. It should be noted that when new data are collected, the normalization part performs a new normalization of the

TABLE 1 Summary statistics of the BioFish data.

Parameter	<i>In situ</i> measuring(n)	Unit	Max	Min	Mean	STD*
pH	50081	N/A	8.31	6.20	7.34	0.43
DO	50005	mg/L	13.99	9.39	10.21	0.48
EL.cond	50264	mS/cm	0.37	0.20	0.34	0.02
BP	50179	%	8.92	1.27	2.36	1.58

*Standard deviation.

overall data set (containing the previous data set and the new data set) for the training model.

2.2 Cruise monitoring module

Cruise monitoring with multiple sensors is conducted by BioFish in this study. It is an aquatic cruise monitoring system that is equipped with multisensors (Supplementary Table S1) and connected to a ship by a data transmission cable Udy et al. (2005). The data of water quality parameters were recorded in real-time with GPS longitudinal and latitudinal positions. In this study, the BioFish swam 10 cm below the water surface. One optical parameter, backscattered particles (BPs, similar to turbidity, measured by a beam attenuation probe to estimate water clarity) (Supplementary Material), and three nonoptical parameters, including electrical conductivity (EL.cond), pH value, and dissolved oxygen (DO), are selected to validate the performance of the framework.

Due to the limitations of power supply, equipment, time, and accessibility, the *in situ* measuring in QCSR was finished within 1 day and the running time was 5 hours. The cruise route is shown in Figure 2, aiming to cover as much of the study area as possible. S1 is the start and end point of the cruise route. Seven stopping points were designed for (S1–S7, see Figure 2) the BioFish calibration with the YSL ProDSS to ensure the accuracy of the data. An overview of the data collected by BioFish in QCSR is displayed in Table 1. The BioFish data were processed by Z-score normalization (Supplementary Material) and satellite-ground synchronization matching (Supplementary Figure S2) before being input into the models (Figure 1A). It should be noted that the normalization section renormalizes the new overall dataset when new data are collected.

Since the high sampling density of BioFish means that multiple BioFish sampling points can be found randomly in a pixel block of size 10 m × 10 m, determining the BioFish sampling points within the same pixel block and deriving their representative values are required. The first step is to specify the spatial information of all BioFish sampling points and pixel grid centroids. The geodesic distance Shamai and Kimmel (2017) between the pixel grid centroid and the BioFish sampling point can be calculated by the *Python*

package *geopy*, with an ellipsoidal model, WGS-84. Then, the pixel grid corresponding to the BioFish sampling point can be extracted by finding the shortest geodesic distance between them. The next step is calculating the representative values of BioFish measurements within each pixel block by the arithmetic mean (AM).

2.3 Water quality monitoring model

In this section, deep neural networks and three traditional machine learning models are used to find the relationship between RST and CMT and compare their performance, respectively.

2.3.1 Deep neural network

The deep neural network (DNN) is the basic form of deep learning and one of the most efficient and powerful tools to model complex nonlinear relationships Rolnick and Tegmark (2018). As the left side of Figure 1B shows, DNN is a connectionist system with multiple hidden layers between the input and output layers. Each hidden layer contains multiple neurons, called nodes. Any node in the l th layer must be connected to any node in the $l + 1$ st layer, and the following equation indicates the nonlinear relationship between the DNN layers shown on the right side of Figure 1B:

$$a_j^{l+1} = f\left(\sum_{i=1}^n a_i^l w_{ij}^l + b_j^l\right),$$

where a_i^l is the activation value of the i th node in the l th layer, a_j^{l+1} is the activation value of the j th node in the $l + 1$ st layer, w_{ij}^{l+1} is the weight between a_i^l and a_j^{l+1} , b_j^{l+1} is the bias value of the j th node in the $l + 1$ st layer, and $f(\cdot)$ is the active function.

The training process is shown on the left side of Figure 1B. Forward propagation refers to the calculation and storage of intermediate variables (including outputs) from the input to the output layer. Back propagation refers to the method of calculating the gradient of neural network parameters and updating the parameters depending on the error between the output and true value. For tuning hyperparameters in this study, *relu* Agarap (2018) was set as the active function and *adam* as the

optimizer of all models. The layer and neural units of models were (256, 256, 256, 256, 256) except El.cond.-spectral value was (256, 256, 256). Additionally, batch size and learning rate were also tuned in a reasonable range.

2.3.2 Multiple linear regression

Linear regression, a typical traditional machine learning model, is a linear approach for estimating the relationship between a dependent variable and one or more independent variables. The case of one independent variable is called simple linear regression; for two or more, the process is called multiple linear regression (MLR) Berger et al. (2017). In this study, the MLR model was built by calling the function in the *Python* package scikit-learn. The parameter to be tuned in this study was the degree of the polynomial features.

2.3.3 Support vector regression

Support vector regression (SVR) is a traditional supervised machine learning that is applied widely in RST inversion Wagle et al. (2020). The SVR model was also conducted by calling the function in the *Python* package scikit-learn. The radial basis function was chosen as the kernel of SVR. The parameters that need to be tuned in this study are the regularization parameter and the kernel coefficient.

2.3.4 Random forest regression

Random forest regression (RFR) is a traditional machine learning algorithm for nonlinear regression. It uses an ensemble learning method that combines a large set of regression trees to make a more accurate regression than a single regression tree Kim et al. (2014). The RFR model was implemented by calling the function in the *Python* package scikit-learn. The n-estimators and random-state need to be tuned.

2.3.5 Evaluation metrics

Evaluating the performance of a model is an essential step before practical application. We split each dataset into a training set and a test set with a ratio of 4:1 and take one at every four intervals as the test data. Several indicators, including the coefficient of determination (R^2), root mean square error (RMSE), mean absolute percentage error (MAPE), and median absolute deviation (MAD), were used to evaluate each regression model's accuracy, stability, and inversion ability (Supplementary Material).

2.4 Water quality assessment model

Improved deep embedded clustering is an unsupervised deep learning algorithm for clustering. The monitoring results obtained from the framework were clustered using IDEC, and points with similar environmental states were grouped based on the combined effect of all measured water quality parameters

TABLE 2 Results of regression model evaluation.

Parameter	Model	R^2	RMSE*	MAPE**	MAD*
pH	MLR	0.55	0.64	0.86	0.41
	SVR	0.74	0.55	0.69	0.21
	RFR	0.73	0.50	0.57	0.17
	DNN	0.89	0.33	0.52	0.10
DO	MLR	0.22	0.85	2.83	0.30
	SVR	0.24	0.83	1.30	0.12
	RFR	0.57	0.65	1.59	0.14
	DNN	0.77	0.49	1.61	0.06
El.cond	MLR	0.23	0.88	9.62	0.20
	SVR	0.33	0.81	1.54	0.08
	RFR	0.52	0.67	1.78	0.10
	DNN	0.86	0.38	1.74	0.06
BP	MLR	0.78	0.44	3.07	0.14
	SVR	0.87	0.38	3.34	0.07
	RFR	0.87	0.38	2.72	0.06
	DNN	0.95	0.26	3.10	0.03

*Units are the same as the respective water quality parameter units.

**Unit is percentage.

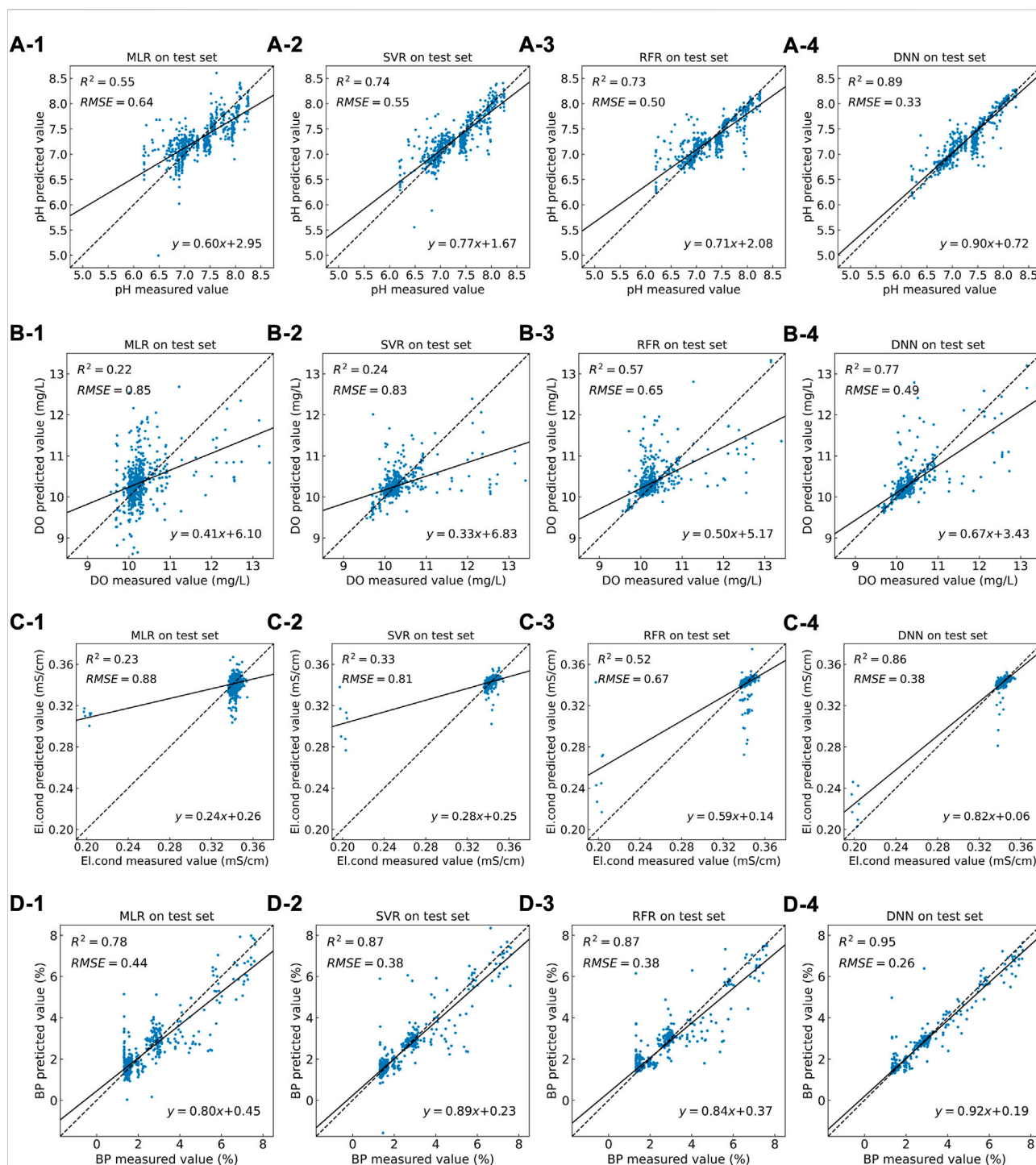
The bold-italic values represent the best regression results, respectively.

(pH, DO, BP, and El.cond in this study), thus dividing the entire reservoir into different areas possessing different environmental states. According to the clustering results, each group's specific water quality characteristics can be understood by analyzing the distribution of each group's characteristic water quality parameters. This characteristic of each group is the main reason why these measurement points are clustered into the same group, and it can also be described as the characteristic factor of this group.

The structure of IDEC includes an encoder and a decoder network Guo et al. (2017) (Supplementary Figure S3). The encoder network is set as a fully connected multilayer perceptron (MLP) with dimensions 4-125-125-500-10. The decoder network is a mirror of the encoder with dimensions 10-500-125-125-4. *relu* was set as the active function and *adam* as the optimizer of all models. The coefficient of cluster loss γ is set to 0.1 and batch size to 256. The convergence threshold δ is set to 0.1%. Also, the update interval T is one iteration. IDEC and CH method was conducted by PyTorch. The number of clusters was determined by the Calinski-harabasz (CH) method Zhao and Fränti (2014).

3 Results

Considering the conceptual merits of the developed framework, we applied the framework to a database of QCSR sampling activity to evaluate its performance on inversion and make the assessment of water quality through clustering results.

**FIGURE 3**

Regression model performance evaluation by comparison of the predicted data and measured data on a test set, where (A), (B), (C), and (D) represent the test results of the pH, DO, El.cond, and BP, respectively and (1), (2), (3), and (4) represent the test results of the MLR, SVR, RFR, and DNN, respectively.

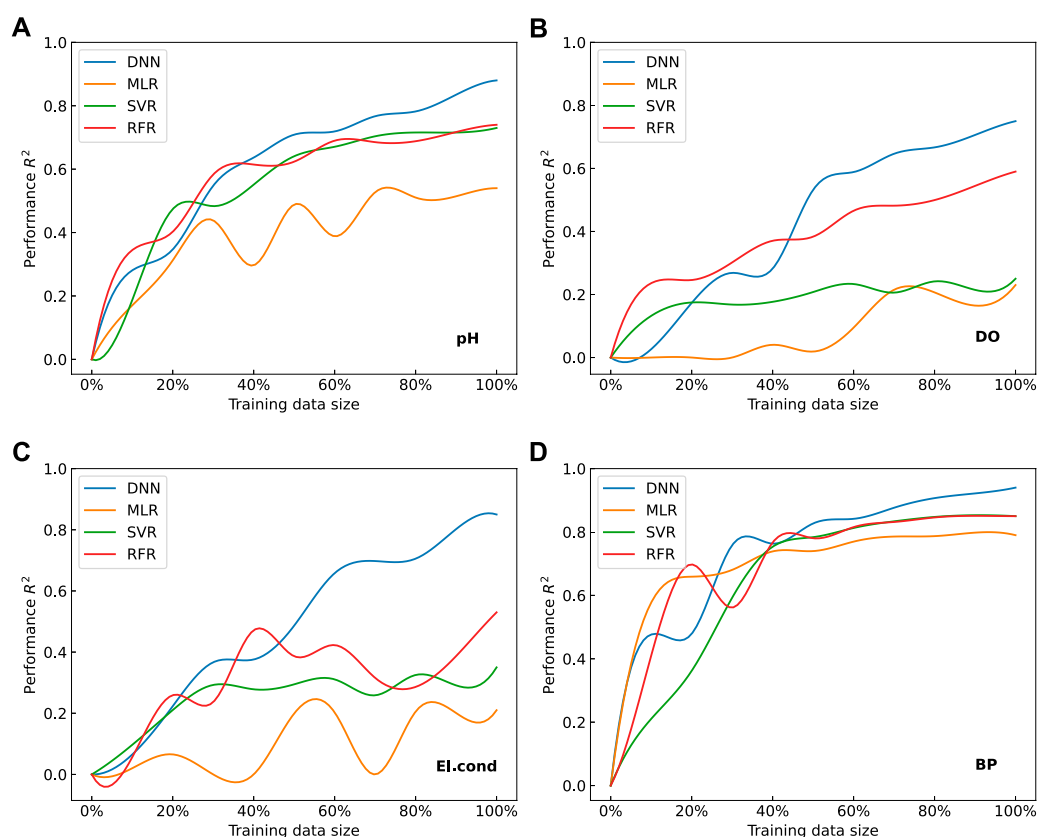


FIGURE 4

Performance of each regression model with increasing training data size, where (A–D) represent the results of the pH, DO, El.cond and BP, respectively.

3.1 Model performance evaluation

Based on the performance of the regression model for four water quality parameters, several results are achieved.

1) DNN represented the best performance in accuracy and stability compared to the other three algorithms. The results for the model performance are summarized in Table 2. Concerning the inversion of pH, SVR, RFR, and DNN delivered satisfactory results. DNN achieved the highest $R^2 = 0.889$ and the lowest RMSE = 0.33, MAPE = 0.52, and MAD = 0.10 that stand for the stability of DNN. As for the DO and El.cond inversion, DNN achieved the highest accuracy with $R^2 = 0.77, 0.86$ compared with MLR, SVR, and RFR. In addition, the lowest RMSE (0.49 for DO and 0.38 for El.cond) and MAD (0.06 for DO and 0.06 for El. Cond) demonstrated that DNN has high stability even though the MAPE of DNN is slightly less than that of SVR.

With respect to the inversion of BP, all models express relatively satisfactory results. In particular, DNN reached a very high accuracy with $R^2 = 0.95$ and relatively low RMSE, MAPE, and MAD.

The comparison of predicted values and the measured values on the test set are shown in Figure 3. It is found that the slope of DNN

test results (0.90 for pH, 0.67 for DO, 0.82 for El.cond, and 0.92 for BP) is much larger than those of MLR, SVR, and RFR. Therefore, DNN significantly improved the inversion accuracy compared with MLR, SVR, and RFR.

2) The performance of each model increases with increasing training data size. We randomly select 0–100% of the data in the original dataset at 10% intervals for training and testing. This process is performed 50 times for each data size, and then the average performance of the model (denoted by R^2) and its standard deviation (Supplementary Material) are calculated at each data size. As the training data size increases, the results of each water quality parameter consistently showed an increasing trend of R^2 (Figure 4). It can be also found that DNN is highly sensitive to training data size. The performance of DNN was not the best among the four models with a small training data size, especially when less than 30% of the training data size was fed. (Figure 4D). When 40% or more of the training data are fed, a critical point is noted, where DNN performance surpasses the other models. In particular, a significant advantage of DNN can be observed as the training data size increases from 50% to 100%. Meanwhile, a more advanced performance of DNN could be expected.

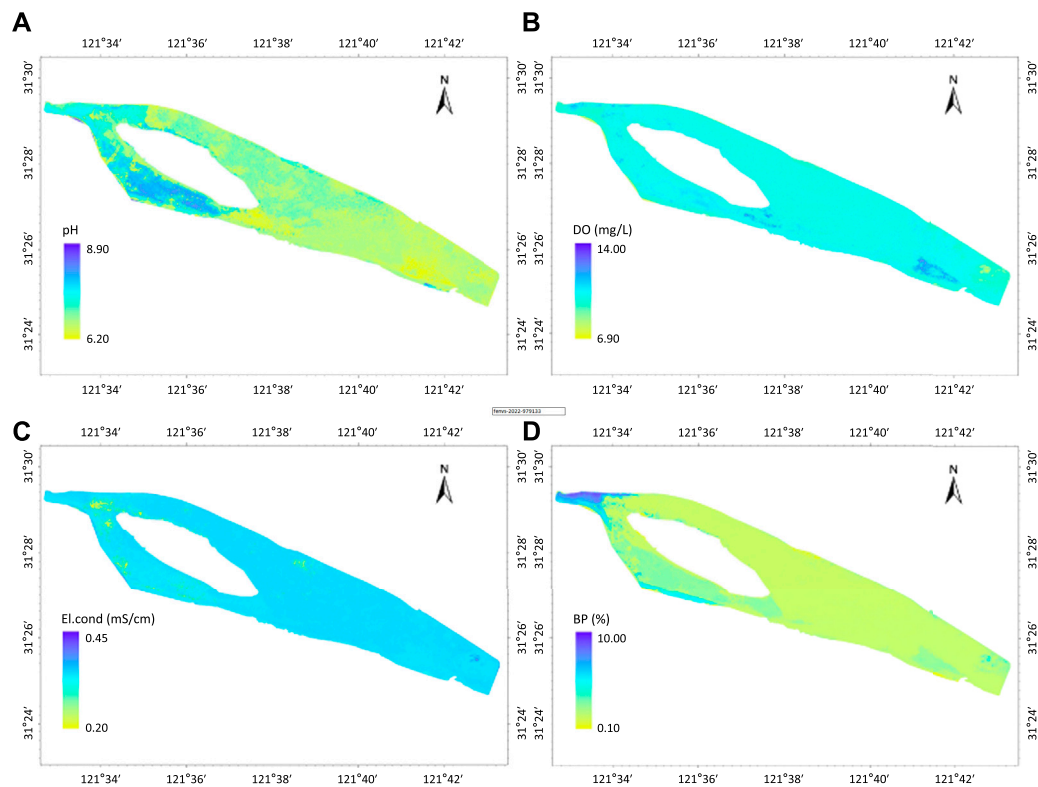


FIGURE 5
Distribution of (A) pH, (B) DO, (C) El.cond, and (D) BP in QCSR based on the framework.

3.2 Application of the developed framework in QCSR

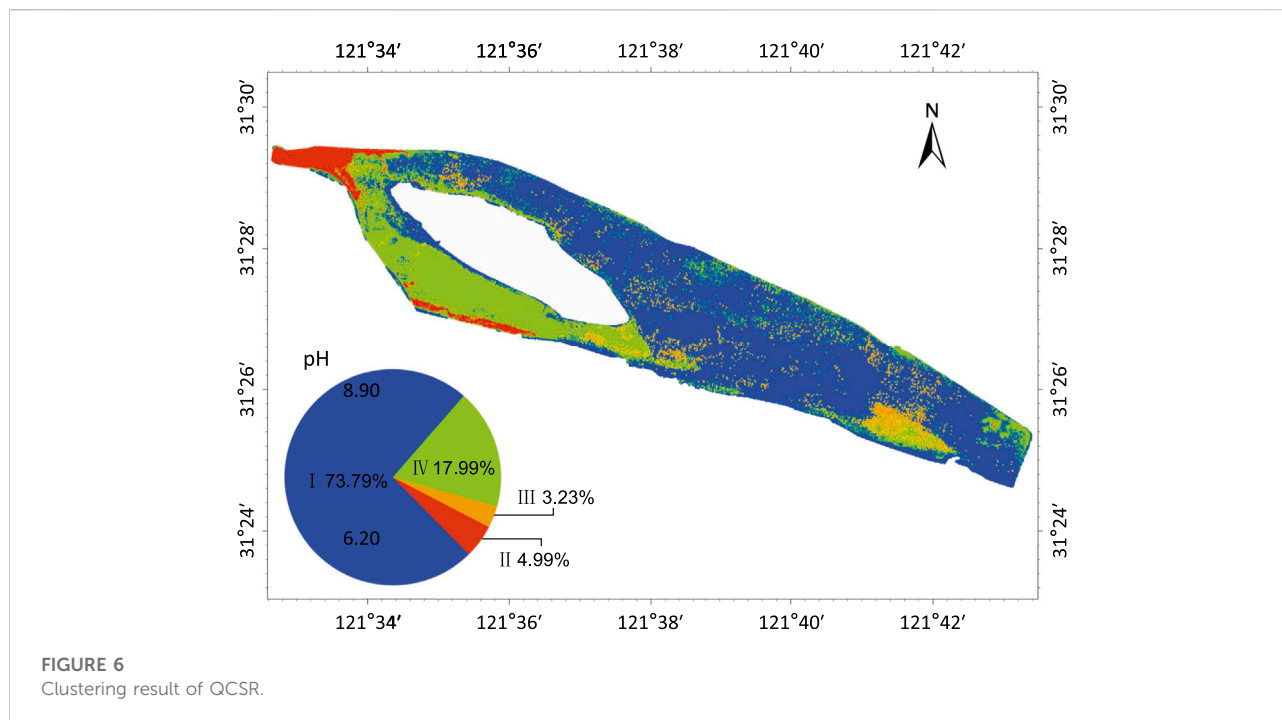
The concentration heat-maps of each parameter (pH, DO, El.cond, and BP) are shown in Figures 5A–D, respectively. The pH value obtained by the developed framework ranges from 6.2 to 8.9, with a mean value of 7.2. The results reveal spatial difference in that pH value decreases from the head region of QCSR to the tail region (see Figure 5A). The inverted DO ranges from 6.90 mg/L to 14.00 mg/L, with a mean value of 10.30 mg/L. The results show a similar spatial difference as that of pH since the concentration of DO decreases from Figure 5B the head region to the tail region, as shown in Figure 5B. Differing from the pH value, a relatively low concentration of DO occurs in the eastern portion of the reservoir, the tail region. The result of El.cond ranges from 0.20 mS/cm to 0.44 mS/cm, with a mean value of 0.34 mS/cm. El.cond observed in the head region is lower than that of the rest area (see Figure 5C). The inverted BP ranges from 0.10 to 10.00%, with a mean value of 2.13%. The results show a similar spatial difference as that of pH since BP decreases from the head to the tail region, as shown in Figure 5D.

TABLE 3 Summary statistics of each group.

Group	Parameter*	Max	Min	STD**	Median
Group I	pH	9.00	6.20	0.25	7.04
	DO	14.00	6.90	0.32	10.13
	El.cond	0.44	0.20	0.01	0.34
	BP	3.02	0.01	0.23	1.57
Group II	pH	8.25	6.50	0.27	7.64
	DO	13.94	6.90	0.64	9.94
	El.cond	0.42	0.20	0.02	0.34
	BP	10.08	4.58	1.26	6.11
Group III	pH	8.30	6.20	0.223	6.95
	DO	14.00	9.15	0.72	12.11
	El.cond	0.35	0.20	0.02	0.34
	BP	7.47	1.23	0.54	2.60
Group IV	pH	9.00	6.20	0.51	7.86
	DO	14.00	6.90	0.45	10.26
	El.cond	0.44	0.20	0.02	0.34
	BP	4.83	1.94	0.52	2.93

*Unit of DO is mg/L; unit of El.cond is mS/cm; unit of BP is percentage.

**Standard deviation.



The entire QCSR can be divided into four groups of water bodies by the CH method (Supplementary Material, Figure 4), which are groups I, II, III, and IV. The summary statistics and distributions of each group obtained by IDEC are shown in Table 3 and Figure 6. Group I occupied 73.79% of the entire QCSR area. It exhibits characteristics that the values for each parameter are in the middle position compared to others. Group I is dominated from the northeast of the central island to the tail region. The proportions of group II and III water were 4.99 and 3.23%, respectively. Group II is characterized by significantly higher BP values than the other groups and is distributed at the head of the reservoir and on the southern shore of the reservoir. Group III shows a higher DO value compared to other groups and is distributed close to the drinking water intake. Group IV has a higher pH value compared to others, indicating a mildly alkaline water body. Also, it is mainly found to the southwest of the central island to a lesser extent in the tail region and near the drinking water intake.

4 Discussion

4.1 Advantages of the novel framework

The design and application of the framework in our case study demonstrated its high performance in the monitoring and assessment of water quality. Compared to the previous studies, the advantages of this framework are summarized as follows.

CMT and RST are mutually integrated into the framework. CMT provides RST with sufficient *in situ* measurements, the prerequisite of the data set. In this study, the training data size provided by BioFish was nearly 500 times as many as the manual method within the same time interval Sagan et al. (2020); in addition, the geographic information of the data is not involved directly in the training and test process as input, which solves the problem of space-time limitation of the spatial interpolation methods to a certain extent. In the case of QCSR, the water quality parameters far from the cruise route, where no cruise route can be used nearby, can still be effectively inverted.

The environmental big data platform established by CMT and RST provides the basis for accurate environmental information interpretation. RST and CMT have the attributes of big data and good complementary so that the environmental big data platform can be built with the cooperation of the two parts. As shown in Figure 4, the results show an increasing trend of R^2 modelwise as the data size enlarges, indicating a significant advantage of environmental data analysis in contrast with the small or medium data platform.

On the big data platform, the adaptability and performance of deep learning ensure accuracy in monitoring and assessment. In Figure 4, break-even points can be observed at which the performance of DNN exceeds those of other traditional machine learning, especially when 40% or more data are fed. Through the encoder network with dimensions 4-125-125-500-10 and decoder network dimensions 10-500-125-125-4, original four-dimensional features (pH, DO, El.cond, and BP) are transferred into the new four-dimensional features, which contain much

more information. Based on the updated four-dimensional features, clustering results are better than those based on the original four-dimensional features, meaning they are very close to the real world.

The novel framework formed a closed loop of water quality research, into which data collection, processing, monitoring, and assessment are packaged. In the framework, monitoring results can be mined for further assessment. Joint regional control strategies are more efficient and effective than single-point control strategies in environmental management and pollution control [Zhang and Yang \(2022\)](#). Deep clustering analysis enables the scientific delineation of joint control regions. Through the character analysis of the divided joint control area, characteristic factors of each area can be identified, which can contribute to defining a joint regional control strategy for the objective area. In this study, each group is managed as a joint control area, in a way that depends on the characteristic factors. Elevated BP (low water clarity) noted in the group II area may cause poor underwater light climate and loss of submerged macrophytes to switch the water body from a macrophyte-dominated state to an algae-dominated one [Huang et al. \(2021\)](#). In addition, the alkaline water body is one of the stimulatives for algae growth [Lin et al. \(2021\)](#). This means that the two water quality parameters, BP and pH, will be the focus of subsequent management and control of the distribution areas of group II and group IV, respectively.

To further ensure the reliability and accuracy of data collection, we have several particular strategies. 1) Seven calibrating points keep BioFish in a well-calibrated condition during the *in situ* measuring in order to assure the measuring accuracy. 2) The day of the satellite transit with cloud cover of less than 10 % was selected as the sampling day.

4.2 Potentiality of the developed framework

The developed framework as well as its three modularized parts show high potential in extensibility.

1) The environmental quality parameters were inverted by the developed framework by a data-driven approach instead of a physics- or chemistry-based one. Being data-driven makes results from the developed framework easily and rapidly transform into inversion of other environmental parameters collected by different sensors or CMT systems. The implementation was in the water scenario in this study. Alternately, this framework can be applicable to the air scenario when using an air quality CMT system.

2) The developed framework can realize the water quality monitoring in a timely manner by shortening the revisit time. The revisit time is defined as the time interval between two successive a satellite or a system's observations on the same ground point on the surface of the Earth [Luo et al. \(2017\)](#). In this study, we chose the Sentinel-2 satellite system with a 5-day revisit

time as the source of RST images. Accordingly, the need for 5-day monitoring of the whole target water bodies can be met with good weather conditions for RST observation and the availability of all parties (e.g., financing and labor). Selecting satellites with a shorter revisit time can increase the monitoring frequency, enabling the whole QCSR monitoring to keep pace with the environmental change of frequency, for example, replacing Sentinel-2 in this article with WorldView-3 (97 min revisit time) [Ye et al. \(2017\)](#).

A satellite with a spatial and spectral resolution provides a more precise inversion result and sharper clustering spatial boundaries by reducing the size of the raster within the objective area. As such, replacing Sentinel-2 in this article with WorldView-3 [Ye et al. \(2017\)](#) would obtain an up-to-date and more accurate result of inversion and clustering.

3) Our experiment in [Section 3.1, 3.2](#) revealed that the performance of DNN is susceptible to the data size and gains a significant improvement as the data size increases. The reason can be seen in [Figure 1B](#) that each training iteration results in a model that is pretrained for the next training iteration after forward and backward calculations, and this process continues iteratively. Thus, we can expect a more robust and accurate model when more data are fed, such as more applications of the framework. More importantly, as the model was fed and trained by massive data, the *in situ* measuring might not be necessary.

4) The deep clustering method dealing with water quality assessment has advantages for big data sets with higher dimensional water quality parameters and multiple time periods. For processing high-dimensional water quality parameters, IDEC can have more objectives to extract and transform water quality features, which can make the clustering results closer to the real situation. In addition, deep clustering of the data for each time period separately allows for delineating newly integrated control areas and their characteristics. In this way, the overall state changes in the target water bodies can be seen at a glance, such as changes in the boundaries of each control area and changes in the characteristics of each control area.

4.3 Future work

Notwithstanding the developed work had several advantages, it is essential to note that improvements can be a part of future work.

RST images are significantly affected by weather conditions, especially cloud cover. An image with less than 35% cloud cover was regarded as a good practice to satisfy environmental monitoring requirements [Marshall et al. \(1994\)](#). To ensure accuracy, the "clear sky" images with less than 10% cloud cover were applied to the framework. Thus, there was a strict weather restriction during the *in situ* measuring. Sometimes the uncertainty of the weather can make *in situ* measurements

fruitless, even though the plan is made according to the weather forecast.

Furthermore, the cruise monitor's running does not synchronize with the satellite's visit to the objective area. For instance, it takes Sentinel-2 less than 2 s to cross the QCSR. This lag prevents the satellite from being in real-time synchronization with the CMT measurements. In order to hurdle the weather limitations and eliminate the lag between RST and CMT measurements, we plan to introduce unmanned aerial vehicles (UAVs) associated with multispectral sensors into the framework. Its lower-than-cloud flight altitude reduces the interference of the cloud. In addition, the synchronized working pace of UAVs allows for simultaneous data collection along with the cruise monitor. As a supplementary element of the framework, UAVs are particularly applicable to small surface water areas like river bays and estuaries.

Last but not least, the performance of deep learning was essentially dependent on the data size. Hence, collecting more data from diverse types of water bodies should be a critical and indispensable work.

5 Conclusion

An innovative framework was developed with three modules: RST, CMT, and deep learning. Deep learning uses the big data platform created by RST and CMT to achieve a robust performance in water quality monitoring and assessment. Our testing revealed that the DNN (a type of deep learning) in the framework has a higher performance in monitoring four water quality parameters (pH, DO, El.cond, and BP) than MLR, SVR, and RFR. DNN is highly sensitive to training data size compared to other models, and the performance increases significantly with the elevated training data size. The application of IDEC on the water quality assessment showed that the entire QCSR was well-defined and divided into four groups as joint control areas, which are group I, group II, group III, and group IV. The characteristic factors of each area were identified, which can contribute to defining a joint regional control strategy for the QCSR. Considering the big data platform is the foundation of this framework, our future work in priority would be collecting more measured data (RST and CMT) from different water bodies to increase the capacity of the big data platform and update the deep learning model in our framework.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization: JQ; data curation: JQ and JB; formal analysis: JQ and LQ; funding acquisition: HL and SN; investigation: JQ, JB, and XX; methodology: JQ; project administration: SN and HL; resources: SN and HL; software: JQ and LQ; supervision: SN, HL, and YB; visualization: JQ; writing—original draft: JQ; writing—review and editing: SN, YB, QH, GY, QZ, and JB.

Funding

This work was supported by the National Natural Science Foundation of China (U2040210 and 31971477), and SIGN II—Amoris, BMBF (02WCL1471J).

Acknowledgments

The authors are grateful for the help from Andre Wilhelms for providing the basic information of BioFish and Xiaojie Zhang during *in situ* measuring. They also acknowledge support from the KIT-Publication Fund of the Karlsruhe Institute of Technology.

Conflict of interest

XX was employed by the company MioTech Research.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2022.979133/full#supplementary-material>

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