Spatial and temporal analysis of groundwater ecosystems

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“Die Welt ist im Wandel. Ich spüre es im Wasser. Ich spüre es in der Erde. Ich rieche es in der Luft.“

- Galadriel (Der Herr der Ringe - Die Gefährten von J. R. R. Tolkien) -

Dedicated to all my loved ones who have accompanied me on this journey.

ABSTRACT

Groundwater is an important source of freshwater, drinking water, service water for irrigation, industrial and geothermal uses. Moreover, groundwater is the largest terrestrial freshwater biome of the world, with ecosystems inhabited mainly by invertebrates (stygofauna) and microbes, that undertake important services, including water purification, as well as nutrient and carbon cycling. This habitat is naturally and anthropogenically threatened in many areas, yet only healthy groundwater ecosystems help to provide these important services. In many parts of the world, even the most basic knowledge of these ecosystems is lacking. Thus, this thesis aims to improve the understanding of ecological processes and conditions in groundwater, which is essential for sustainable resource and environmental management in times of competing groundwater uses. To achieve this groundwater fauna is analysed and assessed in detail on different spatial and temporal scales.

The first study of this cumulative thesis provides an overview on groundwater fauna (stygofauna) research, including the historical evolution of research topics and the development of sampling methods. To investigate the global distribution of groundwater fauna research and identify resulting data gaps, data from 859 studies is reviewed. From this, it is apparent that there has been an exponential increase in the number of groundwater fauna studies over the last ten decades, together with changing paradigms in the research focus. Furthermore, sampling methods have developed from using simple nets, substrate samples and hand-pumps in the beginning to recent advances in molecular methods. Finally, studies on groundwater fauna are spatially unevenly distributed and are dominated by research in Australia and Europe, with few studies in Africa, Asia, and the Americas. This biased view on groundwater fauna hinders the identification of biodiversity patterns and ecosystem functions on a global scale.

The second study uses long-term groundwater data from South-West Germany to identify shifts in groundwater fauna due to natural and/or anthropogenic impacts. Thus, a comprehensive spatial and temporal analysis of metazoan groundwater fauna and abiotic parameters from 16 monitoring wells over two decades is conducted. No overall temporal trends for fauna abundance and biodiversity and no significant large-scale trends in abiotic parameters are observed. Nine wells out of 16 show stable ecological and hydro-chemical conditions at a local level. The remaining wells exhibit shifting or fluctuating faunal parameters between individual years, indicating more complex temporal behaviours on a local scale. On the one hand, these temporal changes can be linked to natural causes, such as decreasing dissolved oxygen contents or fluctuating temperatures. Moreover, by examining aerial images of the surroundings of three individual wells, it is revealed that anthropogenic impacts, such as construction sites, can cause significant shifts in groundwater fauna and changes in the ecological status.

Changes in hydrology and surface conditions are increasingly occurring in densely populated urban areas, which is why investigating urban aquifers becomes increasingly important. Thus, the ecological status of an anthropogenically influenced aquifer is examined in the third study by analysing fauna and hydrogeological, physico-chemical parameters in 39 groundwater monitoring wells in an urban area and compared to a forested area outside the built-up area of the city of Karlsruhe (Germany). Statistical analyses confirm noticeable differences in the spatial distribution of abiotic groundwater characteristics, such as lower groundwater temperature and higher dissolved oxygen content in the forested area, and thus indicate a correlation between abiotic characteristics and land use. Moreover, spatial differences in the species distribution are visible. However, no clear spatial pattern is found regarding faunal diversity and land use. The groundwater ecosystem status index is applied for classification of the ecological status of groundwater, but shows no clear spatial patterns concerning land use and other anthropogenic impacts. Thus, it is therefore not possible to obtain a clear result on the ecological status with existing assessment approaches in urban areas.

This thesis demonstrates that groundwater is a complex ecosystem affected by multiple stressors. Groundwater shows heterogeneous conditions as a habitat, even at a local scale. Moreover, changes in hydro(geo)logy and surface conditions, such as land use, influence groundwater fauna. Thus, this thesis reveals that the understanding of this ecosystem is important to obtain clear information on its ecological status.

KURZFASSUNG

Grundwasser ist eine wichtige Quelle für die Versorgung mit Süßwasser, Trinkwasser sowie mit Brauchwasser für die Bewässerung, ebenso wie für industrielle und geothermische Zwecke. Darüber hinaus ist das Grundwasser das größte terrestrische Süßwasserbiom der Welt mit einem Ökosystem, das hauptsächlich mit wirbellosen Tieren (Stygofauna) und Mikroben besiedelt ist, die wichtigen Aufgaben wie die Wasserreinigung sowie die Erhaltung des Nährstoff- und Kohlenstoffkreislauf übernehmen. In vielen Regionen der Welt ist dieser Lebensraum jedoch durch natürliche und anthropogene Einflüsse bedroht. Dies ist kritisch, da nur gesunde Grundwasserökosysteme zu wichtigen Ökosystemleistungen beitragen. Zudem fehlt in vielen Teilen der Welt selbst das grundlegendste Wissen über diese Ökosysteme. Ziel dieser Arbeit ist es daher, die ökologischen Bedingungen und Prozesse im Grundwasser besser zu verstehen, was in Zeiten konkurrierender Grundwassernutzungen für ein nachhaltiges Ressourcen- und Umweltmanagement unerlässlich ist. Im Einzelnen wird die Grundwasserfauna dafür auf verschiedenen räumlichen und zeitlichen Skalen erfasst und bewertet.

Die erste Studie dieser kumulativen Dissertation liefert einen globalen Überblick über die Grundwasserfaunaforschung, einschließlich der historischen Entwicklung der Forschungsinhalte und der Probenahmeverfahren. Um die globale Verbreitung der Grundwasserfaunaforschung und die bestehenden Datenlücken zu ermitteln, werden Daten von 859 Studien analysiert. Es zeigt sich, dass in den letzten zehn Jahrzehnten die Zahl der Studien zur Grundwasserfauna exponentiell zugenommen hat, was mit einem Paradigmenwechsel bei den Forschungsschwerpunkten einherging. Außerdem haben sich die Probenahmemethoden von der anfänglichen Verwendung einfacher Netze, Substratproben und Handpumpen zu neueren molekularen Analysen weiterentwickelt. Zuletzt zeigt sich, dass Studien zur Grundwasserfauna global ungleichmäßig verteilt sind und von der Forschung in Australien und Europa dominiert werden, während in Afrika, Asien und Amerika nur wenige Studien vorhanden sind. Diese einseitige Sichtweise auf die Grundwasserfauna erschwert die Bestimmung von Biodiversitätsmustern und Ökosystemfunktionen in einem größeren Maßstab.

In der zweiten Studie dieser Arbeit werden Langzeitdaten für Grundwasser aus Südwestdeutschland verwendet, um durch natürliche und/oder anthropogene Einflüsse ausgelöte Veränderungen der Grundwasserfauna zu identifizieren. Dazu wird eine umfassende räumliche und zeitliche Analyse der metazoischen Grundwasserfauna und abiotischer Parameter an 16 Messstellen über zwei Jahrzehnte durchgeführt. Dabei wurden keine großskaligen zeitlichen Trends für die Abundanz und die biologische Vielfalt der Fauna sowie keine signifikanten großräumigen Trends bei den abiotischen Parametern festgestellt. Neun der 16 Brunnen zeigen stabile ökologische und hydrochemische Bedingungen auf lokaler Ebene. Die übrigen Brunnen weisen zwischen einzelnen Jahren wechselnde oder schwankende Faunenparameter auf, was auf komplexere zeitliche Zusammenhänge auf lokaler Ebene hinweist. Diese zeitlichen Veränderungen sind zum einen auf natürliche Ursachen zurückzuführen, wie z. B. abnehmende Gehalte an gelöstem Sauerstoff oder schwankende Temperaturen. Anhand von Luftbilderanalysen der Umgebung von drei einzelnen Brunnen wird zudem festgestellt, dass anthropogene Einflüsse, wie z. B. Baustellen, zu erheblichen Verschiebungen der Grundwasserfaunagemeinschaften und Veränderungen des ökologischen Zustands führen können.

Besonders in dicht besiedelten städtischen Gebieten kommt es zunehmend zu Veränderungen der Hydrologie und der Oberflächenbedingungen, weshalb die Untersuchung städtischer Grundwasserleiter immer wichtiger wird. Daher wird in der dritten Studie der ökologische Zustand eines anthropogen beeinflussten Grundwasserleiters durch die Analyse der Fauna und hydrogeologischer, physikalisch-chemischer Parameter in 39 Grundwassermessstellen in einem städtischen Gebiet im Vergleich zu einem Waldgebiet außerhalb des bebauten Gebietes der Stadt Karlsruhe (Deutschland) untersucht. Die Analysen bestätigen erkennbare Unterschiede in der räumlichen Verteilung der abiotischen Grundwassereigenschaften, wie z. B. niedrigere Grundwassertemperaturen und höhere Konzentrationen an gelöstem Sauerstoff im Waldgebiet, und weisen somit auf einen Zusammenhang zwischen abiotischen Eigenschaften und der Landnutzung hin. Darüber hinaus sind räumliche Unterschiede in der Artenverteilung zu erkennen, während bei der Faunendiversität und der Landnutzung kein klares räumliches Muster erkennbar ist. Zur Klassifizierung des ökologischen Zustands des Grundwassers wird der "Grundwasserökosystem Status Index" herangezogen, der keine klaren räumlichen Muster in Bezug auf die Landnutzung und andere anthropogene Einflüsse erkennen lässt. Eine eindeutige Bewertung des ökologischen Zustands mit den bestehenden Bewertungsansätzen im urbanen Raum ist daher nicht möglich.

Zusammenfassend zeigt diese Arbeit, dass Grundwasser ein komplexes Ökosystem ist, welches von zahlreichen Stressfaktoren beeinflusst wird. Selbst auf lokaler Ebene weist das Grundwasser als Lebensraum heterogene Bedingungen auf. Darüber hinaus beeinflussen Veränderungen der Hydro(geo)logie und der Oberflächenbedingungen, wie etwa durch Landnutzung, die Grundwasserfauna. Schlussendlich zeigt diese Arbeit, wie wichtig das Verständnis dieses Ökosystems ist, um klare Informationen über seinen ökologischen Zustand zu erhalten.

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ACRONYMS AND SYMBOLS

Acronyms

BW	Baden-Württemberg
CLC	CORINE Land Cover
DNA	Deoxyribonucleic Acid
EC-WFD	European Union Water Framework Directive
eDNA	environmental Deoxyribonucleic Acid
EH	Shannon Equitability/Evenness Index
eRNA	environmental Ribonucleic Acid
EPI	Ecophysiological Index
EU	European Union
GDE	Groundwater-Dependent Ecosystems
GFI	Groundwater Fauna Index
GHI	Groundwater Health Index
GWT	Groundwater temperature
H	Shannon Index
HS	Shannon Diversity Index
GESI	Groundwater Ecosystem Status Index
LST	Land Surface Temperature
LUBW	Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg

MDS	MultiDimensional Scaling
NIWA	National Institute of Water and Atmospheric Research
NSW	New South Wales
NZ	New Zealand
PASCALIS	Protocols for the ASsessment and Conservation of Aquatic Life In the Subsurface
PCR	Polymerase Chain Reaction
PHATE	Potential of Heat-diffusion for Affinity-based Trajectory Embedding
PPCS	Postojna–Planina Cave System
QLD	Queensland
RNA	Ribonucleic Acid
UBA	Federal Environmental Agency of Germany - Umweltbundesamt
UK	United Kingdom
VIC	Victoria
WA	Western Australia
wGHI^{N}	weighted Groundwater Health Index Nitrates

Constants

Latin symbols and variables

e.g.	exempli gratia
etc.	et cetera
i.e.	id est

Greek symbols and variables

ρ	Spearman rank correlation coefficient

Operators and math symbols

h	hours

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1

INTRODUCTION

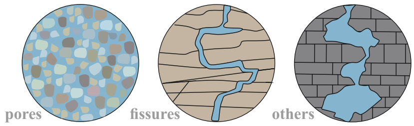
1.1 General motivation

Nearly 71 % of the earth's surface is covered by water (Shiklomanov and Rodda, 2003), which is the basic prerequisite for life. Nevertheless, only three per cent of the total water resources on Earth are freshwater (Meissner and Mampane, 2009), with groundwater accounting for approximately 99 % of all liquid freshwater (Shiklomanov and Rodda, 2003) or 15.9 million km^3 (only the fresh groundwater component) (Ferguson et al., 2021).

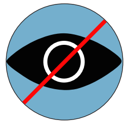
Groundwater is part of the water cycle and, therefore, an open system in contact with terrestrial and aquatic systems. It is recharged via precipitation and infiltration of surface water or artificial recharge and discharged on the surface by springs, wetlands, entering surface water (exempli gratia (e.g.) lakes, rivers, et cetera (etc.)) and exploration, e.g. by wells. Per definition groundwater includes all water below the water table in the subsurface, the so-called saturated zone, where all cavities are entirely filled with water and whose movement is determined exclusively by gravity (Verein Deutscher Ingenieure e.V. (VDI), 1994).

Thus, groundwater

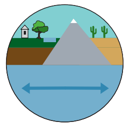
- is present in pores, fissures and other voids within geological formations,



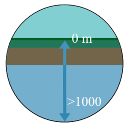
- is invisible, hidden to the naked eye and often poorly known and understood by society,



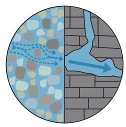
- is a spatially distributed resource, which is virtually ubiquitous and extends laterally under most of the land surface,



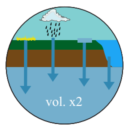
- has a large lateral extent, but also a significant vertical dimension (3D geometry), from very close to the land surface to great depths, down to thousands of metres,



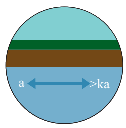
- is generally moving very slowly, except for karst formations, mainly because subsurface lithological matrix offers a hydraulic resistance to flow many orders of magnitude higher than the hydraulic resistance experienced in open channel flow,



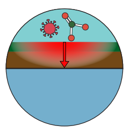
- is stored in large volumes in the subsurface, exceeding annual groundwater replenishment by two orders of magnitude, on average,



- ages commonly vary widely from recent to tens of millennia, while groundwater quality (salinity and other quality parameters) may also be subject to significant variation due to long residence times and contact with the lithological matrix and subsurface biosphere and



- due to the overburden's resistance to flow, groundwater systems are usually better protected against pollution, but once polluted they are much more difficult to remediate, with shallow groundwater domains more vulnerable to pollution than deeper ones (United Nations, 2022).



In addition, groundwater is a vital resource for humanity, as it provides a variety of services. One existing scheme to classify services of whole ecosystems is the Millennium Ecosystem Assessment classification scheme, which divides groundwater ecosystem services into four categories: supporting, provisioning, regulating, and cultural services (Figure 1.1) (Millennium Ecosystem Assessment, 2005). Provisioning services are services that allow humans to use water for specific purposes. One-third of the world population uses groundwater as a source of drinking water (Sampat, 2000). Moreover, groundwater provides 49 % of the water volume for domestic use by the global population (Food and Agriculture Organization of the United Nations (FAO), 2023; Margat and Gun, 2013) and around 25 % of all water for irrigation, serving 38 % of the world's irrigated land. Alongside the use of groundwater for irrigation or other agricultural purposes (69 %) and drinking water/domestic use (22 %), 9 % of the total global amount of groundwater is used as cooling and process water for industrial purposes, mineral water and energy supply (geothermal use: heat and cold storage [1])(Avramov et al., 2010; Job, 2022; Siebert et al., 2010; Stauffer et al., 2013). According to the United Nations (2022), the demand of groundwater is projected to grow by 1 % per year over the next 30 years.

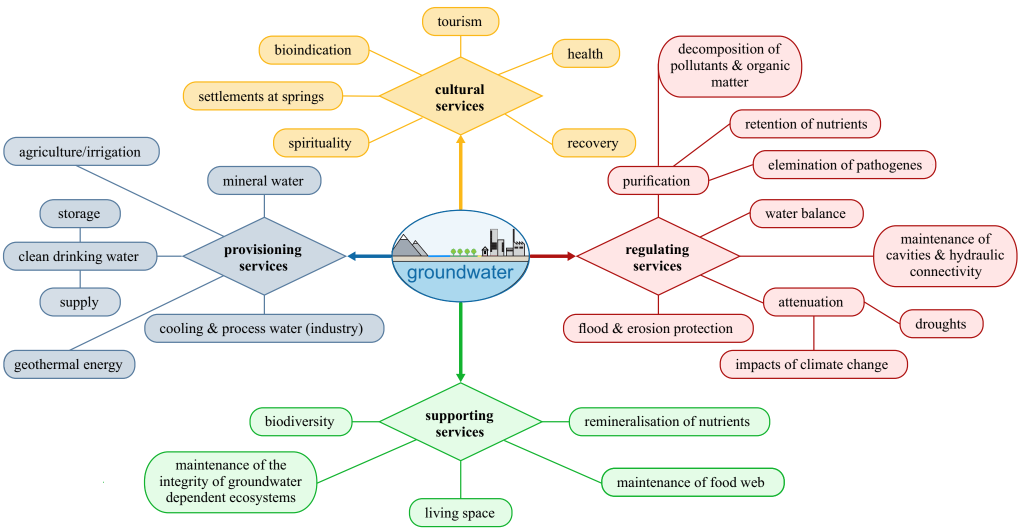


Figure 1.1: Services provided by groundwater and its ecosystem classified according to the Millennium Ecosystem Assessment classification scheme (Millennium Ecosystem Assessment, 2005).

Besides, there are some more important services provided by groundwater. Cultural services include more indirect services linked to leisure activities, local recreation, tourism, traditions, religion or spiritual values associated with a specific site (caves, springs, etc.) (Avramov et al.,

[1] numbers varied between the continents and is estimated by the United Nations, 2022

2010). In addition, there are regulating services, which are in-situ services regulating groundwater systems' quantity and quality regimes. For instance, these services reflect the buffer capacity of aquifers, as groundwater with surface connection is a retention body for higher amounts of surface water, which helps to reduce droughts, as well as floods and protects against erosion (United Nations, 2022).

On the contrary, in-situ services on which groundwater-dependent ecosystems and other groundwater-related environmental features rely are supporting services (United Nations, 2022). Groundwater is also the largest terrestrial freshwater living space of the world (Gibert et al., 1994; Griebler et al., 2014b; Hose et al., 2022) and its ecosystems are essential for energy and material flow (Boulton et al., 2008). For instance, they enable water transmission by bioturbation (movement, burrowing) as higher organisms maintain cavities and thus the hydraulic connectivity (Hose and Stumpp, 2019; Mermillod-Blondin et al., 2023; Mermillod-Blondin and Rosenberg, 2006; Nogaro et al., 2006; Stumpp and Hose, 2017). This contribution is also called ecosystem engineering activity, since organisms (ecosystem engineers) 'directly or indirectly control the availability of resources to other organisms by causing physical state changes in biotic or abiotic materials' (Jones et al., 1997). Moreover, water is purified by microorganisms. During the so-called self-purification of groundwater, microorganisms contribute to the biogeochemical cycling, as well as to the elimination of pathogens, organic matter and anthropogenical contaminants. In addition, they retain nutrients. If the distribution of substances in the underground is prevented solely by microbial degradation or sedimentation (in the case of metals), this is referred to as natural attenuation. Furthermore, groundwater fauna promote microbial growth and contribute to the food web as they process organic matter by grazing biofilms of bacteria (Avramov et al., 2010; Griebler and Avramov, 2015; Mermillod-Blondin et al., 2023). Last but not least, microorganisms and fauna in groundwater can be used as bioindicators. Knowing the natural boundary conditions, changes occurring in the ecological patterns (abundance, activity, species range and community composition) can be used to assess the ecological status of groundwater (Avramov et al., 2010).

Nevertheless, the ecosystem services concept is not yet commonly implemented in the routine of water-regulation practice (Carpenter et al., 2006). However, a 'framework of ecosystem services is a powerful tool to raise awareness in human society of the various benefits we receive and use from ecosystems each day' (Griebler and Avramov, 2015).

1.2 Groundwater ecosystems

Although groundwater is the largest terrestrial freshwater biome of the world (Gibert et al., 1994; Griebler et al., 2014b; Hose et al., 2022), groundwater ecology is a relatively young research discipline with research and knowledge lagging behind that of surface ecosystems such as lakes and streams (Griebler et al., 2014b). However, groundwater ecosystems have been investigated for over a hundred years, with the first description of eyeless and depigmented animals in a cave in 1537 (Mylroie, 2004). Groundwater is a species-rich habitat, with over 25,000 species (up to 100,000 species in Culver and Holsinger (1992) and Martinez et al. (2018)) and communities consisting of a highly diverse biota (Malard et al., 2023; Marmonier et al., 2023).

The basis of groundwater ecosystems and their food web is built by bacteria, archaea and fungi (Griebler and Lueders, 2009; Humphreys, 2006). These microorganisms are ubiquitous in groundwater and build small colonies or occur as single cells, and are mainly attached to sediments as biofilms. Due to the low nutrient and oxygen supply, microbial diversity and activity in aquifers are very low compared to surface water (Griebler and Lueders, 2009). The community structure of groundwater fauna is mainly influenced by the intensity of surface influence, such as the input of carbon and oxygen, and by structure (id est (i.e.) available cavities) of the aquifer (Avramov et al., 2010).

Depending on the pore space in aquifers, groundwater can be colonised by micro-fauna (*Protozoa*, *Rotifera*, *Turbellaria* and *Nematoda*) (see Figure 1.2) and/or by large-bodied meio-fauna (Humphreys, 2006). Thus, pore space and the structure of the aquifer matrix are important determinants of the presence of organisms. Alluvial aquifers with sandy and silty sediments, and therefore small pore spaces, typically inhabit only a few small invertebrates. In contrast, aquifers with larger fractures, karstic voids or coarse sand and gravel deposits show more invertebrates (Hose et al., 2015). Due to their size, vertebrates such as salamanders and fishes occur only in karst and pseudokarst (Humphreys, 2006, 2009). Moreover, the meio- and macro-fauna in groundwater are mainly invertebrates dominated by arthropods. As can be seen in Figure 1.2, Crustaceans (*Copepoda*, *Syncarida*, *Amphipoda*, *Ostracoda* and *Isopoda* (Hose et al., 2014; Humphreys, 2006)) usually make up to 50 % of the species abundance and richness (Korbel and Hose, 2011). Still, also a wide range of other phyla like molluscs (snails), other arthropods (mites, insects (beetles)) and various worms (*Platyhelminthes*, *Annelida*) (Hose et al., 2015; Humphreys, 2009) can be found in groundwater. The group of *Copepoda* (red colour in Figure 1.2) occurs nearly ubiquitously in subterranean habitats, with over 1,000 known groundwater species in six orders (Galassi et al., 2009). Still, species richness in groundwater is largely unknown, and its distribution is only sketchily understood (Galassi et al., 2009; Gibert and Culver, 2009; Gibert and Deharveng, 2002; Stoch and Galassi, 2010).

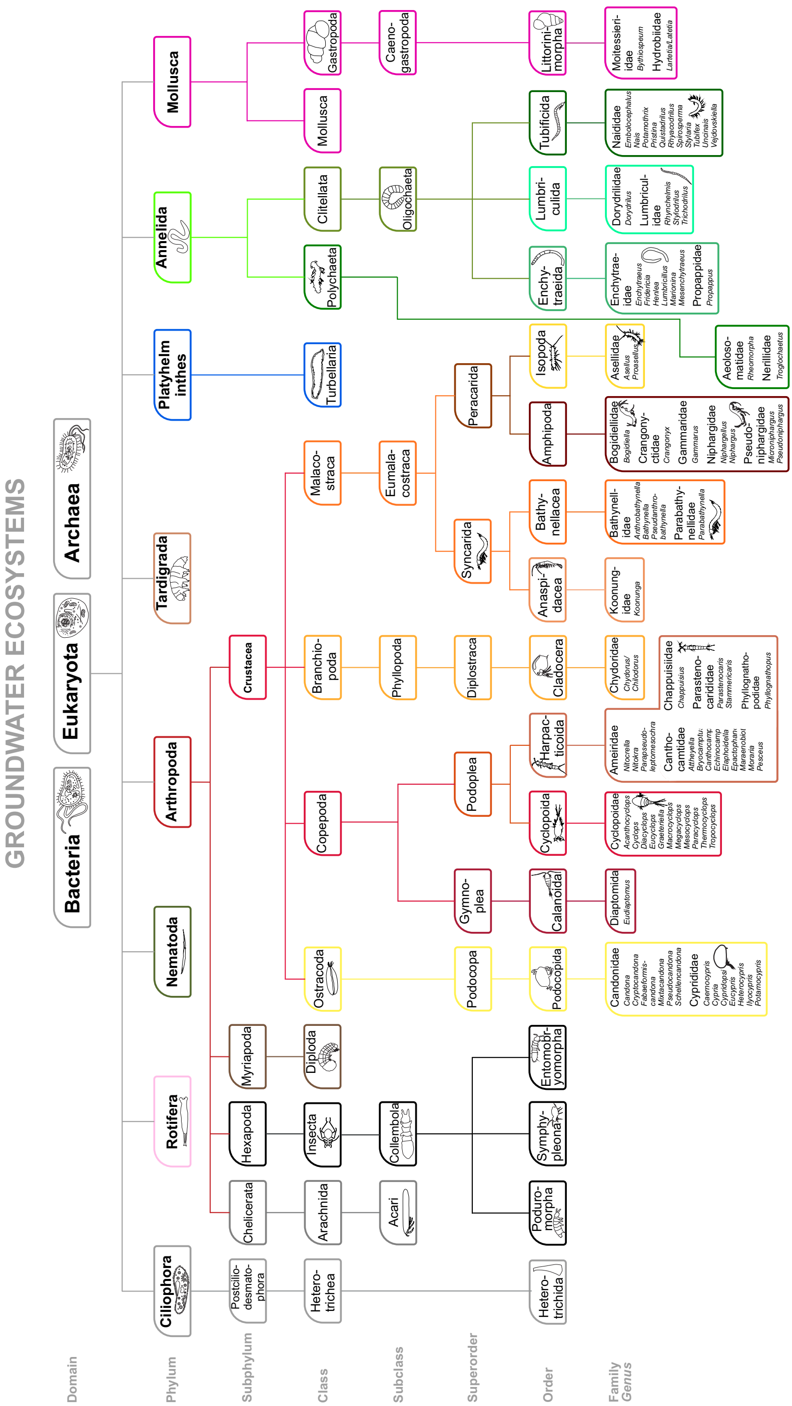


Figure 1.2: Taxonomy of groundwater ecosystems based on the underlying literature of this thesis.

1.2.1 Stygofauna

Fauna populating groundwater is known as stygofauna. In this context, the prefix ‘stygo’ derives from the Greek language and means ‘hateful’. This is in connection with the river Styx from ancient Greek mythology, which flowed underground and carried the souls of the dead to Hades. Thus, in the mythological context, stygobionts were the creatures living in the watery regions of the underworld (Botosaneanu, 1986). First, Lazare Botosaneanu used the term ‘stygofauna’ in the scientific literature in his study Stygofauna Mundi (Botosaneanu, 1986), describing the subterranean aquatic fauna of the world (Goater, 2009).

Groundwater is typified by extremes, like total darkness, lack of space, low oxygen and nutrient content, and no primary production of energy. These extreme conditions hinder the colonisation of this habitat. Thus, stygofauna comprises stygobionts, stygophiles, and stygoxenes species depending on their ecological preferences (Gibert et al., 1994; Hahn, 2006). Stygoxenic fauna inhabits surface water or soil and is transported to groundwater accidentally or occasionally, and is not able to reproduce there (Dumnicka et al., 2017; Mösslacher, 1998; Stein et al., 2010). Stygophilic species are affiliated with ground and surface waters and can survive considerable times in groundwater and reproduce there (Mösslacher, 1998; Stein et al., 2010). They use alluvial sediments or caves as a refuge from predators or changing environmental conditions at the surface (floods, droughts, etc.) (Knight and Penk, 2010). Stygobiontic species are obligate hypogeans and exclusively inhabit groundwater. They are specialised to a subterranean life and spend their entire life cycle in this habitat. Thus, stygobiontic species show morphological, physiological and behavioural adaptations, such as a long, thin body shape and small size, ocular regression and hypertrophy of sensory organs, a lack of pigmentation, a relatively long life span and a reduced metabolic and reproduction rate, which are linked to environmental limitations (Galassi, 2001; Gibert and Culver, 2009; Gibert et al., 1994; Knight and Penk, 2010; Rétaux and Jeffery, 2023). Due to the dependence on food and oxygen supply from the surface, the abundance of stygofauna decreases with depth and distance from input pathways. Thus, stygofauna is rarely found below 100 m ground level or in locations with a dissolved oxygen concentration in groundwater below 0.3 mg/L. Moreover, stygofauna, which is stranded in unsaturated sediments, can hardly survive for more than 48 hours (h) and has limited capacity to recover from disturbances and changes in water quality from natural background (Hose et al., 2015).

Moreover, the number of stygobionts in a groundwater site is generally low compared to the surface diversity (Culver and Sket, 2000; Stoch and Galassi, 2010). The absence of higher amounts of energy in groundwater systems results in low biomass and biodiversity, which is why the food web in aquifers relies on inputs of nutrients and carbon from the surface (Hose et al., 2015). Thus, the colonisation of groundwater differs from that of surface water. Due to isolation and fragmentation stygobionts are characterised by a high degree of short-range endemism (Harvey, 2002), resulting in a low local diversity compared to regional diversity, as much larger differences in species composition among sampling sites are found for surface-dwelling freshwater fauna in comparable spatial units (Gibert and Culver, 2009; Gibert and Deharveng, 2002). In addition, the occurrence of only a few lineages results in an over-representation of a few major taxa and under-representation of others. Moreover, there are many relict species ('living fossils') and truncated food webs with very few predators conceivably caused by a scarce food supply (Gibert and Deharveng, 2002). Pressure for food and resources has resulted in the diversification of niches in some fauna (e.g. Ercoli et al., 2019; Fišer et al., 2019), which is why similar morphological, physiological and behavioural traits are creating low inter-species variability across many biological attributes (Hose et al., 2022). Another characteristic of groundwater is the rarity of stygobiontic species, which is why typically only half of all stygobiontic species in any given region are found at less than five per cent of sites (Castellarini et al., 2004; Hahn, 2015; Martin et al., 2009). There are typically few species in one location, but many across different locations (Dumnicka et al., 2020).

1.2.2 Natural and anthropogenic impacts on groundwater ecosystems

In groundwater, with the exception of karst aquifers, environmental conditions are mostly stable, resulting in a low water flow, a small thermal range and low temperatures, with a variation of 1 – 2 °C over a year and little or no seasonality (Avramov et al., 2010; Gibert et al., 1994; Notenboom, 1991; Taylor and Stefan, 2009). Globally, multiple natural and human stressors threaten groundwater and its specialised ecosystems and have the potential to alter groundwater community structure (e.g. Korbel et al., 2022a) and compromise ecosystem functions, resulting in the deterioration of groundwater health (Hancock, 2002; Hancock et al., 2005). A distinction between quantitative and qualitative impacts can be made in this context. Quantitative impacts affect the volume or structure of a groundwater body (Danielopol et al., 2003). A common impact of this category is groundwater abstraction for drinking water, irrigation and mining activities (see Figure 1.3) (Danielopol et al., 2003; Hancock et al., 2005). The abstraction of groundwater alters groundwater levels and surface water groundwater connectivity, causing desiccation and death for particular stygobiontic biota (Korbel et al., 2019; Patel et al., 2020). These pressures are associated with rising global exploitation of groundwater relating to a general demographic increase. They are particularly prevalent in less developed countries in Asia, Africa and South America (Vörösmarty et al., 2000; Wada et al., 2010). Additionally, mining activities can result in dewatering and removal of surrounding material from the groundwater body (Danielopol et al., 2003; Hancock et al., 2005).

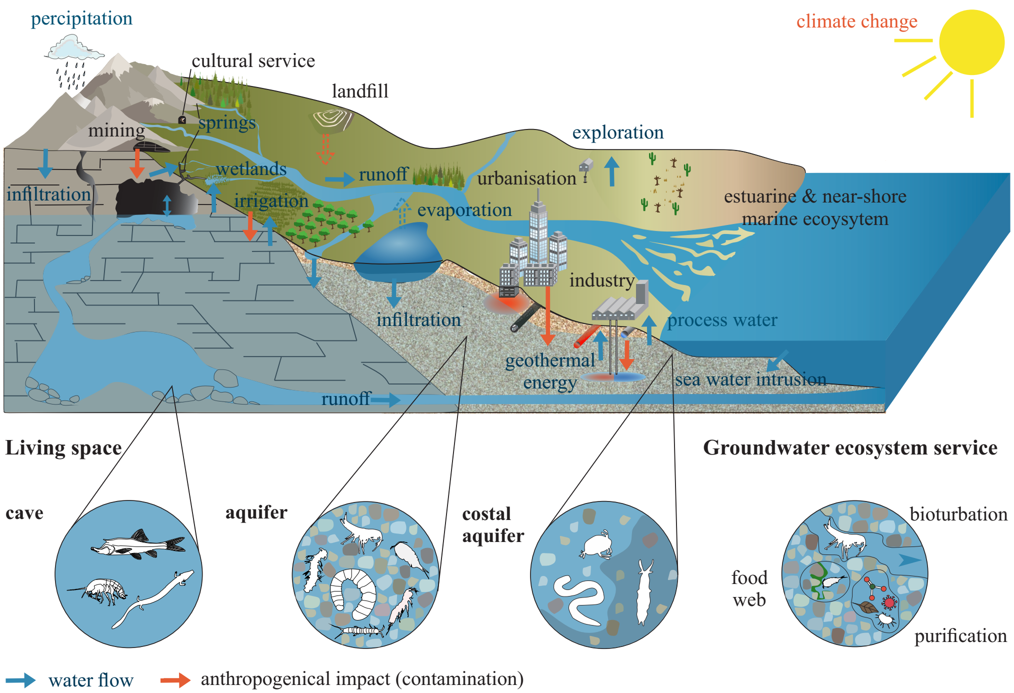


Figure 1.3: Block diagram showing the water cycle, including the water flow (blue arrows) and various anthropogenic impacts (red arrows) on groundwater. Different groundwater fauna habitats and ecosystem services are also illustrated.

An example of a qualitative impact is groundwater contamination (see Figure 1.3 red arrows), which is another frequent threat to stygofauna. Common pollutants derive from heavy industry (Hose et al., 2014), agriculture (Di Lorenzo et al., 2020b; Di Lorenzo and Galassi, 2013; Korbel et al., 2022a), urbanisation (Hallam et al., 2008), surface waters (Danielopol et al., 2003; Kristensen et al., 2018; Uhl et al., 2022) and thermal pollution (Griebler et al., 2016; Menberg et al., 2013a; Taylor and Stefan, 2009; Tissen et al., 2019; Zhu et al., 2010). These various sources of pollution differ in terms of the depth of contamination and its spread. Most of the named pollution sources are located near the land surface (agriculture, urbanisation, surface water), but there are also sources at greater depths (mining, gas and oil exploration). Concerning the spread of contamination, a distinction can be made between point sources (e.g. industry, households) and non-point sources, with diffuse sources and widespread pollution (e.g. agriculture). Latter often includes larger quantities of pollutants (United Nations, 2022). Generally, high sensitivity to organic contaminants and ammonium is observed for stygobiontic invertebrates in field and laboratory studies (Becher et al., 2022; Di Lorenzo et al., 2015; Romano and Zeng, 2013). Previous studies showed that ammonium impacts the organisms' growth and various physiological mechanisms, particularly respiratory metabolism (Romano and Zeng, 2013).

Examples of strong impacts are urban areas, which are characterised by multiple anthropogenic impacts such as dense building development, open geothermal systems, underground car parks and injections of thermal wastewater from industry resulting in local thermal alteration of groundwater by up to several degrees (Menberg et al., 2013a; Taylor and Stefan, 2009; Tissen et al., 2019; Zhu et al., 2010). Temperature changes can affect physico-chemical groundwater characteristics (Griebler et al., 2016) but also microbial processes, community composition and biodiversity, as physiological activity, especially metabolic rates, of stygobiontic species are temperature-dependant (Colson-Proch et al., 2009; Di Lorenzo and Galassi, 2017). Additionally, anthropogenic climate change significantly threatens biogeochemical processes and groundwater ecosystems (Griebler et al., 2016) due to altered recharge events, increased evapotranspiration, temperatures (Figura et al., 2011; Menberg et al., 2014; Tissen et al., 2019) and changing river-groundwater interactions. Threats due to climate change are most severe in areas with semi-arid to arid climates, humid regions of the Northern Hemisphere and (sub-)tropical areas (humid monsoonal countries) (Danielopol et al., 2003).

Finally, all those stressors can impact biodiversity, leading to species extinction and a shift in the community composition as ubiquitous surface-water species outcompete and replace groundwater species (Danielopol et al., 2003). In addition, there are implications for freshwater ecosystems (Hancock et al., 2005; Korbel et al., 2022a), terrestrial vegetation and fauna (Eamus and Froend, 2006) and estuarine and near-shore marine ecosystems (Moore, 1999) due to the ubiquity of groundwater dependence in terrestrial ecosystems (Hancock et al., 2005) (Figure 1.3 blue arrows). However, investigations on groundwater fauna and the impacts of humans on these ecosystems are still rare (M.-J. Dole-Olivier et al., 2009; Gibert and Culver, 2009; Martinez et al., 2018). Thus, there is a need for increased knowledge on subterranean ecosystems, their assessment and protection (Griebler et al., 2014b; Malard et al., 2023).

1.2.3 Assessment and protection approaches

During the last century, the subject of groundwater fauna research shifted from describing newly discovered species towards an ecosystemic and holistic view with research incorporating the whole ecosystem functioning (Danielopol and Marmonier, 1992; Malard et al., 2023). In the same context, social and political recognition of the importance of groundwater increased and topics of conservation and groundwater management began to emerge (Boulton et al., 2003a; Danielopol et al., 2003). Particularly noteworthy is the importance of the Swiss Water Protection Ordinance from 1998 for groundwater research. This was one of the first international authorities to include monitoring of both water quality and ecological criteria for groundwater systems (Danielopol and Griebler, 2008; Griebler et al., 2023; Schweizerischer Bundesrat, 1998). Another milestone and driver for groundwater ecosystem management and research in Europe was the European

Groundwater Directive 2006. This directive attempted to incorporate ecological knowledge into schemes for environmental planning and policies (Griebler et al., 2023; Steube et al., 2009). At the same time, groundwater initiatives in Australia began to gain momentum with the emergence of national policies to monitor groundwater ecosystems' stress and health (Griebler et al., 2023; NGC, 2004). Until now, global groundwater policy has primarily focused on the utilisation of groundwater after extraction and not on aquifer management, which aims to control groundwater abstraction and quality and to preserve groundwater system functions and services (United Nations, 2022).

Early approaches for monitoring groundwater ecosystems in Germany began with Hahn (2006) introducing the Groundwater Fauna Index (GFI), which quantifies relevant ecological conditions in the groundwater as a result of hydrological exchanges between the surface and groundwater. Shortly afterwards and triggered by Australian water management policies and industry, the first attempt to assess, measure and monitor ecosystem health was developed in 2011 in Australia. The Groundwater Health Index (GHI) uses a two-tiered framework consisting of a multi-metric suite of biotic and abiotic indicators (Korbel and Hose, 2011). Commissioned by the Federal Environmental Agency of Germany - Umweltbundesamt (UBA), Griebler et al. (2014b) developed a two-step, ecologically based classification scheme for characterising groundwater ecosystems. This assessment scheme is based on determining biotic and abiotic parameters, which are compared with reference values and are used to distinguish locations with very good or good ecological conditions, or locations that fail these criteria. A different approach is offered by the more recent assessment scheme of Fillinger et al. (2019). The microbial Density-Activity-Carbon index can be used to detect disturbances of groundwater ecosystems and is based on three microbial indicators: prokaryotic cell density, microbial activity and bioavailable carbon.

Despite all the mentioned efforts, there is still a lack of detailed information on groundwater ecosystems in most parts of the world. Even the most basic knowledge, for example, on essential properties, such as structural heterogeneity (e.g. ecosystem size, connectivity to neighbouring systems), inflow and out-flow of matter (e.g. sediment, detritus) and the spatial and temporal distribution of substrates (e.g. dissolved oxygen, pollutants and nutrients) is still missing (Larned, 2012). Furthermore, an almost untouched topic are groundwater foodweb interactions, especially between micro- and macroorganisms, as well as their link to processes of the carbon and nutrient cycle and services, such as attenuation of pollutants (Griebler and Avramov, 2015). Furthermore, international water law should pay more attention to transboundary aquifers, i.e. aquifers with groundwater flow crossing international boundaries, to avoid conflicts between countries. Moreover, there is a notable absence of an overall analysis of spatial and temporal distribution and research into groundwater fauna on a global scale. In some cases, this is certainly due to the fact that 'sharing data and information is often deficient, especially in low-income countries' (United Nations, 2022).

1.3 Objectives and approaches

This thesis aims to improve the understanding of ecological processes and conditions in groundwater, which are essential for sustainable resource and environmental management in times of competing groundwater uses. More specifically, this thesis aims to build a bridge between a basic understanding of biological issues and multidisciplinary approaches to understanding underlying processes. To do so, groundwater fauna is analysed and assessed on different spatial and temporal scales in this study.

In detail, this thesis seeks to

- build a common knowledge basis for an improved understanding, assessment and conservation of groundwater biodiversity on a larger scale. By obtaining a global overview of the historical evolution of stygofauna research, stygofauna sampling methodologies and an analysis of groundwater fauna research's spatial and temporal distribution, the thesis aims to summarise the current knowledge and thus point out knowledge gaps.
- identify shifts in groundwater fauna due to natural or anthropogenic impacts in recent decades and parameters that have a major influence on groundwater ecosystems. Comprehensive analysis of metazoan groundwater fauna and abiotic parameters over two decades, as well as statistical analyses are conducted to distinguish sites with stable and unstable faunal conditions. Also, the impact of specific hydrological and hydro-chemical parameters on this characterisation is assessed.
- assess the ecological status of urban aquifers and to identify parameters required for a more reliable, quantitative, ecological assessment. Groundwater ecosystems beneath an urban area are compared to a natural area, considering the status of their ecosystem and the impact of land use on groundwater faunal communities. They are investigated by analysing local hydrogeological, physico-chemical and faunal data and with the goal to detect causes for faunal changes.
- determine implications for environmental policies for sustainable groundwater management and monitoring requirements for groundwater fauna to ensure these ecosystems are maintained and preserved in the future. The final aim of this thesis is to verify the applicability of biomonitoring of groundwater on different spatial scales.

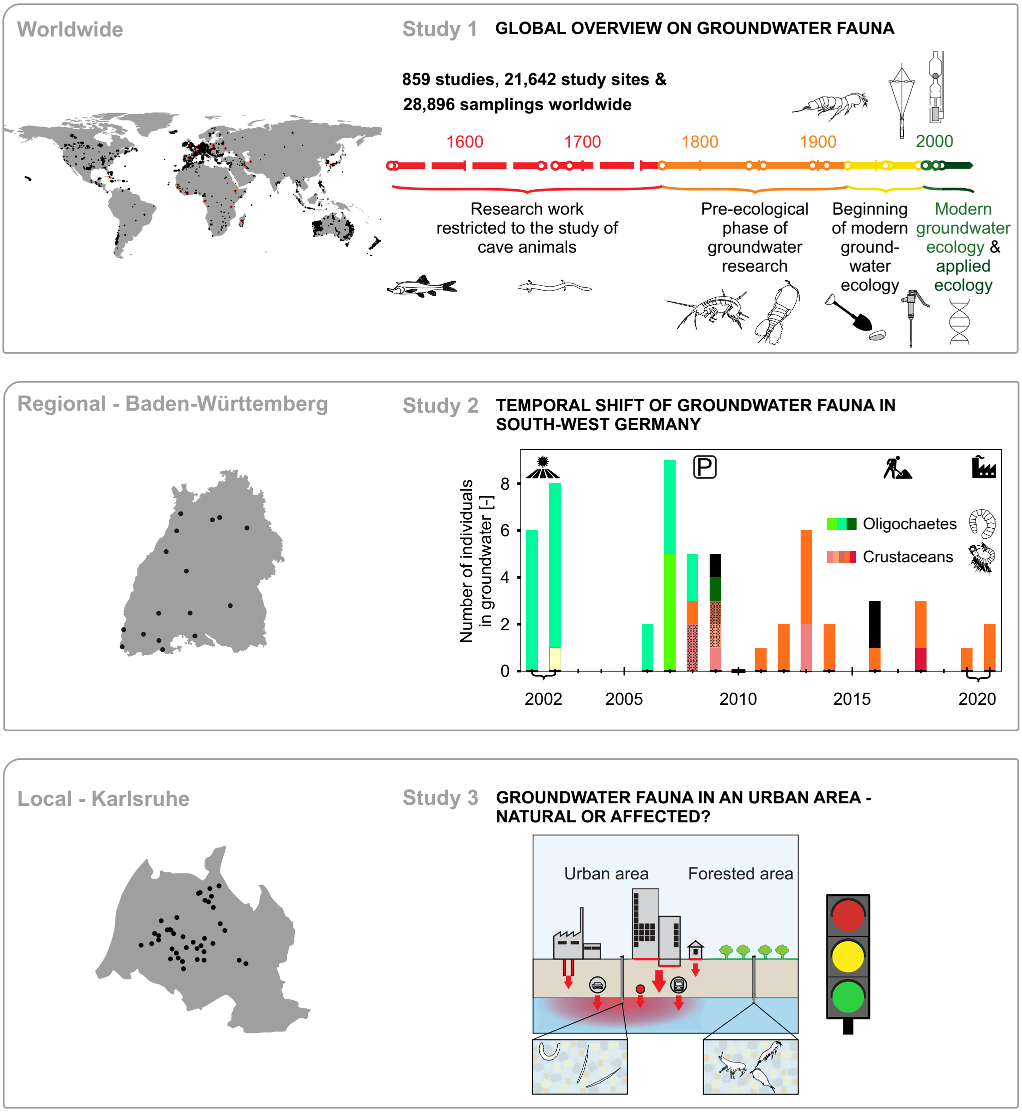


Figure 1.4: Graphical overview of the studies of this thesis on groundwater fauna. The investigations focus on different temporal and spatial scales and aim to better understand ecological processes and groundwater conditions.

1.4 Structure of the thesis

This cumulative thesis combines three individual studies, which are enclosed in Chapters 2, 3 and 4. All studies were submitted to peer-reviewed (ISI-listed) international journals, with Study 1 and Study 3 in Chapters 2 and 4 already published and Study 2 in Chapter 3 being under review.

The thesis is organised as follows:

- Chapter 2: GLOBAL OVERVIEW ON GROUNDWATER FAUNA
  In this review a global overview on groundwater fauna (i.e. stygofauna) research is presented. To achieve this, an extensive review of accessible groundwater fauna data is conducted by analysing data from national and international publications in scientific journals, national reports, doctoral theses, historical writings, books and consisting online databases in various languages. On this basis, an overview of (i) the historical evolution of stygofauna research, (ii) stygofauna sampling methodologies, and (iii) an analysis of the global spatial and temporal distribution of groundwater fauna research and knowledge gaps is provided. So, a common knowledge basis for an improved understanding, assessment and conservation of groundwater biodiversity on a larger scale is built.

- Chapter 3: TEMPORAL SHIFT OF GROUNDWATER FAUNA IN SOUTH-WEST GERMANY
  In this study long-term groundwater data from 16 monitoring wells in Baden-Württemberg (BW) South-West Germany is used to identify shifts in groundwater fauna due to natural or anthropogenic impacts. Therefore, the available groundwater data of the study site is reviewed, and observation wells for additional sampling in 2020 are selected. Metazoan groundwater fauna and abiotic parameters are temporally analysed on different spatial scales. To distinguish wells with stable and unstable faunal conditions and to assess the impact of specific hydrological and hydro-chemical parameters on this characterisation, a multivariate PHATE-analysis is conducted. Moreover, time series of multiple parameters and aerial images of three individual wells are analysed in detail concerning changes in land use, surface condition, and abiotic parameters.

- Chapter 4: GROUNDWATER FAUNA IN AN URBAN AREA - NATURAL OR AFFECTED?
  In this last study, a first assessment of the groundwater fauna in an urban area is provided. Therefore, groundwater fauna beneath residential, commercial and industrial, i.e. urban areas in comparison to a forested area outside the built-up area of Karlsruhe (Germany)

is investigated to determine whether land use impacts groundwater faunal communities. Hence, the groundwater fauna is sampled in 39 groundwater monitoring wells, groundwater temperatures are measured, and chemical properties are analysed. For classification, the Groundwater Ecosystem Status Index (GESI) is applied, which characterises sites regarding the state of their ecosystem. To better understand large-scale relationships and the fine structures of high-dimensional biological data, a PHATE-analysis is conducted.

- Chapter 5: SYNTHESIS
  The major results of the study are summarised and their contribution to improving the understanding of groundwater ecology is described. Finally, perspectives for future research are provided.

2

GLOBAL OVERVIEW ON GROUNDWATER FAUNA

Reproduced from Koch, F., Blum, P., Korbel, K., Menberg, K., (2023) Global overview on groundwater fauna. Ecohydrology 17 (1). 28. https://doi.org/10.1002/eco.2607.

2.1 Introduction

Groundwater is an important source of freshwater, drinking water and service water for irrigation, industrial and geothermal uses (Job, 2022; Siebert et al., 2010; Stauffer et al., 2013). Moreover, groundwater is the largest terrestrial freshwater biome of the world (Griebler et al., 2014a) and is considered as a species-rich habitat (> 100,000 species) with many taxa displaying high endemism (Culver and Holsinger, 1992; Martinez et al., 2018). Groundwater communities consist of a highly diverse biota, including bacteria and archaea, viruses, protozoans, fungi, invertebrates, salamanders and fish (Marmonier et al., 2023). Fauna populating groundwater, known as stygofauna, comprise stygobiontic species (exclusively inhabiting groundwaters), stygophilic species (affiliated with both ground and surface waters) and stygoxenic fauna (accidentally or occasional groundwater inhabitants) (Gibert et al., 1994; Hahn, 2006).

Within groundwater communities, microorganisms play essential roles in water purification through biogeochemical cycling (Griebler and Avramov, 2015) and form biofilms, on which stygofauna feed. Stygofauna have roles in promoting microbial growth (Edler and Dodds, 1996; Mermillod-Blondin et al., 2002), enhancing aquifer water transmission (Hose and Stumpp, 2019; Stumpp and Hose, 2017), organic matter processing (Kinsey et al., 2007; Simon and Benfield, 2001) and contribute to the subterranean food web (Saccò et al., 2022b). Combined, these species provide several functions sustaining groundwater ecosystems, aiding groundwater health and water quality (Mermillod-Blondin et al., 2023).

Globally, groundwater and groundwater fauna are facing common threats, including abstraction (Wada et al., 2014), contamination (Burri et al., 2019) and climate change (Amanambu et al., 2020), all of which place multiple stresses on groundwater ecosystems. Groundwater abstraction for irrigation, potable water and mining activities (Danielopol et al., 2003; Hancock et al., 2005) alter groundwater levels, with duration and rate of abstraction known to strand particular stygobiontic biota, causing desiccation and death (Korbel et al., 2019; Patel et al., 2020). These pressures are particularly prevalent in Africa, Asia and South America (Wada et al., 2010) and are associated with demographic increases (Vörösmarty et al., 2000). Groundwater contamination is another frequent threat to stygofauna, with common pollutants derived from agriculture (Di Lorenzo et al., 2020b; Di Lorenzo and Galassi, 2013; Korbel et al., 2022a), heavy industry (Hose et al., 2014), urbanisation (Hallam et al., 2008), surface waters (Danielopol et al., 2003; Kristensen et al., 2018) and thermal pollution (Menberg et al., 2013a; Taylor and Stefan, 2009; Tissen et al., 2019; Zhu et al., 2010). Additionally, anthropogenic climate change poses a significant threat to groundwater ecosystems and biogeochemical processes (Griebler et al., 2016) due to altered recharge events, increased evapotranspiration, increased temperatures (Figura et al., 2011; Menberg et al., 2014; Tissen et al., 2019) and increased groundwater extraction caused by drying rivers. Climate change threats are most severe in areas with semi-arid to arid climate, humid areas of the Northern Hemisphere and (sub-)tropical areas (humid monsoonal countries) (Danielopol et al., 2003).

The multiple stressors that humans have placed on groundwaters globally (Becher et al., 2022) have the potential to alter groundwater community structure (e.g. Korbel et al., 2022a) and compromise ecosystem functions, resulting in the deterioration of groundwater health (Hancock, 2002; Hancock et al., 2005). Furthermore, these stressors can impact biodiversity and alter surface water groundwater connectivity, leading to species extinction and shift in the community composition as ubiquitous surface water species outcompete and replace groundwater species (Danielopol et al., 2003). Such changes to groundwater regimes, connectivity and biota can have implications for terrestrial vegetation and fauna (Eamus and Froend, 2006), freshwater ecosystems (Hancock et al., 2005; Korbel et al., 2022c) and estuarine and near-shore marine ecosystems (Moore, 1999) due to the ubiquity of groundwater dependence in terrestrial ecosystems

(Hancock et al., 2005). These impacts highlight the need for increased knowledge on subterranean ecosystems, their assessment and protection (Griebler et al., 2014a).

However, investigations on groundwater fauna and the impacts of humans on these ecosystems are still rare (M.-J. Dole-Olivier et al., 2009; Gibert and Culver, 2009; Martinez et al., 2018). A pioneering study of the global diversity of subterranean fauna, 'Stygofauna mundi', highlighted the biodiversity values of these ecosystems identifying 6,634 species of aquatic subterranean dwellers, from a variety of groundwater habitats (Botosaneanu, 1986; Malard et al., 2009). Later studies indicated over 7,800 subterranean species (Juberthie, 2000), with the most recent knowledge of global biodiversity synthesised in the revised edition of Groundwater Ecology and Evolution (Marmonier et al., 2023). As groundwater ecosystem diversity, functions and processes differ across landscapes (Korbel et al., 2013a; Zagmajster et al., 2023), knowledge of these ecosystems must be drawn globally from a variety of bioregions and climatic zones in order to implement effective management. Attempts have been made to improve knowledge of stygofauna diversity patterns in various regions of the world (e.g. Gibert et al., 2009: European Protocols for the ASsessment and Conservation of Aquatic Life In the Subsurface (PASCALIS)-project) with broad-scale studies synthesising current knowledge of groundwater biological and habitat diversity in Europe (Cornu et al., 2013), Thailand and Vietnam in South-East Asia (Brancelj et al., 2013) and Australia (Hose et al., 2015). Despite these studies, there is a notable absence of an overall analysis of spatial and temporal distribution and research into groundwater fauna on a global scale.

The aim of this study is to provide a global overview on groundwater fauna (stygofauna) research. Hence, we conduct an extensive review of accessible groundwater fauna data by analysing data from national and international publications in journals, national reports, doctoral theses, historical writings, books, consisting online databases and others in various languages. In the following, we provide an overview of (i) the historical evolution of stygofauna research, (ii) stygofauna sampling methodologies and (iii) an analysis of the global spatial and temporal distribution of groundwater fauna research and knowledge gaps, with regional summaries. It is envisaged that by encapsulating such data, we can start to build a common knowledge basis for increased understanding, assessment and conservation of groundwater biodiversity on a larger scale. Moreover, we can identify where data is lacking, which has important implications for the implementation of environmental policies for sustainable groundwater management (Danielopol et al., 2003; Tomlinson et al., 2007).

2.2 Historical evolution of groundwater fauna research

According to Griebler et al. (2014a), groundwater ecology is a relatively young discipline with research and knowledge lagging behind that of surface ecosystems such as streams and lakes. Historically, data were collected both opportunistically and sporadically; however, more recent awareness of the importance of groundwater ecosystem processes and services (Mermillod-Blondin et al., 2023) has seen the increase in well-designed ecological research and monitoring programs. Much of this research has broadened the knowledge on the biological distribution of stygofauna (Marmonier et al., 2023) as well as efforts to conserve this biota (see Boulton et al., 2023). This review analyses over 800 publications published prior to 2022 (Table A1.4), providing an overview of the evolution of this research as well as temporal and spatial analysis of research sites, with a summary provided in Figure 2.1.

2.2.1 Early research phase

The earliest written observation in groundwater ecology dates back to 1537 with a sporadic observation in a cave (Figure 2.1) (Mylroie, 2004). The 17th century saw increased research on

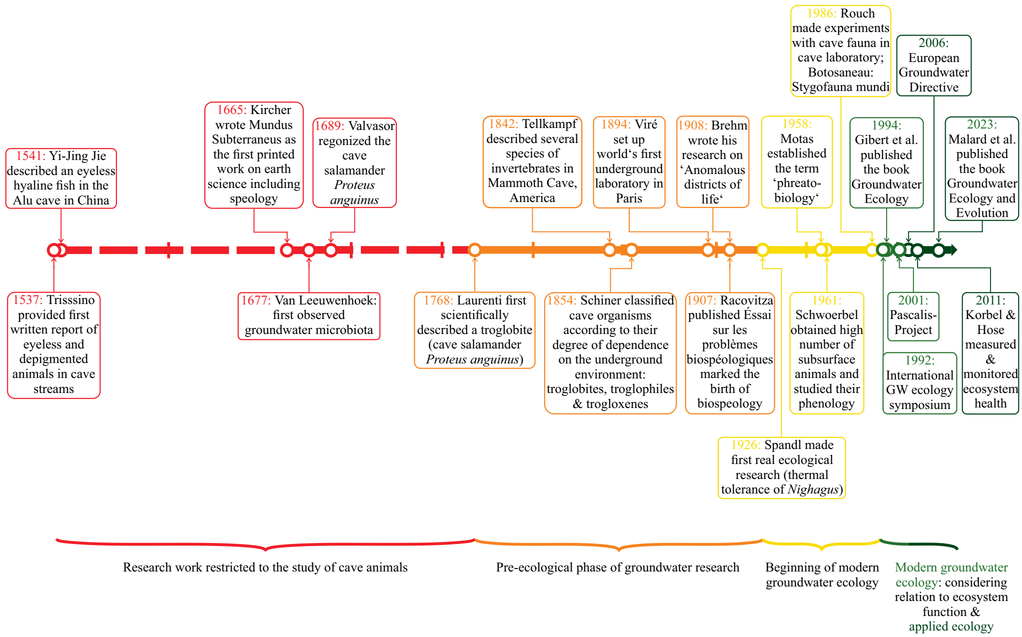


Figure 2.1: Chronology and milestones of groundwater fauna research and chronological overview over the change of research topics. The colouring points out the four phases of groundwater research.

groundwater fauna and microbiology, with the first stygobiontic species identified in scientific writing, namely a cave salamander in Slovenia (Culver and Pipan, 2013; Freiherr von Valvasor, 1689). Early research focused on groundwater fauna, while groundwater microbiology research became established in the second half of the 19th century (Griebler et al., 2014a). Likewise, early research concentrated on cave ecosystems (Figure 2.1, red phase), due to the accessibility of this habitat. During the second half of the 19th century, other subsurface habitats (e.g. aquifers) became more accessible, leading to the discovery of organisms previously unknown to science (Danielopol and Griebler, 2008) and the emergence of groundwater ecology as a research field.

2.2.2 Pre-ecological research phase

In the 18th and 19th centuries, during the so-called 'Pre-ecological phase' of groundwater research (Danielopol and Griebler, 2008), the emphasis of research was on cataloguing new species, their habitats and their biogeographical origin (Danielopol and Griebler, 2008) (Figure 2.2, orange phase). The term 'biospeology' was proposed by Racovitza (1907) and characterised the research activities at this time (Hancock et al., 2005).

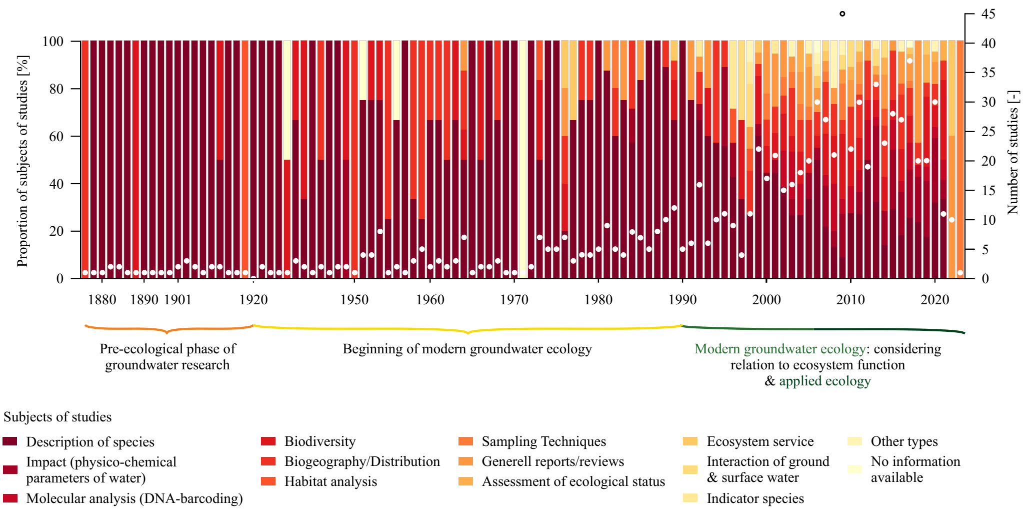


Figure 2.2: Proportion of the different subjects of all considered studies over time (first y-axis) and number of studies over time as white dots (second y-axis).

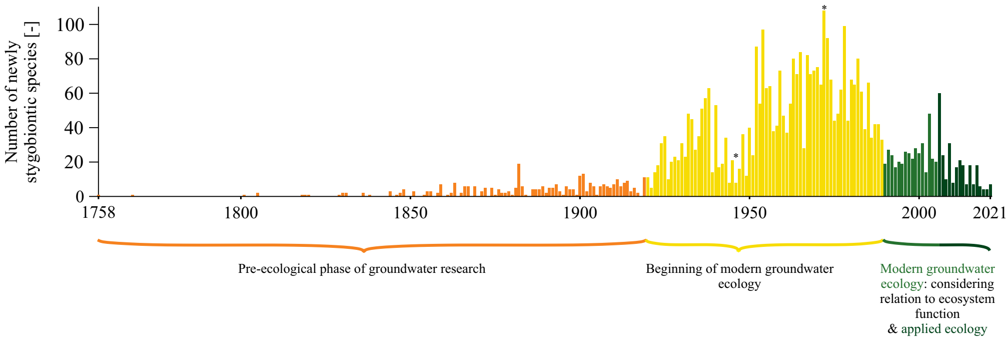


Figure 2.3: Number of newly discovered stygobiontic species mentioned in all considered studies. The colouring points out the four phases of groundwater research (Figure 2.1) and the * marked important years. A list with all 859 used studies is provided in Table A1.4.

2.2.3 Modern ecology research phase

The beginning of the 'modern groundwater ecology phase' (Figure 2.3, yellow phase) began in the 1920s, with a significant increase in the number of studies, sampling events (Figure A1.2) and, consequently, a sharp increase in the reporting of newly discovered stygobiontic species. In this context, the year 1971 is striking. No information on published studies was found for this year; however, many new stygobiontic species were found in this and the following years. One reason for this could be a time delay between the conduction of studies and the actual publication of results. The number of reported new stygobiontic species saw a dip around the early to mid-1940s (coinciding with global unrest), then peaked in 1972 and has shown a general declining trend since this time (Figure 2.3). During this period, the awareness of groundwater fauna increased and paved the way for modern groundwater research with the development of new integrated concepts, sampling methods and knowledge of ecology.

The 'modern groundwater ecology phase' of research saw the emergence of studies on the ecology of unconsolidated sediments (Hancock et al., 2005), sampling of wells and tap water (Brehm, 1930) as well as the ecology of alluvial aquifers and karst systems. Arguably, this began with Spandl (1926) (Hancock et al., 2005), who conducted the first true ecological research of groundwater fauna in his study of the thermal tolerance of the genus *Niphargus* in 1926 (see Figure 2.1). The term 'phreatobiology' was introduced by Motas (1958) to describe the research on the biology of groundwater organisms living in porous, unconsolidated sediments (Danielopol and Marmonier, 1992; Hancock et al., 2005; Motas, 1958). Other important innovations in this period included the description of groundwater and hyporheic fauna in relation to subsurface water chemistry (Danielopol and Marmonier, 1992) and the beginning of groundwater phenology studies (Danielopol and Griebler, 2008) in the 1960s (Schwoerbel, 1961). Moreover, the first experimental studies under conditions in the cave laboratory ‘Laboratoire Souterrain du C.N.R.S’ in Moulis were conducted (Rouch, 1986). Besides the influx of new species discovered in this era, for the first time, studies began to concentrate on the ecosystem functions, e.g. studies on whole subsurface karstic drainage system (Danielopol and Marmonier, 1992).

The early 1990s saw the development of a novel view on biodiversity of subterranean aquatic organisms in relation to ecosystem functioning and services (Danielopol and Griebler, 2008) (Figure 2.3, green phase). The subject of studies shifted from the description of newly discovered species (i.e. descriptive typological approach) towards an ecosystemic and holistic view with research incorporating the whole of ecosystem functioning (Danielopol and Marmonier, 1992)(Figure 3.2). The growing interest on groundwater fauna research is reflected in the exponential increase in the number of studies over time since the 1920s, which peaked in 2009 (Figure 2.2). The importance of ecosystem function and functional traits of groundwater fauna continues to be recognised (Griebler and Avramov, 2015; Hose et al., 2022; Saccò et al., 2021).

Alongside the increased interest in groundwater fauna and ecology developing in the late 1990s, technological advances allowed the usage of Deoxyribonucleic Acid (DNA) methods for the identification of biota. Initially, the use of DNA centred on groundwater microbial studies (Barton et al., 2004; Hebert et al., 2003), with a focus on contamination and remediation (Alfreider et al., 2002; Geets et al., 2001; Ross et al., 2001). The emergence of molecular methods for stygofauna first saw DNA used to study stygofauna phylogeny, which added to our understanding of groundwater species and their evolutionary pathways (Cooper et al., 2002; Lefébure et al., 2006; Leys et al., 2003). Molecular methods were then pioneered for groundwater fauna studies in groundwater karst systems, utilising environmental DNA (environmental Deoxyribonucleic Acid (eDNA)) for the targeted detection of threatened subterranean species which was followed by the use of eDNA for studies in stygofauna biodiversity, ecosystems and routine ecosystem monitoring (Korbel and Hose, 2017). The continued shift in focus towards ecosystem functioning and whole-of-ecosystem analysis (occurring in the late 1990s and early 2000s) followed the path taken in surface ecology research and is likely aided by the emergence of molecular analysis and eDNA allowing the identification of unprecedented numbers of potentially new species.

2.2.4 Applied ecology research phase

During the late 1990s, the responses of fauna to external influences, such as chemical and thermal alterations, anthropogenic and natural and changes in habitat structure on groundwater ecosystems received more attention. By the late 20th century, scientists began to investigate the use of stygofauna as bioindicators, describing the sensitivities of these species to both natural and anthropogenic factors with research on human impacts on groundwater fauna rising in prominence

(Mösslacher and Notenboom, 1999). As scientists continued to discover the functions and roles of stygofauna, and the important biodiversity that groundwater hosts, a new research topic began to emerge and a new sub-phase of groundwater research began—the 'applied ecology phase' (Figure 2.3, dark green).

With increased social and political recognition of the importance of groundwater, the topics of conservation and groundwater management began to emerge as a focus of ecological research (Boulton et al., 2003a; Danielopol et al., 2003). However, due to limited knowledge of stygofauna biodiversity and spatial range, these early studies were largely unrecognised by governments worldwide. Accordingly, the development of new assessment schemes for the monitoring of ecological status or health of groundwater ecosystem received more attention in the 21st century. By 2010, the increased interest in bioindicator species and studies investigating natural and anthropogenic influences on groundwater fauna distributions (Danielopol et al., 2000; Goldscheider et al., 2006; Griebler, 2001; Griebler et al., 2002; Humphreys, 2006; Malard et al., 1994; Marmonier et al., 2000; Mösslacher et al., 2001; Mösslacher and Notenboom, 1999; Notenboom et al., 1995; Sinclair et al., 1993) had paved the way for the first studies attempting to monitor groundwater health and diversity using bioindicator. Groundwater scientists began to apply the notion of 'health' (which had recently been applied globally in environmental policies) to groundwater ecosystems; with connotations to human health, it is deemed an easy way for non-scientists and water managers to understand environmental conditions.

A milestone and driver for groundwater ecosystem management and research in Europe was the European Groundwater Directive 2006, which attempted to incorporate ecological knowledge into schemes for environmental planning and policies (Griebler et al., 2023; Steube et al., 2009). This directive saw the emergence of studies to assess groundwater ecosystems: Hahn (2006) utilising abiotic indicators and detritus, predictive methods (Stoch et al., 2009) to assess groundwater diversity, and Steube et al. (2009) suggesting the combination of both abiotic and biotic factors. Griebler et al. (2010) provided alternate methods for groundwater ecosystem assessments, suggesting the use of natural reference conditions for aquifers of differing typology. At this same time, other countries were also developing policies to conserve and protect groundwater quality and Groundwater-Dependent Ecosystems (GDE). In Australia, groundwater initiatives began to gain momentum in the mid-2000s with the emergence of national policies to monitor groundwater ecosystems' health and stress (Griebler et al., 2023; NGC, 2004); however, the lack of scientific methods to implement such policies was recognised (Boulton et al., 2003b; Hatton and Evans, 1998). The first attempt to assess, measure and monitor ecosystem health, using a two-tiered framework consisting of a multi-metric suite of biotic and abiotic indicators, was in Australia in 2011 (Korbel and Hose, 2011). The development of this 'Groundwater Health Index' (GHI) framework was triggered by Australian water management policies and the heavy reliance on groundwater from irrigation-based industries. Methods to measure groundwater health and monitor groundwater ecosystems continue to be refined and developed (Di Lorenzo et al., 2020a; Fillinger et al., 2019; Griebler et al., 2014b; Koch et al., 2021; Korbel and Hose, 2017), with these management tools being used by governments to monitor groundwater health (e.g. report Korbel et al., 2022a). Integral to these management tools is flexibility with emerging technologies, such as eDNA (Korbel et al., 2022c; Saccò et al., 2022c) able to be integrated into frameworks which allow for the integration of most recent science to inform management decisions.

Other important research areas emerging in the 'applied ecology' phase include attempts to better understand the links between groundwaters and adjoining ecosystems (Boulton et al., 1998; Danielopol and Marmonier, 1992; Hahn, 2006; Hancock et al., 2005; Korbel et al., 2022b,c). Such studies holistically investigated interconnectivity between ecosystem and the dynamic of exchange between the surface, hyporheic and subsurface zones. Again, these studies have been mainly prompted by management decisions and directives, for example understanding the mechanisms behind the loss of river baseflow due to over-extraction of groundwater is required for water allocations and management. As a last milestone, Malard et al. (2023) published the second edition of the book 'Groundwater Ecology and Evolution'. This updated edition synthesises the current state of knowledge on groundwater ecology and evolution and highlights the opportunities and challenges for conserving and managing groundwater ecosystems.

Furthermore, groundwater research has begun to include multidisciplinary approaches combining experts from various fields to refine subterranean ecological patterns (Saccò et al., 2021). It is becoming more common for studies to combine skills of hydrogeology, geomorphology, hydrochemistry, molecular science, ecology and biology to answer complex questions (Burrows et al., 2017; Korbel et al., 2022c). Some other approaches have combined techniques, using isotopes, radiocarbon analysis (^{14}C) and DNA methods for the analyses of environmental samples (Hartland et al., 2011; Saccò et al., 2019). Such multidisciplinary techniques allow for more sophisticated ecological studies including the identification of energy flows and food web structure and biological and water exchanges between connected ecosystems (Hartland et al., 2011).

2.3 Sampling groundwater fauna

Traditionally, environmental sampling involves accessing numerous sites within a limited time frame, ideally with a representative spatial distribution of samples for the area under investigation (Hahn and Matzke, 2005). In the case of groundwater fauna sampling, this represents a great challenge because the living space, i.e. the aquifer, is hard to access (Korbel et al., 2017; Steube et al., 2009). Access points to springs, caves and sediments from the hyporheic zone of rivers are rare and selective (Maurice, 2009), and groundwater wells accessing aquifers are expensive to establish. Moreover, different technical requirements for sampling are required for differing aquifer types (Hahn, 2002; Thulin and Hahn, 2008). Besides access, the patchy distribution and high endemism of groundwater fauna require a larger number of sampling points to obtain representative results (Gibert and Deharveng, 2002; Hahn and Matzke, 2005; Mösslacher, 1998; Thulin and Hahn, 2008). Additionally, the small and sensitive anatomy of stygobiontic species complicates the intact extraction of samples for morphological identification and representative aquifer sampling (Hahn, 2002). Over time several novel methods, described in detail in the Supporting Information (Chapter 5.2), were developed to account for these challenges (Figure 2.4).

2.3.1 Temporal development of sampling methods

As expected, the number of different sampling methods has increased with the number of studies and with the emergence of more advanced methods from the 1960s onwards (Figure 2.5). Hancock et al. (2005) and Danielopol and Griebler (2008) provide a short summary of the historical and technical background of sampling and analysis methods for groundwater ecology including microbiology and fauna. Our study highlights the different types of stygofauna methods used in each period of time, as a proportion of the studies completed (Figure 2.5).

Before and during the ‘pre-ecological phase’ of groundwater research simple nets, substrate samples and hand-pumps were used to sample fauna of wells, caves and springs. More complex methods were developed from 1934 onwards, in particular the rapid and qualitative Karaman–Chappuis method (Karaman, 1933) (Figure 2.4) and the Bou–Rouch method (Bou and Rouch, 1967), which allows pumping of animals living in sandy and gravel sediments and consequently led to discovering more diverse meio- and macro-organismal assemblages (Danielopol and Griebler, 2008). Nevertheless, this method is not strictly representative of in situ conditions as faunal diversity and density are not expressed per volume of sediment and larger species such as amphipods and isopods can be damaged (Malard et al., 2002; Pospisil, 1992).

Sampling methods were further developed between the mid- 1960s and 1990 in the beginning of ‘modern groundwater ecology phase’, with specific traps and pumps offering increased quantitative data (Danielopol and Griebler, 2008). However, issues still exist with such sampling methods, for example the commonly used balance and inverted bottle traps (Boutin and Boulanouar, 1983; Ginet and Decou, 1977) are species-selective, such that representative sampling requires a combination with other methods such as nets. Table 2.1 summarised the most important dis- and advantages and fields of applications of the sampling methods for groundwater fauna.

Recent sampling of stygofauna (‘modern groundwater ecology’ era) is still dominated by sampling well waters (Figure 2.5), with pumping and filtering animals the most common and well-established method for stygofauna studies (Hahn, 2002; Thulin and Hahn, 2008). Additionally, pumping well water enables a simultaneous sampling of fauna, sediment and water (Hahn, 2002) and is

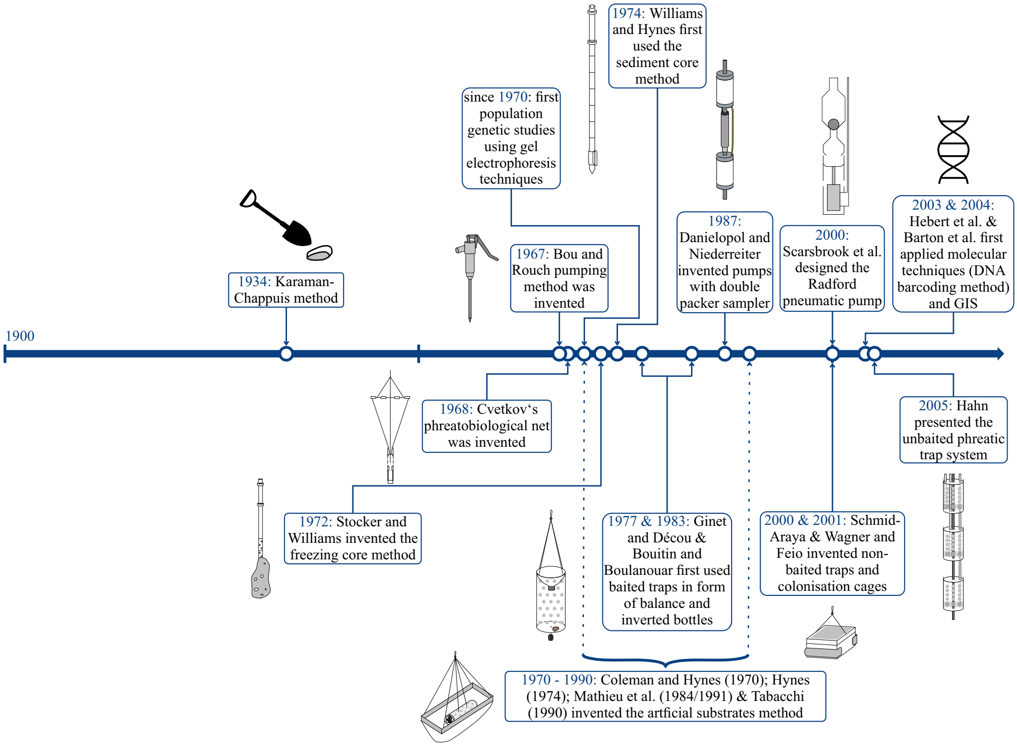


Figure 2.4: Temporal development of sampling methods with sketches of the invention (for more information, see Figure A1.1).

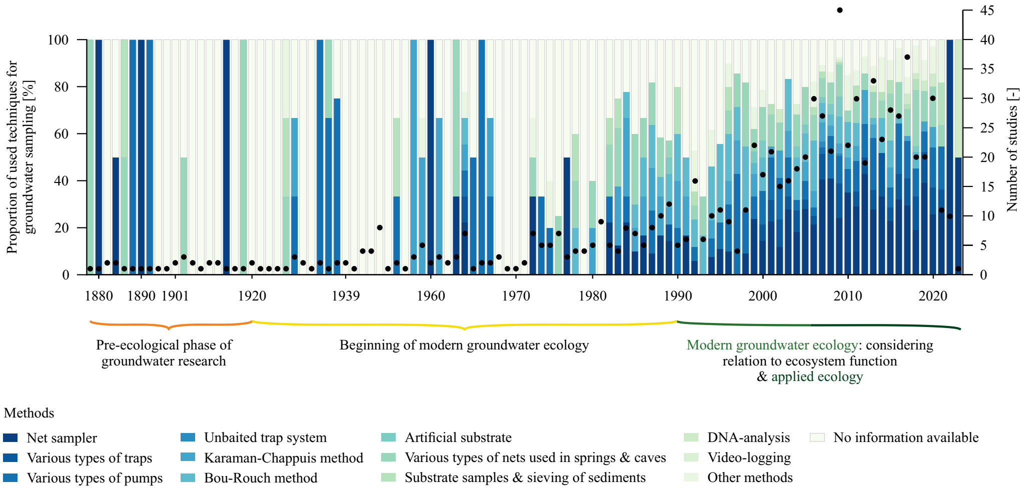


Figure 2.5: Proportion of applied methods for groundwater sampling and number of considered studies over time as black dots (secondary y-axis).

easy to standardise by extracting a defined volume of water (Hahn, 2002). However, pumping is considered as a selective sampling method, because of filtering effects and a resistance against the suction of pump. Hence, large, sessile or more active species can be underrepresented in the samples (Allford et al., 2008). The net sampler or phreatobiological net is a valuable alternative to pumping devices with respect to obtained numbers of taxa and community composition (Hahn and Matzke, 2005; Malard et al., 2002; Thulin and Hahn, 2008) and can be used for largescale faunal surveys (Allford et al., 2008) and wells up to 100-m depth (Hahn, 2002); however, like well sampling from pump, there are issues with these sampling methods collecting representative samples of stygofauna communities.

Table 2.1: Comparison of several methods for groundwater fauna sampling (++ = very good;+ = good; o = moderate; - = negative; – = very negative; NA = information not available) in order of their temporal development (Figure 2.3).

Sampling method		Feasibility	Expenditure of time: Sampling duration	Expenditure of time: Sample preparation	Expenditure of costs	Condition of fauna sample	Efficiency	Potential animal findings	Habitat
Karaman-Chappuis method		++	+	++[1]	++	++	+	Free swimming fauna of interstitial water[1]	Riverbed sediments (subterranean rivers, lakes)[1] & groundwater
Bou and Rouch technique		++[1,2]	+[12]	++	+/o[12]	+[12]	+	Diverse meio- and macro-organisms[3]; swimming organisms & species linked to sand particles[1]	Sandy sediments and gravel of rivers, lakes & shallow groundwater[1], max. depth 6 m^2
Phreatobiological net		++[13]	++[7,13]	++[13]	++[7,13]	++[13]	+[13,14]	Fauna of well water & in the bottom sediments of the well[1]	Large diameter wells[1] in alluvial sediments
Traps	Baited Traps	++	–[1]	++	++[8]	++	+[8,14]	Limited to isopods, amphipods, planarians[1]	Wells, lakes, caves (siphons, pools)[1]
	Non-baited Traps	++	-	++	++[8]	++	+[8,14]	NA	Manly used for the hyporpheos[1], upper part of groundwater body[15]
	Phreatic trap system	o	-[7]	++	+[7]	++	+	NA	Wells
Freezing core method		–[4]	+	–	–[2]	++	++[2]	Interstitial fauna[14]	Stony streambeds[11]; restricted to superficial sediments[14]
Artificial substrates		+	–[1,10]	++	++	++	+[1]	Meiofauna[1]	Caves, along subterranean rivers & streams[1]
Sediment core		++	+	++	++	+	+	NA	In uniform & mixed gravels up to 10 mm in diameter[5] (coarse substrates of stony streams[4])

Sampling method		Feasibility	Expenditure of time: Sampling duration	Expenditure of time: Sample preparation	Expenditure of costs	Condition of fauna sample	Efficiency	Potential animal findings	Habitat
Pump	Centrifugal pump	+	o[8]	++	o	_[9]	NA	Small animals (mites & copepods), larger animals as fragments[9]	Wells, aquifers, hyporheic zones; up to 50 m depth
	Double packer pump	+	o[8]	++	-[7]	NA	+	Small, less tenacious animals & larger animals[13]	
	Pneumatic pump	+	o[8]	++	-[9,14]	++[8,9]	+[14]	Small animals & larger amphipods, isopods[9] and syncarids	
Molecular techniques		o/+	++	-/o	+/o[8]	NA	o[8]	All, including cryptic species[16,17]	Water & sediment[16]
Video-logging		+	NA	NA	NA	-	NA	Very low abundance taxa	Wells in sandy & silty environments6

[1]Malard et al. (2002)
[2]Pospisil (1992)
[3]Danielopol and Griebler (2008)
[4]Boxshall et al. (2016)
[5]Williams and Hynes (1974)
[6]Datry et al. (2003)
[7]Hahn (2005)
[8]Hose and Lategan (2012)
[9]Scarsbrook et al. (2000)
[10]Sket (2018)
[11]Stocker and Williams (1972)
[12]Stubbington et al. (2016)
[13]Allford et al. (2008)
[14]Hahn (2002)
[15]Thulin and Hahn (2008)
[16]Saccò et al. (2022b)
[17]Trontelj et al. (2009)

2.3.2 Discussion of efficiency and representativity

The issue of representative sampling is complicated for stygofauna, with sampling regimes needing to consider the inclusion or exclusion of purged well water in sample design, the volume of water sampled and the extraction rate of pumped waters (see Korbel et al., 2022b). Groundwater wells typically provide an artificial environment, in which there is a large column of water that may be atypical of the surrounding aquifer (particularly in alluvial aquifers) and may be enriched in oxygen organic matter (Hahn and Matzke, 2005). Due to these factors, wells often contain a larger abundance of stygofauna than the surrounding aquifer (Hahn and Matzke, 2005; Roudnew et al., 2014; Sorensen et al., 2013) and may favour taxa that prefer the open water column provided by well casings, thus purging wells prior to sampling becomes important for any study looking at richness and abundance measures (Korbel et al., 2017). However, studies have indicated that there are compositional differences in pre-purged and purged samples (Korbel et al., 2017, 2022b). To date, only 29 studies sample fauna exclusively by pumping aquifer water through purged wells, with Australia playing a leading role (13 studies: Castaño-Sánchez et al., 2020b; Cook et al., 2012; Hartland et al., 2011; Korbel and Hose, 2011, 2015, 2017; Korbel et al., 2019; Sorensen et al., 2013; Terramin, 2018). The issues of purging wells and sample volumes need to be considered in the aims and objectives of monitoring programs, in order to ensure that stygofauna communities are accurately represented (Korbel et al., 2022b).

2.3.3 The evolution of molecular methods for groundwater sampling

A methodological milestone that altered the view on the diversity of groundwater fauna was the application of molecular tools on individual specimens and water samples (see Boulton et al., 2023; Danielopol and Griebler, 2008). Initially, molecular methods for stygofauna were primarily used to identify new species and identify evolutionary processes (e.g. Cooper et al., 2002), which was followed by the adoption of environmental DNA (eDNA) techniques to detect threatened subterranean species (Gorički et al., 2017; Niemiller et al., 2018). However, eDNA promises more than just the identification of single species and their linages; it offers a powerful tool for the rapid, non-invasive assessment of stygofauna within groundwaters, providing information on biodiversity, ecosystem functioning, phylogenetics and trophic interactions from a single sample (see Boulton et al., 2023). This can be seen in the most recent uses of eDNA metabarcoding to identify multiple species within the same environmental sample to characterise stygofauna communities, functions and biodiversity (Korbel et al., 2022b) and their trophic interactions (Saccò et al., 2021, 2022b).

Environmental DNA/Ribonucleic Acid (RNA) methods are based on the concept that organisms shed DNA/RNA in groundwater either while they are alive (e.g. exoskeleton shedding) or leaving DNA when they die. As DNA lasts much longer than RNA (which degrades very quickly), eDNA indicates animals that have either lived, been transient or died in groundwater, with eDNA indicating the animals that are functionally present at the time of sampling. Recent studies have indicated that, due to the low presence of RNA within groundwater, presumably due to low biotic abundances, eDNA is a more viable method for biodiversity studies than environmental Ribonucleic Acid (eRNA) (Korbel et al., 2022c). Both eDNA and eRNA analyses in groundwater follow a conventional workflow (see Boulton et al., 2023) whereby groundwater and/or sediment samples (e.g. from springs, caves and wells) are filtered and membranes frozen (Korbel et al., 2022c). DNA is extracted from the membrane and Polymerase Chain Reaction (PCR) is conducted, samples are then sequenced and results are interpreted using bioinformatics (see Saccò et al., 2022c).

Environmental DNA analysis has several benefits over traditional sampling techniques (see Boulton et al., 2023). This molecular method has increased our knowledge of the breadth of taxa within groundwater ecosystems, as it is able to detect very small protozoans as well as cryptic species (Sbordoni et al., 2000), clarifying genetic difference between morphologically similar specimens and allowing the study of entire phylogenetic lineages (Zakšek et al., 2007). In addition, this method does not require the removal of animals from their habitat, and as such provides a non-intrusive method for monitoring rare and endangered species (Niemiller et al., 2018). Furthermore, eDNA methods allow for the characterisation of entire communities (prokaryotic and eukaryotic) and their functional roles and can elude to potential interactions between taxa (Deiner et al., 2017). Molecular methods are still rare for groundwater stygofauna studies (Fenwick et al., 2021; Korbel et al., 2017, 2022c; Lennon, 2019; Saccò et al., 2022c; Vörös et al., 2017; West et al., 2020), although they show great potential for their ability to identify new species and metabolic functions of groundwater biota (Boulton et al., 2023; Korbel et al., 2017) with improvement in these methods for the detection of stygofauna promising (e.g. Heyde et al., 2023).

However, eDNA methods do not come without limitations. A lack of reference sequence databases (Korbel et al., 2022c) often results in large numbers of unidentified taxa in the bioinformatic processing of sequences (Lennon, 2019; Saccò et al., 2022c), which is compounded by a lack of taxonomic keys for stygofauna in many parts of the world. There are also several knowledge gaps surrounding the use of eDNA within groundwaters, many of which involve the detection of *Crustacea*, a dominant stygofauna taxa. Additional research on primers, the fate and transportation of DNA within aquifers and research on stygofauna DNA shedding capacity (Korbel et al., 2022c; Trimbos et al., 2021) is required before this method can replace traditional sampling (Korbel et al., 2022b; Saccò et al., 2022c).

In summary, net sampling and pumping well water are the dominating sampling methods worldwide. Nevertheless, each of the described methods has its limitations. Hence, a combination of methods, such as net sampling together with pumping and/or DNA-analysis, is recommended (Korbel et al., 2017; Saccò et al., 2022a).

2.4 Global groundwater fauna research

The investigation of the global distribution of groundwater fauna sampling sites, both temporally and spatially, is one of the main aims of this paper. Our analysis revealed the scale of the uneven spatial distribution of sampling events and the number of studies over the world (Table A1.4 and Figure 2.6). Most research in the northern hemisphere is concentrated in Europe, Northern America and Northern Africa. In the southern hemisphere, groundwater fauna research is focused on Australia, with New Zealand researchers increasingly contributing to the knowledge of stygofauna. A lack of temporal sampling in many parts of the world was noted, with repeated sampling over many years mainly occurring in regions of Europe, Australia and America. This lack of replicated sampling has limited the understanding of basic biology and ecology of many species until now. Below a more detailed analysis on stygofauna studies is presented, by geographic region, on the spatial and temporal distribution of studies (Figure 2.6), topic of studies (Figure 2.7a) and sample methods employed (Figure 2.7b).

2.4.1 Africa

Africa, as a whole continent, is one of the least-studied regions of the world in terms of stygobiontic organisms (Tuékam Kayo et al., 2012). We identified a total of 155 studies, 749 sampling sites and 1,505 individual samplings (i.e. individual sampling events at one site, including repeated measurements). Studies concentrated in the Maghreb (Northwest Africa), particularly in Algeria (24 studies, 223 sampling sites, 816 samplings) and Morocco (44; 266; 347), with limited studies in South Africa (9; 20; 20) and Madagascar (4; 9; 11). For the remaining continent, only a few studies and very limited sampling sites exist (Table A1.3). Some apparently un-sampled regions of Africa, especially the Sahara, can be explained by the absence, or at least the low occurrence, of shallow groundwater, as can be seen by the light colours indicating a low groundwater recharge in Figure A1.3. Also, worth mentioning is the number of studies (13) with no information about the exact location of the sampling sites (star symbol in Figure 2.6), which is due to the age of these studies (> 30 years old), which were incompletely available in secondary literature. Similar observations regarding the lack of specific locations of species findings in Africa have been made previously (Tuékam Kayo et al., 2012).

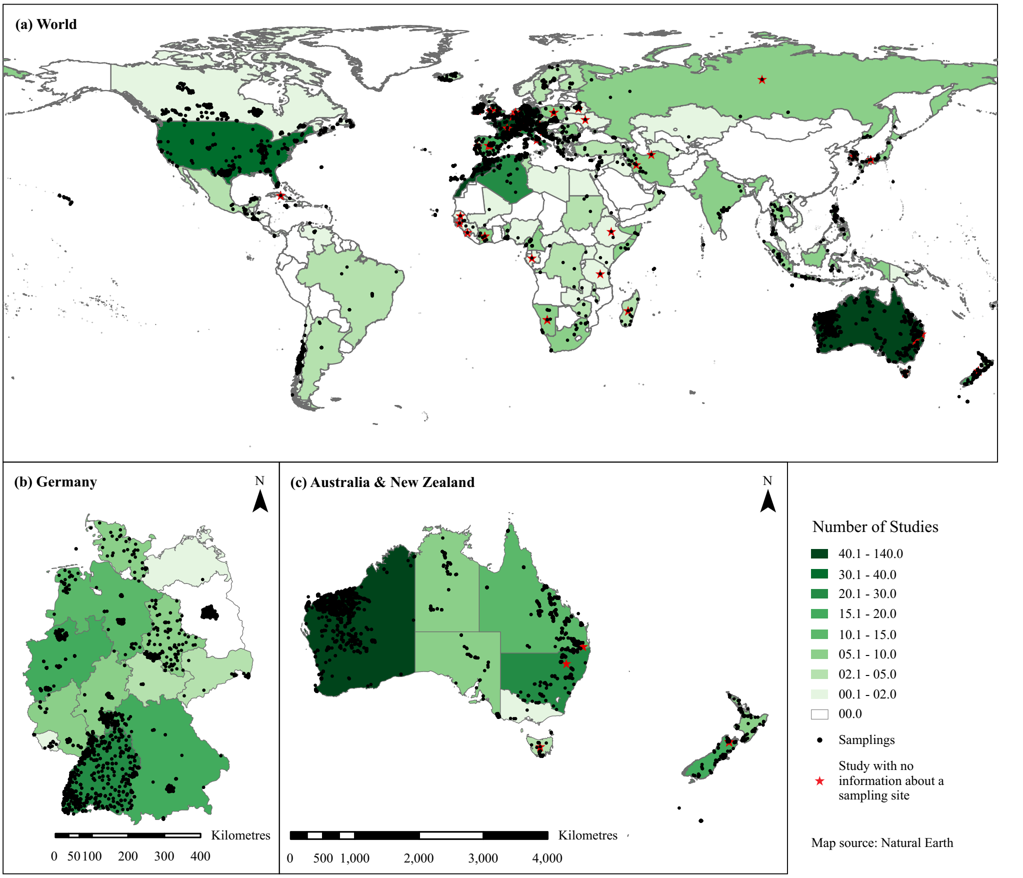


Figure 2.6: Overview of groundwater fauna samplings and number of studies (a) worldwide, (b) within Germany and (c) within Australia. Data sourced from 859 studies (Table A1.4).

More detailed evaluation of the reviewed studies revealed that 70 % of studies in Africa concentrated on the description of newly discovered groundwater fauna (Figure 2.7a). Nevertheless, more than a dozen of studies in Algeria and Morocco conducted eco-toxicological investigations, revealing that faunal richness in some urban and mining areas is linked with groundwater quality and stygofauna abundance decreases with pollution (Aidaoui, 2019; Boughrous, 2007; Boughrous et al., 2007; Boulaassafer et al., 2021; Boulal et al., 2017; Boutin et al., 1995; Boutin and Idbennacer, 1989; El Adnani et al., 2007, 2006; El Moustaine et al., 2013, 2014; Hallam et al., 2008; Hichem et al., 2019; Laid and Zouheir, 2018; Merzoug et al., 2011, 2014; Ramzi et al., 2020) with authors proposing the use of stygofauna as bioindicators of water quality (Merzoug et al., 2011, 2014). Boulaassafer et al. (2021) study on evolutionary processes considerably expanded the knowledge of diversity and geographic range of a freshwater snail genus, and information on endemism and biogeographical distribution of stygobiontic crustacean species of Africa and Madagascar has been recorded (Tuékam Kayo et al., 2012). Additional findings of a new Nematode species in deep (3.6 km) fractured aquifers of South Africa expanded the global knowledge of the understanding of life under extreme conditions such as high temperatures (41 °C), high pressures (1.3 to 6.8 kPa) or low dissolved oxygen concentrations (13 to 72 μM) and food shortages (Borgonie et al., 2011). Other research topics on the African continent such as biodiversity, biogeography and ecosystem service and ecological status are missing so far, as is any concerted effort from governments to monitor ecosystem health and biodiversity. Moreover, groundwater fauna of Africa is mainly sampled by using net samplers (in 25 % of the considered studies) or traps (14 %). In only 3 % of the considered studies pumps are used (Figure 2.7b).

2.4.2 Americas

Combined, the Americas have a total of 57 studies focusing on groundwater fauna, showing a lack of research in this field, given the size of the continents. The distribution of studies is unevenly distributed across the Americas (Figure 2.6). In the United States, the first groundwater fauna research was conducted in 1842 in the Mammoth Cave by Tellkampf (Romero, 2001). Broader investigation started in the 1960s and 1970s, for example conducted by Culver and Holsinger (Culver and Holsinger, 1992; Holsinger and Longley, 1980). As can be seen in Figure 2.6, research is patchy and focussed on the federal state Texas (7 studies, 248 samplings) and the east coast, with the federal states New York (5; 23), Florida (4; 384), West Virginia (3; 443), the District of Columbia (2; 87) and Alabama (1; 1,529), contributing 29 groundwater fauna studies with a comparably large number of 3,368 individual samplings. In contrast to other continents, groundwater fauna is mostly sampled in caves, springs and the interstitial of rivers and is also linked to a limited use of net samplers (only 7 % of all studies; Figure 2.7b). The topic of most studies here is the description of newly discovered species including their traits (e.g. Wilhelm et al., 2006), followed by biogeographical analyses of groundwater fauna. In this context, studies on the influence of the last glaciation event on the present biogeographical distribution of stygobionts have to be emphasised. It is assumed that stygobionts are infrequent north of the glacial border and that more specialised species are unable to migrate into previously glaciated regions. Only less specialised species have invaded groundwater from surface after glacial retreat (Lewis and Reid, 2007; Strayer et al., 1995). Discussions on ecosystem service and biomonitoring on this continent are lacking.

As in North America, the main research focus in Central and South America are the description of newly discovered species (67 % of studies) and biogeographical analyses of groundwater fauna (10 %). In Central America, 14 studies were carried out at 128 sites, with the most studies conducted in Mexico (3 studies, 48 sampling sites). A similar number of studies (10) and samplings

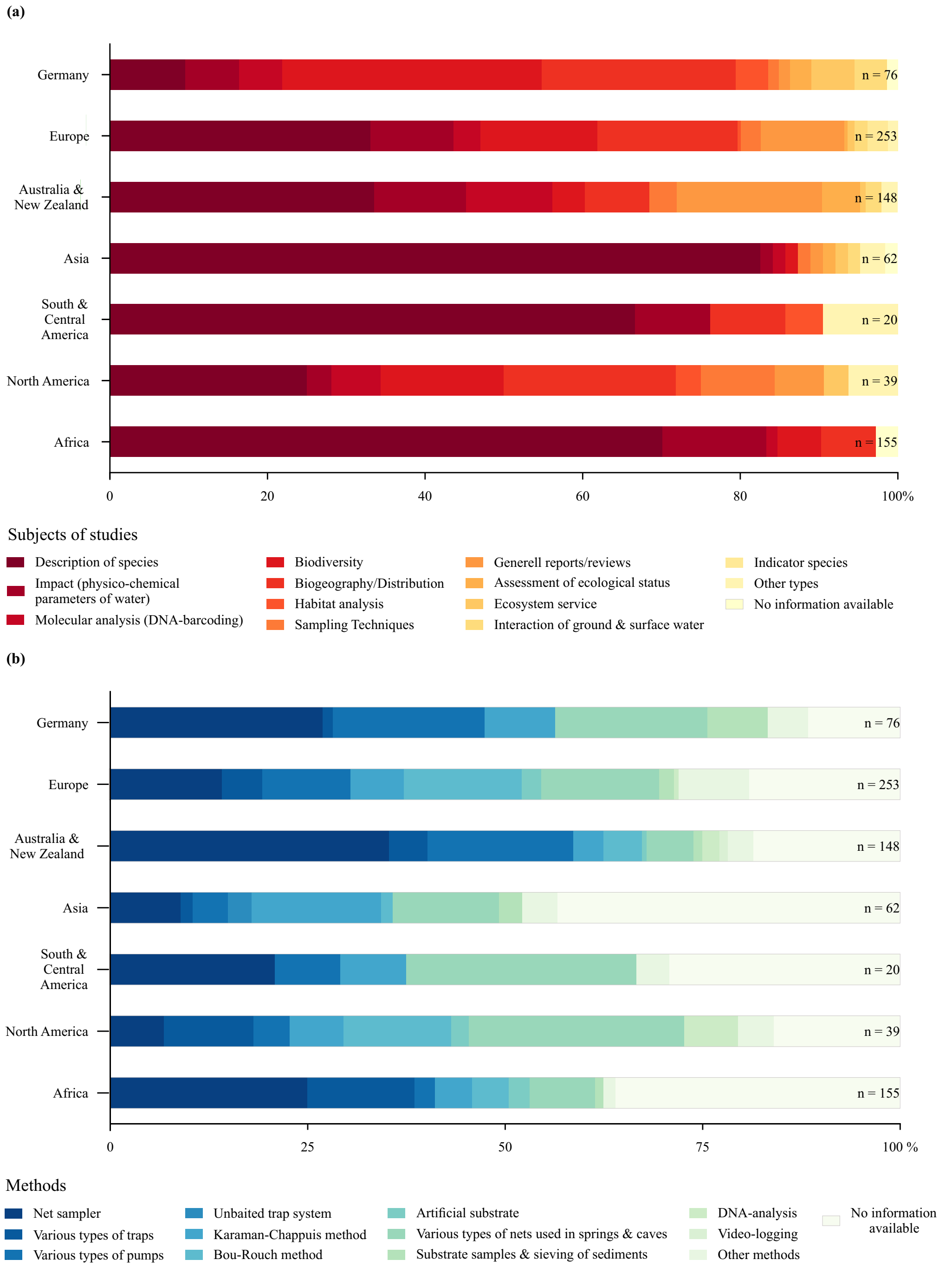


Figure 2.7: (a) Proportion of the different subjects of studies and (b) proportion of main techniques for sampling groundwater fauna for each continent and Germany (n = number of studies).

(235) were identified in South America, with a distinct lack of spatial distribution of studies across the continent (Figure 2.6). Groundwater research was conducted in both Argentina and Brazil, with studies concentrating on the impacts of land use and hydrogeological characteristics on groundwater invertebrate (Davalo Centurião et al., 2020; Tione et al., 2016).

In summary, North America groundwater fauna studies predominantly provide insight into newly discovered species and biogeographical analyses including factors influencing biogeographical distribution of stygobionts (e.g. glaciation), whereas Central and South America studies typically also concentrated on the discovery of new species and anthropogenic influences on these taxa. There were limited studies in porous aquifers, with groundwater fauna being also mostly sampled in caves, springs and the interstitial of rivers. Studies on the influence of aquifer types, climates, aquifer types and human disturbances on stygofauna are in their infancy, with very limited discussions on ecosystem service up to now.

2.4.3 Asia and the Middle East

Although it boasts one of the oldest records of cave fauna (a cave fish identified in China in 1537), studies on groundwater fauna in Asia are limited and unevenly distributed. Overall, 63 studies and 1,286 samplings were recorded in Asia on 745 sampling sites (excluding Russia, Turkey and Cyprus, which are counted as European). The main focus of groundwater fauna studies was the description of newly discovered species (83 %), with 119 new species and seven new genera described in the available studies. Similar to North America, groundwater fauna is mostly sampled in caves, springs and the interstitial of rivers, with the Karaman–Chappuis method and the usage of various types of nets being the dominating sampling methods.

In Eastern Asia, Japan and South Korea dominated the sampling effort (9; 237), with seven and nine groundwater fauna studies, respectively. In 1916, the first groundwater animal of Japan was described, while the first comprehensive and large-scaled study on faunal distribution was published in 1976 (Matsumoto, 1976), with the presence (or absence) of groundwater fauna revealing their potential as bioindicators (Matsumoto, 1976). Recent studies in Japan and South Korea have focused on the understanding of the subclass *Copepoda*, especially on the origin, relationship and distribution patterns of different species by analysing morphological micro-characters and phylogenetic relationships using modern techniques like scanning electron microscopy and molecular techniques (Karanovic, 2020; Karanovic et al., 2013, 2015; Karanovic and Lee, 2012; Karanovic et al., 2012). Berkhoff et al. (2003) was the first groundwater fauna research in South Korea in 2003 and related the distribution of fauna to land use (Berkhoff et al., 2003).

In the eastern part of India, seven studies with 43 samplings have been identified. The description of newly discovered species is the subject of all studies, while two recent studies have applied phylogenetic analyses to examine evolutionary relationships (Bandari et al., 2017; Karanovic and Ready, 2004). The research project 'Biodiversity of subterranean groundwater fauna of India, with special reference to *Copepoda* and *Bathynellacea*' from 2008 to 2013 increased the number of stygobiontic cyclopoid species of India from three to 11 (Totakura and Reddy, 2015). In all, one genus and 17 species have been described.

Within South-east Asia, there have been a total of 25 studies in the following three countries: Indonesia (9 studies; 51 samplings), Philippines (10; 139) and Thailand (6; 637). Descriptions and temporal analyses of species are the subject matter of all these studies, with research on caves dominating (e.g. Culver et al., 2006; Watiroyram et al., 2017). However, Husana and Yamamuro, 2013 have attempted to identify several factors impacting stygofauna distributions. According to Brancelj et al. (2013), 122 stygofauna species have been described within South-East Asia, with 24 species described after this review. Additionally, an extensive study on ecosystem health and monitoring in the Philippines is currently underway (Magbanua, 2022).

A larger number of groundwater fauna studies (27 studies with 129 samplings) can be found in the Middle and Near East. However, 37 % of the studies and 33 % of the samplings were conducted in Iran. Research on groundwater fauna, focused on the amphipod genus *Niphargus*, has been conducted in Iran (Esmaeili-Rineh et al., 2015). Morphological characters and phylogenetic analyses resulted in the identification of 17 new stygofauna species in 2018, along with studies comparing Iranian amphipods with European nipargids (Bargrizaneh et al., 2021; Esmaeili-Rineh et al., 2016, 2017a, 2018, 2015, 2017b; Hekmatara et al., 2013; Mamaghani-Shishvan and Esmaeili-Rineh, 2019). Other studies in Iran used molecular techniques to investigate the distributional ranges of amphipods, revealing that 'there is no evidence to consider that groundwater species are geographically more restricted than surface species' (Esmaeili-Rineh et al., 2020), thus adding to the global understanding stygofauna distribution.

Our findings reveal that in Asia and the Middle East, most studies are still focused on the description of newly discovered species, with limited studies investigating the origin, functioning and distribution of stygofauna or groundwater ecology. Spatially, studies are concentrated in Japan, South Korea, India and Iran. In relation to the large area of this continent, Asia is poorly investigated and more information is required to effectively describe the biodiversity of stygofauna in this region.

2.4.4 Australia and New Zealand

With 133 studies, 4,014 sampling sites and 5,826 samplings in total, extensive research on stygofauna and groundwater ecology is still conducted in different regions across Australia. Studies by Charles Chilton between 1882 and 1925 placed Australia at the forefront of groundwater fauna research in the late 19th and early 20th centuries. Much of the early focus of research on groundwater fauna was on discovery, species descriptions and biogeographic and evolutionary processes (Goater, 2009), with early studies on the origin and evolutions of groundwater biota occurring in western and central Australia (Bradford et al., 2010; Cooper et al., 2002; Leys et al., 2003). In the mid-late 1990s, groundwater fauna research saw a resurgence, as ecological analyses became a requirement for some environmental impact assessment (e.g. in Western Australia in 1998), with specific species gaining legislative protection (e.g. the crustacean *Lasionectes exleyi*). Government policies developed throughout the late 1990s to the early 2000s, aimed at protecting groundwater and their related ecosystems (Goater, 2009; Humphreys, 2006; Playford, 2001).

The close links between groundwater fauna research, water management policies and extractive industries (Hose et al., 2015) have seen sampling efforts unevenly distributed throughout the continent. Studies are focused in areas of intensive mining activities (Hose et al., 2015) and in the Murray Darling Basin, an area heavily reliant on groundwater for agriculture and potable water (Figure 2.6). As a result, the majority of groundwater fauna studies have been conducted in Western Australia (WA), New South Wales (NSW) and Queensland (QLD) (78, 23 and 15 studies, respectively), with notable descriptions of the stygofauna inhabiting Tasmanian cave systems (Eberhard, 1992, 2001) and research in South Australia that have contributed to knowledge stygofauna distribution and ecosystem functioning (e.g. Smith et al., 2016; Zeidler, 1985). Due to legislative requirements for sampling, groundwater fauna research has mainly focused on wells, using net and pump collection methods, with recent government initiatives investigating the effectiveness of sampling methods and eDNA for stygofauna monitoring (Korbel et al., 2022b).

In WA, research has focused on the description of new species (28) and phylogenetics (12), with more recent studies looking at stygofauna diversity (5 studies). Most sampling events in WA have been conducted in the iron-ore-rich areas of the Pilbara region (2,020 of 3,742 samplings). Early studies from the Pilbara unveiled one of the richest stygofauna diversities in the world (Eberhard et al., 2004, 2005; Humphreys, 2001), with descriptions of Amphipods (Bradbury and Eberhard, 2000), Isopods, Ostracods (Karanovic and Marmonier, 2003; Karanovic, 2006), Spelaeogriphaceans (Poore and Humphreys, 1998) and Copepods (De Laurentiis et al., 1999). The biodiversity of the areas was further uncovered in 2004 with extensive surveying detecting stygofauna in 71 % of sampled wells, with an average of 3.8 taxa and 23.3 individuals per sample (Eberhard et al., 2004). The Yilgarn region of WA has also seen a concentration of stygofauna genetics and evolution research, with 979 samplings in its numerous isolated calcrete aquifers, leading to suggestions of evolution within individual calcretes following independent colonisation by their epigean ancestors (‘subterranean island hypothesis’) (Allford et al., 2008; Cooper et al., 2007). West of the Pilbara region, the first discoveries of groundwater fauna occurred in the Cape Range and Barrow Island, with research here continuing (e.g. Saccò et al., 2022d). The Cape Range Province in the Gascoyne region is globally recognised for its subterranean fauna and karst systems (Goater, 2009). Research in calcrete aquifers has added to the global understanding of stygofauna distribution patterns (Humphreys, 2001; Saccò et al., 2020). In the Perth region, with 30 samplings, studies focused on Copepods from basins and craton aquifers (De Laurentiis et al., 2001). Other surveys were the result of legislative requirement on coal and iron ore projects, e.g. surveys in the Enneaba region which resulted in the discovery of an undescribed Bathynellidid (see Hose et al., 2015). More recently, functional ecology (Bradford et al., 2013, 2010; Saccò et al., 2019) and investigations into the use of eDNA techniques for stygofauna (e.g. Heyde et al., 2023) have become the object of stygofauna studies in WA. Such studies are contributing greatly to the worldwide understanding of ecosystem functioning, processes and stygofauna distribution.

Sampling in the Eastern states of Australia (QLD, NSW, Victoria (VIC)) is again linked with mining and agricultural groundwater dependencies. NSW is represented by 23 studies, 255 sampling sites and 794 samplings. The Hunter Valley contains over 20 of the world’s largest coal mines, which resulted in numerous ecological surveys investigating stygofauna (including microbiota). Early work in the Hunter region improved the ecological knowledge of stygofauna, identifying the importance of organic matter supply for stygofauna richness (Hancock and Boulton, 2008), and leading to the discovery of the first stygobiontic beetle in eastern Australia (Watts et al., 2007). Other early work focused on biodiversity within karst ecosystems (e.g. Eberhard and Spate, 1995). However, most sampling sites in NSW (225) are located in the arid to semi-arid regions of the Murray Darling Basin, where industries extracting groundwater dominate (e.g. mining, agriculture). Here, groundwater studies have focused on the ecology of the alluvial deposits of the Namoi and Gwydir River catchments, improving knowledge of the environmental and human influences on stygofauna distribution (Eberhard et al., 2017; Menció et al., 2014), their connectivity with surface waters (e.g. Korbel et al., 2022c), then using this information to develop frameworks for the assessment of groundwater ecosystem health (Korbel et al., 2017, 2022a, 2013a; Korbel and Hose, 2011, 2015, 2017; Korbel et al., 2013b, 2019). Several of these Australian studies have been amongst the first to investigate the use of eDNA as a method for assessing biodiversity (e.g. Asmyhr and Cooper, 2012) and ecosystem functional processes in groundwaters. Others have been conducted in the alluvial aquifers of the Murray, Murrumbidgee, Lachlan and Macquarie catchments (Lennon, 2019; MacDonald, 2017; Nelson, 2020). Moreover, a review by Saccò et al. (2022a) on coastal groundwater ecosystems in Australia points out the importance of stygofaunal communities in coastal aquifers and the threats to them caused by size-reduction of the aquifer, salinization from seawater intrusion, land clearing, anthropogenic contamination and impacts of mining and industry.

In 2011, Korbel and Hose suggested a tiered multi-metric framework for assessing ecosystem health in groundwater, resulting in the Groundwater Health Index (see Section 2.2.4). This framework was first applied in the Gwydir River catchment, demonstrating differences in groundwater fauna and water quality under different land uses and allowing a numerical health ranking (Korbel and Hose, 2011, 2017). The GHI was improved in 2017 (Korbel and Hose, 2017) where its use was expanded into the Namoi and Macquarie catchment (Korbel and Hose, 2017) and is currently being utilised by the NSW government to monitor groundwater health in several of the Murray Darling subcatchments (NSW Department of Planning and Environment, 2022) and has been adapted for Europe (e.g. Di Lorenzo et al., 2020a) and the Philippines (Magbanua, 2022).

In Queensland, sampling of stygofauna is geographically patchy and sparse (15 studies, 1,077 samplings), with many areas of the north and west un-sampled (Glanville et al., 2016). The spatial distribution is clustered around locations with extractive industry and intensive groundwater use (Glanville et al., 2016), for example in the Bowen (188 samplings) and Surat Basins (373 samplings), where Australia's largest known proven coal seam gas reserves are located (Hose et al., 2015). In the Surat Basin, consultant reports (Subterranean Ecology, 2012) fauna diversity in the Horse Creek alluvium and Walloon coal measures near Wandoan were described (Hose et al., 2015). The knowledge of stygofauna biogeography and biodiversity in Queensland has been contributed to by several studies (e.g. Little et al., 2016; Schulz et al., 2013) and is described in Glanville et al. (2016). A special feature of the state is the Queensland Subterranean Aquatic Fauna Database, which contains data from 755 samples of 582 sites provided by the Queensland Government and industry. In recent times, work describing groundwater species has occurred in the Northern Territory (Oberprieler et al., 2021; Rees et al., 2020).

Also, of note in this global region is the stygofauna research conducted in New Zealand (NZ), with 23 studies covering 305 sites. The first research on subterranean fauna in New Zealand was conducted by Charles Chilton (1882) who described the first amphipods. This study focused on range extensions and intraspecific variations, from the southern hemisphere in the alluvial groundwaters of the Canterbury Plains. An extensive sampling effort in the 1970s was mounted by Kuschel in the Waimea Plains, producing a collection of insects, crustaceans and molluscs (Fenwick, 2001). These early studies were followed by assessments of stygofauna distribution patterns (Fenwick and Scarsbrook, 2004; Scarsbrook and Fenwick, 2003; Wilson and Fenwick, 1999), hyporheic fauna (Boulton et al., 1997) and potential human impacts (Sinton, 1984). Such studies were succeeded by investigations into groundwater fauna ecology (Fenwick et al., 2021), interconnected hyporheic zones (Larned et al., 2007), human impacts on stygofauna (Hartland et al., 2011) and ecosystem functioning, including microbial studies (Close et al., 2008; Weaver et al., 2016). Alongside the ecological studies, there have been significant collections of stygofauna in the BioHertitage Project, funded by the National Institute of Water and Atmospheric Research (NIWA), where reference databases from 65 wells were collected with the aim to develop invertebrate indicators of groundwater health (Greenwood and Fenwick, 2019).

Overall research within the Australasian region has aided the global knowledge of stygofauna and their functions. It has been stated that 'Australia is considered world leading in its recognition of the need to protect groundwater resource and their dependent ecosystem through water resource policy' (Goater, 2009). Australia is regarded as a pioneer in the field of stygofauna monitoring programs but has also contributed greatly to the global understanding of stygofauna evolution, distribution, sampling methods, ecosystem functions and processes as well as anthropogenic impacts on these ecosystems (e.g. Bradford et al., 2010; Hose and Stumpp, 2019; Humphreys, 2001; Korbel et al., 2022a, 2019; Leys et al., 2010; Murphy et al., 2009; Saccò et al., 2021). Due to the emergence of policies and legislation based on GDE in this region, researchers have been at the forefront in incorporating global knowledge on groundwater species, ecology and responses to disturbance to lead in the development of applied ecological research. This research is being used by governments to monitor, evaluate and report on groundwater health.

2.4.5 Europe

Groundwater fauna research in Europe dates back to the 17th century, with pioneering work in France (Hertzog, 1933; Moniez, 1889), Italy (Pesce, 1980), Austria (Spandl, 1926), Germany (Kiefer, 1957; Noll, 1939), Slovenia (Freiherr von Valvasor, 1689; Sket, 1999), Switzerland (Graeter and Chappuis, 1913; Schnitter and Chappuis, 1914) and Spain (Camacho, 1989; Notenboom and Meijers, 1985). In total, there are 358 studies in Europe, covering 12,524 sites. As in all continents, early groundwater fauna research in Europe began with descriptions of species and taxonomy as well as the development of more complex sampling methods (e.g. the Karaman–Chappuis method 1933 and the Bou and Rouch, 1967). The application of diverse sampling methods (net sampler, various types of pumps and nets and Bou-Rouch method), particularly in Germany, has led to groundwater fauna research over numerous stygofauna habitats, including interstitial and hyporheic zone of rivers, cave and springs (Figure 2.7b).

Spatial analysis of fauna sampling sites in Europe is concentrated near the latitude of 45 °N, along the Pyrenees in the west to the Dinaric Karst of Slovenia, Serbia, Montenegro and Croatia in the east. At this latitude, richness of aquatic and terrestrial species is high, resulting in the preferential examination of these fauna hotspots in many groundwater studies (Rapoport's rule (Rapoport, 1982)) (Culver et al., 2006; Pipan et al., 2020; Zagmajster et al., 2014). Additionally, as many of these 'hotspots' are located in Europe's vast cave system, some of which have special legislative protection (e.g. Vjetrenica in Bosnia Herzegovina), there has been a concentration of studies in these regions. For example, the Postojna–Planina Cave System (PPCS) in Slovenia is one of the most-studied caves globally, with more known stygobiontic species than any other cave or subterranean location in the world (Culver and Sket, 2000). In addition to research on new species, ecological and species distribution studies have been conducted in these karst environments, highlighting the potential use of copepods as natural tracers of complex water movements in epikarst (Pipan and Culver, 2007). Contrastingly, northern Europe has had a low frequency of sampling, with studies here indicating stygofauna consist mainly of a few old stygobiontic species and ubiquists (Särkkä and Mäkelä, 1998; Thulin and Hahn, 2008).

European studies on groundwater fauna have produced much of the global knowledge on the impact of natural events (e.g. glaciation, earthquakes) on stygofauna distribution and patterns of endemism (Särkkä et al., 1998; Thulin and Hahn, 2008). Due to its status as an island and its glaciation during the last ice age, the United Kingdom (UK) is also interesting for groundwater fauna research; however, there is a distinct lack of research into groundwater ecology in this region with only 10 stygobiontic species, three of them endemic to Ireland or England, having been identified. Moreover, most groundwater taxa in England have been collected in cave systems (Maurice, 2009), with the known distribution of most stygobiontic taxa restricted to an area south of the maximum limit of the Devensian glaciation (Proudlove et al., 2003). Additional knowledge of the impacts of natural events on stygofauna endemism and distribution were uncovered after the 2009 earthquake in L'Aquila, Italy, with authors who observed a decrease in subterranean copepod species abundance as a result of the earthquake-induced aquifer strain and a consequential flushing of fauna (Galassi et al., 2014).

As in Australia, European groundwater ecology research has been advanced through policies and legislative requirements in the 1990s. Particularly worthy of mention is the importance of the Swiss Water Protection Ordinance in groundwater research, which was one of the first international authorities to include monitoring of both water quality (physical–chemical water standards) and ecological criteria for groundwater systems (Danielopol and Griebler, 2008). In 2006, the European Groundwater Directive also triggered groundwater ecological research by stating the importance of protecting groundwater ecosystems, noting ‘research should be conducted in order to provide better criteria for ensuring groundwater ecosystem quality’ (European Union, 2006).

These government initiatives precipitated the PASCALIS project, which was the first project to investigate groundwater biodiversity and endemism patterns across several countries (Gibert and Culver, 2009). PASCALIS not only introduced a standardised sampling technique but also uncovered the spatial distribution of stygofauna (locating 214 species new to six European regions) and 112 species new to science (Gibert and Culver, 2009). This project was important for a global understanding of the importance of hydrological connectivity on biotic distribution within groundwaters. Additional research in Europe during this time also contributed to the global understanding of stygofauna with suggestions that altitude, hydrogeology, palaeographical factors and human activities in a region can interact in complex ways to influence species diversity and compositions (M. J. Dole-Olivier et al., 2009; Gibert and Culver, 2009).

Other research around the 1990s focused on the human impacts, ecotoxicology as well as functional roles of groundwater fauna (Avramov et al., 2013; Becher et al., 2022; Castaño-Sánchez et al., 2020a; Di Lorenzo et al., 2019; Reboleira et al., 2013) leading to the development of bioindicators, which were utilised in more recent applications of ecology into groundwater monitoring frameworks. These studies along with studies indicating stygofauna habitat tolerances and distribution patterns (e.g. M. J. Dole-Olivier et al., 2009) and human impacts on stygofauna (e.g. Di Lorenzo et al., 2015, 2020b; Di Lorenzo and Galassi, 2013) have indicated that groundwater organisms can be used as tools of landscape changes with the absence or presence of communities reflecting the impact of changes in regional groundwater quality (Marmonier et al., 1993). Adding to this research, studies investigated the agricultural impact in alluvial aquifers on groundwater communities, producing threshold values for nitrate, and produced faunal indicators of human impacts and thus groundwater health. Additional studies in Italy building on the Australian groundwater health index (Korbel and Hose, 2017) developed a European-based monitoring framework specific to nitrate (Di Lorenzo et al., 2020a). Castaño-Sánchez et al. (2020b) reviewed existing ecotoxicological studies and presented a database containing experimentally derived species' tolerance data for 28 contaminants and temperature for 46 terrestrial and groundwater species.

Due to the breadth of stygofauna studies in Europe, this region has been at the forefront of developing bioindicators of groundwater condition (e.g. Malard et al., 1996; Marmonier et al., 2018; Mösslacher and Notenboom, 1999). Early attempts to use stygofauna as indicators for monitoring formed in Europe (e.g. Hahn, 2006; Steube et al., 2009; Stoch et al., 2009). Other more recent studies in Germany (see below section) have resulted in the development of ecological assessment frameworks (Fillinger et al., 2019; Griebler et al., 2014b). Marmonier et al. (2018) used two combined methodological approaches to assess the ecological status of groundwater ecosystems in two alluvial plains in France. Composition analysis showed that the species richness, abundance and assemblage composition significantly changed with agricultural land use or urbanisation around the wells, and in wells with low oxygen and high nitrate concentrations, the Ecophysiological Index (EPI) decreased.

The understanding of subterranean biodiversity and human impacts on this ecosystem is a necessary step for incorporating current biological concepts within the framework of groundwater management (Danielopol et al., 2004). Along with Australia, the majority of research on groundwater ecology and applications for management and monitoring frameworks was conducted in Europe (Fillinger et al., 2019; Griebler et al., 2014b, 2010; Hahn, 2006; Koch et al., 2021; Stoch et al., 2009).

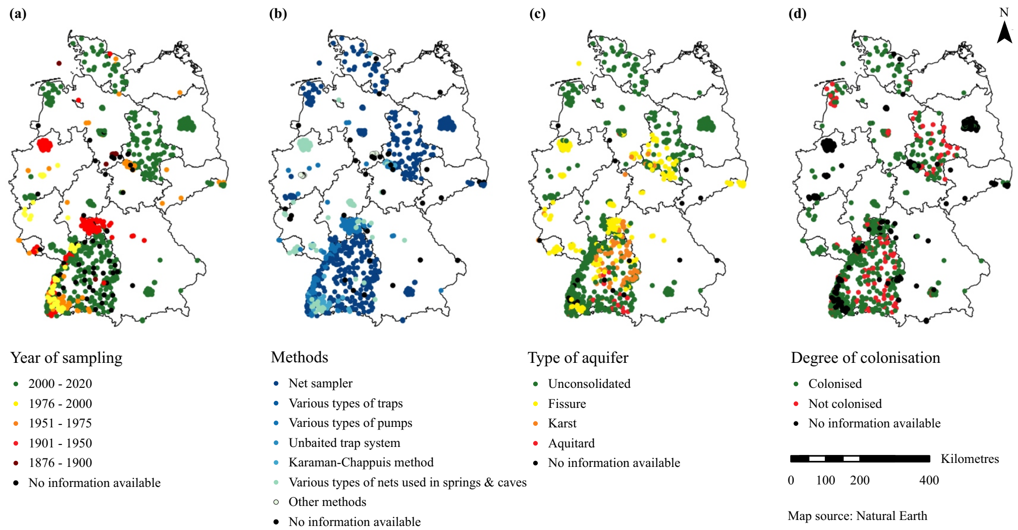


Figure 2.8: Overview over the (a) year of sampling; (b) used main techniques for groundwater sampling; (c) type of the aquifer and (d) the degree of colonisation of every sampling in Germany.

As can be seen, much of the current research on European groundwater health frameworks has been conducted in Germany and Italy (Di Lorenzo et al., 2020a; Stoch et al., 2009) with collaborations between German, Italian and Australian researchers a noted development (Castaño-Sánchez et al., 2020a,b; Danielopol et al., 2003; Di Lorenzo et al., 2019; Galassi et al., 2009; Korbel et al., 2022c; Stumpp and Hose, 2013).

2.4.6 A focus on Germany

Our study indicates that research on groundwater fauna began in Germany in 1876. Since then, there are records of 76 studies, 2,378 sampling sites and 4,232 samplings (sampling density: 1.18×10^{-2} [samplings/km^2]) (Figure 2.8a). Although comparable high sampling densities can be found in Slovenia (4.59×10^{-2} [samplings/km^2]), Luxemburg (2.48×10^{-2}), Austria (1.78×10^{-2}) and Belgium (1.46×10^{-2}), these countries are spatially smaller and have less than half the number of studies and samplings than Germany. The high density and frequency of sampling in Germany have placed Germany at the forefront of stygofauna research.

Much of the sampling effort in Germany has occurred since 2000, with sampling concentrated in the state of Baden-Württemberg (Figure 2.8a). Fauna samplings are dominated by net and pump sampling (wells) and nets (caves and springs) (Figure 2.8b). Sampling methods vary due to aquifer type, for example netting method dominates studies in fractured chalk rock springs of the Baumberge area (Beyer, 1932). Nevertheless, most German research has occurred in unconsolidated aquifers (Figure 2.8c).

In the state of Baden-Württemberg, there have been 28 studies, at 950 sample sites with 2,026 samplings, at a density of 5.6×10^{-2} samplings per square kilometre (area: 35,751 km^2), one of the highest worldwide (Table A1.3). By the early 2000s, 105 taxa, 60 of them stygobionts, had been found in Baden-Württemberg, with studies covering diverse hydrogeology, including karst, quaternary sediments, crystalline and sedimentary rocks (see Figure A1.3). As such, this region has contributed to the global understanding of stygofauna distribution, including the identification of relationships between subterranean fauna distribution and hydrogeological aquifer type (Hahn and Fuchs, 2009). The temporal resolution of data in Baden-Württemberg is also remarkable, with 44 sites sampled annually or bi-annually between 2002 and 2020. Such frequent sampling has enabled the temporal analysis of groundwater fauna assemblages, with results indicating that abiotic, microbiological and faunal parameters displayed limited changes between 2002 and 2014 (Stein et al., 2015).

Colonisation of groundwater by fauna has been a main topic of study within Europe. Stygofauna have surface water origins, with numerous theories surrounding their colonisation of groundwaters (Cooper et al., 2023), resulting in a high degree of endemism, many relict species ('living fossils') and a truncated food web consisting of few predators (Gibert and Deharveng, 2002). Another characteristic of groundwater is the scarcity of stygobiontic species so that often only half of all stygobiontic species in any given region are found at less than 5 % of sites (Castellarini et al., 2004; Hahn, 2015; Martin et al., 2009).

Distribution patterns within Europe are particularly impacted by glaciation (Stein et al., 2012; Stoch and Galassi, 2010). Our survey revealed that stygofauna were found in 63 % (2,662 samples) of samples in Germany. However, in 27 % of these samples, no information on the colonisation status was available, potentially due to the clustered results of older studies (early–mid-1900s), where results of individual measurements were not resolved on a site-specific level but interpreted as an overall result for a wider research area (Figure 2.8d).

The volume of data collected in Germany has resulted in the ability to investigate stygofauna distribution. Studies within Germany have indicated differences in distribution patterns of stygofauna spatially, with investigations of 'stygoregions' (Gibert et al., 2009) used to explain differences in distribution patterns explained by geological events (Hahn and Fuchs, 2009; Stein et al., 2012), such studies have been completed elsewhere in Europe (e.g. Stoch and Galassi, 2010). Studies have indicated that the degree of colonisation varies spatially within Germany, e.g. groundwater fauna is reported to be nearly absent in the Northern Lowlands, because of fine sediments and low oxygen concentrations (Stein et al., 2012). Yet, our analysis shows that 37 % (161 samples) of the samples in this region contained fauna. Nevertheless, the number of samples with no available information is still high (226 samples; 52 %). Additionally, there has been important research conducted on the impacts of geology and water chemistry on stygofauna, with studies investigating the impacts of oxygen concentrations (Stein et al., 2012) and physical habitat characteristics (e.g. aquifer and pore sizes; Hahn, 2006; Hahn and Fuchs, 2009; Hahn and Matzke, 2005; Stein et al., 2012) on stygofauna distribution.

Interestingly, there is a clear difference in the main subjects studied between Germany and the rest of Europe. Within Germany, stygofauna biodiversity (33 %) and biogeography (25 %) are a distinct focus of research, with only 10 % of the studies in our literature review focused on the description of species. This differs from the European context, where 33 % of studies focused on taxonomy and species descriptions and 18 % on biogeographic distribution and evolutionary processes.

Besides the focus on biodiversity and ecology issues, Germany has seen itself at the forefront of applying ecological research to address groundwater management and monitoring requirements. Early approaches for monitoring groundwater ecosystems began in Germany (see Section 2.2.4). Hahn (2006) introduced early frameworks, and Stoch et al. (2009) developed a predictive model for assessing groundwater ecosystems. Further, Steube et al. (2009), supported by the German Federal Environment Agency, suggested the use of biotic and abiotic indicators in groundwater ecosystem assessment and acknowledged difficulties in establishing reference conditions and the need to test proposed methods. Additionally, Griebler et al. (2010) proposed groundwater assessment methods utilising aquifer typology. These significant early developments paved the way for the development of the groundwater health frameworks (Korbel and Hose, 2011, 2017) and, for Griebler et al. (2014b), ecologically-based assessment scheme for groundwater ecosystems. Much of this work has been aimed to support the European Union Water Framework Directive (EC-WFD) 2000. An assessment scheme using microbial indicators has since been developed the microbial Density-Activity-Carbon index (Fillinger et al., 2019), and Germany-based assessment schemes have been applied in numerous studies (Berkhoff, 2010; Gutjahr et al., 2014; Hahn et al., 2020; Koch et al., 2021; Spengler, 2017).

2.5 Conclusion

This study has provided a global perspective on groundwater fauna research including its historical and technical development and spatial distribution.

The main findings of the current study are as follows:

- a continuing, exponential increase in the number of studies on groundwater fauna over the last 10 decades,
- changing research paradigms from the description of newly discovered species and their evolution towards ecosystemic and more holistic analyses of fauna and their functions to the application of ecological management and monitoring programs,
- a change in sampling methods from simple nets and hand pumps to more complex methods,
- the recent emergence of molecular technologies, such as eDNA, which offer the potential to ease sampling and enable vast data collection,
- large gaps in the spatial and temporal distribution of groundwater fauna remain, particularly in Africa, Asia and the Americas,
- due to spatial biases, the knowledge on groundwater biota and their potential functions may be biased towards the intensively sampled aquifers studied in Europe, Australia and New Zealand.

As such, a comprehensive and broad overview of the global geographical distribution of groundwater fauna in diverse climatic zones, aquifer types and associated trends over time is still required. In the future, a shift from local studies to a global perspective is essential in order to provide a common knowledge basis for understanding, assessment, monitoring and conservation of groundwater biodiversity. A worldwide effort to collect information on groundwater ecosystems, functional roles and human impacts on them is required to implement stronger policies and monitoring requirements for groundwater fauna so as to ensure these ecosystems are maintained and preserved into the future.

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3

TEMPORAL SHIFT OF GROUNDWATER FAUNA IN SOUTH-WEST GERMANY

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3.1 Introduction

Groundwater is an important source of freshwater, drinking water and service water for irrigation, geothermal and industrial uses (Job, 2022; Siebert et al., 2010; Stauffer et al., 2013). Furthermore, groundwater ecosystems build the largest terrestrial freshwater biome of the world (Griebler et al., 2014a), which is considered a species-rich habitat (> 100,000 species) with many endemic taxa (Culver and Holsinger, 1992).

However, human activities and natural changes threaten this habitat in many areas (Becher et al., 2022), put pressure on its ecosystem and groundwater communities, and alter general biogeochemical processes (Griebler et al., 2016). Changes in water quality and water volume are driven by natural processes (Goater, 2009), yet groundwater abstraction for irrigation, drinking water and mining activities changes groundwater volume and, therefore, groundwater levels (Danielopol et al., 2003; Hancock et al., 2005). Changes in groundwater quality can also be caused by pollutants originating from agriculture (Di Lorenzo et al., 2020b; Di Lorenzo and Galassi, 2013; Korbel et al., 2022a), urbanisation (Hallam et al., 2008), surface waters (Danielopol et al., 2003; Kristensen et al., 2018), heavy industry (Hose et al., 2014) and thermal pollution (Menberg et al., 2013a; Taylor and Stefan, 2009; Tissen et al., 2019; Zhu et al., 2010). Moreover, climate change, which increases groundwater temperatures (Figura et al., 2011; Menberg et al., 2014; Tissen et al., 2019), puts pressure on groundwater and its ecosystems. Those environmental pressures can alter groundwater fauna community structures (Korbel et al., 2022a) and, therefore, induce changes in groundwater biodiversity and species dominance (Goater, 2009). Typical implications of this are changes in the natural variation of population cycles, shifts in the composition of the community as ubiquitous surface-water species can outcompete and replace groundwater species, and, finally, species extinction (Danielopol et al., 2003). The potential decline or even loss of groundwater communities compromises the functioning of an aquifer and its ecosystem, resulting in deterioration of groundwater health (Hancock, 2002; Hancock et al., 2005).

To assess groundwater's health or ecological status, schemes for monitoring this ecosystem, i.e., biomonitoring, become increasingly important, as already implemented for surface water (Haase et al., 2023). Biomonitoring is defined as the 'use of biological systems (organisms and organism communities) to monitor environmental change over space and/or time [DIN EN 16413]' (Verein Deutscher Ingenieure e.V. (VDI), 2018). More specifically, by repeatedly or permanently monitoring organisms or organism communities, the quality of a habitat environment is recorded and assessed, and the state of an ecosystem and its dynamics in time and space are evaluated (Mösslacher and Notenboom, 1999; Underwood, 1997). For application in groundwater, two strategies are currently available (Friberg et al., 2011; Mösslacher et al., 2001; Mösslacher and Notenboom, 1999). In 'active' biomonitoring, standardised organisms with a known origin from the laboratory are inserted in groundwater, and their behaviour is monitored in this habitat (see the biological early warning system of the GroundCare project Spengler et al. (2017)). In contrast, in 'passive' biomonitoring, bioindicators (wildlife population) are sampled from their natural habitat and their behaviour is examined in the laboratory (Brielmann et al., 2011) or as in most studies, the faunal communities found are analysed to conclude the prevailing conditions (Fuchs et al., 2006; Hahn and Fuchs, 2009; Korbel and Hose, 2015; Stein et al., 2010; Verein Deutscher Ingenieure e.V. (VDI), 2018).

The advantage of biomonitoring compared to monitoring abiotic parameters is that organisms and communities act as remote sensors integrating environmental conditions and stress over their lifetime, undergo quantitative and qualitative alterations and thus can provide information on medium- to long-term environmental conditions and changes (Conti, 2008). Hence, for most existing biomonitoring programs, faunal community composition, different species and taxa, and an abundance of other taxonomic groups are considered (Conti, 2008; Friberg et al., 2011). Macroinvertebrates are often used for biomonitoring as their taxonomy is well known, they are sensitive to many stressors and can be sampled easily and repeatedly over specific time periods, which results in more accurate indications of diversity, richness and composition among all groundwater biota (Conti, 2008; Friberg et al., 2011; Lennon, 2019).

However, until now, a lack of repeated and long-term samplings of groundwater fauna has limited the understanding of the basic biology and ecology of many species, and there is a notable absence of analysis of temporal evolution and variation of groundwater fauna (Koch et al., 2022). Repeated samplings over multiple years can be found in very few locations, mainly in Central Europe and Australia (Goater, 2009; Korbel and Hose, 2017; Marmonier et al., 2000; Menció et al., 2014). Goater (2009) analysed groundwater fauna data from an 8-year monitoring program (1999 - 2007) at 21 wells in Australia, observing changes in stygofauna species presence, population numbers and community assemblages, as well as a shift from an amphipod-dominated to a copepod-dominated system. A second study in Australia conducted four sampling campaigns between 2007 and 2010 at 20 wells to investigate stream–aquifer relationship (Menció et al., 2014). Further ecological research focused on examining environmental and human influences on the distribution of biota and groundwater ecosystem health. A study in New South Wales at 15 sites with six samplings revealed only minor variation in ecological conditions between 2007 and 2015 (Korbel and Hose, 2017). Moreover, ecosystem health benchmarks are associated with aquifer typology rather than applied only to local areas. In Europe, Marmonier et al. (2000) also revealed limited temporal variations in the biodiversity of the interstitial fauna of artificial aquatic systems for three successive years (1995 - 1997). Long-term data on groundwater ecology and chemistry is available across the state of Baden-Württemberg (BW), Germany, from a continuous monitoring program of 44 sites sampled annually or bi-annually between 2002 and 2022 (Fuchs, 2007; Fuchs et al., 2006; Stein et al., 2015), which makes the state of BW one of the most densely investigated areas worldwide concerning groundwater fauna with 2,026 samplings at 950 sites (Koch et al., 2022). The present study uses this dataset to comprehensively analyse the temporal distribution of groundwater fauna and abiotic parameters, while specifically considering changes in natural or anthropogenically impacts, such as temperature, land use and nitrate concentration. Hence, the main objective of this study is to identify changes in groundwater fauna due to natural or anthropogenic stress in recent decades. Furthermore, changes in groundwater ecosystems on different spatial scales and the implications of the observed changes for biomonitoring are assessed. Finally, we identify ecological and physico-chemical parameters most suitable for robust biomonitoring.

3.2 Material and method

The following workflow was developed to address our objective (Figure 3.1). The available groundwater data of the study site (i.e. the state of Baden-Württemberg) was reviewed, and observation wells for additional sampling in 2020 were selected (Figure 3.1, step 1, site selection). Afterwards, the biotic and abiotic data was temporally and statistically analysed on different spatial scales (local to state-wide, Figure 3.1, steps 2 and 3, temporal and statistical analyses). Finally, three individual wells were analysed in detail concerning changes in land use and abiotic parameters (Figure 3.1, step 4, local scale analysis).

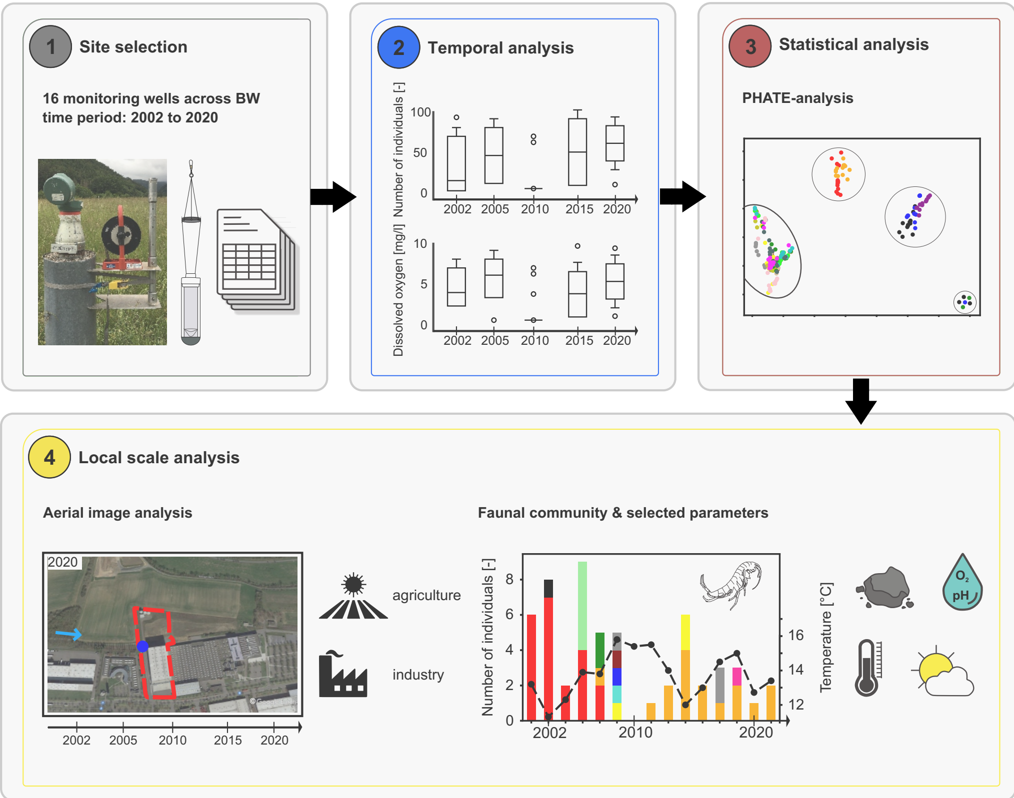

Figure 3.1: Developed workflow including four steps: (1) site selection and database, (2) temporal analysis, (3) statistical analysis and (4) local scale analysis (aerial images by Google LLC. (2022)).

3.2.1 Site selection

The State Office of Environment, Measurements and Nature Conservation (LUBW) maintains an extensive network of up to 2,600 groundwater observation wells (Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg, 2013). In addition, the locations of the groundwater level monitoring network and the database of all monitoring sites in Baden-Württemberg are also considered, which results in 50,000 initial sites. Of these, 304 wells were analysed faunalally at least twice in the past (Fuchs, 2007) (Figure 3.2). The 304 sites were selected based on a representative distribution within the different natural areas and aquifer types in the state of Baden-Württemberg, as well as accessibility and absence of installed measurement devices, pumps, etc. within the wells (Fuchs, 2007). Based on the initial measurement results in 2001/2002, out of the 304 sites, 44 were selected for annually or bi-annually sampling between 2006 and 2022 (Stein et al., 2015). Faunal colonisation, a good area- and aquifer-type coverage and availability of physico-chemical measurements were considered for this selection. Out of these 44, 16 wells were selected for the current study based on spatial coverage of the study area, aquifer type, land use type, well depth, faunal colonisation during the past two decades, availability of time series of physico-chemical parameters, and an average content of dissolved oxygen higher than 1 mg/l, which is a limiting factor for faunal colonisation (Griebler et al., 2014b).

3.2.2 Groundwater sampling

Faunal groundwater sampling in the 16 selected observation wells took place twice in 2001/2002 (for analysis in this study, only data from June - September was used), annually from 2006 to 2014, and then bi-annually in August/September until 2020. At the beginning of each sampling, the depth of the groundwater table and of the well were measured using an electrical contact gauge. Afterwards, water standing in the well (i.e. well water) was taken with a bailor (750 ml Aquasampler of the Bürkle GmbH, Lörrach) from the bottom of the well. In these samples, oxygen concentrations (Intellical LD0101, luminescence-based optical probe; accuracy: $\pm$ 0.1 mg/l), carbonate hardness, pH (PHC101; accuracy: $\pm$ 0.002) and electrical conductivity (TDS-measuring instrument Meditech/TenYua) were measured using an HQ40D portable 2-channel multimeter (Hach Lang GmbH, 2022). Additional samples were taken to determine the amount of sediment and further chemical analyses (such as the content of dissolved carbon, organic nitrogen, phosphate, etc.).

The faunal sampling was conducted using a modified Cvetkov net as described by Hahn and Fuchs (2009). More specifically, a plankton net consisting of a gauze funnel with a mesh size of 73 μm attached to a collection vessel (50 ml centrifuge tube) with a weight was used (Figure 3.1, step 1). With the help of a fishing rod or a winch for larger depths, the net sampler was lowered into the well

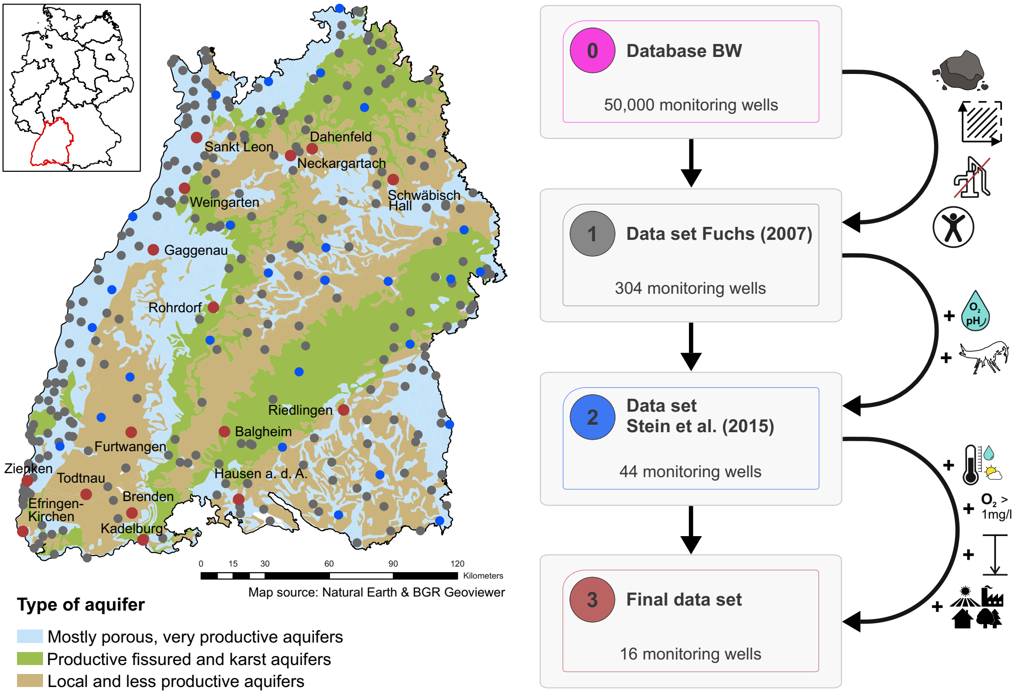

Figure 3.2: Study area, the state of Baden-Württemberg in South-West Germany, including the aquifer types according to the classification of the Federal Institute for Geosciences and Natural Resources (left corner) and selected monitoring wells according to the selection process on the right (Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), 2019).

down to the bottom. To sample as much fauna as possible, the net sampler was quickly raised about 1.5 m and lowered again ten times. The collected samples were stored in a cooling box at about 8 °C until fixation with 96 % ethanol on the same day. The dye Rose Bengal ($C_{20}H_2Cl_4I_4Na_2O_5$ by Thermo Scientific Chemicals), which colours organic matter in a pink hue, is added for easier determination of groundwater fauna. Faunal samples were sorted on order level and determined on species level. Based on this determination, further faunal parameters were calculated, such as the total abundance, number of taxa or species, classification into stygofaunal classes (stygoxenic, stygophil, stygobiontic) and ecological status according to Griebler et al. (2014b).

Hydro-chemical groundwater sampling from pumped aquifer water was performed by the LUBW, with measurement results being provided in an annual catalogue, which is publicly accessible online (Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg, 2022). Of all 144 available parameters, 42 are used in this study, in particular standard cations and anions, heavy metals and inorganic trace substances, pesticides and aromatic hydrocarbons (Table A2.1). Parameters with a lack of temporal resolution are excluded. Annual air temperature data was taken from the German Meteorological Service (DWD Climate Data Center (CDC), 2022).

3.2.3 Statistical analysis

To better understand large-scale spatial relationships and the structure of the high-dimensional groundwater data, a PHATE (Potential of Heat-diffusion for Affinity-based Trajectory Embedding)-analysis is conducted (Moon et al., 2019). This method has shown to provide meaningful results for handling financial data (Grzybowska and Karwański, 2022), prediction of disease outbreaks (Kuchroo et al., 2022), learning of brain activation manifolds (Busch et al., 2022), RNA sequencing (Moon et al., 2019) and investigation of groundwater ecosystems (Koch et al., 2021).

PHATE is a dimensionality reduction method that generates a low-dimensional embedding specific for visualisation. Thus, an accurate, denoised representation of a data set's global and local structures is provided without imposing strong assumptions on the design of the data. The PHATE algorithm computes the pairwise distances from the data matrix. It transforms the distances to affinities to encode local information by applying a kernel function developed to Euclidian distances. Using diffusion processes, global relationships are learnt and encoded using the potential distance. Finally, metric MultiDimensional Scaling (MDS) embeds the likely distance information into low dimensions for visualisation (Moon et al., 2019). Thus, objects with similar characteristics are close to each other in the final graph. In this study, the analysis is conducted using 15 physical, biotical and (hydro-)geological input parameters (Table A2.2).

3.3 Results and discussion

3.3.1 Faunistic overview

Overall, there is no regional pattern in the spatial distribution of faunal abundance and biodiversity (Figure 3.3). Potential reasons for this are a high hydrogeological and hydro-chemical heterogeneity in combination with a small number of monitoring wells, superimposing effects of local influences and site-specific parameters linked to variations in topography and geology. Considering the entire investigation period (2002 - 2020), the faunal colonisation differs across the study area, with between 52 and 1,800 individuals and up to 42 different species per well, respectively (Figure 3.3). There is a visual relationship between abundance and biodiversity, as monitoring wells with many individuals also show more species (and vice versa).

The highest abundances in the state of Baden-Württemberg (BW) were found in the porous aquifers in the northeastern part of BW and in the southern Upper Rhine Valley, while the lowest abundances were found in fractured and karst aquifers, as well as in less productive aquifers (Figure 3.2). The spatial distribution of the faunal community according to taxonomic groups is shown in

Figure 3.3b. In the southeast of the state, Crustaceans (mainly Cyclopoids) dominate. In karst aquifers of the Swabian Alb and the local and less productive fissured aquifers of the southern Black Forest, Amphipods are more frequent (e.g., Balgheim, Todtnau, Brenden). Wells in the northern Black Forest and along the Rhine in more productive aquifers are additionally colonised by Isopods, Harpacticoids, Nematods, Ostracodes and/or Annelids. Synacrids were found only in wells in the northern part of BW (except for Kadelburg), in the north of Upper Rhine Valley and the catchment of the Neckar River in this study (see also Fuchs et al., 2006). This aligns with findings of distribution patterns of groundwater fauna from previous studies (Fuchs, 2007; Fuchs et al., 2006; Hahn and Fuchs, 2009; Stein et al., 2015, 2012).

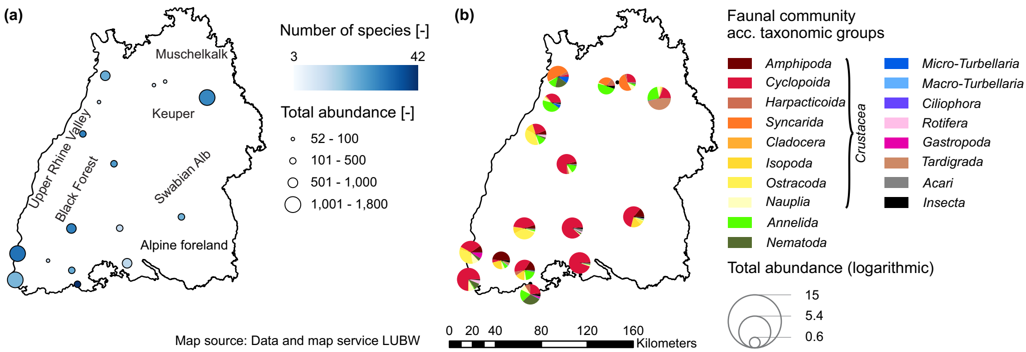

Figure 3.3: Maps of (a) the number of species and the total abundance and (b) the faunal community according to taxonomic groups as a sum of all measurements of all years (2002 – 2020) for each of the 16 monitoring wells in the study area.

3.3.2 Temporal analysis

From 2002 to 2020, the number of individuals of all 16 monitoring wells ranged between 10 and 50 on average per year, with no observable temporal change in the average total abundance or its variation (Figure 3.4a). The same applies to the number of species (Figure 3.4b), which indicates that the large-scale biodiversity was stable over the past two decades. Also, no significant changes are revealed over time for the abiotic parameters, suggesting stable hydro-chemical conditions over time (Figure A2.1). The year 2007 stands out with a high number of individuals and species (Figure 3.4), as well as a low share of stygobiontic species. This year also shows a higher content of dissolved oxygen and electric conductivity (Figure A2.1), hinting at a more pronounced surface influence and disturbed conditions, particularly in Efringen, Rohrdorf, Zienken, Schwäbisch Hall, and Gaggenau.

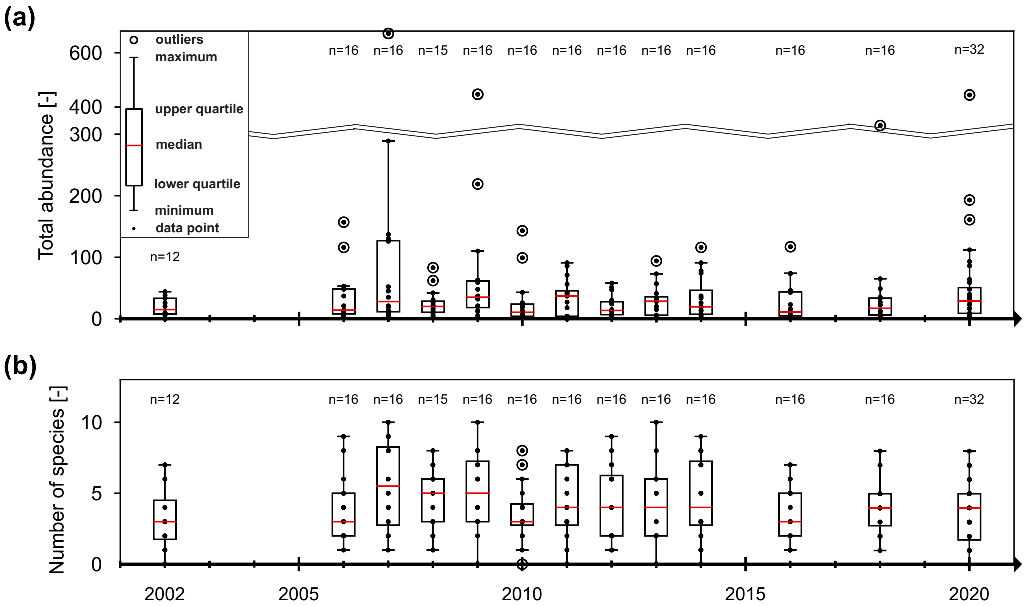

Figure 3.4: Boxplots of important biotic parameters between 2002 and 2020 of all 16 wells combined: (a) total abundance and (b) number of sampled species. "n" indicates the number of measuring points. No sampling was conducted in years with no boxplot.

While there is no apparent trend on the regional scale, there are significant variations between individual years for some individual wells, indicating more complex temporal behaviours on local scale (Figure 3.5). Regarding the faunal parameters, no single well exhibits a significant positive development concerning faunal abundance or biodiversity. Only the well in Schwäbisch Hall shows a slightly increasing trend in abundance over the last five years. This well is characterised by the presence of Tardigrads, which are typical for small surface water bodies, and wells with organic material from the surface (leaves, moss, etc.) (Schminke et al., 2007). Moreover, this well shows a gradual change in the faunal community from one single stygobiontic species to multiple stygobiontic and stygophile species, potentially linked to surface water influence (Schminke et al., 2007). On the other hand, there is a clear decrease in the abundance and faunal diversity in Todtnau und Zienken (Figure 3.5a &b), which in the case of Zienken is linked to decreasing dissolved oxygen contents with < 1 mg/l in 2014 (Figure 3.5e). This could be related to microbial oxygen degradation due to a high organic matter input (Stein et al., 2015). A strong surface influence in Zienken is linked to periods with higher abundances from 2007 to 2009 and 2013 to 2014, which coincided with higher numbers of ubiquitous species from the surface and a higher bacterial count (Stein et al., 2015).

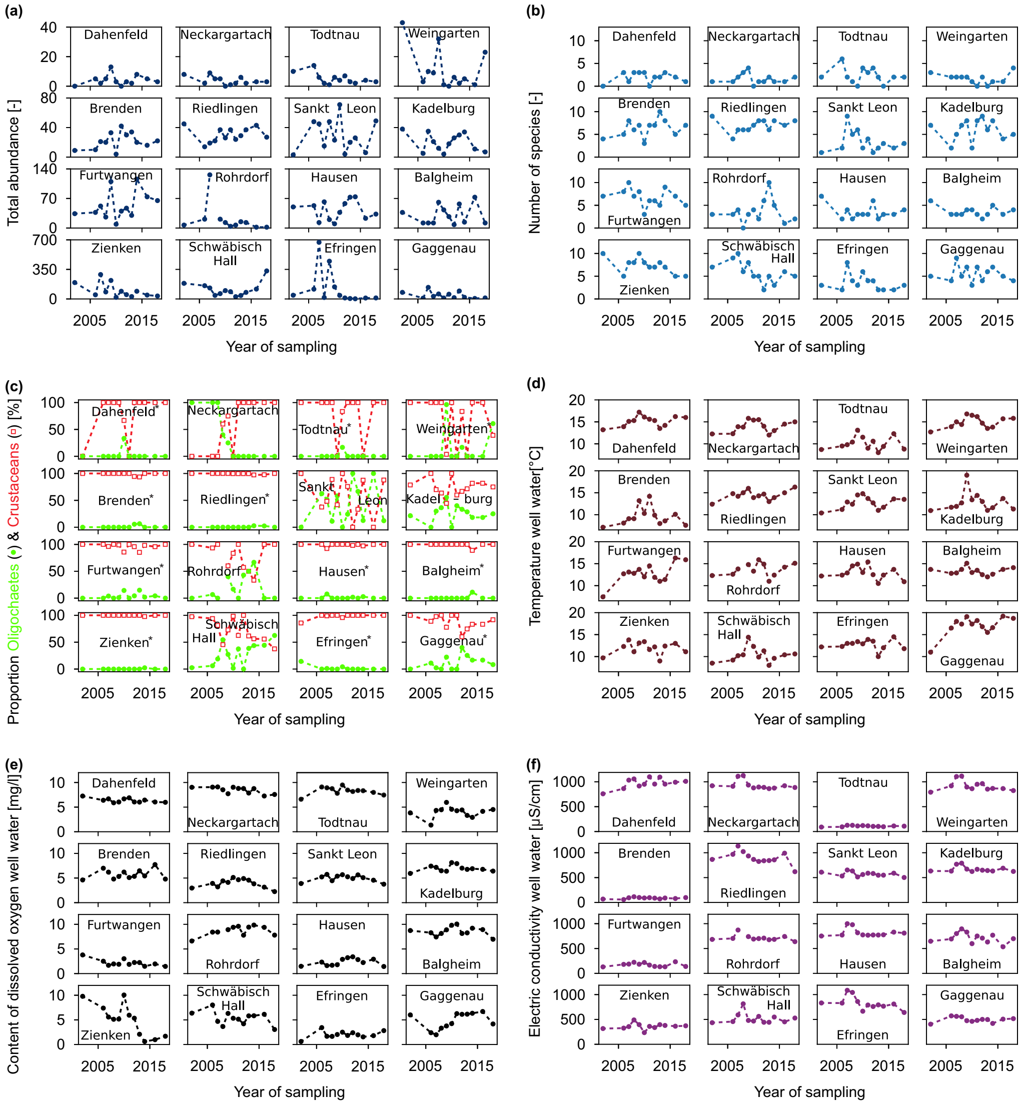

Figure 3.5: Time series of individual monitoring wells for (a) total abundance (please note the different scales of the y-axis); (b) number of species; (c) proportion of Crustaceans and Oligochaetes (* wells with a very good or good ecological status according to the assessment scheme of Griebler et al. (2014b)); (d) temperature of the well water; (e) content of dissolved oxygen of the well water and (f) electric conductivity of the well water.

Fluctuations of abundance and number of species are present in several wells, indicating unstable conditions likely caused by varying surface influence, e.g. in Gaggenau and Efringen (Figure 3.5a and 3.5b). Besides four stygobiontic indicator species in Gaggenau, all other species only appear sporadically, indicating an intermittent surface water input into this well (Figure 3.5b). This could also explain the increase in oxygen concentration after 2006, as well as the higher number of Oligochaetes and Nematodes (Figure 3.5c). These results are consistent with previous studies, which showed that groundwater communities strongly depend on the hydrologic exchange with surface water (Fuchs et al., 2006; Gutjahr et al., 2014; Hose et al., 2015).

An important parameter for the ecosystem status is the ratio of Crustaceans and Oligochaetes, which serves as a basis of the ecological assessment scheme by Griebler et al. (2014b). According to this scheme, monitoring wells with more than 70 % Crustaceans and less than 20 % Oligochaetes have a ‘natural’ status (indicating very good or good ecological conditions). Considering the entire study period, most monitoring wells in this study fall within this category (Figure 3.5c). Only six wells have a proportion of Oligochaetes higher than 20 % in one or multiple years, indicating disturbed conditions: Kadelburg, Schwäbisch Hall, Rohrdorf, Sankt Leon, Weingarten and Neckargartach (Figure 3.5c). While the first four wells show a fluctuating ecological status over time, probably related to varying surface water influence, the latter well shows a distinct change in the ecological status in 2008, which does not seem to be related to other biotic or abiotic parameters in Figure 3.5.

Abiotic parameters show mostly constant conditions in the individual wells (Figure 3.5d, e, f). One notable exception concerning electric conductivity is Efringen, where electric conductivity values decrease over time (Figure 3.5f). This may be caused by the reconstruction of the well from an underfloor to a surface observation well. In terms of well water temperature (Figure 3.5d), several sites show an increasing trend, e.g. Weingarten, Riedlingen and Furtwangen, which is in the same range as observed changes in groundwater temperature in previous studies (Figura et al., 2011; Menberg et al., 2014). More pronounced temperature changes, such as Kadelburg with temperature variations of > 5 °C between individual measurements and Furtwangen with an increase of 4.6 K between 2002 and 2020, are more likely related to varying surface influence or environmental conditions during measurements.

Overall, faunal and abiotic parameters are mostly constant over time in the individual wells of the study area. Nine out of 16 wells (Dahenfeld, Balgheim, Hausen, Riedlingen, Brenden, Kadelburg, Rohrdorf, Furtwangen, Todtnau) show stable conditions over time concerning the variance of the faunal and abiotic parameters (Table A2.3). In contrast, seven wells (Weingarten, Schwäbisch Hall, Efringen-Kirchen, Zienken, Gaggenau, Neckargartach, Sankt Leon) show higher standard deviations and, therefore, unstable conditions. These are often linked to a varying influence of surface water, which aligns with previous studies (Dole-Olivier, 1998; Foulquier et al., 2011; Stein et al., 2012).

3.3.3 Statistical analysis

Overall, the PHATE analysis shows that biodiversity, illustrated by the number of taxa and individuals, and geological conditions, such as the type of aquifer, have the largest impact on the clustering of the monitoring wells into three distinct groups (Figure 3.6). Group I contains monitoring wells in the karst aquifer of the Muschelkalk and Lettenkeuper formations in the northeast of BW and a fissured aquifer in the southern Black Forest, which generally have a low abundance. In contrast, Group II includes samples in all other wells, with the remaining wells of the southern Black Forest (Brenden, Furtwangen) located at the edge of this group. Group III consists of samples that had no groundwater fauna. Previous studies also showed that hydrogeological parameters strongly influence the occurrence and composition of groundwater fauna (Koch et al., 2021; Stein et al., 2012). Geology and hydrological connectivity significantly influence water chemistry and habitat availability and, therefore, biotic distribution (Fuchs, 2007; Fuchs et al., 2006; Hahn, 2006; Korbel et al., 2018; Korbel and Hose, 2015; Tione et al., 2016). For instance, the abundance and species richness of crustacean fauna in the alluvial aquifers are most related to hydrological conditions, oxygen concentrations and geologic structures (Mösslacher, 1998), which is consistent with our findings. Moreover, this is consistent with the results from Korbel et al. (2018), who state that 'sediment size, and thus the size of interstitial voids, is a key limiting factor' for stygofauna.

Temporal variations at the individual sites are also noticeable in the PHATE results by observing the spread of samples of individual locations. Samplings of very stable locations (e.g. Todtnau, Dahenfeld, Balgheim, and Riedlingen) with small parameter fluctuations over time are spatially more concentrated in the PHATE graph than wells with unstable conditions (e.g. Schwäbisch Hall, Weingarten). Generally, sites with stable conditions for both faunal and hydro-chemical parameters (as identified in Table A2.3) are concentrated in the lower right area of Group II as Sub-Group II.a (except for Dahenfeld and Rohrdorf), and the upper-left area as Sub-Group II.b (Figure 3.6). Thus, this result here confirms the categorisation of the wells using the variance of their faunal and hydro-chemical parameters.

While the affiliation of the wells with a specific group is constant over time (except for the mentioned samplings with no fauna), the location of different samplings within the group can be associated with concrete changes in specific parameters, specifically abundance, sediment content and temperature. Despite stable overall conditions, the well in Rohrdorf shows one outlier further down in the graph (orange triangle) representing the measurement in 2007 with significantly more individuals (126) than in other years. The amount of sediment is responsible for a clustering of samplings from different wells (Hausen, Gaggenau, Weingarten, among other) in the upper left corner of Group II, which are from 2009, 2011 and 2012 and lack information about the amount of sediment. The samplings Gaggenau (dark pink dots) show a further outlier in 2002, located more to the right, which is related to a relatively low sediment content < 1 ml. The same applies to Schwäbisch Hall with an outlier (red dots) to the right side of the graph, containing also a low sediment content, little detritus and low abundance (8 individuals). The samplings in Furtwangen (yellow triangles) are also spread over a wide area, with the ones at the bottom of Sub-Group II.a from 2002 and 2020 exhibiting significantly lower temperatures (4.3 °C and 8.7 °C), which are close to the measured temperatures in Brenden (light pink).

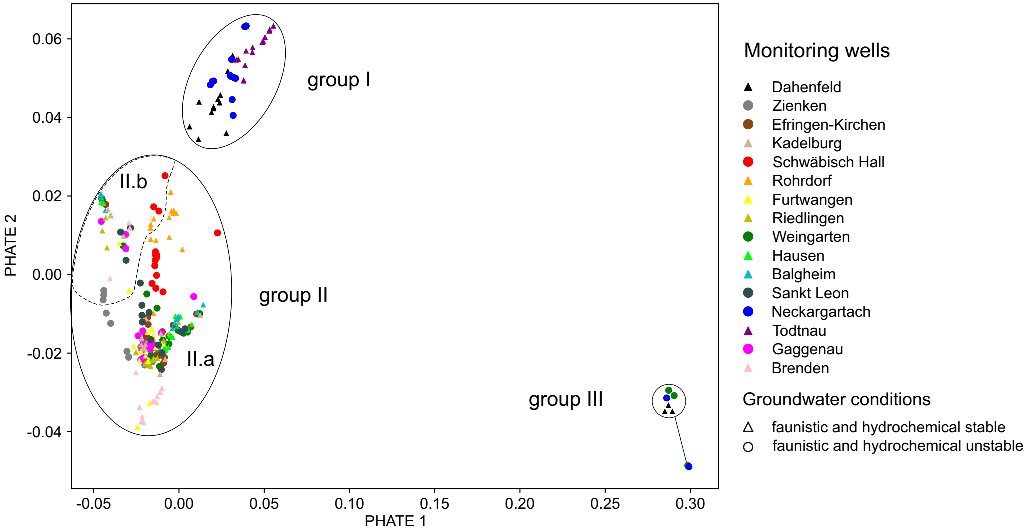

Figure 3.6: Graphical result of the PHATE-analysis for all 16 monitoring wells from 2001/2002 to 2020, presented by the affiliation of the monitoring wells of each sampling.

These findings show that the amount of sediment can be used as an indicator for the pore structure, which determines hydraulic conductivity and living space (Mösslacher, 1998), and can thus be used as a proxy for living conditions. Temperature, on the other hand, can be used as an indicator for surface influence, as it is an indirect marker of the degree of hydrological exchange with the surface (Hahn, 2006; Schönborn, 2003). This was also observed by Koch et al. (2021) on the city scale, where local geology influenced the occurrence of groundwater fauna, the number of individuals and the food supply. Other studies also observed a significant effect of groundwater temperature on fauna, as diversity decreased with increasing temperatures in laboratory and small-scale field studies (see Brielmann et al., 2009; Spengler, 2017).

3.3.4 Local scale analysis

As described above, certain changes in faunal parameters in individual wells can be related to changes in abiotic parameters, for example, to a decreasing dissolved oxygen content as in Zienken, while other changes, such as the fluctuating ecological status in Neckargartach and Sankt Leon, cannot directly be related to varying abiotic parameters (Figure 3.5). Hence, we assess these two unstable wells in more detail with respect to changes at the surface surrounding of the wells and compare them to the well in Todtnau, which shows very stable conditions.

3.3.4.1 Neckargartach

The well in Neckargartach is 35 m deep with filter screens between 27 and 34 m in a fractured and karst aquifer formed by a clay-containing limestone (Figure 3.2). The overall number of individuals is very low (maximum of nine individuals per sampling) and decreases during the observation period (Figure 3.7). Faunal analysis on species level shows a distinct change in the faunal community and dominating species between 2002 and 2020.

Between 2002 and 2007, Oligochaetes dominate the faunal community (Figure 3.7). Most of these individuals belong to the species *Dorydrillus michaelseni*, which is only occasionally found in groundwater and is an indicator of slightly contaminated groundwater (Moog, 2002). In 2008 and 2009, the dominating species was *Chappuisius inopinus* (*Crustacea*: *Harpacticoida*), while from 2011 onwards, mainly Crustaceans were found, with the rare species *Parabathynella badenwuerttembergensis* being the dominating species. Overall, these faunal changes represent a change from stygophil species to domination of stygobiontic species, as well as a simultaneous change from dominating Oligochaetes to Crustaceans and thus to the aforementioned change in the ecological status (Figure 3.5c).

The observed faunal changes coincide with alterations in land use of the surrounding area (Figure 3.8). After the first period with dominating Oligochaetes, a previously unsealed area was first converted into a gravel-covered car park in 2008 and later into an industrial warehouse in 2018. During that time, different crustacean species began to dominate the faunal community (Figure 3.8). Surprisingly, this surface change is not reflected in the well water temperatures, even though groundwater under covered surfaces typically shows higher temperatures than under unsealed surfaces (Tissen et al., 2019 ERL). In Neckargartach, this is likely linked to groundwater inflow from the adjacent agricultural area into the monitoring well (Lang et al., 2004). The nitrate content decreases from 51.4 to 25.9 mg/l during the study period (Figure 3.7), most likely due to the absence or reduction of fertilisation. Also, dissolved oxygen content decreases slightly from 10.9 to 8.0 mg/l (Figure 3.7 & Figure A2.2), which is consistent with the shielding from the surface as main source of oxygen and the change from stygophil to stygobiontic species (Bork et al., 2009; Hahn, 2006; Malard et al., 1996; Mösslacher, 1998; Pospisil, 1999; Sket, 1999).

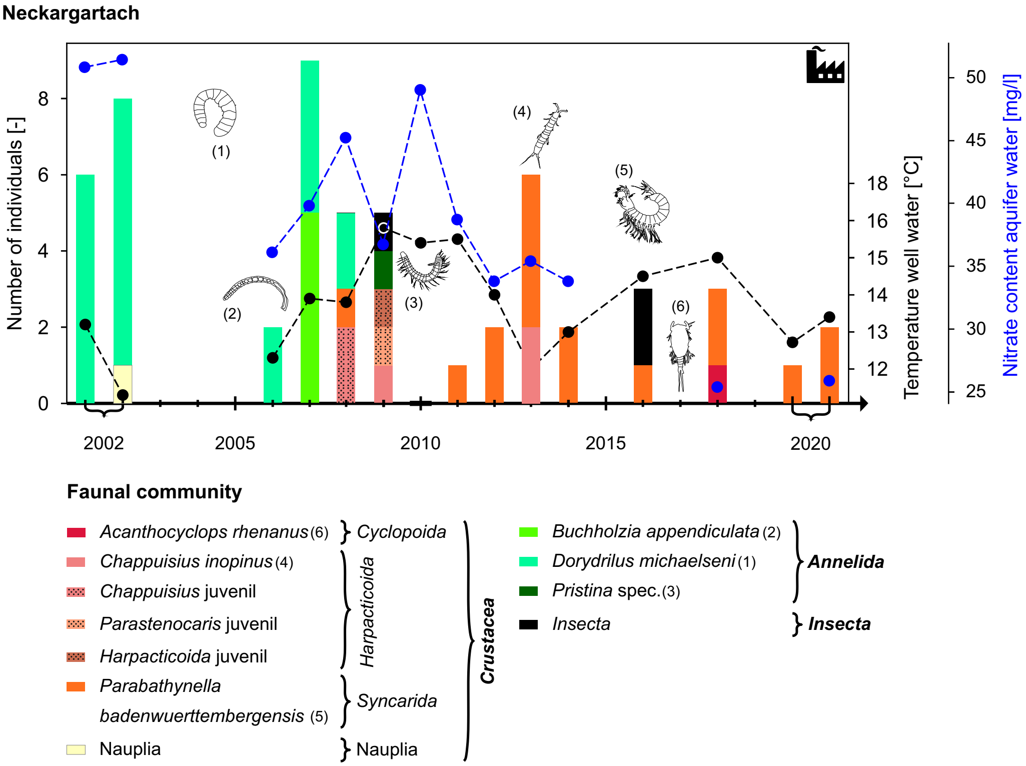

Figure 3.7: Temporal development of the faunal community (abundance and composition of the faunal community; higher taxa in bold letters) and the well water temperature (secondary y-axis) at the bottom of the monitoring well in Neckargartach during the period of investigation (2002 – 2020). No sampling was conducted in years with no bar.

Thus, there is a clear link in Neckargartach between decreasing surface influence, caused by increasing surface sealing, and dissolved oxygen content as well as the composition of groundwater ecosystems, as also observed by Korbel et al. (2013a). In this study, agriculture in areas with different land use affects groundwater ecosystems (composition of stygofauna and microbial assemblages) due to changes in groundwater quality (nitrate and phosphorus contents). Hence, a higher abundance of Cyclopoids, Harpacticoids and Oligochaetes was found under irrigated areas. However, it has to be mentioned that the improvement of the ecological status according to Griebler et al. (2014b) through surface sealing is a site-specific observation for Neckargartach. Generally, surface sealing and the related decrease in dissolved oxygen will more likely lead to the deterioration of groundwater ecosystems (Hervant and Malard, 1999; Korbel et al., 2022a; Mösslacher, 1998).

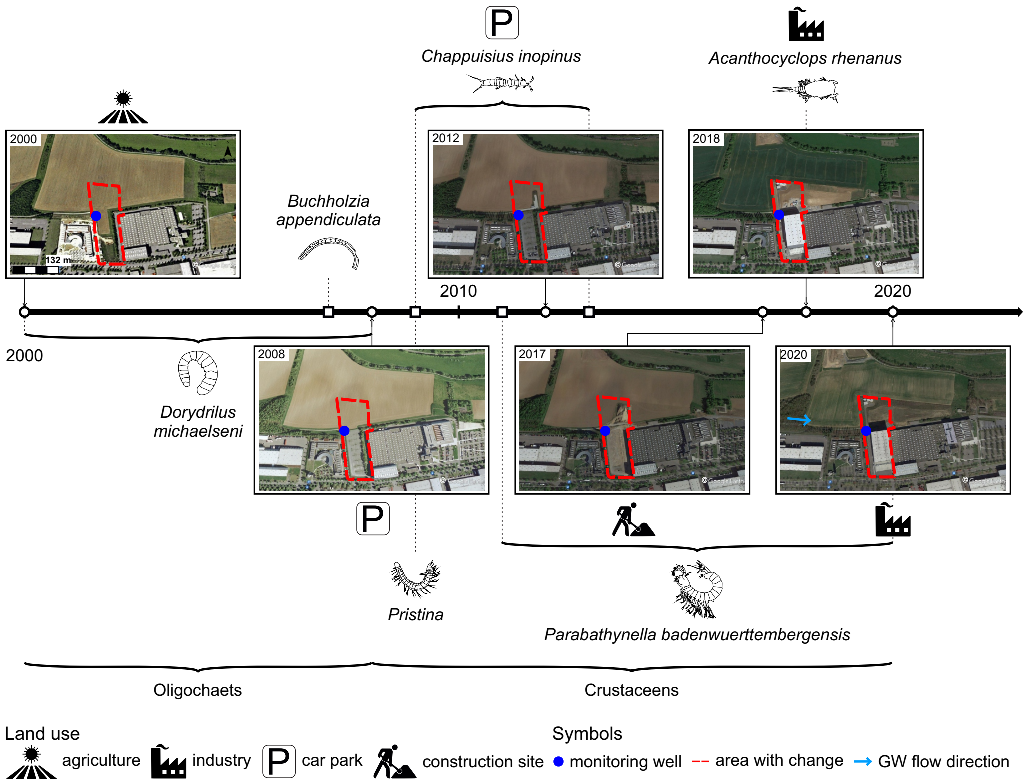

Figure 3.8: Temporal changes of land use using aerial image interpretation and faunal community structure of the monitoring well Neckargartach in the industrial park Böllinger Höfe between 2000 and 2020 (image source: Google Earth Pro (Google LLC., 2022).

3.3.4.2 Sankt Leon

The well Sankt Leon is located next to a field path between a forest and an agricultural area near the village of Sankt Leon (Figure A2.3a), with filter screens between 4 and the well bottom in 10 m, in the quaternary glacial sand and gravels of the Upper Rhine Valley (Figure 3.2). The well shows unstable abiotic and faunal conditions (between 0 and > 400 individuals per sampling, Figure 3.5) and significant variations in the faunal compositions (Figure 3.9).

Common taxa in this well are Nematodes, as well as different Cyclopoids (*Crustacea*). In the first decade, rather ubiquitous species colonise the well in large numbers, with *Graeteriella unisetigera* and *Diacyclops languidoides* (*Crustacea*: *Cyclopoida*) being the dominating species. The latter is one of Germany's most common and widespread groundwater species (Matzke et al., 2009; Schminke et al., 2007). From 2010 onwards, fewer individuals and different taxa can be found, with *Bathynella freiburgensis* (*Crustacea*: *Syncarida*) being the dominating species in recent years.

Overall, the development of the faunal communities over time points to a change from ubiquitous to more stygobiontic species.

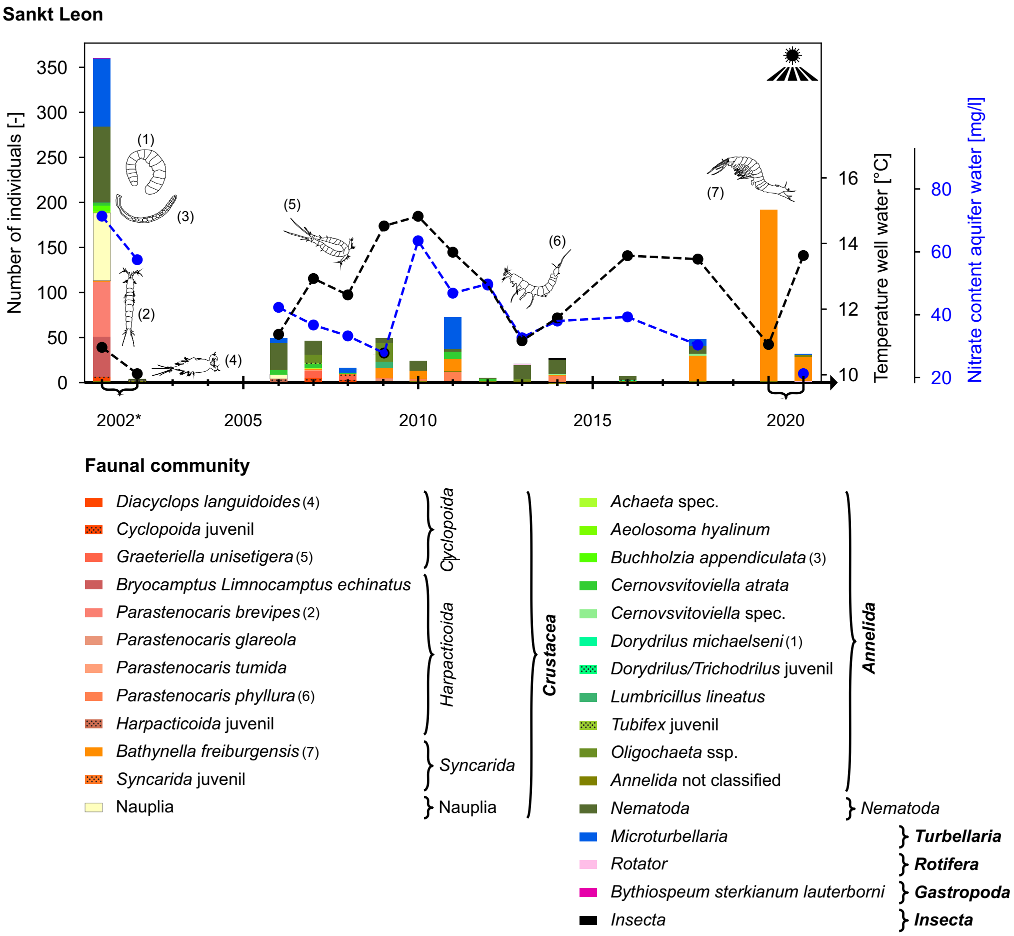

Figure 3.9: Temporal development of the faunal community (abundance and composition of the faunal community; higher taxa in bold letters), of the content of nitrate (data of the LUBW, blue y-axis on the right) and the well water temperature (black y-axis on the right) on the bottom of the well in Sankt Leon between 2002 (* fauna sampling in May and December) and 2020. No sampling was conducted in years with no bar.

Although these faunal changes indicate a weakening surface influence over time, no changes in land use or surface conditions were observed (Figure A2.3a). Well water temperature shows significant fluctuations between 11 °C and 14 °C, yet without visible trend. As *Bathynella freiburgensis* tolerates a large range of temperatures and is typical for the Upper Rhine Valley (Fuchs, 2007; Spengler, 2017), individuals of that species might have a competitive advantage over other species. The nitrate content decreased from 70 mg/l to below 20 mg/l (Figure 3.9). High nitrate contents in the first years are most likely linked to intensive agriculture, in particular asparagus cultivation, which is typical for this region. However, these fluctuations do not seem to correlate with the observed faunal shifts. Furthermore, previous studies showed that a nitrate concentration below 50 mg/l has no direct impact on groundwater fauna (Di Lorenzo et al., 2020b; Di Lorenzo and Galassi, 2013; Fakher el Abiari et al., 1998; Mösslacher and Notenboom, 1999). Accordingly, more detailed and site-specific investigations (e.g. more accurate, in-situ groundwater temperature and dissolved oxygen measurements over depth) would be needed to clarify the drivers of the unstable conditions in Sankt Leon.

3.3.4.3 Todtnau

The well in Todtnau is also located in an agricultural area near a small stream (Prägbach) and the village of Todtnau-Geschwend (Figure A2.3b), with a depth of 39 m and well screens between 5 and 36 m in a fractured crystalline aquifer in the southern Black Forest. The number of individuals and species is generally low (Figure 3.10).

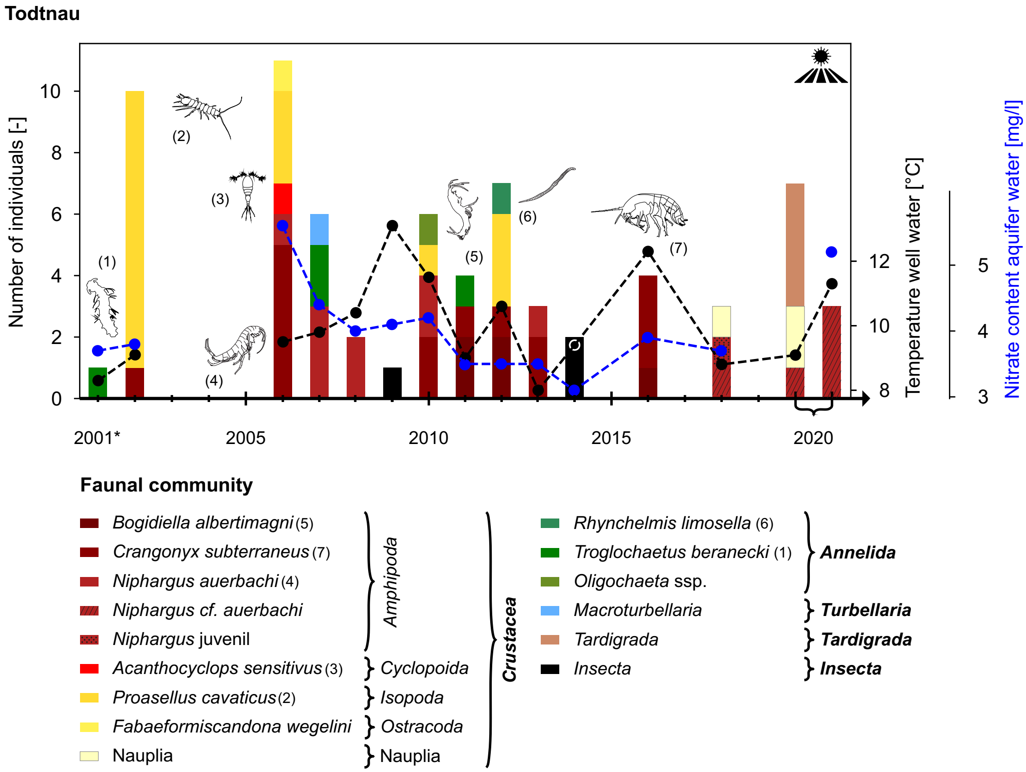

Figure 3.10: Temporal development of the faunal community (abundance and composition of the faunal community; higher taxa in bold letters), of the content of nitrate (data of the LUBW, blue y-axis on the right) and the well water temperature (black y-axis on the right) on the bottom of the well in Todtnau-Geschwend between 2001 (* fauna sampling in November) and 2020. No sampling was conducted in years with no bar.

In contrast to the two wells discussed previously, the well in Todtnau shows stable conditions (Table A2.3, Figure 3.5). Well water temperatures are generally low due to higher altitude in the Black Forest. The same applies to electric conductivity related to filter screens in crystalline rocks and organic matter content due to the depth of the well. Despite its location in an agricultural area, the nitrate content is below the geogenic background (Figure 3.10). However, despite stable physico-chemical conditions and no change in land use or surface conditions, certain changes in the faunal community can be observed as different species occur in different years, yet without any visible trends.

The well in Todtnau is colonised by stygobiontic species only, except for *Collembola* (*Insecta*) in two years, which live in the soil and on the water's surface. These are also the samplings that show a non-natural status of the ecosystem according to Griebler et al. (2014b) due to the absence of *Crustacea* (Figure 3.5c). The most common species during the past 20 years is *Crangonyx subterraneus* (*Crustacea*: *Amphipoda*), which is widespread, ecologically very flexible and inhabits all kinds of underground habitats, but prefers fractures and gravels (Schminke et al., 2007). The species *Proasellus cavaticus* (*Crustacea*: *Isopoda*) is also commonly present at this location. Individuals of this species can be up to 1 cm long and, therefore, prefer larger cavities, e.g. caves and fractured aquifers, such as the one in Todtnau. Another common species is *Niphargus auerbachi* (*Crustacea*: *Amphipoda*), a comparably big, stygobiontic groundwater species. The groundwater species *Troglochaetus beranecki* (*Annelida*: *Polychaeta*) found in 2001, 2007 and 2011 is cold-stenotherm, has low water chemistry requirements (Schminke et al., 2007) and also inhabits deep groundwater wells (Matzke et al., 2009). It is also noted that juvenile crustaceans, especially niphargids, are predominant in the last two years of sampling. This may indicate a recovery of the population after a lack of colonisation in 2014. Years without colonisation may point to bad living conditions with a lack of nutrients and, therefore, challenging living conditions. In general, the faunal composition in Todtnau reflects the hydrogeological conditions of the well, with many species typical of large cavities and higher altitudes.

3.4 Conclusion

This study analyses the faunal composition and abiotic parameters of 16 groundwater measurement wells in the German state of Baden-Württemberg over the past two decades. Statistical analyses are used to distinguish wells with stable and unstable faunal conditions and to assess the impact of specific hydrological and hydro-chemical parameters on this characterisation. Time series of individual wells are also discussed in combination with past aerial images to analyse the impact of changes in surface conditions.

Considering the entire study area, we observed no long-term changes or trends in abiotic or faunal parameters, indicating generally stable and ecological good conditions. However, temporal fluctuations in faunal parameters, such as total abundance and number of species, and thus unstable conditions are observed for seven out of 16 wells. In some cases, these changes are directly related to gradual changes in abiotic parameters, such as decreasing abundances due to reduced dissolved oxygen contents. Yet more often, there are no clear patterns in individual abiotic parameters; instead, superimposing effects of multiple parameters linked to increasing or weakening surface influence lead to changes in groundwater fauna. Results from a multivariate PHATE analysis confirm these findings and highlight the hydrogeological setting, the content of sediment and detritus in the well and the temperature as influential factors.

Examining faunal changes on species level for selected wells reveals that unstable conditions can be linked to changes in surface sealing by anthropogenic construction measures, which even changed the ecological status at one specific site. However, variable faunal composition and fluctuating abundances were also observed for sites with no visual changes in land use and surface influence and also (although less prominent) for a deep, well-shielded site with very stable abiotic groundwater conditions. Thus, more long-term studies of groundwater ecology with higher spatial and temporal resolution are necessary to further improve our understanding of faunal shifts over time.

These findings have direct implications for large-scale biomonitoring in groundwater, which is becoming increasingly important. Transferability of local observations to a larger scale is very limited due to small-scale heterogeneities in hydrogeological conditions and superimposing, site-specific effects. Noticeable environmental changes for wells in the state of Baden-Württemberg were often linked to changes in dissolved oxygen content, well water temperature and sediment content. Accordingly, these parameters should be accurately and representatively measured in the water column of the well (if possible depth-resolved) and assessed in combination with hydrogeological and surface conditions to obtain more reliable biomonitoring results. Furthermore, the observed faunal fluctuations in wells in natural, unaffected areas with stable abiotic conditions stress that reference locations for ecological groundwater assessments and biomonitoring have to be carefully selected and ideally be based on multi-annual data.

Acknowledgments

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4

GROUNDWATER FAUNA IN AN URBAN AREA - NATURAL OR AFFECTED?

Reproduced from Koch, F., Menberg, K., Schweikert, S., Spengler, C., Hahn, H.J., Blum, P. (2021) Groundwater fauna in an urban area - natural or affected?. Hydrology and Earth System Sciences 25. 3053-3070. https://doi.org/10.5194/hess-25-3053-2021.

4.1 Introduction

In Germany, 70 % of the drinking water demand is met by groundwater, for which the quality is the product of multiple physical–chemical and biological processes (German Environment Agency, 2018). Groundwater ecosystems are responsible for several services that help to provide clean drinking water, which is a vital resource for humanity (Griebler and Avramov, 2015). Bacteria and fauna also play an important role in the biological self-purification of groundwater by the retention of organic matter, natural attenuation of pollutants, storing and buffering of nutrients as well as the elimination of pathogens. Organic matter and pollutants can be degraded and converted to biomass or bound by microbial activity. Protozoa and higher organisms can graze resulting biofilms, loosen the substrate and, therefore, stimulate biological self-purification (Boulton et al., 2008; Griebler and Avramov, 2015; Hancock et al., 2005). Healthy groundwater ecosystems can provide clean drinking water; however, they are sensitive to external influences such as chemical and thermal disturbances. The latter drives hydro-geochemical and biological processes in groundwater systems which are typically isothermal (Brielmann et al., 2009, 2011). Groundwater fauna mainly consist of stygobiontic species which spend their entire life in groundwater and are adjusted to this habitat (Hahn, 2006). Hence, in central Europe, they are assumed to be cold stenotherm, which means that they prefer cold temperatures. A variability in temperature tolerance among groundwater faunal groups and species is reported in various studies, which explains why the use of individual temperature thresholds is more useful for capturing different preferences. According to Spengler (2017), faunal diversity is generally declining at a temperature above 14 °C. Various authors reported species-specific temperature preferences between 8 and 16 °C (for individuals of the species *Niphargus inopinatus* and *Proasselus cavaticus*; Brielmann et al., 2009, 2011) and a specific temperature threshold of up to 19 °C (for *Parastenocaris phyllura*; Glatzel, 1990). Above these thresholds, the mortality of individuals raises until groundwater fauna is almost absent, for example at 22 °C in the study of Foulquier et al., 2011. However, temperature sensitivity is not only an issue at species level but also for the communities as a whole. Spengler (2017) reported 12 °C to be a temperature threshold value indicated by a shift in community structure for faunal communities of groundwater of the Upper Rhine valley.

Nevertheless, in German and European legislation, as in many countries globally, groundwater is not yet recognised as a habitat worthy of protection, and there is no common understanding of the best practice for assessing the ecological status of groundwater (Hahn et al., 2018; Spengler and Hahn, 2018). The assessment of surface water is typically based on biological and physical–chemical criteria and is also supported by hydro-morphological criteria (European Water Framework Directive and German legislation; article 5 – "Regulation on the Protection of Surface Water"). While groundwater quality is mostly assessed by physical– chemical and quantitative criteria, very few quantifiable ecological criteria are available for the assessment of the health of groundwater ecosystems. The availability of ecological criteria can only be increased by conducting a large number of studies dealing with the analyses of groundwater ecosystem health by investigating groundwater fauna. Results from previous faunal groundwater analyses are contained in a Germany-wide data record (Berkhoff, 2010; Gutjahr, 2013; Hahn, 2005; Spengler, 2017; Spengler and Hahn, 2018; Stein et al., 2012). The study by Hahn and Fuchs (2009) focuses on defining stygoregions based on different hydrogeological units located in Baden-Württemberg, Germany. They conclude that the observed patterns of groundwater communities reflect a high spatial and temporal heterogeneity in aquifer types with respect to habitat structure, food and oxygen supply. Although there are various studies on this topic (e.g. Deharveng et al., 2009; M.-J. Dole-Olivier et al., 2009; Gibert and Deharveng, 2002; Malard et al., 2002), stygobiontic biodiversity is still likely to be underestimated.

Regional investigations on the spatial variation in groundwater fauna, i.e. stygobiont occurrences, and corresponding environmental parameters, such as geological site characteristics and altitude, are rare (M. J. Dole-Olivier et al., 2009; Gibert and Culver, 2009). An approach for elucidating groundwater biodiversity patterns in six European regions was conducted in the PASCALIS (Protocol for the Assessment and Conservation of Aquatic Life In the Subsurface) project (Gibert and Culver, 2009), which aimed at mapping biodiversity and endemism patterns (Deharveng et al., 2009) and shows that regional processes, such as hydrological connectivity, in a specific habitat (e.g. river floodplains as in Ward and Tockner (2001)) have a much stronger influence on species composition than local habitat features, such as permeability and saturation. Within a region, hydrogeology, altitude, palaeographical factors and human activities can interact in complex ways to produce dissimilar patterns of species compositions and diversity (Gibert and Culver, 2009). The PASCALIS sampling protocol recommends selecting hydro-geographic basins that are not strongly affected by human activities, such as groundwater pollution (Malard et al., 2002), and do not biogeographically classify a groundwater system (Stein et al., 2012). In urban areas, anthropogenic impacts such as a dense building development, underground car parks, open geothermal systems and injections of thermal wastewater from industry result in local thermal alteration of groundwater by up to several degrees (e.g. Menberg et al., 2013a; Taylor and Stefan, 2009; Tissen et al., 2019; Zhu et al., 2010). According to Brielmann et al. (2011), annual temperature fluctuations in aquifers caused by shallow geothermal energy systems range between 4 °C in winter and $\leq$ 20 °C in summer. In 2000, the European Union European Union (EU) Water Framework Directive defined the release of heat in the groundwater as pollution, whereas the cooling of the groundwater is not mentioned. Until now, there are scientifically derived threshold values for groundwater temperature in the case of thermal (heat) pollution published, but none of these have been implemented in official regulations or water law (Blum et al., 2021; Hähnlein et al., 2010, 2013). This results in a tension between conservation, exploitation and thermal use of groundwater. However, as seen in an aquifer ecosystem downstream from an industrial facility in Freising (Germany), where groundwater is used for cooling, resulting in a warm thermal plume, no relation between faunal abundance and groundwaterr temperature could be identified (Brielmann et al., 2009). Investigation of hydro-geochemical parameters, microbial activities, bacterial communities and groundwater faunal assemblages indicates that bacterial diversity increased with temperature, while faunal diversity decreased with temperature (Brielmann et al., 2009). Similar results are provided by Griebler et al. (2016), where potential impacts of geothermal energy use and storage of heat on groundwater are investigated. Temperature changes in groundwater correspond to changes in groundwaterr chemistry, biodiversity, community composition, microbial processes and function of the ecosystem. How exactly groundwater communities react to changes in the temperature and concentration of nutrients, dissolved organic carbon and oxygen is not yet fully understood (Brielmann et al., 2009, 2011; Castaño-Sánchez et al., 2020a; Spengler, 2017).

Several approaches exist that allow a local assessment of the ecological state of groundwater based on different faunal, hydro-chemical and physical parameters. Korbel and Hose (2011, 2017) introduced the Groundwater Health Index GHI, which is a tiered framework for assessing the health of groundwater ecosystems. Here, both biotic and abiotic attributes of groundwater ecosystems are used as benchmarks for ecosystem health. Their study shows that ecosystem health benchmarks are probably more associated with aquifer typology than being applicable for local areas. This index is applied and tested by Di Lorenzo et al. (2020a) in unconsolidated aquifers in Italy located in nitrate vulnerable zones. They refined the index (weighted Groundwater Health Index Nitrates ($wGHI^N$)) and demonstrated its applicability on shallow and deep aquifers and also revealed that this new index is limited due to low correlations between the indicators. Commissioned by the UBA, Griebler et al. (2014b) developed a concept for an ecologically based assessment scheme for groundwater ecosystems, which builds on the assessment of Korbel and Hose (2011, 2017). This two-step scheme characterises groundwater on two different levels by using the most important physical–chemical parameters, such as content of dissolved oxygen and microbiological and faunal characteristics, i.e. the number of oligochaetes and crustaceans, and comparing these to reference values for natural, undisturbed and ecologically intact groundwater ecosystems (Griebler et al., 2014b).

Furthermore, the GFI, introduced by Hahn (2006), quantifies the relevant ecological conditions in the groundwater as a result of hydrological exchanges between surface and groundwater. It incorporates ecologically important groundwater parameters, such as the relative amount of detritus, variation in groundwater temperature and concentration of dissolved oxygen (Hahn, 2006). Gutjahr et al. (2014) used the GFI as part of a proposal for a groundwater habitat classification on a local scale, which introduced five types of faunal habitats as a result of surface water influence, the content of dissolved oxygen and amount of organic matter. Moreover, in the study of Berkhoff (2010), the GFI was used to examine the impact of the surface water influence on groundwater with the aim of developing a faunal monitoring concept for hydrological exchange processes in the surrounding river bank filtration plants. Spengler and Hahn (2018) argued for the definition of a regional and ecological temperature threshold and an ecology-based assessment of thermal stress in groundwater.

The objective of this study is to investigate, specifically, the groundwater fauna beneath residential, commercial and industrial, i.e. urban, areas in comparison to a forested area outside the built-up area of Karlsruhe to determine whether land use has an impact on groundwater faunal communities. Hence, in 39 groundwater monitoring wells in Karlsruhe, Germany, the groundwater fauna are sampled, the groundwater temperatures are measured and chemical properties are analysed. In our study, the classification scheme developed by Griebler et al. (2014b) is applied. The wells are characterised regarding the state of their ecosystem. Finally, we aim to distinguish areas with natural groundwater ecology from anthropogenically disturbed areas.

4.2 Material and methods

4.2.1 Study site

The study is performed in Karlsruhe, a city in the Upper Rhine valley in southwestern Germany. The urban region covers an area of 173 km^2 and has about 310,000 inhabitants (Amt für Stadtentwicklung - Statistikstelle, 2018). The Cenozoic continental rift valley is filled with Tertiary and Quaternary sediments, which are dominated by sands and gravels with minor contents of silt, clay and stones (Geyer et al., 2011). Sporadic layers with lower permeabilities lead to a separation of up to three aquifer levels (Wirsing and Luz, 2007). The upper aquifer is unconfined, with a water table between 2 and 10 m below the ground. The flow direction is northwest of the Rhine, with groundwater flow velocities ranging between 0.5 and 1.5 m/d (Technologiezentrum Wasser, 2018).

Based on the land use plan of Karlsruhe, about 20 % of the area (i.e. urban area, city centre, neighbouring districts, and parts of the Hardtwald forest and several outskirts) is covered by buildings. The rest is vegetation ($\sim$ 56 %) and artificial surface covers ($\sim$ 24 %), showing the complexity and heterogeneity of the urban environment. According to Benz et al. (2016), the annual mean Groundwater temperature (GWT) in Karlsruhe in the years 2011 and 2012 was 13.0 ± 1.0 °C. Distinct temperature hot spots occur mainly below the city centre, where building densities are highest. In the northwestern part of Karlsruhe, the increase in GWT was about 3 K warmer than the annual mean Land Surface Temperature (LST), which is mainly caused by several groundwater reinjections of thermal wastewater (Benz et al., 2016).

In general, groundwater in the region of Karlsruhe is of good quality, and the local drinking water supplier (Stadtwerke Karlsruhe) only needs to remove oxidised iron and manganese from the pumped groundwater. However, two main contaminations which affect groundwater quality are known in the urban area (Stadt Karlsruhe, 2006). A contaminant plume, which contains a polycyclic aromatic hydrocarbons concentration of up to 500 μg/L, of 200 m length over the entire aquifer thickness is located at a former gas plant in the east of Karlsruhe (Figure A3.2b; Kühlers et al., 2012). Moreover, three parallel contamination plumes, of 2.5 km length each, can be found in the southeast of Karlsruhe (Figure A3.2b), where highly volatile chlorinated hydrocarbons (7 – 26 μg/L) and their degradation products were detected (Wickert et al., 2006).

4.2.2 Material and sampling

From 2011 to 2014, samplings of groundwater parameters and fauna were performed in 39 groundwater monitoring wells in the city area of Karlsruhe, of which eight wells are in the forested area and 31 in the residential, commercial and industrial areas (urban area). At the beginning of each sampling process, temperature and electrical conductivity were measured with an electric contact gauge (type 120-LTC; Hydrotechnik) at a depth interval of 1 m. Using a bailer (aqua sampler; Cole-Parmer), water from the bottom of the groundwater monitoring wells was sampled, and the pH value (MultiLine type 3430; Xylem Analytics, Weilheim, Germany) and the contents of dissolved oxygen (MultiLine type 3430; Xylem Analytics, Weilheim, Germany), iron, nitrate (NO_3^-) and phosphate (PO_4^{3-} ; (RQflex® plus 10 Reflectoquant®; Merck KGaA, Darmstadt, Germany) were measured.

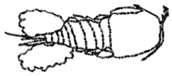
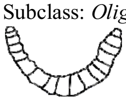
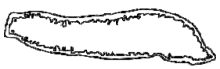
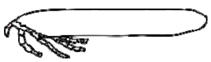
In accordance with the suggestion made by Hahn and Gutjahr (2014), several integrative samplings (i.e. repeated samples taken over a period of time) were conducted to capture an ecological representation of groundwater fauna which reflects the occurring species at a community level. Every well was sampled at least three times. From 2011 – 2012, 22 measurement wells (mainly in the Hardtwald and the northwest of Karlsruhe) were sampled six times at a minimum interval of 2 months. In 2014, 17 measurement wells, mainly located in the south or in the inner city, were sampled three times (see Table A3.2). As the aim of this study is to provide a first-tier screening of the groundwater ecological status, we sampled the fauna in the monitoring wells in accordance with the sampling manual of the European PASCALIS project (Malard et al., 2002) and the procedure described by Hahn and Fuchs (2009), using a modified Cvetkov net.

Furthermore, the relative amount of sediment as an indication of the nutrient availability and the cavity system was measured. Before the fauna sample from the net sampler was passed over a sieve with a mesh size of 74 μm, the sediment was separated and classified into different categories (sand, fine sand, ochre, detritus, and silt). It should be noted that the detritus content was not recorded quantitatively but on the basis of estimated frequency classes. The estimation of the relative amounts of sediment per sample is based on Table A3.1 in the Supplement. Mann–Whitney tests (U tests) were applied to detect the potential impacts of groundwater characteristics (physical–chemical parameters), geology and well design on the groundwater quality as well as on groundwater fauna. Samples were regarded as significantly different if the p value was $< 5.0 \times 10^{-2}$.

To better understand large-scale relationships and the fine structures of high-dimensional biological data, the PHATE analysis introduced by Moon et al. (2019) (`https://github.com/KrishnaswamyLab/PHATE`, last access: 15 April 2021) was used. This dimensionality reduction method generates a low-dimensional embedding specific for visualisation, which provides an accurate, denoised representation of both local and global structures of a data set without imposing strong assumptions on the structure of the data. The PHATE algorithm computes the pairwise distances from the data matrix and transforms the distances to affinities to encode local information by applying a kernel function, which is developed to Euclidian distances. By using diffusion processes, global relationships are learnt and encoded using the potential distance. Finally, the potential distance information is embedded into low dimensions for visualisation with metric MDS (Moon et al., 2019). Objects that are close to each other in the final graph, therefore, have similar characteristics.

Crustaceans, especially amphipods and copepods represent the majority of groundwater fauna. The identification keys from the following studies were used to identify the different groups in the samples: Einsle (1993), Janetzka et al. (1996), Meisch (2000), Schellenberg (1942), and Schminke et al. (2007). The sampled fauna for this study can be assigned to the subphylum *Crustacea* and four other subordinate taxa (Table 4.1).

Table 4.1: Overview of the sampled fauna, divided into the subphylum *Crustacea* and other subordinate taxa.

Subphylum: *Crustacea*	**Size [mm]**	**Habitats**	**Species number**
Order: *Cyclopoida* 	0.4 - 0.7[1]	Fresh and marine water, groundwater[1]	298 species and subspecies worldwide[2], 8 stygobiotic species in Germany[3]
Order: *Harpacticoida* 	< 0.5[4]	Marine, freshwater, semi-terrestrial environments and groundwater[5]	599 (sub-)species worldwide[2], 20 stygobiotic species in Germany[3], 17 stygophile* & stygobiotic species in Baden-Württemberg[6]
Genus: *Parastenocaris*	0.3 - 0.5[1]	Tertiary relict living in cavity rooms of streams, in groundwater and moss[1]	206 (sub-)species worldwide[2] (16 stygophile & stygobiotic species in Baden-Württemberg[1])
Order: *Bathynellacea* 	0.5 - 5.4[7]	Cavity systems[7] and in groundwater[8] (foreign tropical origin)[9]	Exclusively 160 stygobiotic species worldwide[9], 8 species in Germany[3]
Order: *Amphipoda* 	0.5 – 30[1]	Sea, fresh water[1] and in healthy groundwater ecosystems (important ecosystem service providers[10] & biodiversity indicators in Europe[11])	321 stygophile & stygobiotic species in Europe[12], 24 stygobiotic species in Germany[3]
Other subordinate taxa	**Size [mm]**	**Habitats**	**Species number**
Subclass: *Oligochaeta* 	< 1 – 3[13]	Colonise every habitat, groundwater[13]	100 species worldwide[14] and 27 stygobiotic species in Europe[13]
Phylum: *Nematoda* 	1 – 3[9]	Colonise every habitat[9], can live under unfavourable conditions[15]	20,000 species worldwide[16], 60 stygobiotic species in Europe, 6 species in Germany[3]
Class: *Turbellaria* 	0.4 – 5[17]	Sea, brackish and fresh water and groundwater[17]	3,400 species worldwide[17], 7 stygobiotic species in Germany[3]
Subclass: *Acari* 	a few mm[9]	Colonize every habitat, also groundwater, have high demands on water quality[9]	< 5,000 water mite species wordlwide[18], 10 stygobiotic species in Germany[3]

[1]Fuchs et al. (2006)	[7]Sauermost and Freudig (1999b)	[13]Sauermost and Freudig (1999c)
[2]Galassi (2001)	[8]Camacho (2006)	[14]Batzer and Boix (2016)
[3]Zaenker et al. (2020)	[9]Hunkeler et al. (2006)	[15]Hahn et al. (2013)
[4]Hahn (1996)	[10]Boulton et al. (2008)	[16]Eckert et al. (2008)
[5]Galassi et al. (2009)	[11]Stoch et al. (2009)	[17]Sauermost and Freudig (1999a)
[6]Fuchs (2007)	[12]Botosaneanu (1986)	[18]Di Sabatino et al. (2000)

*Stygophile organisms are found primarily in surface water, but they can survive in shallow groundwater for a while (Preuß and Schminke, 2004).

4.2.3 Classification scheme by Griebler et al. (2014)

Commissioned by the Federal Environmental Agency of Germany (UBA), Griebler et al. (2014b) developed a two-step, ecologically based classification scheme for the characterisation of groundwater ecosystems and also defined spatially dependent reference values of ecologically intact groundwater ecosystems. In order to enable a statement about the exposure of the groundwater at a specific site, biotic and abiotic parameters, which are determined and compared with reference values, are used to distinguish locations with very good or good ecological conditions or locations which fail these criteria, i.e. affected areas (Figure 4.1). If an ecological assessment of groundwater ecosystems, which is based on the groundwater fauna analysis, takes place, some faunal criteria must be considered. Invertebrates avoid habitats that are ochred or have a low dissolved oxygen content. Thus, unstressed or natural habitats are defined as areas, with a dissolved oxygen content > 1.0 mg/l, that are not ochred and have an existing fauna, i.e. an amount of > 50 % of stygobites, of > 70 % of crustaceans and of < 20 % of oligochaetes (Figure 4.1). This allows a qualitative interpretation of the ecological condition of the groundwater system. If the results indicate affected ecological conditions, i.e. one or more biological and/or ecological indicators are out of the reference range, then an assessment according to the level 2 scheme is necessary. This requires a determination of the reference values at local reference locations, which are protected and have a weak surface influence, and a subsequent comparison of these values with measured data. As our aim is a first-tier screening of an urban area, we only apply level 1 in our study.

4.3 Results and discussion

4.3.1 Physical and chemical parameters

First, the groundwater conditions in the study area are evaluated by their physical–chemical characteristics. The following values are average values of the individual samplings from each monitoring well. In order to allow for a spatially differentiated assessment, the study site (city area of Karlsruhe) is classified into different zones based on land use types provided by the European seamless vector data of the CORINE Land Cover (CLC) inventory (European Environment Agency, 2016). Based on this data, the city area is subdivided into (1) forested area (forest; local name – Hardtwald) and (2) industrial, commercial and residential areas (urban area; Figure 4.2a). For simplification, the phrases forest and urban area are used in the following. A more detailed subdivision in the urban area did not appear reasonable due to the heterogeneous structure.

As expected, measured GWTs at the bottom of the wells with 8.5 to 39.0 m depth, are mainly constant over the repeated measurements. The lowest GWTs, ranging between 10.5 and 10.9 °C,

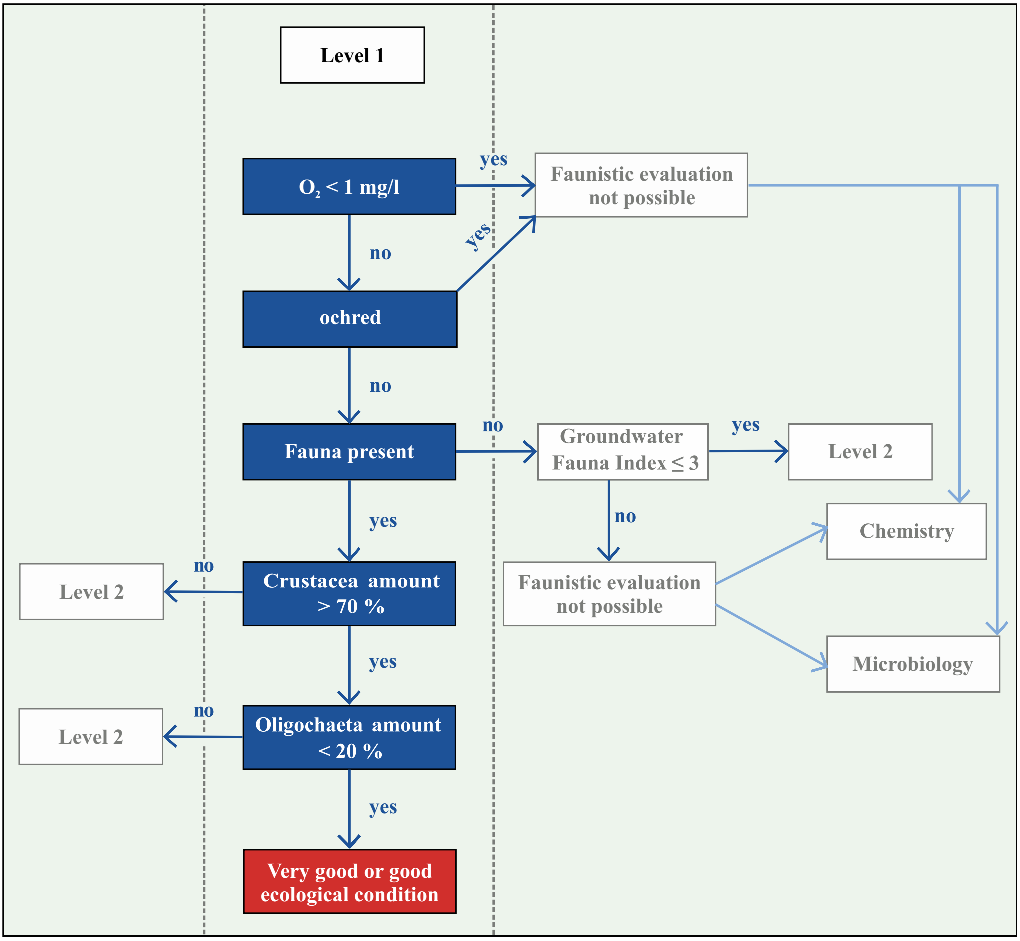


Figure 4.1: Classification scheme by Griebler et al. (2014b), according to level 1 for groundwater ecosystems, on the basis of groundwater fauna (modified after Griebler et al. (2014b)).

were measured in the eight wells of the forested area (Table A3.2). In contrast, the highest average GWT, at 17.5 °C, was measured in a well near the city hospital (T113; Figure 4.2a). The mean value of all wells is 13.5 ± 2.1 °C, which is similar to the results from Benz et al. (2014), with 13.0 ± 1.0 °C. According to Benz et al. (2017), annual shallow GWTs vary between 6 and 16 °C in the area of Karlsruhe, which is in line with the temperatures measured during fauna sampling (Figure 4.3a). For the urban area in the northwestern part of the city, Figure 4.2a shows a clear warming trend, which was also observed by Menberg et al. (2013a,b). The increased GWT in this area can be traced back to effects of urban infrastructures and industries, which use groundwater for cooling purposes.

The dissolved oxygen content acts as a limiting factor for groundwater fauna, since groundwater is usually undersaturated, with a varying oxygen content between 0 and 8 mg/l (Griebler et al., 2014b; Kunkel et al., 2004). In this study, the average content of dissolved oxygen in all wells is between 1.0 and 12.8 mg/l (Figure 4.3b and Figure A3.2a). As expected, the monitoring wells located in the forested area (Hardtwald) show the highest content, while the lowest values are found in urban areas and are likely linked to aquifer contamination and other anthropogenic effects (dissolved oxygen content of forested versus urban area; U test – p value = 5.3×10^{-3}; n = 8; 31). Urban water can be polluted in multiple ways, which affects the chemical and biological oxygen consumption in the groundwater. The higher the pollution and/or biological activity, the lower the dissolved oxygen (Griebler et al., 2014b; Kunkel et al., 2004). Moreover, it seems that, with a greater depth of the measurement wells, the dissolved oxygen content increases (U test – p value = < 10^{-13}; n = 39). This can be explained by the fact that shallow wells can have a low water column in which oxygen can rapidly be consumed by groundwater microorganisms, chemical reactions and/or groundwater fauna. In the upper, unscreened part of deeper wells, dissolved oxygen can be consumed, while in the lower, screened part, oxygen is continuously being refilled by oxic groundwater from the surroundings (Malard et al., 2002). Furthermore, reducing conditions in the overlaying soil can result in a low content of dissolved oxygen in groundwater.

Nitrate is often named as an important pollutant in groundwater. The natural and geogenic concentration of nitrate in groundwater is usually under 10 mg/l (Griebler et al., 2014b). In our study area, the average nitrate content of all wells varies between 1.3 and 14.7 mg/l. In the urban area, the average nitrate concentrations are generally higher and correlate with the content of dissolved oxygen (U test – p value = 4.0×10^{-3}; n = 39), showing the link between nitrate content and oxygen consumption. Wells with a dissolved oxygen content below 1.5 mg/l have an average nitrate content of 1.5 mg/l, most likely caused by nitrate reduction under anoxic conditions. Groundwater with reducing conditions (< 5 mg/l dissolved oxygen) has an average nitrate content of about 7 mg/l, which is in contrast to groundwater with oxidising conditions that has 9 mg/l, which promotes the oxidation of ammonium to nitrate. The lowest nitrate concentrations are found in the forested area (Figures 4.3c and A3.2c), where atmospheric nitrogen is held back by forest soils (U test – p value = 1.7×10^{-3}; n = 8), and fertilisation is prohibited due to water protection regulations in the forested area (Aber et al., 1998; Schönthaler and Adrian-Werburg, 2008). Moreover, the average concentrations of iron and phosphate are low and, in most cases, below the detection limit of the test (Figure A3.2d, e) and also below the natural and geogenic concentrations within the study site (phosphate – 0.05 mg/l; Griebler et al., 2014b; iron – 3.3 mg/l; Kunkel et al., 2004).

Considering these findings, clear differences in the spatial distribution patterns of abiotic groundwater characteristics are noticeable. The forested area shows lower average GWT than the urban area (U test – p value = 3.3×10^{-5}; n = 8; 31), lower nitrate concentrations (U test – p value = 4.1×10^{-3};

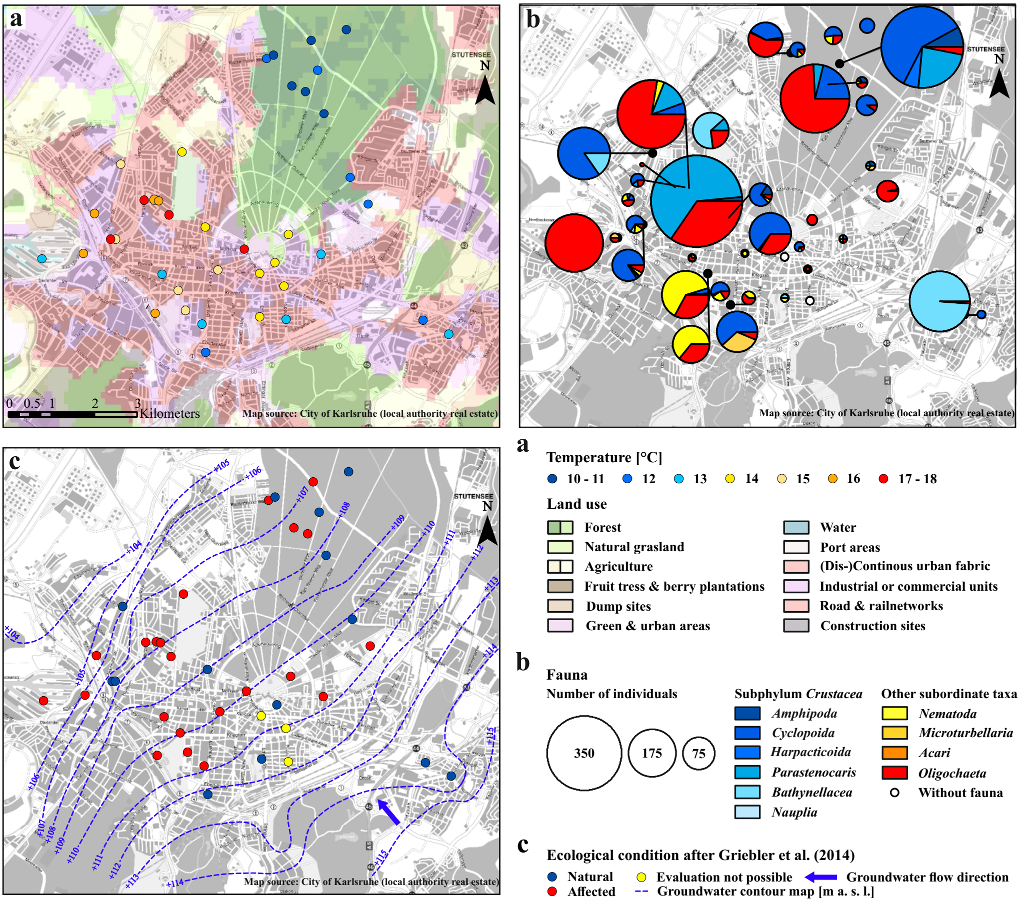


Figure 4.2: Overview map of the city area of Karlsruhe. (a) Land use plan (European Environment Agency, 2016) and average groundwater temperature of the multiple measurements (degrees Celsius) at the bottom of the monitoring wells. (b) Detailed groundwater fauna – colours of the circles show the different taxa in the sample (percent), and the size indicates the number of individuals. (c) faunal evaluation, after Griebler et al. (2014b), and groundwater contour map in metres above sea level (modified after the local authority real estate of Karlsruhe).

$n = 8$; 31) and higher dissolved oxygen concentrations (U test – p value = 5.3×10^{-3}; $n = 8$; 31), which indicates a correlation between abiotic groundwater characteristics and land use in the study area. Moreover, no impact of groundwater originating from the urban area is observed on the wells in the forested area, as the groundwater flow direction in Karlsruhe is northwest (see Section 4.2.1 and Figure 4.2c). Further investigations demonstrated that, besides one larger and two smaller contamination sites (still with concentrations below the threshold values, however; Figure A3.2b), only minor groundwater pollution is documented in Karlsruhe (see the Chapter 5.2). The chemical and physical parameters considered in the long-term monitoring system are within the range of local background and below threshold values of the drinking water ordinance of Germany (see the

Supplement for more information). Thus, the main documented impacts on groundwater quality in the study area are related to temperature and oxygen.

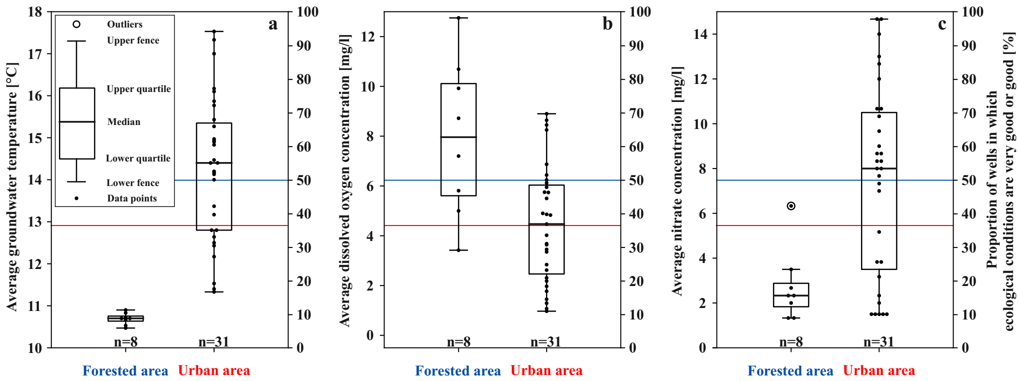


Figure 4.3: Box plots of the physical and chemical parameters for the forested and urban area in the study site and the proportion of wells in which ecological conditions are very good or good (in percentage), indicated by the blue (forested area) and red (urban area) lines (secondary axis). (a) Average temperature of the repeated measurements (degrees Celsius) at the bottom of the monitoring wells. (b) Average content of dissolved oxygen (milligrams per litre) of the monitoring wells. (c) Average nitrate content (milligrams per litre) of each monitoring well (*n* is the number of wells).

4.3.2 Groundwater fauna

The biotic communities of the groundwater consist of microorganisms and invertebrates (in particular crustaceans; Griebler et al., 2014b). In the pool of samples, 3,666 individuals were detected in 37 of 39 wells, which means that 95 % of the wells are colonised (Table A3.3). With 2,047 individuals, the group of *Crustacea* was found to be the most abundant (56 %). A total of 976 individuals (27 %) of the order of *Cyclopoida* dominated this group, followed by the genus *Parastenocaris*, with 599 individuals (16 %), the order of *Bathynellacea* (371), *Amphipoda* (66), *Harpacticoida* (33) and nauplia. The communities of the monitoring wells also frequently contained oligochaetes (1,343 individuals, 37 %). Furthermore, individuals of the phylum *Nematoda* (228 individuals) and *Microturbellaria* (46 individuals) were also often present.

Overall, there is a noticeable difference in the spatial distribution of species within the study area. Individuals of the subphylum *Crustacea* were found in larger numbers, with respect to the number of wells, in the monitoring wells in the forested area (690 individuals in eight wells) compared to those in the urban area (1,357 individuals in 31 wells). Furthermore, no individuals of the order *Bathynellacea* and only 135 individuals of the genus *Parastenocaris* were found in the forested area. In contrast, larger numbers of the latter species as well as of oligochaetes are characteristically found in the wells in the urban area. However, in contrast to the abiotic characteristics, no clear pattern of faunal diversity and land use was observed, as crustaceans and individuals of other subordinate taxa were found both in the forested and in the urban area.

Stygobiontic amphipods, i.e. large-bodied invertebrates, which, due to their size, have a habitat preference for open spaces such as wells (Table 4.1; e.g. Hahn and Matzke, 2005; Korbel et al., 2017), were found in only three wells (Figure 4.2b). A total of 46 individuals of this order were detected in the forest and 20 individuals in the urban area (Figure 4.4a, b). Although statistical analysis showed no clear differences between the abundance of amphipods and land use (U test – p value = 1.5×10^{-1}; n = 8; 31), the higher number of individuals in the forest area could support the hypothesis that amphipods indicate healthy groundwater ecosystems as they react most sensitively to disturbances such as pollutants (Korbel and Hose, 2011) and groundwater temperature. In laboratory experiments with a thermal tank, Brielmann et al. (2011) found that 77 % of the individuals of the studied amphipods (*Niphargus inopinatus*) preferred areas with a temperature between 8 and 16 °C. In addition, Spengler (2017) and Issartel et al. (2005) observed maximum temperatures of up to 17 °C. The lack of a statistically significant correlation might also be related to the low number of wells (n = 8 in the forested area) and individuals (n = 46). Amphipods are important ecosystem service providers in terms of bioturbation and organic decomposition (Boulton et al., 2008). As observed in laboratory experiments (Smith et al., 2016), they actively move, with migration speeds between 1.7 and 3.5×10^4 m per year. In most cases when amphipods were found, higher concentrations of individuals of the order *Cyclopoida* were also identified (abundance of *Amphipoda* versus *Cyclopoida*; U test – p value = 9.6×10^{-5}; n = 39). Individuals of the latter order were generally found in larger quantities in the majority of the wells (479 in the forested area and 497 in the urban area), as they are the largest group of crustaceans in this environment (Fuchs et al., 2006) and can tolerate a wide temperature range (e.g. upper thermal limit of 26.9 ± 0.2 °C in laboratory tests by Castaño-Sánchez et al., 2020a; Spengler, 2017).

The order *Harpacticoida*, which includes the genus *Parastenocaris*, have an elongated body shape and a stem-chiselling movement, which is why they are predestined for living in cavities and groundwater (Fuchs, 2007; Hahn, 1996) and prefer sand and gravel as a substrate (Galassi et al., 2009). Larger numbers of *Parastenocaris* (464 individuals), which can tolerate GWT from 8 to > 20 °C (Fuchs et al., 2006), e.g. *Parastenocaris phyllura* withstood up to 22.5 °C in laboratory tests (Glatzel, 1990), were found in the urban area, especially in the northwestern area (Figure 4.2b). This area is characterised by GWTs between 16 and 18 °C, the highest at the study site. This observation is comparable with previous studies (Hahn, 2006; Hahn et al., 2013; Spengler, 2017), which showed that the genus *Parastenocaris* is particularly non-competitive and can often be found isolated in structurally burdened and physically and chemically altered areas. Accordingly, only 135 individuals were detected in the forested area.

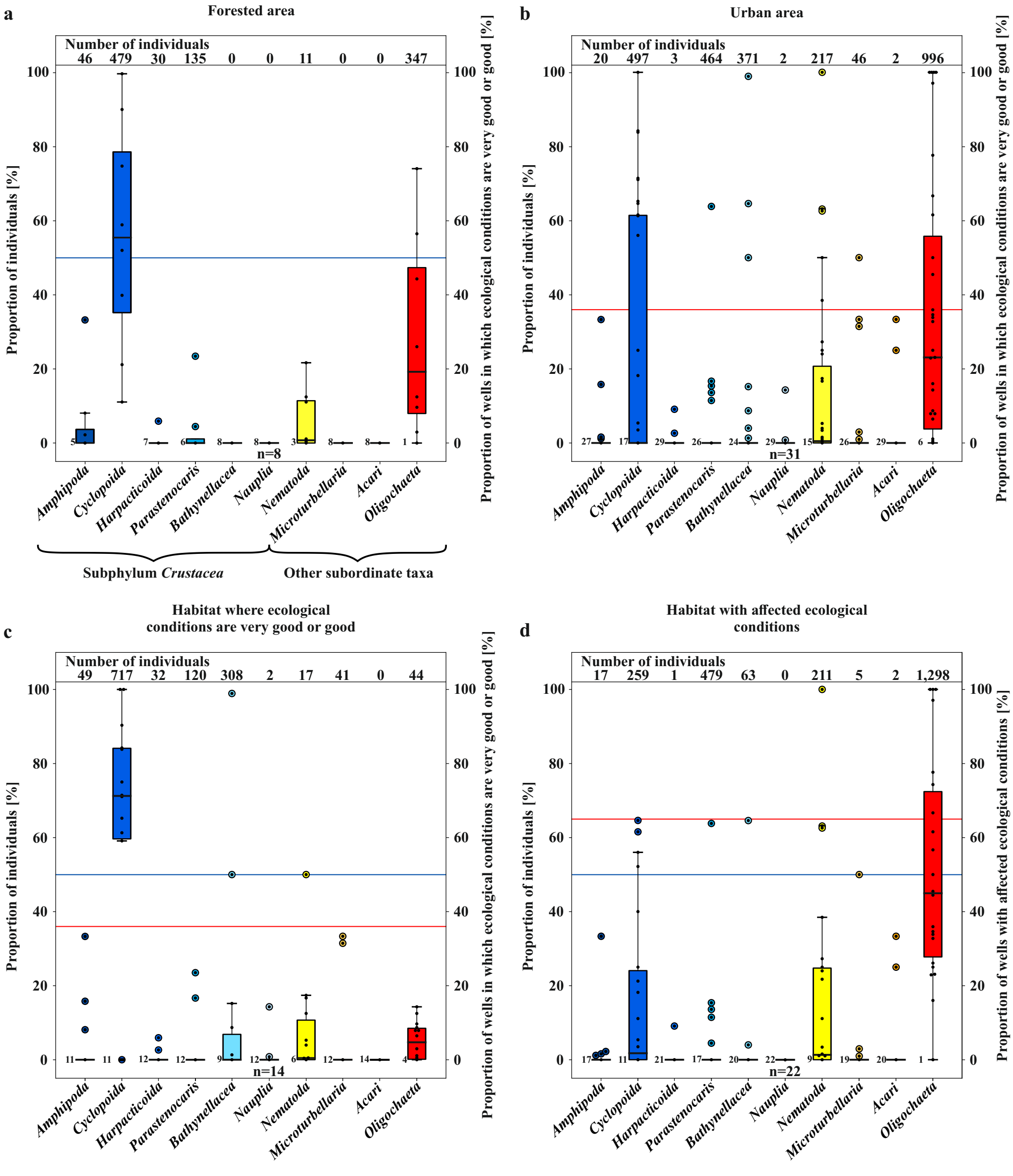


Figure 4.4: Box plots of the amount of fauna (percent). (a) Proportion of individuals and wells in which ecological conditions are very good or good (secondary axis; percent) in the forested area. (b) Proportion of individuals and wells in which ecological conditions are very good or good (percent) in the urban area. (c) Proportion of individuals and wells in which ecological conditions are very good or good (percent), divided based on the results of the classification scheme by Griebler et al. (2014b). (d) Proportion of individuals and wells with affected ecological conditions (percent), divided based on the results of the classification scheme by Griebler et al. (2014b). The colour of the boxes shows the different taxa in the samples (n is the number of wells).

In addition, quantities of *Bathynellacea* (371 individuals) were found in five monitoring wells all located in the urban area at a depth of 9.0 to 13.5 m with a GWT of 12 – 15 °C (Figure 4.4b). This order typically inhabits the interstitial groundwater, which is characterised by a dominant exchange with the surface water and high variations in GWT and can tolerate temperatures up to 18 °C (Stein et al., 2012). Interestingly, one location in the southern city area with 272 individuals is characterised by a high fluctuation in GWT (standard deviation of 3.4 °C) and a rather high nitrate content (8.3 mg/l) compared to wells in the forested area, which are both indications for a disturbed and stressed habitat. Besides the group of crustaceans, oligochaetes, which can tolerate a wide temperature range, were also found in large abundance in the study site. A significant amount of the subclass *Oligochaeta* (996 individuals) was found in the urban area (Figure 4.4b), compared to an overall number of 1,343 individuals. In general, the number of oligochaetes is larger in locations with high GWT (12.6 – 17.3 °C) and nitrate concentrations up to 14 mg/l, which is above the geogenic concentration of 10 mg/l and higher compared to wells in the forested area.

Finally, nematodes and microturbellarians were found at locations with unfavourable living conditions, such as a low dissolved oxygen content or a high amount of fine substrates, as also reported by Hahn et al. (2013), and both can tolerate high temperature ranges (*Turbellaria* – 2 – 20 °C (Herrmann, 1985); *Acari* – 9.1 – 18.5 °C (Wiecek et al., 2013)). Here, both were found in larger quantities in the urban area of Karlsruhe (Figure 4.4b). This area has the lowest content of dissolved oxygen and a relatively higher amount of detritus (> 2).

Eventually, correlation analysis between groundwater fauna and the chemical parameters showed that stygobites are only slightly affected by groundwater chemistry (Hahn, 2006; Schmidt et al., 2007; Stein et al., 2010). Only the Spearman rank correlation coefficient (ρ) between the number of taxa and the dissolved oxygen content is significant, with a value of $\rho = 0.55$ (p value = 3.0×10^{-4}; $n = 39$). Moreover, it is assumed that groundwater fauna can usually cope well with short-term changes in physical–chemical parameters (Griebler et al., 2016). Previous studies showed that some species can even benefit from pollutants (Matzke, 2006; Zuurbier et al., 2013). In case of nitrate, numerous studies emphasise that nitrate at concentrations below 50 mg/l does not directly affect groundwater fauna (Di Lorenzo et al., 2020b; Di Lorenzo and Galassi, 2013; Fakher el Abiari et al., 1998; Mösslacher and Notenboom, 2000). As the highest average nitrate content per well is below 15 mg/l in this study, a direct negative effect of the nitrate concentration on the groundwater fauna is unlikely. Thus, nitrate is only mentioned as one measured parameter and is not discussed as a potential anthropogenic impact in this study.

The natural influences on porosity, groundwater flow and nutrient delivery were also discussed as being a primary influence on natural stygobite distribution in previous studies (Hahn, 2006; Korbel and Hose, 2015). An important natural influence is the local geology, as fine sands and silts are typically rather harsh environments, resulting in an impoverishment of specific groundwater fauna such as *Crustacea* (Hahn, 1996). The city of Karlsruhe is located on carbonate (Würm) gravel and river terrace sands, pervaded by bands of drifting sand and inland dune sands. These sediments are highly water permeable and show vertical seepage of water movement almost exclusively. Flood sediments (on top of river gravel) and bog formations, are located in the east and west of Karlsruhe (Regierungspräsidium Freiburg, 2019). This local geology limits the cavity size and, therefore, has impacts on the habitat of the groundwater fauna (Wirsing and Luz, 2007). For example, individuals of the genus *Parastenocaris* typically inhabit small-scale cavity systems (Spengler, 2017). Individuals of this genus can be found both in the wells drilled in gravel (four wells) and in drifting sand sediments (three wells; abundance of *Parastenocaris* versus geological units; U test – p value = 1.4×10^{-9}; $n = 39$). Amphipods are predominantly found in measurement wells located in the Würm gravel (in five of seven wells; abundance of *Amphipoda* versus geological units; U test – p value = 9.0×10^{-11}; $n = 39$). Moreover, it seems that differences in the geological units have an influence on the total amount of individuals (U test – p value = 1.7×10^{-9}; $n = 39$) and the relative amount of detritus (U test – p value = 3.0×10^{-3}; $n = 39$). As these results show, regional geology seems to have an influence on the occurrence of specific groundwater taxa and on the number of individuals and on food supply, in terms of available organic matter. However, it is not possible to give a reliable estimate of the strength of the anthropogenic impacts, e.g. if they are strong enough to overrule the regional selective forces. Hence, this should be investigated in more detail in future studies.

Limitations regarding the sampling method must be considered when interpreting the faunal results. In this study, a simple basic screening of well water was conducted using a net sampler and bailer to examine conditions in the groundwater monitoring wells (39 wells with an average diameter of 132.5 mm, which corresponds to an area of 0.003 ‰ of the total urban area). According to the sampling manual of the PASCALIS project, ‘the use of a phreatobiological net alone is considered as [being] a satisfactory method for sampling groundwater fauna in large diameter wells’ (Malard et al., 2002). Yet, several studies (e.g. Scheytt, 2014) report that scooped samples of wells are not representative, and therefore, the water remaining in a well has to be purged and discarded before sampling. Nevertheless, pumping can result in the selection of the taxa, especially in the presence of very fine sediments, and can result in changes in the sediment composition in the surrounding of the wells and, therefore, in habitat conditions. Other studies, on the other hand, found no significant differences in hydro-chemical values (temperature, pH, dissolved oxygen, etc.) between the surrounding groundwater and the standing water in a well (Hahn and Matzke, 2005; Korbel et al., 2017). The sampled groundwater fauna of corresponding wells and aquifers were also shown to be similar with respect to the types of faunal communities. However, in terms of total abundance, and the numbers of individuals per litre, monitoring wells appear to exhibit larger numbers caused by filtration effects (Hahn and Gutjahr, 2014; Hahn and Matzke, 2005; Korbel et al., 2017). As the aim of this study is to provide an overview of the groundwater fauna community and to receive a first impression of groundwater ecology, sampling the fauna by using a net sampler is sufficient. In order to achieve a representative sampling of groundwater fauna in the aquifer and to reflect the occurring species at a community level, a more comprehensive sampling method is required, e.g. the use of a defined standard sampling method, using a pump, to collect animals (Malard et al., 2002). Care should also be taken when interpreting faunal results of sites that are sampled in different years. To improve comparisons of the biotic communities, a consistent sampling period of every well is necessary in the future.

4.3.3 Classification scheme by Griebler et al. (2014)

In three wells, evaluation with the classification scheme by Griebler et al. (2014b) was not possible due to ocherous conditions in two monitoring wells and low dissolved oxygen content (< 1 mg/l) in the third well. According to the classification scheme by Griebler et al. (2014b), unstressed (meaning no natural or anthropogenic stressors) or natural groundwater habitats have more than 70 % of crustaceans and less than 20 % of oligochaetes. In 36 % of the sampled wells, i.e. 14 out of 39, these criteria were fulfilled, indicating very good or good ecological conditions or, in other words, a natural groundwater habitat (Figure 4.4c). These natural areas tend to contain more individuals of the orders of *Amphipoda*, *Cyclopoida* and *Bathynellacea*. Monitoring wells, which do not fulfil these criteria and are accordingly defined as affected areas not having natural ecological conditions, contain more oligochaetes and also nematodes, which is partly explained by the criteria of this classification scheme (Figure 4.4d).

Surprisingly, only 50 % of the wells in the forest, which is also the catchment area of the drinking water supply of Karlsruhe, are described as being natural groundwater habitats. An identical number of wells yielded habitats with affected ecological conditions. The main difference between natural and affected wells in the forested area arises from the occurrence of specific species. A total of 86 % – 100 % of species found in natural wells are crustaceans, in contrast to affected wells with only 33 % – 67 % (Table A3.2 and A3.3). However, the abiotic parameters scarcely differ between natural and affected wells (average values for GWT – 10.8 and 10.6 °C; dissolved oxygen – 7.1 and 8.8 mg/l; nitrate – 2.5 and 3.0 mg/l), indicating that there are other processes or parameters that influence the groundwater fauna in these wells. A reason could be the varying local geology, as mentioned above. Moreover, food supply is one of the most limiting parameters for the survival of groundwater fauna (Datry et al., 2005; Hahn, 2006). If the organic carbon supply varies on a small scale, this can influence the microbiology and, therefore, the groundwater fauna as well, although short-term changes in nutrient supply can be compensated by groundwater fauna.

In contrast to the forest land, the majority of wells (65 %) in the urban area are categorised as affected habitats. As expected, this indicates anthropogenically influenced groundwater ecosystems beneath the studied urban area. Once more, no significant differences between the abiotic parameters of natural and affected wells are observed (e.g. median of dissolved oxygen – 4.7 and 5.8 mg/l; median of nitrate – 7.2 and 7.8 mg/l). On the other hand, the remaining 35 % of the wells in the urban area show natural ecological conditions even though some of them are located in areas with anthropogenic impacts such as increased groundwater temperatures. Hence, no distinct spatial pattern of the ecological condition with respect to land use could be identified.

In future, a further subdivision of a study area in more land use categories could be beneficial for specifically looking at typical anthropogenic impacts. Furthermore, the integration of more biological criteria is useful to improve the results of the assessment, according to Griebler et al. (2014b). Because of heterogeneous groundwater ecosystems in Germany, it is likely that the reference values provided by Griebler et al. (2014b) do not reflect the situation in Karlsruhe correctly. Considering site-specific characteristics and reference values would lead to a more robust assessment. Other assessments, like the similarly structured GHI or wGHI^N (Di Lorenzo et al., 2020a; Korbel and Hose, 2017) can, additionally, be used. Moreover, there are a few newly developed indexes, like the D–A–C (prokaryotic cell density – D; activity – A; bioavailable carbon – C) Index, which is based on microbiological indicators and shows whether groundwater reserves deviate from natural references (Fillinger et al., 2019), which can be used in the future. As mentioned in the introduction, another way of quantifying the relevant ecological conditions in the groundwater is the GFI. During the preparation of this study, the GFI was tested on the data (see Chapter 5.2); however, it did not provide any additional information or valuable insights and was therefore excluded. The influence of multiple stressors, such as the pollution of the groundwater through industrial plants, etc., and their effects on the governing parameters can bias the GFI. In general, the GFI seems to be suitable only for unpolluted and anthropogenically undisturbed groundwater with sufficient oxygen concentrations (> 1 mg/l). Moreover, under urban areas, changes in GWT are caused by anthropogenic heat inputs (Benz et al., 2014; Menberg et al., 2013b; Tissen et al., 2018) rather than being related to surface water influences. Hence, the GFI appears to be unsuitable for the assessment of the groundwater fauna in an urban setting. The same outcome emerges for the Shannon diversity index, which was also tested during the preparation of the study and showed no clear distribution pattern according to faunal diversity and was therefore not considered further.

4.3.4 PHATE analysis

A PHATE analysis is conducted using the following input parameters: depth, GWT, nitrate and phosphate content, the relative amount of detritus, geological unit, number of taxa, number of individuals, Shannon diversity, number of crustaceans and oligochaetes (according to Griebler et al. (2014b)) and the abundance of amphipods as well as of individuals of the orders *Cyclopoida* and

Bathynellacea and the genus *Parastenocaris*. The content of dissolved oxygen is not considered in this analysis since it was always above the limit of 1 mg/l, except in one case. Thus, dissolved oxygen is not expected to have an influence on the groundwater fauna in our study area.

There are four groups, which can be assigned predominant characteristics, that can be distinguished in the PHATE visualisation (Figures 4.5 and A3.3 - A3.4). A total of three measurement wells (group IV) contain neither oligochaetes nor crustaceans, indicating unfavourable living conditions. In contrast, the nine wells of group III contain high amounts of oligochaetes (100 % of oligochaetes according to the scheme of Griebler et al. (2014b), and an average GWT of 14.3 °C; Table A3.4). However, diversity and abundance was found to be low in group III.

An even higher average GWT of 15.0 °C was found for group II, which mostly consists of wells drilled in drifting sand sediments. Surprisingly, these wells also show the highest diversity ($\geq$ three taxa per well), the highest Shannon diversity (see Chapter 5.2), and the highest number of individuals in total and of individuals of the genus *Parastenocaris*. Individuals of this genus are often found isolated in altered areas (Spengler, 2017). Moreover, in five wells of group II, individuals of the order *Bathynellacea*, which can tolerate temperatures up to 18 °C and typically inhabit interstitial groundwater (Stein et al., 2012), were found. The presence of individuals of the genus *Parastenocaris* and the order *Bathynellacea* in group II suggests that they may act as type species for urban situations. The observation that group II shows the highest GWT and the highest Shannon diversity is in contrast to findings of previous studies that noticed decreased diversity at elevated temperatures (Brielmann et al., 2009). These diverging observations suggest that faunal quantities, such as diversity or abundance, are not always suitable indicators for changes within organism communities. For example, if species disappear due to increased temperatures and are substituted by more tolerant species, the difference in diversity may be marginal and the change in the community may not be noticeable.

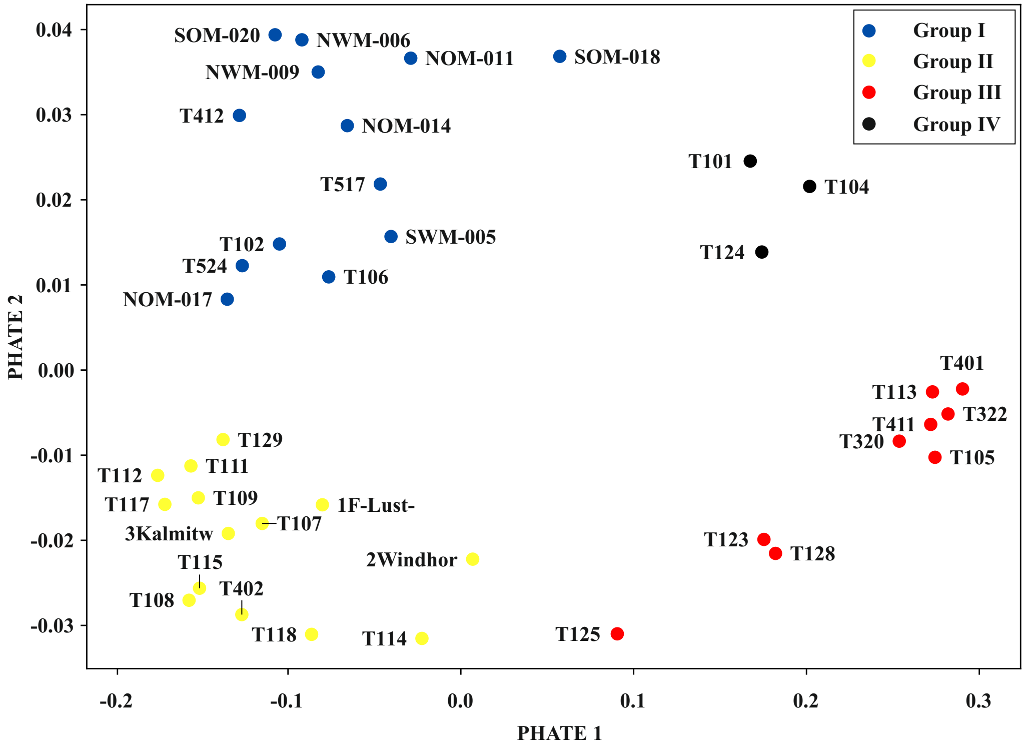


Figure 4.5: PHATE visualisation showing similarities between measurement wells. Different colours indicate the four clearly separable groups.

Wells of group I (blue) are drilled predominantly in Würm gravel (geological unit of group I versus group II; *U* test – *p* value = 8.2×10^{-3}; $n = 13; 14$), while having the lowest GWT (GWT of group I versus group II; *U* test – *p* value = 2.0×10^{-5}; $n = 13; 14$). These wells show a moderate diversity and number of individuals, yet have the highest average number of crustaceans and the highest number of amphipods and individuals of the order *Cyclopoida*. Considering these findings and the *U* test results (see Table A3.5), the grouping of the measurement wells seems to be influenced by the composition of the groundwater organism communities, the faunal diversity (numbers of taxa and individuals) and the geological unit and the GWT (Figures A3.3 - A3.4).

Considering the spatial distribution of the grouped wells in the study area, it becomes apparent that all wells in the forested area fall within group I (Figure 4.5). Those wells which are located outside the forested area are in locations with nearby green areas (parks, recreational areas, etc.). In contrast, the wells of the other three groups are heterogeneously distributed within the urban area. Many of the measurement wells of groups III and IV are associated with suspected or known contaminated sites (Figure A3.2b). Overall, a spatial pattern of abiotic groundwater characteristics

(GWT and nitrate content) and the occurrence of particular species (*Parastenocaris*) within the study area is apparent in the PHATE analysis, which confirms the classification according to land use. Yet again, no clear spatial pattern regarding faunal diversity in the study area could be identified, although a tendency of clustering of wells from group III with higher diversity and number of individuals can be seen in the northwestern area of the city.

4.4 Conclusion

The aim of this study is to provide a first assessment of the ecological state of groundwater in an urban area and to distinguish areas with a natural state of groundwater ecology from anthropogenically affected areas. To achieve this, we examine the groundwater fauna and abiotic parameters in 39 groundwater monitoring wells in residential, commercial and industrial areas (31 wells) and a forested area (eight wells) outside the built-up area of Karlsruhe, Germany, using the simple classification scheme by Griebler et al. (2014b) to characterise the sampled monitoring wells.

We found a noticeable difference in the spatial distribution of abiotic groundwater characteristics and special species within the study area. The forested area shows lower GWT, lower nitrate concentrations and higher dissolved oxygen concentrations, which indicates a correlation between abiotic groundwater characteristics and land use. Moreover, amphipods are more abundant in wells in the forested than in urban area. However, in both the rural forested and in the urban area, crustaceans and individuals of other subordinate taxa were widely found, and therefore, no clear spatial pattern regarding faunal diversity and land use was found. In terms of faunal quantity, crustaceans were found in larger numbers, with respect to the number of wells, in the monitoring wells in the forested area compared to those in the urban area. Larger numbers of the genus *Parastenocaris* and of nematodes and oligochaetes were found to be characteristics for wells in the urban area.

Furthermore, no clear spatial pattern of ecological groundwater conditions, according to the classification scheme by Griebler et al. (2014b), could be observed. Surprisingly, only 50 % of the sampled wells in the forested area were described as natural (undisturbed) groundwater habitats, while the other four were characterised as habitats with affected ecological conditions. Yet, the majority of wells (65 %) in the urban area were classified as affected locations, suggesting that there are noticeable differences in the groundwater ecosystems between the surrounding forested and urban areas. The level 2 assessment from Griebler et al. (2014b) can help to achieve a more reliable and quantitative ecological assessment of urban aquifers as it divides groundwater ecosystems into ecological grades according to the intensity of anthropogenic disturbance. It is based on the use of local reference values and the collaboration with experts; however, is challenging to apply.

Therefore, further studies with large-scale and repeated measurement campaigns are needed to verify our findings. This should also include other cities and the determination of undisturbed local reference values which are required for a more reliable, but also quantitative, ecological assessment of urban aquifers. Moreover, a wider range of indicators should be considered in a classification scheme, such as temperature, porosity of the aquifer, groundwater flow, pollutants and nutrient supply, especially when investigating urban areas. In addition, an important adaptation for an improved evaluation method is the determination of fauna at species level, which will provide more information (i.e. about stygobionts, stygophiles and stygoxenes) and also consider the endemism of stygobiontic species. In this context, classification schemes should pay more attention to the different groundwater species and their potential use as indicator species. Finally, city and energy planning should seriously consider urban groundwater ecosystems as they provide valuable information for a sustainable use of the subsurface.

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5

SYNTHESIS

5.1 Summary and conclusion

Groundwater is an important global resource that harbours a complex ecosystem, which provides important services, including water purification, as well as nutrient and carbon cycling. Nevertheless, this ecosystem has hardly been investigated and even the most basic knowledge is still lacking in many parts of the world. This thesis aims to improve the understanding of ecological processes and conditions in groundwater, which are essential for sustainable resource and environmental management in times of competing groundwater uses. Therefore, a common knowledge basis on groundwater fauna is built, changes in faunal and abiotic parameters due to natural or anthropogenic influence are investigated, indicator parameters are identified, and implications for biomonitoring on different scales are discussed. Thus, groundwater fauna is described and assessed on different spatial and temporal scales (see Figure 5.1).

Since information on groundwater ecosystems is still lacking in many parts of the world, it is necessary to gain a **global overview on groundwater fauna** and to build up inventory and carry out analyses of available data. Thus, this thesis provides an overview on groundwater fauna (stygofauna) research, including the historical evolution of research topics and the development of sampling methods, and secondly, it identifies the global distribution of groundwater fauna research and existing data gaps. Data from 859 studies, such as from national and international publications

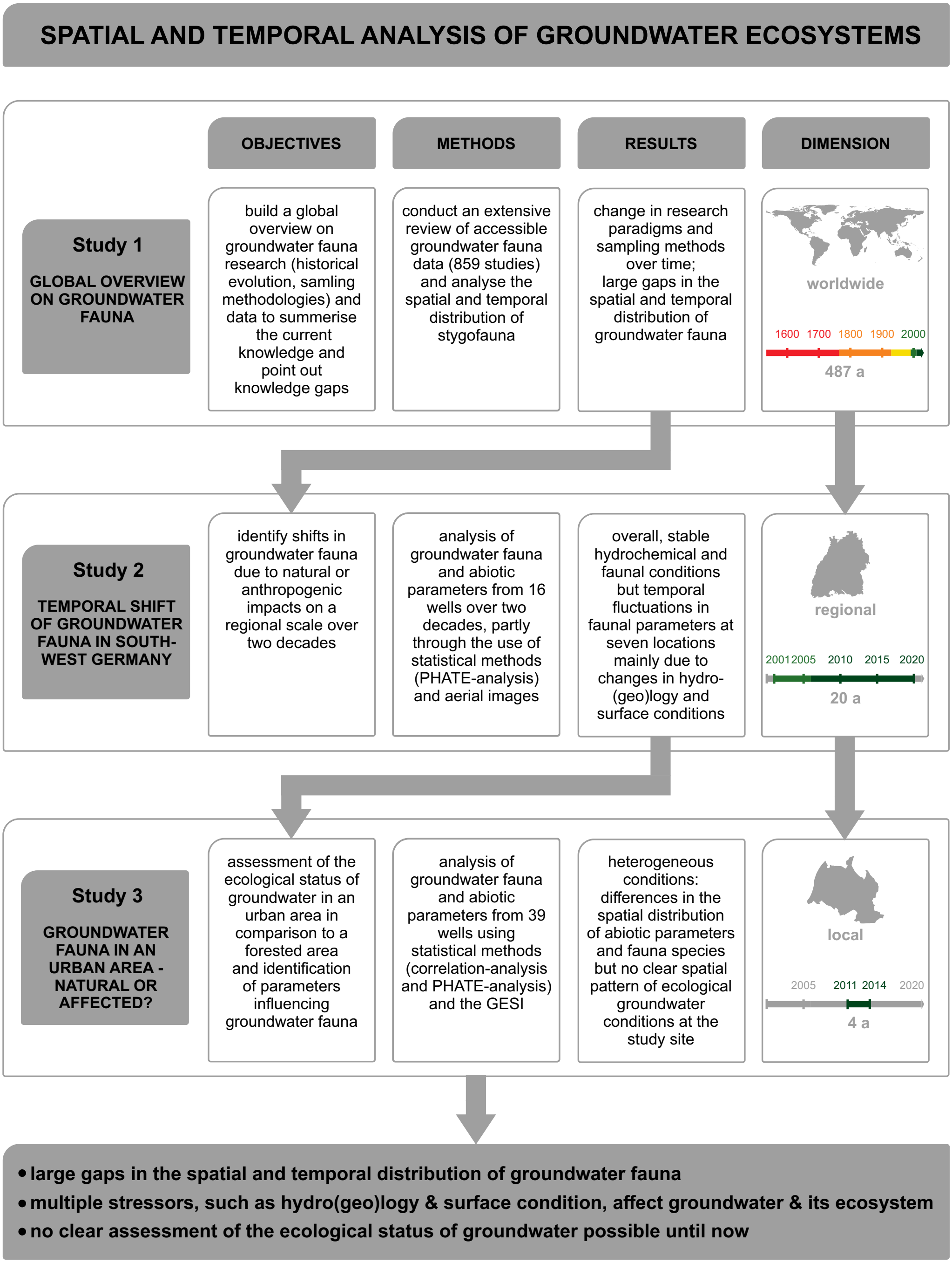

Figure 5.1: Objectives, methods, results and dimension of the three collected studies in this thesis.

in scientific journals, national reports, doctoral theses, historical writings, books, online databases and others, is analysed and an extensive review of accessible groundwater fauna data is conducted.

In the early research phase, sporadic observations of fauna date back to 1537, but it was not until the 17th century that groundwater fauna research increased. During the ‘pre-ecological research phase’, the emphasis of research was still on cataloguing new species, their habitats and their biogeographical origin. It was in the 1920s that the research focus changed from the description of newly discovered species and their evolution towards ecosystemic and more holistic analyses of fauna and their functions to the application of ecological management and monitoring programs. The growing interest in groundwater fauna research is reflected in the exponential increase in the number of studies over time since the 1920s, which peaked in 2009. Moreover, sampling methods have developed from using simple nets, substrate samples and hand-pumps in the beginning to recent molecular analyses (e.g. eDNA), which offer the potential to ease sampling and enable vast data collection. Until now, net sampling and pumping well water have been the dominating sampling methods worldwide. In the early 2000s, during the ‘applied ecological phase’, the first policies to conserve and protect groundwater quality and GDE are developed in Switzerland, Germany and Australia.

Studies on groundwater fauna are spatially uneven and are dominated by research in Europe and Australia, with few studies in Africa, Asia and the Americas. In Africa, very limited information about stygofauna distribution (i.e. the geographical spread of groundwater fauna), ecosystem services and ecological status is available, with information on associated trends over time also missing. American groundwater fauna studies predominantly provide insight into newly discovered species and biogeographical analyses, including factors influencing biogeographical distribution of stygobionts. In relation to its large area, Asia is poorly investigated, and studies are concentrated in Japan, South Korea, India and Iran. Moreover, most studies in Asia and the Middle East still focus on describing newly discovered species, with limited studies investigating the origin, functioning and distribution of stygofauna or groundwater ecology. These gaps in global research bias the view on groundwater biota, hindering the identification of biodiversity patterns and ecosystem functions on a wider geographic and climatic scale. Matters are quite different in Australia and large parts of Europe. Australia is regarded as a pioneer in the field of stygofauna monitoring programs. Australian studies also contributed greatly to the global understanding of stygofauna evolution, distribution, sampling methods, ecosystem functions and processes, anthropogenic impacts on these ecosystems and the recognition of the need to protect groundwater resources and their ecosystems. In Europe, research began with descriptions of species and taxonomy, as well as the development of more complex sampling methods. Moreover, European studies on groundwater fauna have contributed much to the global knowledge on the impact of natural events and resulted in the development of ecological assessment frameworks (Fillinger et al., 2019; Griebler et al., 2014b; Hahn, 2006). The high density and frequency of sampling and the research focus on biodiversity and ecology issues have placed Germany at the forefront of stygofauna research and the application of ecological research to address groundwater management and monitoring requirements. This first global overview on groundwater fauna research is important to understand biodiversity and to determine future research fields. Thus, a worldwide effort to collect information on groundwater ecosystems, their functional roles and anthropogenic impacts on them is required to implement stronger policies and monitoring requirements for groundwater fauna.

One approach to improve the understanding of groundwater biodiversity and thus enhance a comprehensive assessment and protection of the ecosystem and the development of potential measures is biomonitoring. As already implemented for surface water (Haase et al., 2023), ecosystem monitoring can help to assess its health or ecological status. Thus, organisms and communities act as remote sensors integrating environmental conditions and stress over their lifetime, and provide information on medium- to long-term environmental conditions and changes (Conti, 2008). In this thesis, long-term groundwater data from **South-West Germany** is used to identify **shifts in groundwater fauna** due to natural or anthropogenic impacts. Available groundwater data of the study area (i.e. the state of Baden-Württemberg) is reviewed, and observation wells for additional sampling in 2020 are selected. In total, 16 observation wells are selected based on spatial coverage of the study area, aquifer type, land use type, well depth, faunal colonisation during the past two decades, availability of time series of physico-chemical parameters, and an average content of dissolved oxygen higher than 1 mg/l. Afterwards, the biotic and abiotic data is temporally and statistically analysed on different spatial scales (local to state-wide). Comprehensive analysis of metazoan groundwater fauna and abiotic parameters from 16 monitoring wells over two decades reveals no overall temporal trends for fauna abundance, biodiversity in terms of number of species, as well as no significant large-scale trends in abiotic parameters. This indicates that large-scale biodiversity and hydro-chemical conditions were stable over the past two decades on a regional scale. Nevertheless, there are significant variations between individual years for some specific wells, indicating a more complex temporal behaviour on a local scale. While nine wells out of 16 show stable ecological and hydro-chemical conditions, the remaining seven wells exhibit shifting or fluctuating faunal parameters. At some locations, these temporal changes are linked to gradual natural changes in abiotic parameters, such as decreasing dissolved oxygen contents or fluctuating temperatures. More often, however, there are no clear patterns in the abiotic parameters of individual wells. Instead, changes in groundwater fauna are caused by superimposing effects of multiple parameters linked to increasing or weakening surface influence (Schwäbisch Hall, Gaggenau and Efringen). Moreover, most monitoring wells in this study have a ‘natural’ status according to the assessment scheme of Griebler et al. (2014b). Only six wells (Kadelburg, Schwäbisch Hall, Rohrdorf, Sankt Leon, Weingarten and Neckargartach) have a proportion of Oligochaetes higher than 20 % in one or multiple years, indicating disturbed conditions. Abiotic parameters show mostly constant conditions in the individual wells.

A multivariate PHATE-analysis suggests that, besides the hydrogeological setting, varying contents of sediment and detritus impact faunal abundance. Finally, three individual wells are analysed in detail, as certain changes in faunal parameters in those individual wells could not be directly related to varying abiotic parameters. Thus, two unstable wells are analysed with respect to changes at the surface surrounding and compared to a deeper and rural well, which shows very stable conditions. By examining aerial images of the surroundings of individual wells over time, anthropogenic impacts, such as construction sites in Neckargartach were identified, and seem to cause significant shifts in groundwater fauna from dominating Oligochaetes to Crustaceans and thus to the aforementioned change in the ecological status. In Sankt Leon, faunal changes indicate a weakening surface influence over time, without visible changes in land use or surface conditions and thus no drivers of the unstable conditions. However, variable faunal composition and abundances are also observed for sites with very stable abiotic conditions in anthropogenically less affected areas, such as in Todtnau. These findings indicate that hydro(geo)logical changes and surface conditions, such as land use, should be assessed in line with hydro-chemical parameters to understand changes in groundwater fauna better. Accordingly, reference sites for natural conditions in ecological assessment and biomonitoring schemes for groundwater protection should be selected very carefully.

Changes in hydrology and surface conditions are increasingly occurring in densely populated urban areas, making it more challenging to find uninfluenced reference sites in such regions. Moreover, there are increasing conflicts over the use of groundwater, which is why the investigation of urban aquifers is becoming increasingly important for sustainable resource and environmental management. As groundwater quality is the product of multiple physical–chemical and biological processes and healthy groundwater ecosystems help to provide clean drinking water, it is necessary to assess their ecological conditions. Previous analyses within the framework of the global review have shown that faunal groundwater investigations are still scarce in urban areas. Therefore, this thesis assesses the **groundwater fauna in an urban area**. For this purpose, the ecological status of an anthropogenically influenced aquifer is examined by analysing fauna and hydrogeological, physico-chemical parameters in 39 groundwater monitoring wells in the residential, commercial and industrial, i.e. urban areas (31 wells) in comparison to a forested area (eight wells) outside the built-up area of the city of Karlsruhe (Germany). Analyses confirm noticeable differences in the spatial distribution of abiotic groundwater characteristics, such as lower GWT, lower nitrate concentrations and higher dissolved oxygen concentrations in the forested area. This indicates a correlation between abiotic groundwater characteristics and land use. Moreover, spatial differences in species distribution are observed, as amphipods are more abundant in wells in the forested than in the urban area, and larger numbers of the genus *Parastenocaris* and of nematodes and oligochaetes are typical for wells in the urban area. However, no clear spatial pattern is found for faunal diversity and land use as crustaceans and individuals of other subordinate taxa are widely found in both the rural forested and the urban area. Moreover, correlation analyses between groundwater fauna and the abiotic parameters show that local geology influences the occurrence of specific groundwater taxa, the number of individuals and food supply. A PHATE-analysis reveals that similarities between wells can best be explained by the composition of the groundwater organism communities, the faunal diversity, the geological unit and GWT. Again, no clear spatial pattern regarding faunal diversity in the study area could be identified. For classification, the groundwater ecosystem status index GESI is applied, in which a threshold of more than 70 % of crustaceans and less than 20 % of oligochaetes serves as an indication for very good and good ecological conditions. Only 35 % of the wells in the residential, commercial and industrial areas and 50 % of wells in the forested area fulfil these criteria. However, no clear spatial patterns concerning land use and other anthropogenic impacts, particularly with respect to GWT are found. Thus, this study reveals heterogeneous faunal conditions in urban and also in ‘natural’ groundwater as a habitat, which do not allow a clear assessment of the ecological status with existing assessment approaches.

Summing up, groundwater is a complex system affected by multiple stressors, thus showing heterogeneous conditions as a habitat even at a local scale. Changes in hydro(geo)logy and surface conditions, such as land use, influence groundwater fauna. Thus, this thesis reveals the need to improve our understanding of this ecosystem further and to obtain clear information on its ecological status.

5.2 Perspective and outlook

Despite a continuing, exponential increase in the number of studies on groundwater fauna over the last ten decades, there is more inter- and transdisciplinary work required for a comprehensive assessment and protection of groundwater ecosystems worldwide. Studies 1 to 3 (Chapters 2 - 4) of the present thesis highlight the need for further investigation of this complex ecosystem. Based on the findings of this thesis, further research on the following specific subjects is suggested:

(I) Application of biomonitoring

Findings from this study can help to design and refine robust ecological monitoring and management tools for agencies and local authorities. To ensure representative results of future groundwater fauna sampling campaigns, it is advisable to employ shorter sampling intervals, e.g. on a monthly basis, to also address the effects of seasonality. Additionally, future research should focus on identifying and analysing reference sites for different settings, including forests, green areas, cities, industrial areas, and surface waters, to account for small-scale heterogeneities in hydrogeological conditions and land use. These measures are crucial for the transferability of findings from local biomonitoring to larger scales and in the long run, as well as to identify sites at high risk. The principle is that we can only protect what we know.

(II) Development and use of a standardised assessment scheme

Investigations on groundwater fauna and the impacts of humans on the corresponding ecosystems are still rare. Until now, there is no common understanding of the best practice for assessing the ecological status of groundwater on a larger scale, although there are some approaches available, such as the GFI, GHI and the scheme according to Griebler et al. (2014b). Each of these approaches has advantages and disadvantages, as well as limited applicability due to the amount of data required and the complexity of the area to be analysed. Therefore, the aim must be to develop a more reliable, but also quantitative, ecological assessment. As a basis for a new assessment scheme, approaches from the surface water assessment could be considered, adapted and further developed for groundwater specific aspects. The present thesis offers findings for developing a new and standardised assessment scheme for groundwater health. It has been shown that various parameters, such as surface conditions (e.g. built-up areas, underground infrastructure, sealing, etc.), hydrogeological (e.g. type of aquifer, geological unit, size of pore cavities, groundwater flow), and physico-chemical (e.g. electric conductivity, temperature, content of dissolved oxygen, pollutants and nutrient supply) influence the health of the ecosystem. Thus, a more comprehensive range of indicators should be considered in an assessment scheme in the future. This is particularly true when investigating urban areas.

(III) Development of a standardised sampling method

To record groundwater biodiversity, comprehensive data on fauna is needed. Therefore, fauna sampling in groundwater should become standard practice alongside groundwater quality measurements and physico-chemical analyses. Likewise, it has to be ensured that representative samples of the entire faunal community are available. This is complicated for stygofauna as different sampling regimes need to be considered. Over time, several novel methods, described in detail in Chapter 2, were developed to account for these challenges. In summary, net sampling and pumping well water are the dominating sampling methods worldwide. Nevertheless, each of the described methods has its limitations. Hence, a combination of methods, such as net sampling together with pumping and/or DNA-analysis, is recommended (Korbel et al., 2017; Saccò et al., 2022c).

(IV) Development of a common global database

Huge data sets are required to obtain extensive knowledge of stygofauna biogeography and biodiversity. Fauna databases are a useful tool for managing and sharing large amounts of data. An example of a national database is the Queensland Subterranean Aquatic Fauna Database in Australia, which contains data from 755 samples of 582 sites provided by the Queensland Government and industry. Moreover, a smaller reference database, with 65 wells in New Zealand was developed during the BioHertitage Project, funded by the National Institute of Water and Atmospheric Research (NIWA) (Greenwood and Fenwick, 2019). In addition to national databases, there are transnational databases and databases that only cover individual groups of organisms, such as the European groundwater crustacean data set (EGCD). This database comprises a total of 21,700 occurrence data collectively representing 12 orders, 46 families, 165 genera and 1,570 species and subspecies of obligate groundwater crustaceans in Europe (European Union, 2020). To better record and protect biodiversity in the future and to be able to quantify a loss of biodiversity, a larger-scale overview is also required. The global data set from Chapter 2 of this thesis provides an initial basis for this.

(V) Map optimisation and expansion

One of the main aims of this thesis is to provide a global overview on stygofauna research, including an investigation on the global spatial and temporal distribution of groundwater fauna sampling sites. Based on data from 859 studies, Study 1 in Chapter 2 provides a world map giving an overview of groundwater fauna samplings and the number of studies. It would be desirable to provide this map interactively and online with regular updates to have a common knowledge basis for understanding, assessment, monitoring and conservation of groundwater biodiversity.

(VI) Extended studies on groundwater fauna in urban aquifers

Urban aquifers are complex and harbour a mostly unexplored ecosystem with a huge biodiversity of invertebrates and microorganisms. However, this thesis and various studies show that multiple stressors cause changes in groundwater quality and living conditions (Becher et al., 2022). Further large-scale studies in other cities with repeated measurement campaigns are needed to verify and extend the current knowledge. Moreover, sustainable management of the subsurface is essential in this special environment, which is characterised by different interests and conflicts of use. Thus, urban groundwater ecosystems should seriously be considered in city and energy planning.

(VII) Adaption and revision of national and international law

In many countries, legislation does not yet recognise groundwater as a habitat worthy of protection. In the mid-2000s, national policies to monitor groundwater ecosystems' health and stress emerged in Australia. Governments are using stygofauna to monitor, evaluate and report on groundwater health. A favourable example of groundwater ecosystem management and research in Europe is the European Groundwater Directive 2006, which attempted to incorporate ecological knowledge into schemes for environmental planning and policies. In September 2023, proposals by the European Parliament Environment Committee to amend the EU Commission's draft regarding the revision of the Water Framework Directive, Groundwater and Environmental Quality Standard Directives were voted for in plenary. The Environment Committee advocated for better research and more effective groundwater protection and its biocoenoses. Findings on the effects of heat input should also be considered throughout the EU when making provisions for groundwater protection. Thus, a new article (6aa) is inserted in the directive to improve protection of groundwater ecosystems:

‘The Commission shall [...] publish an assessment of the impacts of physico-chemical elements, like pH, oxygenation, and temperature, on health of groundwater ecosystems, accompanied, where appropriate, by a legislative proposal to revise this Directive accordingly, to set the corresponding parameters, provide for harmonised monitoring methods, and define what would constitute a "good ecological status" for groundwater’ (European Parliament, 2023).

This is an important step, yet to implement stronger policies and monitoring requirements for protecting groundwater ecosystems, a worldwide effort to collect information on groundwater ecosystems, functional roles and human impacts is required.

(VIII) Impacts of climate change

Climate change significantly threatens biogeochemical processes and groundwater ecosystems (Griebler et al., 2016). These impacts are on-going, and surface temperature may not have reached subsurface areas yet, as can be seen in Study 2 (Chapter 3). According to Schmidt et al. (2023) it seems that the aquifers are still developing towards a new equilibrium. How climate change affects ecosystems and their services, such as drinking water supply, should be the subject of future research. Therefore, more data on groundwater quantity and quality is needed, which will increase the demand for ecological monitoring in the future.

APPENDICIES

Appendix Study 1

This Appendix refers to Study 1 (Chapter 2). The content was published in the journal Ecohydrology as a supporting information and is available online at: `https://doi.org/10.1002/eco.2607`.

S1 Groundwater fauna sampling methods

S1.1. Pumping of well water

Pumping well water and filtering animals from it is one of the most common and well-established method for sampling groundwater fauna (Hahn, 2002; Thulin and Hahn, 2008). Furthermore, this method enables a simultaneous sampling of fauna, sediment and water (Hahn, 2002), and is easy to standardize by extracting a defined volume of water (Hahn, 2002). As reported in literature, the volume of pumped water varies between 20 to 1,000 L (Malard et al., 2002; Thulin and Hahn, 2008). An additional benefit of this method is that species can be extracted from several microhabitats (Allford et al., 2008; Hahn, 2002). However, existing studies also show the disadvantages of this method. Pumping is considered as a selective sampling method because of filtering effects and a resistance against the suction of pump. Hence, large, sessile or more active species can be underrepresented in probes (Allford et al., 2008). According to Hahn (2005) pumping might also alter the sediment structure in fine sediments and is quite expensive (up to 10,000 €) (Hahn, 2005). There are also issues with collecting representative stygofauna samples from wells that have not been purged (see Korbel et al., 2017).

Commonly used pumps for sampling groundwater fauna are centrifugal pumps, such as pressure pumps (e.g. Grundfos MP1) (Malard et al., 2002) as well as pumps with double packer samples and pneumatic pumps. Pumps with double packer sampler were first used by Danielopol and Nierreiter in 1987 and allow a selective sampling at defined depths (Danielopol and Niederreiter, 1987). Packers (i.e. expanding plugs) temporarily isolate an interval of a borehole, with a possible diameter between 2.5 and 7.5 cm (Pospisil, 1992), from which water is pumped (Price and Williams, 1993). The best method of obtaining undamaged invertebrates from deep groundwater wells (> 8 m below ground) is the use of a pneumatic pump, like the Radford pneumatic pump (Scarsbrook et al., 2000). This type of pump is built of a submersible pump placed around a pneumatic cylinder supplied with compressed air and water is pump to the surface with a pumping rate of 0.25 m^3 per hour (Scarsbrook et al., 2000).

S1.2. Netsampling

A second commonly used method for sampling groundwater fauna is the net sampler or phreatobiological net. It is a valuable alternative to pumping devices with respect to obtained numbers of taxa and community composition (Hahn and Matzke, 2005; Malard et al., 2002; Thulin and Hahn, 2008) and can be used for large-scale faunal surveys (Allford et al., 2008) up to a well depth of 100 m (Hahn, 2002). Particularly suited for large wells dug in alluvial plains, organisms can be collected using a net sampler. Different methods for net sampling have been adopted around the world (e.g. Environmental Protection Authority (EPA), 2016; Hancock and Boulton, 2008), with a variety of mesh sizes (e.g. 50, 63, 74 or 150 μm) and the number of repeat hauls of nets at each site (e.g. Hancock and Boulton, 2008). The basic concept is the net is lowered and sediment agitated to capture stygofauna within the well. More information about the design and application of the net sampler can be found in the Supporting Information (Figure A1.1). Down- and upward movements (at least ten times) of the net in the well capture animals swimming in well water and whirled up from the bottom sediments (Boulton et al., 2008; Eberhard et al., 2009; Malard et al., 2002). However, net sampling does not provide information about the aquifer and is selective due to filtering effects of the well design (Allford et al., 2008), with some species of stygobiontic fish know to evade capture by nets. Nets can also become clogged with sediment reducing their efficiency, and this method can only sample organisms living within the well environment thus may not be truely representative of the wider aquifer community structure (Korbel et al., 2017).

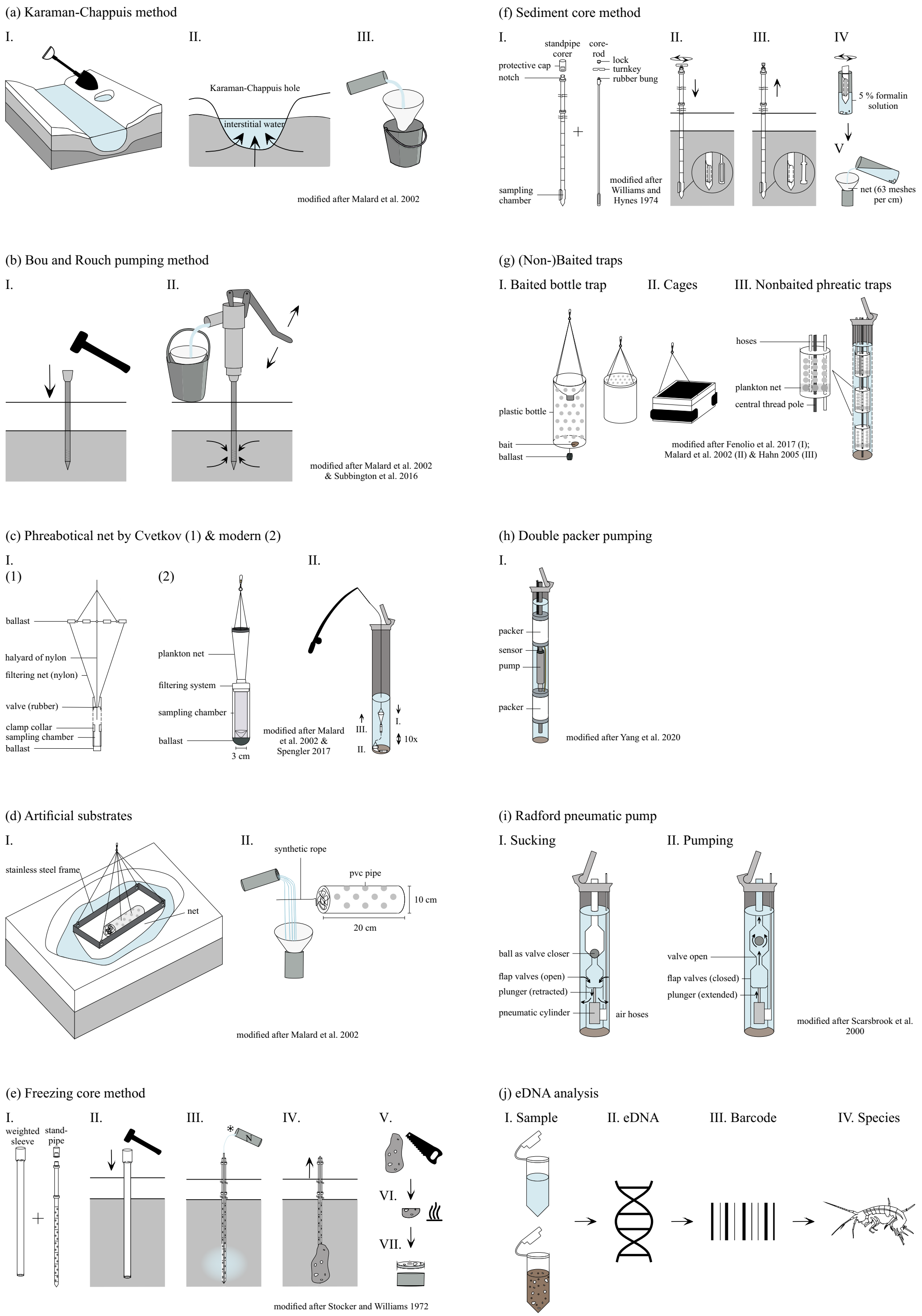

Figure A1.1: Detailed schemes of the different sampling techniques.

S1.3. Traps

Another method to sample fauna in wells, caves and the hyporheic zone is based on the principle that animals move actively or passively into traps (Hahn, 2002). In contrast to the methods presented above, traps exhibit a diverse design and function and can be either baited or non-baited. Non-baited traps and colonisation cages are mainly used for sampling the hyporheos (Malard et al., 2002) and therefore not in the focus of this study. Baited traps, where a bait is placed in a net or container that is left for at least 12 hours in a well, are commonly used for sampling stygofauna. The most popular design is the balance and inverted bottle trap (see also Figure A1.1). However, it must be mentioned that this method is species-selective, so that a combination with other methods (e.g. a net sampler) is highly recommended. Depending on the type of bait, the method can also influence physico-chemical parameters of well water (Malard et al., 2002). In 2005 Hahn presented the unbaited phreatic trap system, which allows sampling water from the well and the surrounding aquifer at defined depths. Here, three unbaited traps are fixed to a central pole in a well and the content of the traps is monthly pumped at the surface. As a result, this method provides newly colonized, artificial biotopes with a higher abundance in the traps than in the surrounding aquifer (Hahn, 2005).

S1.4. Further methods

Another rapid and qualitative method for groundwater fauna sampling is the Karaman-Chappuis method. In this method small holes are dug in riverbed sediments (Danielopol and Marmonier, 1992) and animals which flow into with the interstitial water are removed with the water and filtered afterwards (Malard et al., 2002) (Figure A1.1). As mentioned above, the sampling method of Bou and Rouch (1967) allows pumping animals living in sandy sediments and gravel of defined sections. This method uses steel pipes hammered into sediments to at least 2 m depth and extraction of groundwater from the pipe with a hand pump (also called Bou-Rouch pump). Afterwards, the water is filtered (Malard et al., 2002). However, this sampling is not strictly representative of in-situ conditions as faunal diversity and density are not expressed per volume of sediment. Also, amphipods as well as isopods can be damaged (Malard et al., 2002; Pospisil, 1992).

A rarely applied method is the freezing core method, during which a standpipe with a protective cap, two insulated copper rods and a weighted sleeve are drilled into a streambed. Then, fauna is paralysed by creating an electrical field for 10 minutes (Boxshall et al., 2016) and the cap is removed and liquid nitrogen is inserted for another 15 minutes. Afterwards, the core is removed with a vertical pull (Stocker and Williams, 1972) and prepared for analysis. This technique is the only method to obtain quantitative data (Hahn, 2002; Pospisil, 1992). However, it has the distinct disadvantage of destroying the habitat (Stocker and Williams, 1972) and is thus rarely applicable to groundwater (Hahn, 2002).

Similar to traps, the method of artificial substrates is often used in cave studies, and to study the distribution of groundwater fauna along subterranean rivers and streams. These substrates consist of a 20 cm long PVC pipe filled with a synthetic rope of 25 m length and with a diameter of 0.5 cm and placed in a net. After one month the pipe is pulled out of the lake or stream (Malard et al., 2002).

Developed by Williams and Hynes (1974) the sediment core method uses a standpipe corer to sample the hyporheos. For this purpose, a pipe with a diameter of 2.5 cm is drilled into the sediment up to 1 m depth. Afterwards a core-rod is placed inside the pipe and the pipe is rotated in order to fill the chamber of the core-rod. After rotating the core rod again to close the open wall of the pipe, the pipe is pulled out of the sediment. The disadvantages of this method are the selective sampling of species in case of a large average grain size (Williams and Hynes, 1974), the perturbation of the sediment caused by the mechanical stress, and a possible flight reaction of animals (Pospisil, 1992).

S1.5. New technologies

State-of-the-art methods for detection of groundwater fauna have been found in more recent studies. Video logging is an in-situ method to observe animals and aquifer conditions by inserting a video-camera in wells with transparent Perspex tubes (Pospisil, 1992). Using this method, biogenic structures, like worm galleries, < 0.05 mm are detectable in shallow depths up to 10 m (Datry et al., 2003).

S2 Additional Figures

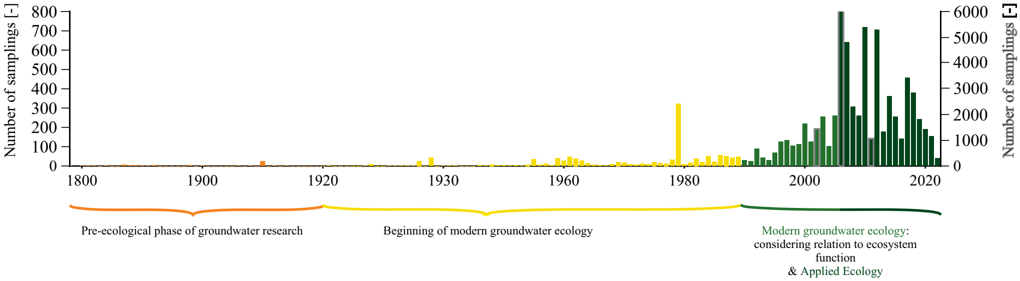

Figure A1.2: Number of samplings [-] over time.

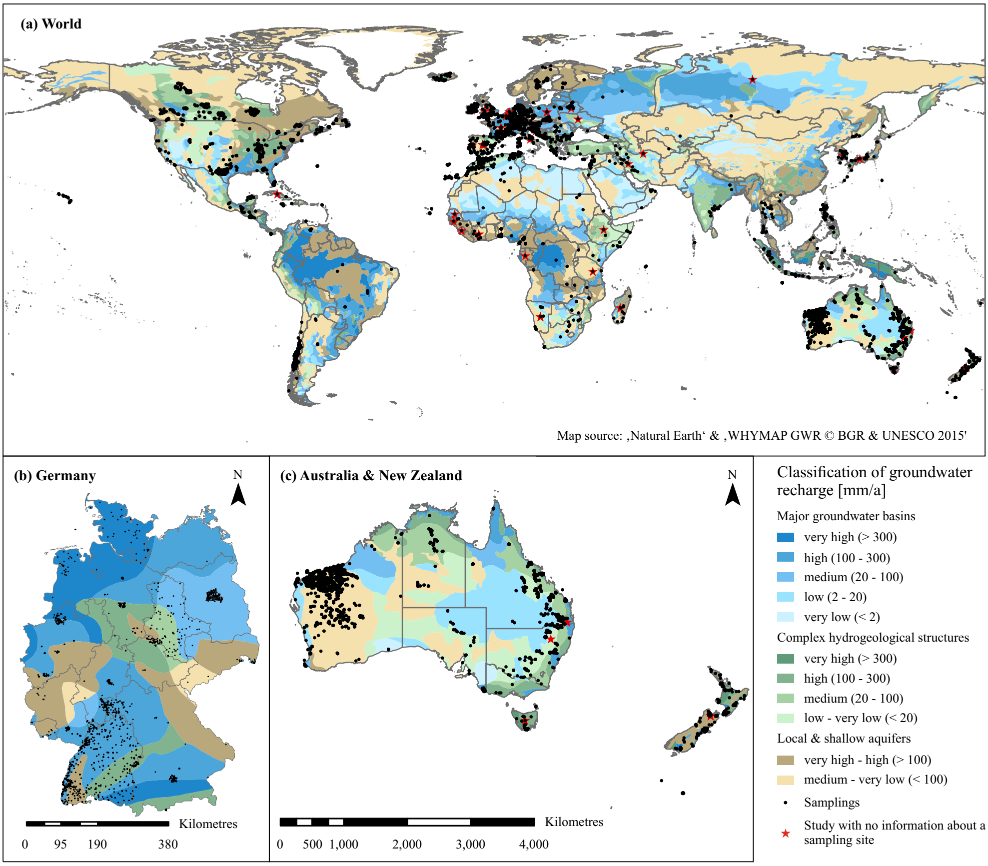

Figure A1.3: Overview over groundwater fauna samplings and the classification of groundwater recharge [mm/a] worldwide (a), of Germany (b) and of Australia (c), including data from about 800 studies worldwide (see Table A1.4 in the Supporting Information).

S3 Additional Table

Table A1.3: Number of studies [-], of sampling sites [-] and of samplings [-], country area [km^2] and sampling density [sampling site/km^2] or [samplings/km^2] per country and continent.

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
Africa	Algeria	24	223	816	2,308,858	9.66E-05	3.53E-04
	Benin	6	55	119	116,113	4.74E-04	1.02E-03
	Cameroon	6	79	79	464,319	1.70E-04	1.70E-04
	Central African Republic	1	3	3	617,984	4.85E-06	4.85E-06
	Côte d'Ivoire	6	5	9	320,677	1.56E-05	2.81E-05
	Democratic Republic of the Congo	5	5	8	2,325,240	2.15E-06	3.44E-06
	Egypt	2	2	2	1,001,078	2.00E-06	2.00E-06
	Eritrea	1	1	1	122,538	8.16E-06	8.16E-06
	Ethiopia	2	2	2	1,127,375	1.77E-06	1.77E-06
	Gabon	1	1	1	259,968	3.85E-06	3.85E-06
	Guinea	1	2	2	244,302	8.19E-06	8.19E-06
	Guinea-Bissau	1	1	1	32,829	3.05E-05	3.05E-05
	Kenya	2	2	2	585,702	3.41E-06	3.41E-06
	Libya	1	1	1	1,623,759	6.16E-07	6.16E-07
	Madagascar	4	9	11	592,982	1.52E-05	1.86E-05
	Malawi	3	3	3	119,398	2.51E-05	2.51E-05

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
	Mali	2	2	2	1,252,723	1.60E-06	1.60E-06
	Morocco	44	266	347	591,744	4.50E-04	5.86E-04
	Namibia	6	11	11	822,714	1.34E-05	1.34E-05
	Nigeria	1	1	1	907,499	1.10E-06	1.10E-06
	Republic of Cabo Verde	2	6	6	3,883	1.55E-03	1.55E-03
	Senegal	2	2	2	196,225	1.02E-05	1.02E-05
	Sierra Leone	1	1	1	71,612	1.40E-05	1.40E-05
	Somalia	8	12	14	639,222	1.88E-05	2.19E-05
	South Africa	9	20	20	1,219,505	1.64E-05	1.64E-05
	Sudan	3	8	8	1,857,639	4.31E-06	4.31E-06
	Tanzania	2	1	1	939,006	1.06E-06	1.06E-06
	Tunisia	5	15	17	156,613	9.58E-05	1.09E-04
	Uganda	1	1	1	241,854	4.13E-06	4.13E-06
	Zambia	1	1	3	751,914	1.33E-06	3.99E-06
	Zanzibar	1	1	1	2,499	4.00E-04	4.00E-04
	Zimbabwe	3	7	10	389,338	1.80E-05	2.57E-05
	Sum:	155	749	1505	Average:	1.08E-04	1.39E-04
Asia	Georgia	1	5	48	66,615	7.51E-05	7.21E-04
	India	7	32	43	3,144,310	1.02E-05	1.37E-05
	Indonesia	9	48	51	1,879,826	2.55E-05	2.71E-05
	Iran	10	43	43	1,622,509	2.65E-05	2.65E-05
	Iraq	2	3	3	399,119	7.52E-06	7.52E-06
	Israel	5	10	13	21,901	4.57E-04	5.94E-04

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
	Japan	7	45	46	6,876	6.54E-03	6.69E-03
	Kazakhstan	1	1	1	2,714,265	3.68E-07	3.68E-07
	Lebanon	2	4	4	10,000	4.00E-04	4.00E-04
	Malaysia (Borneo)	2	2	2	327,885	6.10E-06	6.10E-06
	Oman	3	12	14	311,213	3.86E-05	4.50E-05
	Philippines	10	129	139	293,237	4.40E-04	4.74E-04
	Republic of Korea	9	227	237	92,620	2.45E-03	2.56E-03
	Syrian Arab Republic	2	2	2	185,674	1.08E-05	1.08E-05
	Thailand	6	179	637	514,454	3.48E-04	1.24E-03
	Turkmenistan	1	1	1	470,850	2.12E-06	2.12E-06
	Vietnam	1	2	2	328,892	6.08E-06	6.08E-06
	Sum:	63	745	1286	Average:	6.78E-04	8.01E-04

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
Europe	Austria	33	1418	1495	83,993	1.69E-02	1.78E-02
	Belarus	1	25	25	207,499	1.20E-04	1.20E-04
	Belgium	11	412	447	30,670	1.34E-02	1.46E-02
	Bulgaria	2	49	52	112,760	4.35E-04	4.61E-04
	Croatia	7	75	74	55,078	1.36E-03	1.34E-03
	Cyprus	1	2	2	5,395	3.71E-04	3.71E-04
	Czech Republic	5	223	249	78,759	2.83E-03	3.16E-03
	United Kingdom	16	595	684	243,783	2.44E-03	2.81E-03
	Federation of Bosnia and Herzegovina	2	30	39	28,814	1.04E-03	1.35E-03
	Finland	3	21	26	333,059	6.31E-05	7.81E-05
	France	47	2654	2813	539,175	4.92E-03	5.22E-03
	Corsica	1	3	3	8,666	3.46E-04	3.46E-04
	Germany	76	2378	4232	357,674	6.64E-03	1.18E-02
	Baden-Württemberg	28	950	2026	36,123	2.63E-02	5.61E-02
	Bavaria	17	429	697	70,024	6.13E-03	9.95E-03
	Berlin	1	181	181	889	2.04E-01	2.04E-01
	Brandenburg	0	0	0	30,038	0	0
	Bremen	0	0	0	386	0	0
	Hamburg	0	0	0	774	0	0
	Hesse	9	141	156	21,012	6.71E-03	7.42E-03
	Lower Saxony	13	141	179	47,595	2.96E-03	3.76E-03
	Mecklenburg-Western Pomerania	1	1	1	23,208	4.31E-05	4.31E-05

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
	North Rhine-Westphalia	16	199	383	34,537	5.76E-03	1.11E-02
	Rhineland-Palatinate	8	71	194	20,096	3.53E-03	9.65E-03
	Saarland	1	12	12	2,654	4.52E-03	4.52E-03
	Saxony	3	24	24	18,167	1.32E-03	1.32E-03
	Saxony-Anhalt	8	131	280	20,665	6.34E-03	1.35E-02
	Schleswig-Holstein	7	51	51	15,436	3.30E-03	3.30E-03
	Thuringia	5	47	48	16,068	2.93E-03	2.99E-03
	Greece	5	18	20	131,353	1.37E-04	1.52E-04
	Iceland	4	69	92	102,390	6.74E-04	8.99E-04
	Ireland	10	140	154	69,445	2.02E-03	2.22E-03
	Italy	25	2143	2279	251,203	8.53E-03	9.07E-03
	Sardinia	4	8	8	24,114	3.32E-04	3.32E-04
	Sicily	1	1	1	25,763	3.88E-05	3.88E-05
	Kosovo	1	1	1	10,913	9.16E-05	9.16E-05
	Luxembourg	1	72	74	2,608	2.76E-02	2.84E-02
	Macedonia	4	8	8	25,385	3.15E-04	3.15E-04
	Montenegro	4	20	20	13,727	1.46E-03	1.46E-03
	Netherlands	5	10	10	37,102	2.70E-04	2.70E-04
	Norway	1	1	1	319,477	3.13E-06	3.13E-06
	Poland	10	54	81	313,428	1.72E-04	2.58E-04
	Portugal	5	64	64	87,971	7.28E-04	7.28E-04
	Madeira	1	7	7	811	8.63E-03	8.63E-03
	Romania	7	45	71	236,377	1.90E-04	3.00E-04
	Russia	6	18	74	16,980,192	1.06E-06	4.36E-06

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
	Serbia	1	1	1	56,483	1.77E-05	1.77E-05
	Slovakia	1	44	133	48,458	9.08E-04	2.74E-03
	Slovenia	17	766	933	20,327	3.77E-02	4.59E-02
	Spain	19	871	972	494,272	1.76E-03	1.97E-03
	Balearic Islands	1	2	2	5,117	3.91E-04	3.91E-04
	Sweden	3	26	187	446,174	5.83E-05	4.19E-04
	Switzerland	13	231	480	41,436	5.57E-03	1.16E-02
	Turkey	3	17	19	780,080	2.18E-05	2.44E-05
	Ukraine	1	2	2	571,999	3.50E-06	3.50E-06
	Sum:	358	12522	15833	Average:	3.81E-03	4.50E-03
Central America	Bermuda	1	21	22	62	3.37E-01	3.53E-01
	Cuba	2	4	5	109,929	3.64E-05	4.55E-05
	Curaçao	1	2	2	463	4.32E-03	4.32E-03
	El Salvador	1	27	27	20,539	1.31E-03	1.31E-03
	Guatemala	2	3	3	108,811	2.76E-05	2.76E-05
	Haiti	1	2	1	26,892	7.44E-05	3.72E-05
	Honduras	1	3	4	112,237	2.67E-05	3.56E-05
	Jamaica	1	8	8	11,033	7.25E-04	7.25E-04
	Mexico	3	46	48	1,957,845	2.35E-05	2.45E-05
	Panama	1	10	10	74,530	1.34E-04	1.34E-04
	Saint-Martin	1	2	3	68	2.93E-02	4.39E-02
	Sum:	10	128	133	Average:	3.39E-02	3.67E-02

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
North-America	Canada	2	299	299	9,945,528	3.01E-05	3.01E-05
	United States of America	34	2815	3456	7,942,143	3.54E-04	4.35E-04
	Alabama	1	1529	1529	133,822	1.14E-02	1.14E-02
	Arizona	2	2	10	295,070	6.78E-06	3.39E-05
	Arkansas	1	5	5	137,540	3.64E-05	3.64E-05
	California	1	14	14	409,737	3.42E-05	3.42E-05
	Colorado	1	8	27	269,202	2.97E-05	1.00E-04
	Connecticut	1	1	1	12,708	7.87E-05	7.87E-05
	District of Columbia	2	87	87	162	5.36E-01	5.36E-01
	Florida	4	384	384	146,732	2.62E-03	2.62E-03
	Georgia	2	19	19	152,164	1.25E-04	1.25E-04
	Hawaii	1	15	15	16,848	8.90E-04	8.90E-04
	Idaho	1	1	1	216,254	4.62E-06	4.62E-06
	Illinois	2	10	10	150,153	6.66E-05	6.66E-05
	Indiana	1	251	256	94,332	2.66E-03	2.71E-03
	Kansas	1	1	84	212,826	4.70E-06	3.95E-04
	Kentucky	2	181	181	104,578	1.73E-03	1.73E-03
	Maryland	1	4	4	25,467	1.57E-04	1.57E-04
	Massachusetts	1	2	2	21,162	9.45E-05	9.45E-05
	Michigan	2	2	3	250,100	8.00E-06	1.20E-05
	Montana	1	1	1	379,492	2.64E-06	2.64E-06
	New Hampshire	2	2	5	24,266	8.24E-05	2.06E-04
	New York	5	23	23	136,933	1.68E-04	1.68E-04

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
	Ohio	1	2	2	116,044	1.72E-05	1.72E-05
	Oklahoma	1	47	47	180,637	2.60E-04	2.60E-04
	Pennsylvania	1	1	1	119,357	8.38E-06	8.38E-06
	South Dakota	1	2	2	199,304	1.00E-05	1.00E-05
	Tennessee	2	18	18	109,298	1.65E-04	1.65E-04
	Texas	7	148	248	685,339	2.16E-04	3.62E-04
	Utah	1	27	30	219,762	1.23E-04	1.37E-04
	Virginia	2	3	3	102,236	2.93E-05	2.93E-05
	West Virginia	3	24	443	62,735	3.83E-04	7.06E-03
	Wisconsin	1	1	1	169,361	5.90E-06	5.90E-06
	Sum:	36	3114	3755	Average:	1.92E-04	2.33E-04
South America	Argentina	3	10	22	2,784,305	3.59E-06	7.90E-06
	Brazil	4	25	25	8,472,664	2.95E-06	2.95E-06
	Chile	2	130	180	736,274	1.77E-04	2.44E-04
	Venezuela	1	8	8	912,684	8.77E-06	8.77E-06
	Sum:	10	173	235	Average:	4.80E-05	6.60E-05
Oceania	Papua New Guinea	1	2	2	455,743	4.39E-06	4.39E-06
	Fiji	1	1	1	18,930	5.28E-05	5.28E-05
	Seychelles	1	3	3	436	6.89E-03	6.89E-03
	Maldives	1	4	4	109	3.68E-02	3.68E-02
	Sum:	4	10	10	Average:	1.09E-02	1.09E-02

Continent	Country	Number of studies [-]	Number of sampling sites [-]	Number of samplings [-]	Area [km^2]	Sampling density [sampling sites/km^2]	Sampling density [samplings/km^2]
	Australia	133	4014	5826	7,622,937	5.27E-04	7.82E-04
	Australian Capital Territory	0	0	0	2,349	0	0
	Jervis Bay Territory	0	0	0	76	0	0
	Lord Howe Island	0	0	0	14	0	0
	Macquarie Island	0	0	0	119	0	0
	New South Wales	23	255	794	801,935	3.18E-04	9.90E-04
	Northern Territory	6	45	74	1,348,468	3.34E-05	5.49E-05
	Queensland	15	732	1077	1,730,136	4.23E-04	6.22E-04
	South Australia	10	70	90	983,875	7.11E-05	9.15E-05
	Tasmania	4	46	46	68,115	6.75E-04	6.75E-04
	Victoria	1	1	3	227,945	4.39E-06	1.32E-05
	Western Australia	78	2865	372	2,528,139	1.13E-03	1.53E-03
	Esperance			2	55,661		3.59E-05
	Gascoyne			92	135,065		6.81E-04
	Goldfields			779	714,525		1.09E-03
	Kimberley			21	419,245		5.01E-05
	Mid-West			720	466,795		1.54E-03
	Perth			30	6,417		4.68E-03
	Pilbara			2020	506,778		3.48E-03
	South West			17	24,802		6.85E-04
	Wheat Belt			38	159,457		2.38E-04
	Christmas Island			23	136		1.69E-01
	New Zealand	23	305	436	266,886	1.14E-03	1.63E-03
	Sum:	146	4327	6404	Average:	8.35E-04	1.21E-03

S4 Literature search

An extensive review of accessible groundwater fauna data was conducted by analysing information from national and international publications in peer-reviewed journals, national reports, doctoral theses, historical writings, books and existing online databases. Literature was searched by using web platforms such as Scopus and Google Scholar, as well as specific ecological databases, like ZOBODAT. Moreover, detailed searches were conducted on the homepages of universities or research institutes of known researchers in the field, social networks (ResearchGate), libraries from research institutes and museums (including their virtual services), conference proceedings and by direct request addressed to authorities and experts in the field (including companies).

The research terms, used for the literature research, include the following keywords:

- groundwater fauna/biology/biodiversity/ecology/habitat,
- stygo/aquifer/subterranean fauna,
- stygobiont/stygobiontic species names,
- authors names and
- fauna sampling methods (pumps, corer, nets, etc.).

To increase the breadth of searches, a combination of keywords, together with region/country names, proved useful. Keywords were also searched using English, German and less often French, Spanish and Italian.

From the set of results only studies including stygobiontic groundwater fauna and from groundwater-specific sample sites such as wells, boreholes, springs, interstitial/hyporheic zones of rivers and caves with sole groundwater sources (troglobiont/stygobiontic colonisation) were used for this review.

Notwithstanding the limitations to the completeness of the database (access to studies prior to 1990, as well as theses and national reports may be limited), the study compiled 859 studies. The meta-analysis included studies dating from 1880 to 2022, with more recent literature used within the continent and method related sections of the paper but not in the data analysis.

Table A1.4: Overview over the used literature for the world map divided by continents.

Africa	Abdelhakim, M. (2007). Contribution a l'étude de la faune stygobie de la region des Tlemcen (Nord-Ouest Algerien). Université Abou Bekr Belkaid -.
	Abdenour, T. (2018). Bio-Evaluation de la qualité des eaux souteraine de la region de Souk Naamane et Ain M'Lila (Oum El Bouaghi, Haute Plaine de l'est Algerien).
	Aidaoui, S. C. E. (2019). Recherches phréatobiologiques dans la région du Nord-Constantinois [Université Larbi Ben M'hidi Oum El Bouaghi]. http://bib.univ-oeb.dz:8080/jspui/bitstream/123456789/9125/1/These AIDAOUI.pdf
	Bader, C. (1989). Wassermilben (Acari: Hydrovolziidae Hydrachnellae) aus Algerien. Bijdragen Loi de Dierkunde, 59(1), 33–42.
	Baratti, M., Yacoubi-Khebiza, M., & Messana, G. (2004). Microevolutionary processes in the stygobitic genus Typhlocirolana (Isopoda Flabellifera Cirolanidae) as inferred by partial 12S and 16S rDNA sequences. Journal of Zoological Systematics and Evolutionary Research, 42(1), 27–32. https://doi.org/10.1111/j.14390469.2004.00232.x
	Barnard, K. H. (1916). Contributions to the crustacean fauna of South Africa 5 The Amphipoda. Annals of the South African Museum, 15(3), 105–302.
	Barnard, K. H. (1966). The occurrence of the genus Ingolfiella (Crustacea, Amphipoda) in South Africa, with description of a new species. Annals and Magazine of Natural History, 9(100–102), 189–197. https://doi.org/10.1080/00222936608656044
	Belaidi, N., Taleb, A., Mahi, A., & Messana, G. (2011). Composition and distribution of stygobionts in the Tafna alluvial aquifer (north-western Algeria). Subterranean Biology, 8, 21–32. https://doi.org/10.3897/subtbiol.8.1227
	Belazuc, J., & Ruffo, S. (1954). Due nuove specie del genere Metacrangonyx Chevreux (Amphipoda-Gammaridae) delle acque interne del Nord Africa francese. La Tipografica Veronese.
	Belengfe, C. S., Togouet, S. H. Z., Thiery, G., Moanono, P., Oumarou, P. F., Kayo, R. T., & Abraham, F. (2019). Impact of physicochemical parameters on biodiversity and groundwater quality in Tiko , Cameroon. International Journal of Fisheries and Aquatic Studies, 7(6), 39–46.
	Berrady, I., Essafi, K., & Mathieu, J. (2000). Comparative physico-chemical and faunal studies of two thermal springbrooks near Sidi Harazem (Morocco). Annales de Limnologie, 36(4), 261–274. https://doi.org/10.1051/limn/2000024

Birstein, J. A. (1972). Une nouvelle espece africaine du genre Stenase//us (Crustacea Isopoda Asellota) du bassin du Niger. International Journal of Speleology, 4, 9–18.

Bodon, M., Ghamizi, M., & Giusti, F. (1999). The Moroccan stygobiont genus Heideella (Gastropoda, Prosobranchia: Hydrobiidae). Basteria, 63(1–3), 89–105.

Borgonie, G., García-Moyano, A., Litthauer, D., Bert, W., Bester, P. A., Van Heerden, E., Möller, C., Erasmus, M., & Onstott, T. C. (2011). Nematoda from the terrestrial deep subsurface of South Africa. Nature, 474(7349), 79–82. https://doi.org/10.1038/nature09974

Boughrous, A. A. (2007). Biodiversité, écologie et qualité des eaux souterraines de deux régions arides du Maroc: le Tafilalet et la région de Marrakech. In Université Cadi Ayyad Faculté Des Sciences Semlalia Marrakech. Université Cadi Ayyad Marrakech.

Boughrous, A. A., Boulanouar, M., Yacoubi-Khebiza, M., & Coineau, N. (2007). The first Microcharon (Crustacea, Isopoda, Microparasellidae) from the Moroccan North Saharan Platform. Phylogeny, origin and palaeobiogeography. Contributions to Zoology, 76(1), 21–34. https://doi.org/10.1163/18759866-07601003

Boughrous, A. A., Yacoubi-Khebiza, M., Boulanouar, M., Boutin, C., & Messana, G. (2007). Groundwater quality in two arid areas of Morocco: Impact of pollution on biodiversity and paleogeographic implications. Environmental Technology, 28(11), 1299–1315. https://doi.org/10.1080/09593332808618887

Boulaassafer, K., Ghamizi, M., & Delicado, D. (2018). The genus mercuria boeters, 1971 in Morocco: First molecular phylogeny of the genus and description of two new species (caenogastropoda, truncatelloidea, hydrobiidae). ZooKeys, 782, 95–128. https://doi.org/10.3897/zookeys.782.26797

Boulaassafer, K., Ghamizi, M., Machordom, A., Albrecht, C., & Delicado, D. (2021). Hidden species diversity of Corrosella Boeters, 1970 (Caenogastropoda: Truncatelloidea) in the Moroccan Atlas reveals the ancient biogeographic link between North Africa and Iberia. Organisms Diversity and Evolution, 21, 393–420. https://doi.org/10.1007/s13127-021-00490-3

Boulal, M., Boulanouar, M., Ghamizi, M., & Boutin, C. (2017). Qualité de l'eau et faune aquatique des puits dans la région de Tiznit (Anti-Atlas occidental, Maroc). Bulletin de La Société d'histoire Naturelle de Toulouse, 153, 25– 41.

Boulal, M., Boulanouar, M., Yacoubi-Khebiza, M., & Boutin, C. (2002). Biodiversity of the stygobiontic cirolanids (Crustacea, Isopoda) from the Mediterranean Basin: II - Systematics, ecology and historical biogeography of Typhlocirolana tiznitensis n.sp., the first representative of the genus, South of Moroccan High. Bulletin de La Société Historique National Toulouse, 145, 11–28.

Boulanouar, M., Yacoubi-Khebiza, M., Messouli, M., & Coineau, N. (1995). Un nouveau Microcharon (Isopoda, Janiroidea) du Maroc — origine et biogéographie historique. Contributions to Zoology, 65(1), 53–64.

Boulvert, Y., & Juberthie, C. (1998). République Centrafricaine. In Encyclopaedia Biospeologica (pp. 1583–1592).

Boutin, C. (1994). Phylogeny and biogeography of metacrangonyctid amphipods in North Africa. Hydrobiologia, 287(1), 49–64. https://doi.org/10.1007/BF00006896

Boutin, C. (1997). Stygobiologie et géologiehistorique: L'émersion des terres de Méditerranée orientale datée a partir des amphipodes Metacrangonyctidae actuels (micro-crustacés souterrains). Geobios, 30, 67–74. https://doi.org/10.1016/s0016-6995(97)80071-x

Boutin, C., & Boulanouar, M. (1984). Premières données sur la faune des puits des environs de Marrakech (Maroc Occidental). Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Verhandlungen, 22(3), 1762–1765. https://doi.org/10.1080/03680770.1983.11897572

Boutin, C., Boulanouar, M., Coineau, N., & Messouli, M. (2002). Biodiversity in the stygobiontic cirolanids (Crustacea: Isopoda) from the Mediterranean Basin. I. A new species of Typhlocirolana in Morocco, taxonomic, ecological and biogeographic data. Journal of Natural History, 36(7), 797–817. https://doi.org/10.1080/00222930010028920

Boutin, C., Boulanouar, M., & Yacoubi-Khebiza, M. (1995). Un test biologique simple pour apprécier la toxicité de I'eau et des sédiments d'un puits. Toxicité comparée, in vitro, de quelques métaux lourds et de I'ammonium, visà-vis de trois genres de crustacés de la zoocénose des puits. Hydroécologie Appliquée, 7, 91–109. https://doi.org/10.1051/hydro:1995006

Boutin, C., & Coineau, N. (1988). Pseudoniphargus maroccanus n. sp. (subterranean amphipod), the first representative of the genus in Morocco. Phylogenetic relationships and paleobiogeography. Crustaceana. Supplement., 13, 1–19.

Boutin, C., & Idbennacer, B. (1989). Faune stygobie du sud de l'Anti-Atlas Marocain: Premiers résultats. Revue Des Sciences de l'Eau, 2(4), 891–904. https://doi.org/10.7202/705061ar

Boutin, C., & Messouli, M. (1988). Longipodacrangonyx maroccanus, n. gen., n. sp., Nouveau Representant du groupe Metacrangonyx dans les eaux souterraines du Maroc. Crustaceana. Supplement., 13, 256–271.

Braga, J. M. (1951). Sur deux Stenasellus (Crust. Isopoda) de la Guinee Portugaise. Anais Da Faculdade de Ciencias Universidade Do Porto, 35(1), 50–56.

Budde-Lund, G. (1908). Isopoda von Madagaskar und Ostafrika. Mit Diagnosen verwandter Arten. In A. Voeltzkow (Ed.), Reise in Ostafrika in den Jahren 1903-1905 (p. 86). E. Schweizbartsche Verlagsbuchhandlung.

Capart, A. (1951). Thermobathynella adami gen. et sp. nov., Anaspidacé du Congo Belge. Bulletin de l'Institut Royal Des Sciences Naturelles de Belgique, 27, 1–4.

Chappuis, P. A. (1934). Voyage de Ch. Alluaud et P. A. Chappuis en Afrique Occidentale Française (Dec. 1930-Mars 1931) I Copepoda Harpacticoida. Archiv Für Hydrobiologie, 26, 1–49.

Chappuis, P. A. (1951). Isopodes et Copépodes cavernicoles. Revue de Zoologie et de Botanique Africaines, 44, 342– 359.

Chappuis, P. A. (1953). Un nouvel isopode Psammique du Maroc: Microcerberus Remyi. Vie et Milieu Observatoire Océanologique - Laboratoire Arago, 4(4), 659–663. https://doi.org/hal- 02561157

Chevreux, E. D. (1901a). Amphipods des eaux souterraines de France et d'Algerie. Bulletin de La Société Zoologique de France, 26, 168–239.

Chevreux, E. D. (1901b). Mission scientifique de M. Ch. Alluand aux Iles Séchelles. Extrait Des I1∼nioi∼∼dee.s La Soçzete;Oologiyue de Frnncc, 14(1), 388–438.

Chevreux, E. D. (1913). Amphipoda. Voyage de Ch. Alluaud et R. Jeannel en Afrique Orientale (1911-1912), Résultats scientifiques. Crustacés II. In C. Alluaud & R. Jeannel (Eds.), Voyage de Ch. Alluaud et R. Jeannel en Afrique Orientale (1911-1912), Résultats scientifiques. (pp. 11–22). Schultz, A.

Coineau, N. (1967). Acanthobathynella, Nouveau genre de Syncaride africain (Cote d''Ivoire). Comptes Rendus de l'Académie Des Sciences, 256, 1988–1990. ''

Cottarelli, V. (1982). Una nuova Parastenocaris (Crustacea, Copepoda, Harpacticoida) di Sierra Leone: Parastenocaris cataractae n. sp. Problemi Attuali Di Scienza e Di Cultura, 255, 27–33.

Cottarelli, V., & Bruno, M. C. (1995). First record of Parastenocarididae (Crustacea, Copepoda, Harpacticoida) from subterranean waters of Ethiopia and the description of three new species. Journal of African Zoology, 109(5–6), 467–479.

Dakki, M., Himmi, O., Qninba, A., Benhoussa, A., El Alami el Moutaouakil, M., El Bouni, A., Rattal, A., Yahyaoui, A., & Ramdani, M. (2009). Etude Nationale sur la Biodiversite - Faune Aquatique Continentale. Observatoire Nationale de l'Environment du Maroc (ONEM) - Royaume du Maroc.

De Bovee, F., Yacoubi-Khebiza, M., Coineau, N., & Boutin, C. (1995). Influence du substrat sur la répartition des Crustacés stygobies interstitiels du Haut-Atlas occidental. International Revue of Geoscience and Hydrobiology, 80(3), 453–468.

De Grave, S., Piscart, C., Kayo, R. P. T., & Anker, A. (2017). A new groundwater-dwelling species of Euryrhynchina from Cameroon (Malacostraca, Decapoda, Euryrhynchidae). Zootaxa, 4254(1), 120–126. https://doi.org/10.11646/zootaxa.4254.1.8

Diviacco, G., & Ruffo, S. (1985). Nuovi bogidiellidi delle acque sotterranee africane (Crustacea amphipoda). Monitore Zoologico Italiano, Supplemento, 20(7), 135–148. https://doi.org/10.1080/03749444.1985.10736694

Dole-Olivier, M.-J., Hafid, H., & Piscart, C. (2018). A new groundwater species of Pseudoniphargus (Amphipoda: Pseudoniphargidae) from Algeria. Zootaxa, 4482(1), 125–139. https://doi.org/10.11646/zootaxa.4482.1.5

Dumont, H. J. (1981). Cteniobathynella essameuri n. sp., the first representative of the Bathynellacea (Crustacea) in the Central Sahara. Revue d'Hydrobiologie Tropicale, 14(1), 59–62.

Dumont, H. J. (1984). Nilobathynella predynastica n . g ., n . sp . (Crustacea: Bathynellacea) from the Nile valley in Nubia. Hydrobiologia, 110, 171–175.

Dumont, H. J., & Dumont, H. J. (1981). On a collection of zooplankton from somalia, with a description of three new species of copepoda. Monitore Zoologico Italiano, Supplemento, 14(1), 103–111. https://doi.org/10.1080/03749444.1981.10736615

el Adnani, M., Boughrous, A. A., Yacoubi-Khebiza, M., el Gharmali, A., Sbai, M. L., Errouane, A. S., Loukili Idrissi, L., & Nejmeddine, A. (2007). Impact of mining wastes on the physicochemical and biological characteristics of groundwater in a mining area in Marrakech (Morocco). Environmental Technology, 28(1), 71–82. https://doi.org/10.1080/09593332808618762 el Adnani, M., Boughrous, A. A., Yacoubi-Khebiza, M., Sbai, M. L., & Nejmeddine, A. (2006). Mine tailings impact on the physico-chemical and biological characteristics of underground waters in Marrakech mining area (Morocco). 2006 1st International Symposium on Environment Identities and Mediterranean Area, ISEIM, 287–293. https://doi.org/10.1109/ISEIMA.2006.344970

el Moustaine, R., Chahlaoui, A., & Rour, E. H. (2013). Groundwater fauna can be used as indicators of anthropogenic impacts on aquifers: A case study from Meknes area, Morocco. International Journal of Biosciences (IJB), 3(10), 139–152. https://doi.org/10.12692/ijb/3.10.139-152

el Moustaine, R., Chahlaoui, A., & Rour, E. H. (2014). Relationships between the physico-chemical variables and groundwater biodiversity: a case study from Meknes area, Morocco. International Journal of Conservation Science, 5(2), 203–214.

Fakher el Abiari, A., Oulbaz, Z., Messouli, M., & Coineau, N. (1999). A new species of Pseudoniphargus (Crustacea, Amphipoda) from subterranean water of northeastern Morocco: Historical biogeography and evolutionary aspects. Contributions to Zoology, 68(3), 161–171.

Ferrara, F., & Lanza, B. (1978). Skotobaena monodi, espece nouvelle de cirolanide phreatobie de la somalie (Crustacea isopoda). Monitore Zoologico Italiano, Supplemento, 10(1), 105–112. https://doi.org/10.1080/03749444.1978.10736861

Ferrara, F., & Monod, T. (1972). Contribution a l'etude de la grotte de Sof Omar (Ethiopie meridionale) No. 2.- sur un genre nouveau de Cirolanide troglobie a l'Afrique Nord Orientale. Annales de Speleologie, 27, 200–204.

Fiers, F., & Lagnika, M. (2015). Four new representatives of the genus Allocyclops Kiefer, 1932 from semiconsolidated subsoil aquifers in Benin (Copepoda, Cyclopoida, Cyclopidae). Subterranean Biology, 16(1), 1–36. https://doi.org/10.3897/subtbiol.16.4467

Fryer, G. (1956). New species of cyclopoid and harpacticoid copepods from sandy beaches of Lake Nyasa. Annals and Magazine of Natural History, 12(9), 225–249.

Fryer, G. (1957). A new species of Parabathynella (Crustacea: syncarida) from the psammon of Lake Bangweulu, Central Africa . Annals and Magazine of Natural History, 10(110), 116–120. https://doi.org/10.1080/00222935708655936

Ghamizi, M. (2020). New stygobiont genus and new species (Gastropoda, Hydrobiidae) from the Rif (Morocco). Ecologica Montenegrina, 31, 50–56. https://doi.org/10.37828/em.2020.31.11

Ghamizi, M., Bodon, M., Boulal, M., & Giusti, F. (1999). Atebbania bernasconii, a new genus and species from subterranean waters of the Tiznit Plain, southern Morocco (Gastropoda: Hydrobiidae). Journal of Molluscan Studies, 65(1), 89–98. https://doi.org/10.1093/mollus/65.1.89

Ghamizi, M., & Boulal, M. (2017). New stygobiont snail from groundwater of Morocco (Gastropoda: Moitessieriidae). Ecologica Montenegrina, 10, 11–13. https://doi.org/10.37828/em.2017.10.2

Ghlala, A., Della Valle, D., & Messana, G. (2009). First record of the genus Typhlocirolana Racovitza, 1905 (Isopoda: Cirolanidae) from Tunisia and description of a new species from the National park of Ichkeul. Zootaxa, 2176, 57– 64.

Giani, N., Martin, P., & Juget, J. (1995). A new species of Phreodrilidae (Oligochaeta), Astacopsidrilus naceri sp. nov., from Morocco (North Africa), with notes on the biogeography of the family. Canadian Journal of Zoology, 73(12), 2375–2381. https://doi.org/10.1139/z95-277

Glöer, P., Mabrouki, Y., & Taybi, A. F. (2020). A new genus and two new species (gastropoda, hydrobiidae) from Morocco. Ecologica Montenegrina, 28(2020), 1–6. https://doi.org/10.37828/em.2020.28.1

Green, J. (1964). Two new species of Parabathynella (Crustacea: Syncarida) from Lake Albert, Uganda. Proceedings of the Zoological Society of London, 142, 585–592.

Griffiths, C. L. (1974). The Gammaridean and Caprellid Amphipoda of Southern Africa. University Cape Town.

Griffiths, C. L. (1989). The Ingolfiellidea (Crustacea: Amphipoda) of southern Africa, with descriptions of two new species. Cimbebasia, 11, 59–70.

Griffiths, C. L. (1991). A new ingolfiellid (Crustacea: Amphipoda) from subterranean waters in western Namibia. Cimbebasia, 13, 75–79.

Grindley, J. R. (1963). A new Protojanira (Crustacea, Isopoda) from a Cape Peninsula cave. Annals of the Transvaal Museum, 24(4), 271–274.

Gurney, R. (1908). A new species of Cirolana from a fresh-water spring in the Algerian Sahara. In E. Korschelt (Ed.), Zoologischer Anzeiger (32nd ed., pp. 682–685). Verlag von Wilhelm Engelmann.

Hallam, F., Yacoubi-Khebiza, M., Oufdou, K., & Boulanouar, M. (2008). Groundwater quality in an arid area of Morocco: Impact of pollution on the biodiversity and relationships between crustaceans and bacteria of health interest. Environmental Technology, 29(11), 1179–1189. https://doi.org/10.1080/09593330802180237

Harrath, A. H., Mansour, L., Lagnika, M., Sluys, R., Boutin, C., Alwasel, S., Poch, A., & Riutort, M. (2016). A molecular analysis of the phylogenetic position of the suborder Cavernicola within the Tricladida (Platyhelminthes), with the description of a new species of stygobiont flatworm from Benin. Zoological Journal of the Linnean Society, 178(3), 482–491. https://doi.org/10.1111/zoj.12430

Harrath, A. H., Sluys, R., Ghlala, A., & Alwasel, S. (2012). The first subterranean freshwater planarians from North Africa, with an analysis of adenodactyl structure in the genus dendrocoelum (platyhelminthes, tricladida, dendrocoelidae). Journal of Cave and Karst Studies, 74(1), 48–57. https://doi.org/10.4311/2011LSC0215

Henry, J.-P., & Magniez, G. J. (1981). Un Aselle cavernicole d ’ Algérie: Proasellus notenboomi n . sp . (Isopoda , Asellota) et nouvelles données sur les Asellides d ’ Afrique du Nord Author (s): Jean-Paul Henry and Guy Magniez Published by: BRILL Stable URL: http://www.jstor.org/stabl. Crustaceana, 41(2), 206–215.

Hichem, K., Ramzi, H., & Djemoi, M. (2019). Biodiversity and distribution of groundwater fauna in the oum-elbouaghi region (Northeast of Algeria). Biodiversitas, 20(12), 3553–3558. https://doi.org/10.13057/biodiv/d201213

Holsinger, J. R. (1992). Sternophysingidae, a new family of subterranean Amphipods (Gammaridea: Crangonyctoidea) from South Africa, with description of Sternophysinx calceola, n. sp. and comments on phylogenetic and biogeographic relationships. Journal of Crustacean Biology, 12(1), 111–124.

Holthuis, L. B. (1980). Caridina Lanzana , A New Troglobitic Shrimp from Somalia (Crustacea Decapoda) . Monitore Zoologico Italiano. Supplemento, 13(1), 1–10. https://doi.org/10.1080/00269786.1980.11758546

Iannilli, V., Holsinger, J. R., Ruffo, S., & Vonk, R. (2006). Two new genera and two new species of the subterranean family Bogidiellidae (Crustacea, Amphipoda) from groundwaters in northern Oman, with notes on the geographic distribution of the family. Zoot, 1208, 37–56.

Iannilli, V., Krapp, T., & Ruffo, S. (2011). Freshwater amphipods from Madagascar with description of a new familiy, three new genera and six new species (Crustacea, Amphipoda). Botanica Zoologia, 35, 93–137.

Jaume, D., & Vonk, R. (2012). Discovery of Metacrangonyx in inland groundwaters of Oman (Amphipoda: Gammaridea: Metacrangonyctidae). Zootaxa, 3335, 54–68.

Karaman, G. S. (1990). Contribution to the knowledge of the Amphipoda 193. Bogidiella stocki, a new species from the Sinai peninsula (Amphipoda, Bogidiellidae). Beaufortia, 41(20), 141–149.

Karaman, G. S. (1992). New data on four Subterranean species of the suborder Gammaridea from Near East Region. Bulletin of Natural History Museum, Belgrade, Ser. B., 47, 75–89.

Karaman, G. S., & Pesce, G. L. (1980). On three subterranean amphipods from North Africa. Bulletin Zoologisch Museum, 7(20), 197–207.

Karanovic, I. (2001). Meischcandona gen. nov. from Africa, with a key to the genera of the subfamily Candoninae (Crustacea, Ostracoda). Bulletin de l'Institut Royal Des Sciences Naturelles de Belgique Biologie, 71, 93–99.

Kensley, B. (1995). A new genus of aquatic cave-dwelling isopod from Namibia (Crustacea: Isopoda: Asellota). Cimbebasia, 14, 1–15.

Khaldoun, L. (2015). Recherches phréatobiologiques dans la région de Khenchela (Sud Est Algérien): Qualité de l'eau des puits, Biodiversité, Écologie et Biogéographie des espèces stygobies. Universite Larbi Ben M#Hidi, Oum El Bouaghi.

Khaldoun, L., Merzoug, D., & Boutin, C. (2013). Faune aquatique et qualité de l'eau des puits et sources de la région de Khenchela (Aurès, Algérie nord-orientale). Bulletin de La Société Zoologique de France, 138(1–4), 273–292.

Khalloufi, N., Béjaoui, M., & Delicado, D. (2017). A new genus and species of uncertain phylogenetic position within the family Hydrobiidae (Caenogastropoda, Truncatelloidea) discovered in Tunisian springs. European Journal of Taxonomy, 328, 1–15. https://doi.org/10.5852/ejt.2017.328

Khalloufi, N., Béjaoui, M., & Delicado, D. (2020). Two new genera and three new subterranean species of hydrobiidae (Caenogastropoda: Truncatelloidea) from Tunisia. European Journal of Taxonomy, 648, 1–27. https://doi.org/10.5852/ejt.2020.648

Kiefer, F. (1952). Haplocyclops Gudrunae n. g. et n. sp., ein neuer Ruderfusskrebs (Crustacea Copepoda) aus Madagaskar. Zoologischer Anzeiger, 149, 240–243.

Lagnika, M., Ibikounlé, M., Boutin, C., & Sakiti, N. G. (2016). Groundwater biodiversity and water quality of wells in the Southern region of Benin. Comptes Rendus Chimie, 19(7), 798–806. https://doi.org/10.1016/j.crci.2015.08.009

Lagnika, M., Ibikounlé, M., Mazou, F., Sakiti, N. G., & Boutin, C. (2014). Diversité faunistique et qualité physicochimique de l ' eau des puits à Parakou (Bénin , Afrique de l ' Ouest). Bulletin de La Société d'histoire Naturelle de Toulouse, 150, 59–72.

Lagnika, M., Ibikounlé, M., Montcho, J. C., Wotto, V. D., & Sakiti, N. G. (2014). Caractéristiques physico-chimiques de l'eau des puits dans la commune de Pobè (Bénin, Afrique de l'ouest). Journal of Applied Biosciences, 79, 6887–6897. https://doi.org/10.4314/jab.v79i1.13

Lagnika, M., Messouli, M., Ibikounlé, M., Sakiti, N. G., Boutin, C., & Coineau, N. (2016). First record of groundwater amphipods (Crustacea) from Benin; range extension of the genus Pseudoniphargus to South of the Sahara, in western Africa. Bulletin de La Société d'histoire Naturelle de Toulouse, 152, 21–30.

Laid, L., & Zouheir, B. (2018). Diversite benthique et qualite des eaux souterraine de la region D'Ain M'Lila. Universite de Larbi Bn M'Hidi.

Löffler, H. (1963). Ergebnisse der Zoologischen Nubien-Expedition 1962 Teil XVIII Zur Binnenwasserfauna einiger Kleingewässer und Brunnen im nördlichen Sudan. Annalen Des Naturhistorischen Museums in Wien, 66, 489– 494.

Lylia, R., Ramzi, H., Hichem, K., Djemoi, M., & Menouar, S. (2020). Groundwater Quality in Two Semi-Arid Areas of Algeria: Impact of Water Pollution on Biodiversity. Journal of Bioresource Management, 7(3), 16–34. https://doi.org/10.35691/jbm.0202.0137

Magniez, G. J. (1975). Stenasellus kenyensis n.sp., Crustacea Isopoda Asellota des eaux souterraines du Kénya. International Journal of Speleology, 6(4), 325–332. https://doi.org/10.5038/1827-806x.6.4.3

Magniez, G. J. (1978). Magniezia gardei n.sp. (Crustacca Isopoda Asellote): un Sténasellide des eaux souterraines du Maroc sud-oriental. International Journal of Speleology, 9, 321–329. https://doi.org/10.5038/1827-806x.9.3.9

Mahi, A., Di Lorenzo, T., Haicha, B., Belaidi, N., & Taleb, A. (2019). Environmental factors determining regional biodiversity patterns of groundwater fauna in semi-arid aquifers of northwest Algeria. Limnology, 20(3), 309–320. https://doi.org/10.1007/s10201-019-00579-x

Mahi, A., Taleb, A., Belaidi, N., & Messana, G. (2017). Typhlocirolana longimera sp. n. (Crustacea, Isopoda, Cirolanidae) from north-western algerian ground waters with notes on Algerian Typhlocirolana. Subterranean Biology, 22(1), 27–41. https://doi.org/10.3897/subtbiol.22.11824

Marmonier, P., Boulal, M., & Idbennacer, B. (2005). Marococandona, a new genus of Candonidae (Crustacea, Ostracoda) from Southern Morocco: Morphological characteristics and ecological requirements. Annales de Limnologie, 41(1), 57–71. https://doi.org/10.1051/limn/2005006

Mathieu, J., Essafi, K., & Chergui, H. (1999). Spatial and temporal variations of stygobite Amphipod populations in interstitial aquatic habitats of karst/floodplain interfaces in France and Morocco. Annales de Limnologie, 35(2), 133–139. https://doi.org/10.1051/limn/1999018

Merzoug, D., Khiari, A., Boughrous, A. A., & Boutin, C. (2011). Faune aquatique et qualité de leau des puits et sources de la région dOum-El-Bouaghi (Nord-Est algérien). Hydroecologie Appliquee, 17, 77–97. https://doi.org/10.1051/hydro/2010001

Merzoug, D., Khiari, A., Tamrabet, L., & Saheb, M. (2014). Bio-Evaluation de la qualite des eaux souterraines: Cas de la nappe phreatique Mechta Lehteb region d’Oum-El-Bouaghi (Nord-Est de l’Algerie) Bio-evaluation Of The Groundwater Quality: Case Of Mechta Lehteb (oum Ebouaghi, Neast Algeria). Le Journal de l’Eau et de l’Environnement, 7(13), 92–104. https://www.asjp.cerist.dz/en/article/39413

Messana, G., Argano, R., & Baldari, F. (1978). Microcerberus (Crustacea isopoda microcerberidea) from the indian ocean. Monitore Zoologico Italiano, Supplemento, 10(1), 69–79. https://doi.org/10.1080/03749444.1978.10736858

Messana, G., & Chelazzi, L. (1984). Haptolana Somala N. Sp., A Phreatobic Cirolanid Isopod (Crustacea) from the Nogal Valley (Northern Somalia). Monitore Zoologico Italiano. Supplemento, 9, 291–298. https://doi.org/10.1080/00269786.1984.11758584

Messouli, M., Boutin, C., Yacoubi-Khebiza, M., & Coineau, N. (2001). Pseudoniphargus (Subterranean Crustacean Amphipod) from Morocco: Systematics , Phylogeny and Ecological and Biogeographic Aspects. 13th International Congress of Speleology, 391–394.

Messouli, M., El Alami Filali, A., Coineau, N., & Boutin, C. (2008). Metacrangonyx antennatus, a new species of the family Metacrangonyctidae (Crustacea, Amphipoda) from ground waters in south-western Morocco. Subterranean Biology, 6, 43–50.

Monod, T. (1925). Niphargopsis bryophilus et var petiti, gen., sp. et var. nov., amphipode nouveau des eaux douces de Madagascar. Bulletin Societe Zoologique de La France, 40, 40–49.

Monod, T. (1934). Typhlocirolana fontis (Gurney) à Hassi-Chebaba. In L.-G. Seurat (Ed.), Etudes Zoologiques sur le Sahara Central: Mission du Hoggar III (4th ed., pp. 87–89). Société d'Histoire Naturelle de l'Afrique du Nord.

Nkemegni, G. N., Zébazé Togouet, S. H., Fomena, A., Pountougnigni, O. F., & Piscart, C. (2015). Aquatic invertebrate fauna of wells in a tropical mountain climate, western Cameroon. African Journal of Aquatic Science, 40(4), 393– 401. https://doi.org/10.2989/16085914.2015.1113922

Noua, A. (2016). Contribution à l'étude de la qualité biologique et physico-chimique de l'eau des écosystèmes aquatiques et des puits de la région d'Oum El-Bouaghi (Hautes plaines de l'Est algérien). Universite Guelma.

Parisi, B. (1921). Un nuovo crostaceo cavernicolo: Typhlocaris lethaea n. sp. Atti Della Società Italiana Di Scienze Naturali e Del Museo Civico Di Storia Naturale Di Milano, 59, 241–248.

Pesce, G. L., Tetè, P., & De Simone, M. (1981). Ricerche in Africa dell'Instituto di Zoologia de l'Aquila: VI. Ricerche faunistische in acque sotterranee del Maghreb (Tunesia, Algeria, Marocca) e dell'Egitto. In Natura Società italiana di Scienze Naturali del Museo Civico di Storia Naturale et Acquario di Milano (Vol. 72, Issues 1–2, pp. 63–98).

Pinkster, S., & Goedmakers, A. (1975). On two new freshwater species of the genus Gammarus from North Africa (Crustacea, Amphipoda). Beaufortia, 23(301), 93–103.

Por, F. D. (1968). Copepods of some land-locked basins on the islands of Entedebir and Nocra (Dahlak Archipelago, Red Sea). Reports Istrael South Red Sea Expedition, 1962, 31, 32–50.

Racovitza, E. G. (1912). Cirolanides (Première Série). In Biospeologica (5th ed., Issue 17, pp. 203–329). Archives de Zoolodie Experimentale et Génerale.

Ramzi, H., Hichem, K., Lylia, R., Djemoi, M., & Menouar, S. (2020). Impact of Anthropic Pressure on the Quality and Diversity of Groundwater in the Region of Sighus Oum-El-Bouaghi and El Rahmounia, Algeria. Journal of Bioresource Management, 7(3), 85–105. https://doi.org/10.35691/jbm.0202.0142

Remy, P. (1938). Voyage de Ch. Allaud et P. A. Chappuis en Afrique occidentale francaise (1930-1931). No. X. Un Stenasellus en Afrique Occidentale Francaise: S. chappuisi n. sp. de la Cote d'Ivoire. Archives de Zoologie Experimentale Generale, Notes et Revue, 79(2), 69–74.

Roth-Woltereck, E. (1955). Vorläufige Mitteilung über eine neue Höhlengarneele (Decapoda Atyidae) aus Belgisch Kongo. Revue de Zoologie et Botanique Africaine, 51, 197–207.

Ruffo, S. (1951). Ingolfiella leleupi n. sp. nuovo Antipodo troglobio del congo. Revue de Zoologie et de Botanique Africaines, XLIV, 189–209.

Ruffo, S. (1953). Anfipodi di acque interstiziali raccolti dal Dr. C. Delamare Deboutteville in Francia, Spagna e Algeria. Vie et Milieu (France), 4(4), 669–681.

Ruffo, S. (1964). Studi sui crostacei anfipodi. Bolletino Di Zoologia, 31(2), 1019–1034. https://doi.org/10.1080/11250006409441133

Ruffo, S. (1970). Studi sui crostacei anfipodi. Lxiv. bogidiella somala n.sp. delle acque sotterranee della somalia (crustacea amphipoda). Monitore Zoologico Italiano, Supplemento, 3(6), 159–171. https://doi.org/10.1080/03749444.1970.10736763

Ruffo, S. (1974). Studi sui Crostacei Anfipodi 77. Nuovi Anfipodi interstiziali delle coste del Sud Africa. Atti Dell'Istituto Veneto Di Scienze, Lettere Ed Arti, 132, 399–419.

Ruffo, S. (1979). Studi sui Crostacei anfipodi. 90. Descrizione di due nuovi anfipodi anoftalmi dell'Iran e del Madagascar (Phreatomelita paceae n.gen. n.sp., Dussartiella madegassa n.gen. n.sp.). Bolletino Del Museo Civico Di Storia Naturale Di Verona, 6, 419–440.

Ruffo, S. (1982). Studi sui crostacei anfipodi. 92. nuovi anfipodi di acque sotterranee della somalia. Monitore Zoologico Italiano, Supplemento, 17(3), 97–113. https://doi.org/10.1080/03749444.1982.10736661

Ruffo, S. (1984). Studi sui Crostacei Anfipodi 95. Bogidiella nubica n. sp. from interstitial waters of the Sudan (Crustacea: Amphipoda). Hydrobiologia, 110, 131–134.

Ruffo, S. (1985). Un nuovo ingolfiellideo delle acque sotterranee della namibia: Stygobarnardia caprellinoides N. gen. N. sp. Atti Della Società Italiana Di Scienze Naturali e Del Museo Civico Di Storia Naturale Di Milano, 126(1–2), 43–53.

Schminke, H. K. (1979). Nannobathynella eburnea sp. n. und die Verbreitung der Bathynellidae (Bathynellicea, Syncarida) in den Tropen. Archiv Fur Hydrobiologie, 86(1), 112–124.

Schminke, H. K. (1980). Agnathobathynella ecclesi Gen. N., Sp. N. aus Malawi und die Formenvielfalt der Familie Bathynellidae (Crustacea, Bathynellacea). Bijdragen Tot de Dierkunde, 50(1), 145–154.

Schminke, H. K. (2009). Monodicaris gen. n. (Copepoda, Harpacticoida, Parastenocarididae) from West Africa. Crustaceana, 82(3), 367–378. https://doi.org/10.1163/156854008X363713

Schminke, H. K., & Wells, J. B. J. (1974). Nannobathynella africana sp. n. and the zoogeography of the family Bathynellidae (Bathynellacea, Malacostraca). Archiv Für Hydrobiologie, 73(1), 122–129. https://doi.org/10.1127/archiv-hydrobiol/73/1974/122

Serban, E., & Coineau, N. (1982). Lamtobathynella pentodonta n.g., n.sp., Leptobathynellidé nouveau d'Afrique (Côte d'lvoire) (Malacostraca, Bathynellacea). International Journal of Speleology, 12(1/4), 63–74. https://doi.org/10.5038/1827-806x.12.1.7

Sket, B. (1969). Eine neue Art der Stenasellinae (Isopoda, Asellota) aus Senegal. Bulletin Scientifique de La France et de La Belgique A, 14(11–12), 386–387.

Soyer, J. (1965). Une nouvelle Parastenocaris africaine. Biologia Gabonica, 1(3), 277–281.

Stock, J. H., & Vonk, R. (1992). Marine interstitial Amphipoda and Isopoda (Crustacea) from Santiago, Cape Verde Islands. Bijdragen Tot de Dierkunde, 62(1), 21–36. https://doi.org/10.1163/26660644-06201002

Thurston, M. H. (1973). A new species of Paramelita from South Africa. Annals of the South African Museum, 62(5), 159–168.

Toumi, H., Bejaoui, M., & Boumaiza, M. (2013). Contribution to the ecological study of epigean Cladocera and Copepoda (Cyclopoida) from groundwater in Northern Tunisia. Nature & Technology, 8, 12–18.

Tuékam Kayo, P. R., Marmonier, P., Boutin, C., Nola, M., Zébazé Togouet, S. H., Hubert, S., & Piscart, C. (2012). Les crustacés aquatiques souterrains d ' Afrique et de Madagascar: bilan et enjeux. Spelunca, 128, 43–46.

Tuékam Kayo, P. R., Marmonier, P., Zébazé Togouet, S. H., Nola, M., & Piscart, C. (2012). An annotated checklist of freshwater stygobiotic crustaceans of Africa and Madagascar. Crustaceana, 85(12–13), 1613–1631. https://doi.org/10.1163/15685403-00003134

Vonk, R., & Jaume, D. (2010). Glyptogidiella omanica gen. et sp. Nov., an inland groundwater bogidiellid from Oman with enlarged coxal plate V (Crustacea, Amphipoda). Zootaxa, 2657, 55–65. https://doi.org/10.11646/zootaxa.2657.1.5

Wägele, J.-W. (1983). Protocerberus Gen. N. und Afrocerberus Gen. N., Neue Limnische Microcerberidea aus Afrika. Bulletin Zoölogisch Museum, Universiteit van Amsterdam, 9(8), 10.

Wells, J. B. J. (1964). Six new species of Parastenocaris (Crustacea, Copepoda) from Southern Rhodesia. Annals and Magazine of Natural History, 7(76), 193–204. https://doi.org/10.1080/00222936408651458

Yacoubi-Khebiza, M., Messouli, M., Coineau, N., & Fakher el Abiari, A. (2001). Contribution to the Knowledge of the Groundwater Communities from Northern Morocco. 26th Brazilian Congress of Speleology, 11–15.

Zébazé Togouet, S. H., Boulanouar, M., Njiné, T., & Boutin, C. (2013). First discovery of a Stenasellidae (Crustacea, Isopoda, Aselloidea) in the ground waters of Cameroon (Central Africa): description, origin and palaeogeographic implications of Metastenasellus camerounenesis n.sp. Bulletin de La Société Historique National Toulouse, 149, 153–166.

Zébazé Togouet, S. H., Boutin, C., Njiné, T., Kemka, N., Ola, M. N., & Menbohan, S. F. (2009). First data on the groundwater quality and aquatic fauna of some wells and springs from Yaounde (Cameroon). Journal Europeen d'Hydrologie, 40(1), 51–74. https://doi.org/10.1051/water/2009005

Zébazé Togouet, S. H., Chinche, S. B., & Pountougnigni, O. F. (2019). Assessment and Management of Groundwater Fauna and Quality in the Town of Limbe, Cameroon. In S. O. Ojwach, P. N. Mahambi, C. Kowenje, & G. Baba (Eds.), Modern and Traditional Methods of Water Resource Management in Africa: Water Perspectives in Emerging Countries (pp. 96–108). Cuvillier Verlag.

Asia	Bandari, E., Shaik, S., & Ranga Reddy, Y. (2017). A phylogenetic review of the genus Atopobathynella Schminke, 1973 (Crustacea, Malacostraca, Bathynellacea) with three new species from southeastern India. Journal of Natural History, 51(35–36), 2143–2184. https://doi.org/10.1080/00222933.2017.1360528
	Bargrizaneh, Z., Fišer, C., & Esmaeili-Rineh, S. (2021). Groundwater amphipods of the genus Niphargus Schiødte, 1834 in Boyer-Ahmad region (Iran) with description of two new species. Zoosystema, 43(7), 127–144. https://doi.org/https://doi.org/10.5252/ zoosystema2021v43a7
	Berkhoff, S. E., Hahn, H. J., Cho, J.-L., & Kim, H.-S. (2003). Development of regional models of groundwater fauna in South Korea. Proceedings of the Korean Society of Soil and Groundwater Environment Conference, 240–243. http://www.koreascience.or.kr/article/CFKO200311922146241.view
	Birstein, J. A., & Ljovuschkun, S. I. (1968). A representative of the new for the USSR familiy Bogidiellidae (Crustacea, Amphipoda) in subterranean waters of Central Asia. Zoologicheskii Zhurnal, 5, 676–683.
	Boonyanusith, C., Brancelj, A., & Sanoamuang, L. (2013). First representatives of the genus Fierscyclops Karanovic, 2004 Copepoda, Cyclopidae) from South East Asia. Journal of Limnology, 72(S2), 275–289. https://doi.org/10.4081/jlimnol.2013.s2.e13
	Bork, J., Berkhoff, S. E., Bork, S., & Hahn, H. J. (2009). Using subsurface metazoan fauna to indicate groundwatersurface water interactions in the Nakdong River floodplain, South Korea. Hydrogeology Journal, 17(1), 61–75. https://doi.org/10.1007/s10040-008-0374-2
	Bork, J., Bork, S., Berkhoff, S. E., & Hahn, H. J. (2008). Testing unbaited stygofauna traps for sampling performance. Limnologica, 38(2), 105–115. https://doi.org/10.1016/j.limno.2007.10.001
	Botosaneanu, L. (2003). New stygobiontic Isopods (Isopoda: Cirolanidae, Anthuridae) from caves in Sulawesi, Indonesia. Bulletin de l'Institut Royal Des Sciences Naturelles de Belgique, Biologie, 73, 91–105.
	Botosaneanu, L., & Sket, B. (1999). A new freshwater stygobiotic species of Cyathura (Isopoda: Anthuridae) from Bohol Island, the Philippines. Acta Biologica Slovenica, 42(2), 27–33.
	Brancelj, A., Boonyanusith, C., Watiroyram, S., & Sanoamuang, L. (2013). The groundwater-dwelling fauna of East Asia. Journal of Limnology, 72(S2), 327–344. https://doi.org/10.4081/jlimnol.2013.s2.e16

Bruno, M. C., & Cottarelli, V. (1999). Harpacticoids From Groundwaters in the Philippines: Parastenocaris Mangyans, New Species, Epactophanes Philippinus, New Species, and Redescription of Phyllognathopus Bassoti (Copepoda). Journal of Crustacean Biology, 19(3), 510–529.

Chilton, C. (1921). Niphargus philippensis, a new species of amphipod from the underground waters of the Philippine Islands. The Philippine Journal of Science, 17, 516–523.

Chilton, C. (1923). A blind Amphipod from a mine in Bengal. Records Indian Museum, 25, 195–196.

Cho, J.-L., & Park, J. G. (2015). Two new species of Arisubathynella Park and Eun, 2012 (Malacostraca: Syncarida: Parabathynellidae) from South Korea. Journal of Crustacean Biology, 35(2), 241–254. https://doi.org/10.1163/1937240X-00002308

Cottarelli, V., Bruno, M. C., & Berera, R. (2006). A new species of Parastenocaris from Mindoro Island, Philippines: Parastenocaris distincta sp. nov. (Crustacea: Copepoda: Harpacticoida: Parastenocarididae). Zootaxa, 1368, 57–68. https://doi.org/10.11646/zootaxa.1368.1.5

Cottarelli, V., Bruno, M. C., & Berera, R. (2010). First record of parastenocarididae from thailand and description of a new genus (copepoda: Harpacticoida). Journal of Crustacean Biology, 30(3), 478–494. https://doi.org/10.1651/093201.1

Deharveng, L., Rahmadi, C., Suhardjono, Y. R., & Bedos, A. (2021). The towakkalak system, a hotspot of subterranean biodiversity in Sulawesi, Indonesia. Diversity, 13(8), 1–24. https://doi.org/10.3390/d13080392

Esmaeili-Rineh, S., Heidari, F., Fišer, C., & Akmali, V. (2016). Description of new endemic species of the genus Niphargus Schiodte, 1849 (Amphipoda: Niphargidae) from a karst spring in Zagros Mountains in Iran. Zootaxa, 4126(3), 338–350. https://doi.org/10.11646/zootaxa.4126.3.2

Esmaeili-Rineh, S., Mamaghani-Shishvan, M., Fišer, C., Akmali, V., & Najafi, N. (2020). Range sizes of groundwater amphipods (Crustacea) are not smaller than range sizes of surface amphipods: A case study from Iran. Contributions to Zoology, 89(1), 1–13. https://doi.org/10.1163/18759866-20191418

Esmaeili-Rineh, S., Mirghaffari, S. A., & Sharifi, M. (2017). The description of a new species of Niphargus from Iran based on morphological and molecular data. Subterranean Biology, 58(22), 43–58. https://doi.org/10.3897/subtbiol.22.11286

Esmaeili-Rineh, S., Mohammad-Niakan, A., & Akmali, V. (2018). Niphargus Sarii Sp. N., A new subterranean Niphargid (Crustacea: Amphipoda) from Iran based on molecular and morphological characters.
Acta Zoologica Academiae Scientiarum Hungaricae, 64(2), 113–132. https://doi.org/10.17109/AZH.64.2.113.2018

Esmaeili-Rineh, S., Sari, A., Delić, T., Moškrič, A., & Fišer, C. (2015). Molecular phylogeny of the subterranean genus (Crustacea: Amphipoda) in the Middle East: A comparison with European Niphargids.
Zoological Journal of the Linnean Society, 175(4), 812–826. https://doi.org/10.1111/zoj.12296

Esmaeili-Rineh, S., Sari, A., Fišer, C., & Bargrizaneh, Z. (2017). Completion of molecular taxonomy: description of four amphipod species (Crustacea: Amphipoda: Niphargidae) from Iran and release of database for morphological taxonomy.
Zoologischer Anzeiger, 271, 57–79. https://doi.org/10.1016/j.jcz.2017.04.009

Gupta, L. P. (1989). Studies on Crustacea of Bihar. I. Two new Ostracods from Subterranean waters of Monghyr.
In Publication Division (Ed.), Records of the zoological survey of India (Vol. 85, Issue 4, pp. 563–572). Zoological Survey of India.

Hekmatara, M., Zakšek, V., Heidari Baladehi, M., & Fišer, C. (2013). Two new species of Niphargus (Crustacea: Amphipoda) from Iran. Journal of Natural History, 47(21–22), 1421–1449. https://doi.org/10.1080/00222933.2012.743616

Herbst, H. V. (1986). Copepoda: Cyclopoida aus dem Meeres- und Brack-wasser-Interstitial. In L. Botosaneanu (Ed.), Stygofauna Mundi (pp. 313–320). Brill, Leiden.

Holsinger, J. R., Reddy, Y. R., & Messouli, M. (2006). Bogidiella indica, A New species of subterranean Amphipod Crustacean (Bogidiellidae) from wells in Southeastern India, with remarks on the biogeographic Importance of recently discovered Bogidiellids on the Indian Subcontinent. Subterranean Biology, 4, 45–54.

Karaman, G. S. (1988). New genera and species of the su bterranean family Bogidiellidae from the Near East (Contribution to the knowledge of the Amphipoda 179). Studia Marina, 19, 31–51.

Karaman, G. S. (1989). Metacrangonyx ortali n. sp., a new subterranean member of the family Crangonyctidae from Dead Sea region. (Contribution to the knowledge of the Amphipoda 178). Studia Marina, 20, 33–49.

Karaman, G. S. (1992). New data on four Subterranean species of the suborder Gammaridea from Near East Region.
Bulletin of Natural History Museum, Belgrade, Ser. B., 47, 75–89.

Karanovic, T. (2020). Four new cyclopina (Copepoda, cyclopinidae) from South Korea. ZooKeys, 992, 59–104. https://doi.org/10.3897/zookeys.992.54856

Karanovic, T., Grygier, M. J., & Lee, W. (2013). Endemism of subterranean Diacyclops in Korea and Japan, with descriptions of seven new species of the languidoides-group and redescriptions of D. brevifurcus Ishida, 2006 and D. suoensis Ito, 1954 (Crustacea, Copepoda, Cyclopoida). In ZooKeys (Vol. 267). https://doi.org/10.3897/zookeys.267.3935

Karanovic, T., Kim, K., & Grygier, M. J. (2015). A new species of Schizopera (Copepoda: Harpacticoida) from Japan, its phylogeny based on the mtCOI gene and comments on the genus Schizoperopsis. Journal of Natural History, 49(41–42), 2493–2526. https://doi.org/10.1080/00222933.2015.1028112

Karanovic, T., & Lee, W. (2012). A new species of Parastenocaris from Korea, with a redescription of the closely related P. biwae from Japan (Copepoda: Harpacticoida: Parastenocarididae). Journal of Species Research, 1(1), 4– 34. https://doi.org/10.12651/jsr.2012.1.1.004

Karanovic, T., & Ready, Y. R. (2004). A new genus and species of the family diosaccidae (Copepoda: Harpacticoida) from the groundwaters of India. Journal of Crustacean Biology, 24(2), 246–260. https://doi.org/10.1651/C-2433

Karanovic, T., Yoo, H., & Lee, W. (2012). A new cyclopoid copepod from Korean subterranean waters reveals an interesting connection with the Central Asian fauna (Crustacea: Copepoda: Cyclopoida). Journal of Species Research, 1(2), 156–174. https://doi.org/10.12651/jsr.2012.1.2.156

Kawakatsu, M., & Mitchell, R. W. (1989). Record of a trolobitic Planarian from Tanette Cave located in the Maros Karst, Sulawesi (Celebes), Indonesia. Bulletin of Fuji Women's College, 27(2), 35–40.

Kiefer, F. (1981). Ein Neuer Brunnenbewohnder Cyclopide (Copepoda, Cyclopoida) aus Syrien. Andrias, 1, 101–102.

Kurt Schminke, H. (1988). A new genus and species of Syncarida (Crustacea: Malacostraca) from Borneo. Journal of Natural History, 22(3), 631–637. https://doi.org/10.1080/00222938800770431

Leclerc, P., Deharveng, L., Ng, P. K. L., Juberthie, C., & Decu, V. (2001). Indonesie. In C. Juberthie & V. Deou (Eds.), Encyclopædia Biospeologica (Volume 3, pp. 1805–1823). Société internationale de Biospéologie.

Lopez, M. L. D., Magbanua, F. S., Mamaril, A. C., & Papa, R. D. S. (2017). Variations in microcrustacean (Crustacea: Cladocera, copepoda) assemblages from selected groundwater-dependent ecosystems in the greater Lluzon and Mmindoro island faunal regions (pPhilippines): Insights to tropical groundwater ecology. Inland Waters, 7(4), 428– 439. https://doi.org/10.1080/20442041.2017.1368597

Magniez, G. J. (2001). Stenasellus stocki n. sp., nouvel Isopode Stenasellidae des eaux souterraines de Sumatra (Indonésie). Bulletin Mensuel de La Société Linnéenne de Lyon, 70(6), 159–164. https://doi.org/10.1163/156854002760095534

Mamaghani-Shishvan, M., & Esmaeili-Rineh, S. (2019). Two new species of groundwater amphipods of the genus Niphargus Schiödte, 1849 from northwestern Iran. European Journal of Taxonomy, 546, 1–23. https://doi.org/10.5852/ejt.2019.546

Matsumoto, K. (1976). An introduction to the Japanese groundwater animals with reference to their ecology and hygienic significance. International Journal of Speleology, 8, 141–155. https://doi.org/10.5038/1827-806x.8.1.13

Nadushan, R. M., Emadi, H., Fatemi, S. M. R., & Samanpajuh, M. (2010). Assessment of the ecological status of the shallow Lake Neor (Iran) using a macroinvertebrate community structure. WIT Transactions on Ecology and the Environment, 135, 169–177. https://doi.org/10.2495/WP100151

Ng, P. K. L., & Sket, B. (1996). The freshwater crab fauna (Crustacea: Decapoda: Brachyura) of the Philippines. IV. On a collection of Parathelphusidae from Bohol. Proceedings of the Biological Society of Washington, 109(4), 695–706.

Park, J. G., & Cho, J.-L. (2013). New genus and two new species of parabahtynellidae (Malacostraca: Syncarida) from South Korea. Journal of Crustacean Biology, 33(6), 866–881. https://doi.org/10.1163/1937240X-00002184

Pesce, G. L., & Apostolov, A. M. (1985). Elaphoidella margaritae sp.n., a new phreatobitic harpacticoid from subterranean waters of Thailand (Crustacea, Copepoda, Canthocamptidae). Acta Zoologica Bulgarica, 28, 70–75.

Pesce, G. L., & Argano, R. (1981). Richerche nell'asia sudorientale: Stenasellidi del sud-est asiatico: Stenasellus brignolii n. sp. di Thailandia (Crustacea, Isopoda: Asellota). Bolletino Del Museo Del Civico Storia Naturale Di Verona, 8, 435–441.

Ruffo, S. (1994). New stygobiont amphipods (crustacea amphipoda) from the philippine islands. Tropical Zoology, 7(2), 355–366. https://doi.org/10.1080/03946975.1994.10539265

Sawicki, T. R., Holsinger, J. R., & Sket, B. (2005). Redescription of the subterranean amphipod crustacean Flagitopisa philippensis (Hadzioidea: Melitidae), with notes on its unique morphology and clarification of the taxonomic status of Psammogammarus fluviatilis. Raffles Bulletin of Zoology, 53(1), 59–68.

Schminke, H. K. (2008). First report of groundwater fauna from Papua New Guinea: Kinnecaris Jakobi, 1972 redefined (Copepoda, Harpacticoida, Parastenocarididae), and description of a new species. Crustaceana, 81(10), 1241– 1253. https://doi.org/10.1163/156854008X374568

Schwoerbel, J. (1986). Acari: Limnohalacaridae and Hydrovolziidae. In L. Botosaneanu (Ed.), Stygofauna Mundi (pp. 643–647). Brill, Leiden.

Senna, A. R., Mugnai, R., & Reddy, Y. R. (2013). A new species of Bogidiella (Crustacea: Amphipoda: Bogidiellidae) from bore wells in Andhra Pradesh, Southern India. Zoologia, 30(4), 451–457. https://doi.org/10.1590/S198446702013000400013

Shinoda, S. (2006). Investigation of the subterranean species, which has appeared in the spring water in Tokyo: Vol. No. 164.

Smith, R. J. (2011). Groundwater, spring and interstitial Ostracoda (Crustacea) from Shiga Prefecture, Japan, including descriptions of three new species and one new genus. Zootaxa, 37(3140), 15–37. https://doi.org/10.11646/zootaxa.3140.1.2

Stock, J. H. (1991). A new species of Psammogammarus (Amphipoda, Melitidae) from river alluvia in in Luzon, Philippines. Stygologia, 6(4), 227–233.

Stock, J. H. (1992). Bogidiella (Amphipoda) in Japanese Inland Waters. Crustaceana, 62(3), 273–282. https://doi.org/29.13.72.197

Tomikawa, K., & Nakano, T. (2018). Two new subterranean species of Pseudocrangonyx Akatsuka & Komai, 1922 (Amphipoda: Crangonyctoidea: Pseudocrangonyctidae), with an insight into groundwater faunal relationships in western Japan. Journal of Crustacean Biology, 38(4), 460–474. https://doi.org/10.1093/jcbiol/ruy031

Totakura, V. R., & Reddy, Y. R. (2015). Groundwater cyclopoid copepods of peninsular India, with description of eight new species. In Zootaxa (Vol. 3945). Magnolia Press. https://doi.org/10.11646/zootaxa.3963.3.9

Wagele, J. W., Coleman, C. O., & Hosse, U. (1987). Two new hypogean species of Cyathura from Melanesia (Crustacea, Isopoda, Anthuridea): further Tethyan relicts? Stygologia, 3(1), 89–106.

Watiroyram, S. (2021). Attheyella (Canthosella) thailandica sp. nov. (Copepoda, Harpacticoida, Canthocamptidae) from caves in Thailand. Subterranean Biology, 37, 57–73. https://doi.org/10.3897/subtbiol.37.55376

Australia	Allford, A., Cooper, S. J. B., Humphreys, W. F., & Austin, A. D. (2008). Diversity and distribution of groundwater fauna in a calcrete aquifer: Does sampling method influence the story? Invertebrate Systematics, 22(2), 127–138. https://doi.org/10.1071/IS07058 Asmyhr, M. G., & Cooper, S. J. B. (2012). Difficulties barcoding in the dark: The case of crustacean stygofauna from eastern Australia. Invertebrate Systematics, 26(5–6), 583–591. https://doi.org/10.1071/IS12032 Balke, M., Watts, C. H. S., Cooper, S. J. B., Humphreys, W. F., & Vogler, A. P. (2004). A highly modified stygobiont diving beetle of the genus Copelatus (Coleoptera, Dytiscidae): Taxonomy and cladistic analysis based on mitochondrial DNA sequences. Systematic Entomology, 29(1), 59–67. https://doi.org/10.1111/j.13653113.2004.00229.x Boulton, A. J., Fenwick, G. D., Hancock, P. J., & Harvey, M. S. (2008). Biodiversity, functional roles and ecosystem services of groundwater invertebrates. Invertebrate Systematics, 22(2), 103–116. https://doi.org/10.1071/IS07024 Boulton, A. J., Humphreys, W. F., & Eberhard, S. M. (2003). Imperilled subsurface waters in Australia: Biodiversity, threatening processes and conservation. Aquatic Ecosystem Health and Management, 6(1), 41–54. https://doi.org/10.1080/14634980301475 Boulton, A. J., Scarsbrook, M. R., Quinn, J. M., & Burrell, G. P. (1997). Land-use effects on the hyporheic ecology of five small streams near Hamilton, New Zealand. New Zealand Journal of Marine and Freshwater Research, 31(5), 609–622. https://doi.org/10.1080/00288330.1997.9516793 Bousfield, E. L. (1964). Insects of Campbell Island. Talitrid Amphipod Crustaceans. Pacific Insects Monograph, 7, 45– 57. Bradbury, J. H., & Eberhard, S. M. (2000). A new stygobiont melitid amphipod from the Nullarbor Plain. Records of the Western Australian Museum, 20(1), 39–50. Bradbury, J. H., & Williams, W. D. (1999). Key to and checklist of the freshwater amphipods of Australia. Technical Reports of the Australian Museum, 14(14), 1–21. https://doi.org/10.3853/j.1031-8062.14.1999.354 Bradford, T., Adams, M., Humphreys, W. F., Austin, A. D., & Cooper, S. J. B. (2010). DNA barcoding of stygofauna uncovers cryptic amphipod diversity in a calcrete aquifer in Western Australia's arid zone. Molecular Ecology Resources, 10(1), 41–50. https://doi.org/10.1111/j.1755-0998.2009.02706.x

Bradford, T. M., Adams, M., Guzik, M. T., Humphreys, W. F., Austin, A. D., & Cooper, S. J. B. (2013). Patterns of population genetic variation in sympatric chiltoniid amphipods within a calcrete aquifer reveal a dynamic subterranean environment. Heredity, 111(1), 77–85. https://doi.org/10.1038/hdy.2013.22

Brown, L., Finston, T. L., Humphreys, G., Eberhard, S. M., & Pinder, A. M. (2015). Groundwater oligochaetes show complex genetic patterns of distribution in the Pilbara region of Western Australia. Invertebrate Systematics, 29(5), 405–420. https://doi.org/10.1071/IS14037

Castaño-Sánchez, A., Hose, G. C., & Reboleira, A. S. P. S. (2020). Salinity and temperature increase impact groundwater crustaceans. Scientific Reports, 10(12328), 1–9. https://doi.org/10.1038/s41598-020-69050-7

Cawthorn, T. (1963). Discovery of subterranean fresh water fauna on the eastern side of North West Cape. In The Western Australian Naturalist (Volume 7, pp. 129–132). Western Australian Naturalist Club.

Chambers, J., Nugent, G., Sommer, B., Speldewinde, P., Neville, S., Beatty, S., Chilcott, S., Eberhard, S. M., Mitchell, N., D'Souza, F., Barron, O., McFarlane, D., Braimbridge, M., Robson, B., Close, P., Morgan, D., Pinder, A. M., Froend, R., Horwitz, P., . . . Davies, P. (2013). Adapting to climate change: a risk assessment and decision making framework for managing groundwater dependent ecosystems with declining water levels: Development and Case Studies.

Chilton, C. (1881). On some Subterranean Crustacea. Transactions and Proceedings of the New Zealand Institute, 14, 174–180.

Chilton, C. (1882). On some subterranean Crustacea: Art. III.—Notes on, and a new Species of Subterranean Crustacea. and Proceedings of the New Zealand Institute, 15, 87–94.

Chilton, C. (1893). The subterranean Crustacea of New Zealand: with some general remarks on the fauna of caves and wells. Transactions of the Linnean Society of London Second Series Zoology, 6, 163–284. https://doi.org/https://doi.org/10.1111/j.1096-3642.1894.tb00481.x

Chilton, C. (1898a). A new freshwater amphipod from New Zealand. Annals and Magazine of Natural History, 1(Series 7), 423–426.

Chilton, C. (1898b). LXV.— A new freshwater Amphipod from New Zealand. Annals and Magazine of Natural History, 7(1:6), 423–426. https://doi.org/10.1080/00222939808677996

Chilton, C. (1909a). The Crustacea of the subantarctic islands of New Zealand. In C. Chilton (Ed.), Subantarctic Islands of New Zealand (Vol. 2, pp. 599–613). Philosophical Institute of Canterbury printed by John Mckay, Gouvernment Printer.

Chilton, C. (1909b). The fresh water Amphipoda of New Zealand. Transactions of the New Zealand Institute, 41, 53– 59.
Chilton, C. (1912). Miscellaneous notes on some New Zealand Crustacea. Transactions of the New Zealand Institute, 44, 128–135.
Cho, J. L., Park, J. G., & Humphreys, W. F. (2005). A new genus and six new species of the Parabathynellidae (Bathynellacea, Syncarida) from the Kimberley region, Western Australia. Journal of Natural History, 39(24), 2225–2255. https://doi.org/10.1080/00222930400014148
Cho, J.-L. (2005). A primitive representative of the Parabathynellidae (Bathynellacea, Syncarida) from the Yilgarn Craton of Western Australia. Journal of Natural History, 39(39), 3423–3433. https://doi.org/10.1080/00222930500345806
Cho, J.-L., Humphreys, W. F., & Lee, S. D. (2006). Phylogenetic relationships within the genus Atopobathynella Schminke (Bathynellacea: Parabathynellidae). Invertebrate Systematics, 20(1), 9–41. https://doi.org/10.1071/IS05019
Cook, B. D., Abrams, K. M., Marshall, J. C., Perna, C. N., Choy, S., Guzik, M. T., & Cooper, S. J. B. (2012). Species diversity and genetic differentiation of stygofauna (Syncarida:Bathynellacea) across an alluvial aquifer in northeastern Australia. Australian Journal of Zoology, 60(3), 152–158. https://doi.org/10.1071/ZO12061
Cooper, S. J. B., Bradbury, J. H., Saint, K. M., Leys, R., Austin, A. D., & Humphreys, W. F. (2007). Subterranean archipelago in the Australian arid zone: Mitochondrial DNA phylogeography of amphipods from central Western Australia. Molecular Ecology, 16(7), 1533–1544. https://doi.org/10.1111/j.1365-294X.2007.03261.x
Cooper, S. J. B., Hinze, S., Leys, R., Watts, C. H. S., & Humphreys, W. F. (2002). Islands under the desert: Molecular systematics and evolutionary origins of stygobitic water beetles (Coleoptera:Dytiscidae) from central Western Austalia. Invertebrate Systematics, 16(4), 589–598. https://doi.org/10.1071/IT01039
Cooper, S. J. B., Saint, K. M., Taiti, S., Austin, A. D., & Humphreys, W. F. (2008). Subterranean archipelago: Mitochondrial DNA phylogeography of stygobitic isopods (Oniscidea:Haloniscus) from the Yilgarn region of Western Australia. Invertebrate Systematics, 22(2), 195–203. https://doi.org/10.1071/IS07039
De Laurentiis, P., Pesce, G. L., & Humphreys, W. F. (1999). Copepods from ground waters of Western Australia, IV. Cyclopids from basin and craton aquifers (Crustacea: Copepoda: Cyclopidae). Records of the Western Australian Museum, 19, 243–257.

De Laurentiis, P., Pesce, G. L., & Humphreys, W. F. (2001). Copepods from ground waters of Western Australia, VI. Cyclopidae (Crustacea: Copepoda) from the Yilgarn Region and the Swan Coastal Plain. Records of the Western Australian Museum, Supplement, 64(1), 115–131. https://doi.org/10.18195/issn.0313-122x.64.2001.115-131

Dillon, P., Kumar, A., Kookana, R., Leijs, R., Reed, D., & Parsons, S. (2009). Managed Aquifer Recharge - Risks to Groundwater Dependent Ecosystems - A Review. In Water for a Healthy Country Flagship Report to Land & Water Australia.

Eberhard, S. M. (1992). The invertebrate cave fauna of Tasmania: ecology and conservation biology. University of Tasmania.

Eberhard, S. M. (2001). Cave fauna monitoring and management at Ida Bay, Tasmania. Records of the Western Australian Museum, Supplement, 64(1), 97. https://doi.org/10.18195/issn.0313-122x.64.2001.097-104

Eberhard, S. M., Anderson, M., & Rutlidge, H. (2017). Impact of groundwater drawdown on stygofauna in the hyporheic zone. Australian Groundwater Conference "Groundwater Futures Science to Practice," 195.

Eberhard, S. M., & Giachino, P. M. (2011). Tasmanian trechinae and psydrinae (Coleoptera, Carabidae): A taxonomic and biogeographic synthesis, with description of new species and evaluation of the impact of Quaternary climate changes on evolution of the subterranean fauna. Subterranean Biology, 9(1), 1–72. https://doi.org/10.3897/subtbiol.9.2516

Eberhard, S. M., Halse, S. A., & Humphreys, W. F. (2005). Stygofauna in the Pilbara region, north-west Western Australia: A review. Journal of the Royal Society of Western Australia, 88(4), 167–176.

Eberhard, S. M., Halse, S. A., Scanlon, M. D., Cocking, J., & Barron, H. J. (2004). Assessment and conservation of aquatic life in the subsurface of the Pilbara region, Western Australia. In J. Gibert (Ed.), Symposium on World Subterranean Biodiversity (pp. 61–68). Subterranean Ecology, Scientific Environmental Services.

Eberhard, S. M., Halse, S. A., Williams, M. R., Scanlon, M. D., Cocking, J., & Barron, H. J. (2009). Exploring the relationship between sampling efficiency and short-range endemism for groundwater fauna in the Pilbara region, Western Australia. Freshwater Biology, 54(4), 885–901. https://doi.org/10.1111/j.1365-2427.2007.01863.x

Eberhard, S. M., Leys, R., & Adams, M. (2005). Conservation of subterranean biodiversity in Western Australia: using molecular genetics to define spatial and temporal relationships in two species of cave-dwelling Amphipoda. Subterranean Biology, 3, 13–27.

Eberhard, S. M., Watts, C. H. S., Callan, S. K., & Leijs, R. (2016). Three new subterranean diving beetles (Coleoptera: Dytiscidae) from the Yeelirrie groundwater calcretes, Western Australia, and their distribution between several calcrete deposits including a potential mine site. Records of the Western Australian Museum, 31(1), 27–40. https://doi.org/10.18195/issn.0312-3162.31(1).2016.027-040

Fenwick, G. D. (2001). The freshwater amphipoda (Crustacea) of New Zealand: A review. Journal of the Royal Society of New Zealand, 31(2), 341–363. https://doi.org/10.1080/03014223.2001.9517658

Fenwick, G. D., Greenwood, M., Williams, E., Milne, J., & Watene-Rawiri, E. (2018). Groundwater ecosystems: functions, values, impacts and management.

Finston, T. L., Bradbury, J. H., Johnson, M. S., & Knott, B. (2004). When morphology and molecular markers conflict: A case history of subterranean amphipods from the Pilbara, Western Australia. Animal Biodiversity and Conservation, 27(2), 83–94.

Finston, T. L., Francis, C. J., & Johnson, M. S. (2009). Biogeography of the stygobitic isopod Pygolabis (Malacostraca: Tainisopidae) in the Pilbara, Western Australia: Evidence for multiple colonisations of the groundwater. Molecular Phylogenetics and Evolution, 52, 448–460. https://doi.org/10.1016/j.ympev.2009.03.006

Finston, T. L., Johnson, M. S., Humphreys, W. F., Eberhard, S. M., & Halse, S. A. (2007). Cryptic speciation in two widespread subterranean amphipod genera reflects historical drainage patterns in an ancient landscape. Molecular Ecology, 16(2), 355–365. https://doi.org/10.1111/j.1365-294X.2006.03123.x

Glanville, K., Schulz, C., Tomlinson, M., & Butler, D. (2016). Biodiversity and biogeography of groundwater invertebrates in Queensland, Australia. Subterranean Biology, 17, 55–76. https://doi.org/10.3897/SUBTBIOL.17.7542

Greenwood, M., & Fenwick, G. D. (2019). Suitability of invertebrate data for assessing groundwater ecosystem health.

Guzik, M. T., Abrams, K. M., Cooper, S. J. B., Humphreys, W. F., Cho, J.-L., & Austin, A. D. (2008). Phylogeography of the ancient Parabathynellidae (Crustacea: Bathynellacea) from the Yilgarn region of Western Australia. Invertebrate Systematics, 22(2), 205–216. https://doi.org/10.1071/IS07040

Guzik, M. T., Austin, A. D., Cooper, S. J. B., Harvey, M. S., Humphreys, W. F., Bradford, T., Eberhard, S. M., King, R. A., Leys, R., Muirhead, K. A., & Tomlinson, M. (2010). Is the Australian subterranean fauna uniquely diverse? Invertebrate Systematics, 24(5), 407–418. https://doi.org/10.1071/IS10038

Guzik, M. T., Cooper, S. J. B., Humphreys, W. F., Ong, S., Kawakami, T., & Austin, A. D. (2011). Evidence for population fragmentation within a subterranean aquatic habitat in the Western Australian desert. Heredity, 107(3), 215–230. https://doi.org/10.1038/hdy.2011.6

Hancock, P. J. (2015). Bylong Coal Project Environmental Impact Statement - Stygofauna Impact Assessment.

Hancock, P. J., & Boulton, A. J. (2008). Stygofauna biodiversity and endemism in four alluvial aquifers in eastern Australia. Invertebrate Systematics, 22(2), 117–126. https://doi.org/10.1071/IS07023

Hancock, P. J., & Boulton, A. J. (2009). Sampling groundwater fauna: Efficiency of rapid assessment methods tested in bores in eastern Australia. Freshwater Biology, 54(4), 902–917. https://doi.org/10.1111/j.1365-2427.2007.01878.x

Harding, J., Mosley, P., Pearson, C., & Sorrell, B. (2004). Freshwaters of New Zealand. The Caxton Press.

Hartland, A., Fenwick, G. D., & Bury, S. J. (2011). Tracing sewage-derived organic matter into a shallow groundwater food web using stable isotope and fluorescence signatures. Marine and Freshwater Research, 62(2), 119–129. https://doi.org/10.1071/MF10110

Hose, G. C., Asmyhr, M. G., Cooper, S. J. B., & Humphreys, W. F. (2014). Down under down under: Austral groundwater life. In A. Stow, N. Maclean, & G. I. Holwell (Eds.), Austral Ark: The State of Wildlife in Australia and New Zealand (pp. 512–536). Cambridge University Press. https://doi.org/10.1017/CBO9781139519960.026

Hose, G. C., Murray, B. R., & Eamus, D. (2004). Water quality guidelines to protect groundwaterdependent ecosystems. In Ecological Management & Restoration (Vol. 5, Issue 1, pp. 78–80).

Hose, G. C., Sreekanth, J., Barron, O., & Pollino, C. (2015). Stygofauna in Australian groundwater systems: Extent of knowledge. In Report to Australian Coal Association Research Program. Macquarie University and CSIRO. CSIRO.

Humphreys, W. F. (2000). The hypogean fauna of the Cape Range Peninsula and Barrow Island, Northwestern Australia. In H. Wilkens, D. C. Culver, & W. F. Humphreys (Eds.), Subterranean Ecosystems (pp. 581–601). Elsevier.

Humphreys, W. F. (2001). Groundwater calcrete aquifers in the Australian arid zone: the context to an unfolding plethora of stygal biodiversity. Records of the Western Australian Museum Supplement, 64(1), 63–83. https://doi.org/10.18195/issn.0313-122x.64.2001.063-083

Humphreys, W. F. (2006). Aquifers: The ultimate groundwater-dependent ecosystems. Australian Journal of Botany, 54(2), 115–132. https://doi.org/10.1071/BT04151

Humphreys, W. F., & Adams, M. (1991). The subterranean aquatic fauna of the North West Cape peninsula, Western Australia. Records of the Western Australian Museum, 15(2), 383–411.

Humphreys, W. F., Watts, C. H. S., Cooper, S. J. B., & Leijs, R. (2009). Groundwater estuaries of salt lakes: Buried pools of endemic biodiversity on the western plateau, Australia. Hydrobiologia, 626(1), 79–95. https://doi.org/10.1007/s10750-009-9738-4

Jaume, D., Boxshall, G. A., & Humphreys, W. F. (2001). New stygobiont copepods (Calanoida; Misophrioida) from Bundera sinkhole, an anchialine cenote in north-western Australia. Zoological Journal of the Linnean Society, 133(1), 1–24. https://doi.org/10.1006/zjls.2000.0288

Karanovic, I. (2003). Towards a Revision of Candoninae (Crustacea: Ostracoda): Description of Two New Genera from Australian Groundwaters. Species Diversity, 8(4), 353–383. https://doi.org/10.12782/specdiv.8.353

Karanovic, I. (2005a). A new Canoninae genus (Crustacea: Ostracoda) from subterranean waters of Queensland, with a cladistic analysis of the tribe Candonopsini. Memoirs of the Queensland Museum, 50(2), 303–319.

Karanovic, I. (2005b). Towards a revision of Candoninae (Crustacea: Ostracoda): Australian representatives of the subfamily, with descriptions of three new genera and seven new species. New Zealand Journal of Marine and Freshwater Research, 39(1), 29–75. https://doi.org/10.1080/00288330.2005.9517292

Karanovic, I. (2007). Candoninae (Ostracoda) from the Pilbara Region in Western Australia. In Crustaceana Monograph (7th ed.). brill.

Karanovic, I., & Marmonier, P. (2002). On the genus Candonopsis (Crustacea: Ostracoda: Candoninae) in Australia, with a key to the world recent species. Annales de Limnologie, 38(3), 199–240. https://doi.org/10.1051/limn/2002018

Karanovic, I., & Marmonier, P. (2003). Three new genera and nine new species of the subfamily Candoninae (Crustacea, Ostracoda, Podocopida) from the Pilbara region (Western Australia). Beaufortia, 53(1), 1–51.

Karanovic, T. (2004). Subterranean Copepods from arid Western Australia. In J. C. von Vaupel Klein (Ed.), Crustaceana Monograph (3rd ed.). Brill.

Karanovic, T. (2005). Two new genera and three new species of subterranean cyclopoids (Crustacea, Copepoda) from New Zealand, with redescription of Goniocyclops silvestris Harding, 1958. Contributions to Zoology, 74(3–4), 223–254. https://doi.org/10.1163/18759866-0740304002

Karanovic, T. (2006). Subterranean copepods (Crustacea, Copepoda) from the Pilbara region in Western Australia. Records of the Western Australian Museum, Supplement, 70(1), 239. https://doi.org/10.18195/issn.0313122x.70.2006.001-239

Karanovic, T., Eberhard, S. M., Perina, G., & Callan, S. K. (2013). Two new subterranean ameirids (Crustacea:Copepoda: Harpacticoida) expose weaknesses in the conservation of short-range endemics threatened by mining developments in Western Australia. Invertebrate Systematics, 27(5), 540–566. https://doi.org/10.1071/IS12084

Korbel, K. L., Chariton, A., Stephenson, S., Greenfield, P., & Hose, G. C. (2017). Wells provide a distorted view of life in the aquifer: Implications for sampling, monitoring and assessment of groundwater ecosystems. Scientific Reports, 7(40702), 1–14. https://doi.org/10.1038/srep40702

Korbel, K. L., Hancock, P. J., Serov, P., Lim, R. P., & Hose, G. C. (2013). Groundwater Ecosystems Vary with Land Use across a Mixed Agricultural Landscape. Journal of Environmental Quality, 42(2), 380–390. https://doi.org/10.2134/jeq2012.0018

Korbel, K. L., & Hose, G. C. (2011). A tiered framework for assessing groundwater ecosystem health. Hydrobiologia, 661(1), 329–349. https://doi.org/10.1007/s10750-010-0541-z

Korbel, K. L., & Hose, G. C. (2015). Habitat, water quality, seasonality, or site? Identifying environmental correlates of the distribution of groundwater biota. Freshwater Science, 34(1), 329–342. https://doi.org/10.1086/680038

Korbel, K. L., & Hose, G. C. (2017). The weighted groundwater health index: Improving the monitoring and management of groundwater resources. Ecological Indicators, 75, 164–181. https://doi.org/10.1016/j.ecolind.2016.11.039

Korbel, K. L., Lim, R. P., & Hose, G. C. (2013). An inter-catchment comparison of groundwater biota in the cottongrowing region of north-western New South Wales. Crop and Pasture Science, 64(11–12), 1195–1208. https://doi.org/10.1071/CP13176

Korbel, K. L., Stephenson, S., & Hose, G. C. (2019). Sediment size influences habitat selection and use by groundwater macrofauna and meiofauna. Aquatic Sciences, 81(39), 10. https://doi.org/10.1007/s00027-019-0636-1

Larned, S. T., Datry, T., & Robinson, C. T. (2007). Invertebrate and microbial responses to inundation in an ephemeral river reach in New Zealand: Effects of preceding dry periods. Aquatic Sciences, 69(4), 554–567. https://doi.org/10.1007/s00027-007-0930-1

Leijs, R., Bloechl, A., & Koenemann, S. (2011). Bogidiella veneris, a new species of subterranean amphipoda (Bogidiellidae) from Australia, with remarks on the systematics and biogeography. Journal of Crustacean Biology, 31(3), 566–575. https://doi.org/10.1651/11-3476.1

Leijs, R., Roudnew, B., Mitchell, J., & Humphreys, B. (2009). A new method for sampling stygofauna from groundwater fed marshlands. Speleobiology Notes, 1, 12–13.

Lennon, J. (2019). Inter catchment comparisons of groundwater communities from the Lower Murray Darling Basin. Maquarie University.

Leys, R., Roudnew, B., & Watts, C. H. S. (2010). Paroster extraordinarius sp. nov., a new groundwater diving beetle from the Flinders Ranges, with notes on other diving beetles from gravels in South Australia (Coleoptera: Dytiscidae). Australian Journal of Entomology, 49(1), 66–72. https://doi.org/10.1111/j.1440-6055.2009.00738.x

Leys, R., & Watts, C. H. S. (2008). Systematics and evolution of the Australian subterranean hydroporine diving beetles (Dytiscidae), with notes on Carabhydrus. Invertebrate Systematics, 22(2), 217–225. https://doi.org/10.1071/IS07034

Leys, R., Watts, C. H. S., Cooper, S. J. B., & Humphreys, W. F. (2003). Evolution of subterranean diving beetles (Coleoptera: Dytiscidae: Hydroporini, Bidessini) in the arid zone of Australia. Evolution, 57(12), 2819–2834. https://doi.org/10.1111/j.0014-3820.2003.tb01523.x

Little, J., Schmidt, D. J., Cook, B. D., Page, T. J., & Hughes, J. M. (2016). Diversity and phylogeny of south-east Queensland Bathynellacea. Australian Journal of Zoology, 64(1), 36–47. https://doi.org/10.1071/ZO16005

Main, D., Gundawardene, N., Callan, S. K., & Durrant, B. (2018). Eliwana Project: Subterranean Fauna Assessment 2017. Biologic Environmental Survey.

Mees, G. F. (1962). The Subterranean Freshwater Fauna of Yardie Creek Station, North West Cape, Western Australia. In J. E. Glover (Ed.), Journal of the Royal Society of Western Australia Incorporated (Vol. 45, Issue 1, pp. 24–32). The Royal Society of Western Australia, Inc. Western Australian Museum. https://doi.org/10.1038/104578b0

Menció, A., Korbel, K. L., & Hose, G. C. (2014). River-aquifer interactions and their relationship to stygofauna assemblages: A case study of the Gwydir River alluvial aquifer (New South Wales, Australia). Science of the Total Environment, 479–480(1), 292–305. https://doi.org/10.1016/j.scitotenv.2014.02.009

Mittra, A., Halse, S. A., & Curran, M. (2020). Lake Wells Potash Project Subterranean Fauna Assessment.

Moulds, T. (2010). Stygofauna baseline survey. In Murray Drainage and Water Management Plan and Associated Studies.

Moulds, T. (2020). Dual Phase Survey for Subterranean Fauna for the Yogi Magnetite Project , Yalgoo , Western Australia (Issue Report Number 2018ISJ0702_F01_20200304).

Murphy, N. P., Adams, M., & Austin, A. D. (2009). Independent colonization and extensive cryptic speciation of freshwater amphipods in the isolated groundwater springs of Australia's Great Artesian Basin. Molecular Ecology, 18(1), 109–122. https://doi.org/10.1111/j.1365-294X.2008.04007.x

Murray, B. R., Hose, G. C., Eamus, D., & Licari, D. (2006). Valuation of groundwater-dependent ecosystems: A functional methodology incorporating ecosystem services. Australian Journal of Botany, 54(2), 221–229. https://doi.org/10.1071/BT05018

Nelson, R. (2021). Challenges to improved integrated management of the Murray–Darling Basin. In B. T. Hart, N. Byron, M. J. Stewardson, N. R. Bond, & C. A. Pollino (Eds.), Murray-Darling Basin, Australia (1st ed., pp. 339– 361). Elsevier. https://doi.org/10.1016/b978-0-12-818152-2.00016-4

NRA Environmental Consultants. (2017). King Vol Project: Potential Impact to Environmental Values of Groundwater Dependent Ecosystems.

Oberprieler, S., Rees, G., Nielsen, D., Shackleton, M., Watson, G., Chandler, L., & Davis, J. (2021). Connectivity, not short-range endemism, characterises the groundwater biota of a northern Australian karst system. Science of the Total Environment, 796, 148955. https://doi.org/10.1016/j.scitotenv.2021.148955

Page, T. J., Humphreys, W. F., & Hughes, J. M. (2008). Shrimps down under: Evolutionary relationships of subterranean crustaceans from Western Australia (Decapoda: Atyidae: Stygiocaris). PLoS ONE, 3(2), 1–12. https://doi.org/10.1371/journal.pone.0001618

Pesce, G. L., De Laurentiis, P., & Humphreys, W. F. (1996). Copepods from ground waters of Western Australia, 2. The genus Halicyclops (Crustacea: Copepoda: Cyclopidae). Records of the Western Australian Museum, 18(1), 77–85.

Pinder, A. M., Eberhard, S. M., & Humphreys, W. F. (2006). New phallodrilines (Annelida: Clitellata: Tubificidae) from Western Australian groundwater. Zootaxa, 1304, 31–48. https://doi.org/10.11646/zootaxa.1304.1.3

Poore, G. C. B., & Humphreys, W. F. (1998). First record of Spelaeogriphacea from Australasia: a new genus and species from an aquifer in the arid Pilbara of Western Australia. CrustaceanaCrustaceana, 71(7), 721–742. https://doi.org/10.1163/156854098X00013

Rees, G., Oberprieler, S., Nielsen, D., Watson, G., Shackleton, M., & Davis, J. (2020). Characterisation of the stygofauna and microbial assemblages of the Beetaloo Sub-Basin, Northern terrotory.

Reeves, J. M., De Deckker, P., & Halse, S. A. (2007). Groundwater Ostracods from the arid Pilbara region of northwestern Australia: Distribution and water chemistry. Hydrobiologia, 585(1), 99–118. https://doi.org/10.1007/s10750-007-0632-7

Saccò, M., Blyth, A. J., Humphreys, W. F., Karasiewicz, S., Meredith, K. T., Laini, A., Cooper, S. J. B., Bateman, P. W., & Grice, K. (2020). Stygofaunal community trends along varied rainfall conditions: Deciphering ecological niche dynamics of a shallow calcrete in Western Australia. Ecohydrology, 13(1), 1–19. https://doi.org/10.1002/eco.2150

Saccò, M., Blyth, A. J., Douglas, G., Humphreys, W. F., Hose, G. C., Davis, J., Guzik, M. T., Martínez, A., Eberhard, S. M., & Halse, S. A. (2022). Stygofaunal diversity and ecological sustainability of coastal groundwater ecosystems in a changing climate: The Australian paradigm. Freshwater Biology, August, 1–17. https://doi.org/10.1111/fwb.13987

Saccò, M., Blyth, A. J., Humphreys, W. F., Cooper, S. J. B., White, N. E., Campbell, M., Mousavi-Derazmahalleh, M., Hua, Q., Mazumder, D., Smith, C., Griebler, C., & Grice, K. (2021). Rainfall as a trigger of ecological cascade effects in an Australian groundwater ecosystem. Scientific Reports, 11(1), 1–15. https://doi.org/10.1038/s41598021-83286-x

Saccò, M., Humphreys, W. F., Stevens, N., Jones, M. R., Taukulis, F., Thomas, E., & Blyth, A. J. (2022). Subterranean carbon flows from source to stygofauna: a case study on the atyid shrimp Stygiocaris stylifera (Holthuis, 1960) from Barrow Island (WA). Isotopes in Environmental and Health Studies, 58(3), 247–257. https://doi.org/10.1080/10256016.2022.2071873

Scarsbrook, M. R., & Fenwick, G. D. (2003). Preliminary assessment of crustacean distribution patterns in New Zealand groundwater aquifers. New Zealand Journal of Marine and Freshwater Research, 37(2), 405–413. https://doi.org/10.1080/00288330.2003.9517176

Scarsbrook, M. R., Fenwick, G. D., Duggan, I. C., & Haase, M. (2003). A guide to the groundwater invertebrates of New Zealand: Vol. No. 51.

Schmidt, S. I., Hellweg, J., Hahn, H. J., Hatton, T. J., & Humphreys, W. F. (2007). Does groundwater influence the sediment fauna beneath a small, sandy stream? Limnologica, 37(2), 208–225. https://doi.org/10.1016/j.limno.2006.12.002

Schulz, C., Steward, A. L., & Prior, A. (2013). Stygofauna presence within fresh and highly saline aquifers of the Border Rivers region in Southern Queensland. Proceedings of the Royal Society of Queensland, 118, 27–35. https://doi.org/10.5962/p.357777

Sinton, L. W. (1984). The Microinvertebrates in a sewage polluted aquifer. Hydrobiologia, 119, 161–169.

Sirisena, K. A., Daughney, C. J., Moreau-Fournier, M., Ryan, K. G., & Chambers, G. K. (2013). National survey of molecular bacterial diversity of New Zealand groundwater: Relationships between biodiversity, groundwater chemistry and aquifer characteristics. FEMS Microbiology Ecology, 86(3), 490–504. https://doi.org/10.1111/15746941.12176

Smith, R. J., Paterson, J. S., Launer, E., Tobe, S. S., Morello, E., Leijs, R., Marri, S., & Mitchell, J. G. (2016). Stygofauna enhance prokaryotic transport in groundwater ecosystems. Scientific Reports, 6(Article No. 32738), 1–7. https://doi.org/10.1038/srep32738

Stantec. (2017). Report Keith Satellite Operations stygofauna assessment.

Stantec. (2018). Report ABRA Subterranean Fauna Level 2 Assessment.

Stevens, N. (2018). Report ABRA Subterranean Fauna Level 2 Assessment.

Stock, J. H. (1984). First record of Bogidiellidae (Crustacea, Amphipoda) from the Pacific: Bogidiella (Xystriogidiella n. subgen.) capricornea new species from the Great Barrier Reef. Bulletin of Marine Science, 34(3), 380–385.

Stumpp, C., & Hose, G. C. (2013). The Impact of water table drawdown and drying on subterranean aquatic fauna in in-vitro experiments. PLoS ONE, 8(11), 10. https://doi.org/10.1371/journal.pone.0078502

Subterranean Ecology. (2007). Pardoo Direct Shipping Ore Project Troglofauna Survey Phase 2 and 3 Results: Vol. Project Nu.

Taiti, S., & Humphreys, W. F. (2001). New aquatic Oniscidea (Crustacea: Isopoda) from groundwater calcretes of Western Australia. Records of the Western Australian Museum, Supplement, 64(1), 133–151. https://doi.org/10.18195/issn.0313-122x.64.2001.133-151

Terramin. (2018). Bird in Hand Gold Project.

Tomlinson, M., & Boulton, A. J. (2010). Ecology and management of subsurface groundwater dependent ecosystems in Australia - a reviw. Marine and Freshwater Research, 61, 936–949. https://doi.org/10.1071/MF09267

Trotter, A., & Halse, S. A. (2012). Iron Valley Project: Subterranean Fauna Assessment.

van der Heyde, M., White, N. E., Nevill, P., Austin, A. D., Stevens, N., Jones, M., & Guzik, M. T. (2023). Taking eDNA underground: Factors affecting eDNA detection of subterranean fauna in groundwater. Molecular Ecology Resources, 23, 1257–1274. https://doi.org/10.1111/1755-0998.13792

Watts, C. H. S., Hancock, P. J., & Leys, R. (2007). A stygobitic Carabhydrus Watts (Dytiscidae, Coleoptera) from the Hunter Valley in New South Wales, Australia. Australian Journal of Entomology, 46(1), 56–59. https://doi.org/10.1111/j.1440-6055.2007.00585.x

Watts, C. H. S., Hancock, P. J., & Leys, R. (2008). Paroster peelensis sp. nov.: A new stygobitic water beetle from alluvial gravels in northern New South Wales (Coleoptera: Dytiscidae). Australian Journal of Entomology, 47(3), 227–231. https://doi.org/10.1111/j.1440-6055.2008.00650.x

Watts, C. H. S., & Humphreys, W. F. (2000). Six new species of Nirridessus Watts and Humphreys and Tjirtadessus Watts and Humphreys (Coleoptera: Dytiscidae) from underground waters in Australia. Records of the South Australian Museum, 33(2), 127–144

Watts, C. H. S., & Humphreys, W. F. (2001). A new genus and six new species of Dytiscidae (Coleoptera) from underground waters in the Yilgarn palaeodrainage system of Western Australia. Records of the South Australian Museum, 34(2), 99–114.

Watts, C. H. S., & Humphreys, W. F. (2003). Twenty-five new Dytiscidae (Coleoptera) of the genera Tjirtudessus Watts & Humphreys, Nirripirti Watts & Humphreys and Bidessodes Regimbart from underground waters in Australia. Records of the South Australian Museum, 36(2), 135–187.

Watts, C. H. S., & Humphreys, W. F. (2004). Thirteen new Dytiscidae (Coleoptera) of the genera Boongurrus Larson Tjirtudessus Watts & Humphreys and Nirripirti Watts & Humphreys, from underground waters in Australia. Transactions of the Royal Society of South Australia, 128(2), 99–129.

Watts, C. H. S., & Humphreys, W. F. (2006). Twenty-six new dytiscidae (Coleoptera) of the genera Limbodessus guignot and Nirripirti Watts & Humphreys, from underground waters in Australia. Transactions of the Royal Society of South Australia, 130(1), 123–185. https://doi.org/10.1080/3721426.2006.10887055

Watts, C. H. S., & Humphreys, W. F. (2009). Fourteen new Dytiscidae (Coleoptera) of the genera Limbodessus guignot, Paroster sharp, and Exocelina broun from underground waters in Australia. Transactions of the Royal Society of South Australia, 133(1), 62–107. https://doi.org/10.1080/03721426.2009.10887112

West, K. M., Richards, Z. T., Harvey, E. S., Susac, R., Grealy, A., & Bunce, M. (2020). Under the karst: detecting hidden subterranean assemblages using eDNA metabarcoding in the caves of Christmas Island, Australia. Scientific Reports, 10(1), 1–15. https://doi.org/10.1038/s41598-020-78525-6

Whitley, G. P. (1944). New sharks and fishes from Western Australia. In A. F. B. HUll & T. Iredale (Eds.), Australian Zoologist (Volume 10, pp. 252–273). Royal Zoological Society of New South Wales.

Wilson, G. D. F., & Keable, S. J. (1999). A new genus of phreatoicidean isopod (Crustacea) from the north Kimberley region, Western Australia. Zoological Journal of the Linnean Society, 126(1), 51–79. https://doi.org/10.1111/j.1096-3642.1999.tb00607.x

Wilson, G. D. F., & Keable, S. J. (2004). A new family and genus of phreatoicidea (Crustacea: Isopoda) from artesian springs in southwestern Queensland, Australia. Memoirs of the Queensland Museum, 49(2), 741–759.

Wilson, G. D. F., & Ponder, W. F. (1992). Extraordinary new subterranean isopods (Peracarida: Crustacea) from the Kimberley Region, Western Australia. Records of the Australian Museum, 44(3), 279–298. https://doi.org/10.3853/j.0067-1975.44.1992.36

Zeidler, W. (1985). A new species of Crustacean (Syncarida: Anaspidacea: Koonungidae), from sinkholes and caves in the south-east of South Australia. Transactions of the Royal Society of South Australia, 109(3), 63–75.

Oceania	Magniez, G. J. (2001). Stenasellus stocki n. sp., nouvel Isopode Stenasellidae des eaux souterraines de Sumatra (Indonésie). Mensuel de La Société Linnéenne de Lyon, 70(6), 159–164. https://doi.org/10.1163/156854002760095534 Ruffo, S. (1994). New stygobiont amphipods (crustacea amphipoda) from the philippine islands. Tropical Zoology, 7(2), 355–366. https://doi.org/10.1080/03946975.1994.10539265 Schminke, H. K. (2008). First report of groundwater fauna from Papua New Guinea: Kinnecaris Jakobi, 1972 redefined (Copepoda, Harpacticoida, Parastenocarididae), and description of a new species. Crustaceana, 81(10), 1241– 1253. https://doi.org/10.1163/156854008X374568
America North America	Batzer, D., & Boix, D. (2016). Invertebrates in Freswater Wetlands: An International Perspective on their Ecology. In Springer. Springer International Publishing. https://doi.org/10.1007/978-3-319-24978-0_9 Bruno, M. C., Loftus, W. F., & Perry, S. A. (2001). Preliminary data on microcrustacean communities from ground waters in the southern Everglades. Water Resources Investigations Report, 01(4011), 89–97. Cannizzaro, A. G., Gibson, J. R., & Sawicki, T. R. (2020). A new enigmatic genus of subterranean amphipod (Amphipoda: Bogidielloidea) from Terrell County, Texas, with the establishment of Parabogidiellidae, fam. nov., and notes on the family Bogidiellidae. Invertebrate Systematics, 34(5), 504–518. https://doi.org/10.1071/IS19061 Chengalath, R. (1982). A faunistic and ecological survey of the littoral Cladocera of Canada. Canadian Journal of Zoology, 60(11), 2668–2682. https://doi.org/10.1139/z82-343 Christman, M. C., Culver, D. C., Madden, M. K., & White, D. (2005). Patterns of endemism of the eastern North American cave fauna. Journal of Biogeography, 32(8), 1441–1452. https://doi.org/10.1111/j.13652699.2005.01263.x Claret, C., Marmonier, P., Dole-Olivier, M.-J., Creuzé Des Châtelliers, M., Boulton, A. J., & Castella, E. (1999). A functional classification of interstitial invertebrates: Supplementing measures of biodiversity using species traits and habitat affinities. Archiv Fur Hydrobiologie, 145(4), 385–403. https://doi.org/10.1127/archivhydrobiol/145/1999/385 Culver, D. C. (1976). The Evolution of Aquatic Cave Communities. The American Naturalist, 110(976), 945–957. Culver, D. C., & Fong, D. W. (1994). Small scale and large scale biogeography of subterranean crustacean faunas of the Virginias. Hydrobiologia, 287(1), 3–9. https://doi.org/10.1007/BF00006891

Culver, D. C., & Holsinger, J. R. (1992). How many species of troglobites are there? In A. J. Flurkey (Ed.), Journal of Caves and Karst Studies (Vol. 54, Issue 2, pp. 79–80). The National Speleological Society.

Edler, C., & Dodds, W. K. (1996). The ecology of a subterranean isopod, Caecidotea tridentata. Freshwater Biology, 35(2), 249–259. https://doi.org/10.1046/j.1365-2427.1996.00497.x

Elliott, W. R., Reddell, J. R., Rudolph, D. C., Graening, G. O., Briggs, T. S., Ubick, D., Aalbu, R. L., Krejca, J. K., & Taylor, S. J. (2017). The Cave Fauna of California. In S. Bennett (Ed.), Proceedings of the California Academy of Sciences (Vol. 64, Issue Supplement 1). California Academy of Sciences.

Fenolio, D. B., Niemiller, M. L., Gluesenkamp, A. G., Mckee, A. M., & Taylor, S. J. (2017). New distributional records of the stygobitic crayfish cambarus cryptodytes (decapoda: Cambaridae) in the Floridan aquifer system of Southwestern Georgia. Southeastern Naturalist, 16(2), 163–181. https://doi.org/10.1656/058.016.0205

Gibert, J., Culver, D. C., Dole-Olivier, M.-J., Malard, F., Christman, M. C., & Deharveng, L. (2009). Assessing and conserving groundwater biodiversity: Synthesis and perspectives. Freshwater Biology, 54(4), 930–941. https://doi.org/10.1111/j.1365-2427.2009.02201.x

Holsinger, J. R. (1992). Four new species of subterranean amphipod crustaceans (Artesiidae, Hadziidae, Sebidae) from Texas, with comments on their phylogenetic and biogeographic relationships. Texas Memorial Museum, Speleological Monographs, 3, 1–22.

Holsinger, J. R., & Longley, G. (1980). The subterranean amphipod crustacean fauna of an artesian well in Texas. In Smithsonian Contributions to Zoology (Issue 308). Smithsonian Institution Press. https://doi.org/10.5479/si.00810282.308

Huebner, C. B., & Vinson, M. R. (2016). Groundwater Invertebrate fauna of the Bear River Range, Utah. Western North American Naturalist, 64(1), 131–134.

Hunt, G. W., & Stanley, E. H. (2000). An evaluation of alternative procedures using the Bou-Rouch method for sampling hyporheic invertebrates. Canadian Journal of Fisheries and Aquatic Sciences, 57(8), 1545–1550. https://doi.org/10.1139/cjfas-57-8-1545

Hutchins, B. T. (2018). The conservation status of Texas groundwater invertebrates. Biodiversity and Conservation, 27(2), 475–501. https://doi.org/10.1007/s10531-017-1447-0

Hutchins, B. T., & Orndorff, W. (2009). Effectiveness and adequacy of well sampling using baited traps for monitoring the distribution and bundance of an aquatic subterranean isopod. Journal of Cave and Karst Studies, 71(3), 193–203. https://doi.org/10.4311/jcks2008lsc0037

Keany, J., Christman, M. C., Milton, M., Knee, K. L., Gilbert, H., & Culver, D. C. (2019). Distribution and structure of shallow subterranean aquatic arthropod communities in the parklands of Washington, D.C. Ecohydrology, 12(1), 1–11. https://doi.org/10.1002/eco.2044

Kinsey, J., Cooney, T. J., & Simon, K. S. (2007). A comparison of the leaf shredding ability and influence on microbial films of surface and cave forms of Gammarus minus Say. Hydrobiologia, 589(1), 199–205. https://doi.org/10.1007/s10750-007-0739-x

Kolasa, J., Strayer, D. L., & Bannon-O'Donnell, E. (1987). Microturbellarians from interstitial waters, streams, and springs in southeastern New York. Journal of the North American Benthological Society, 6(2), 125–132.

Külköylüoğlu, O., Yavuzatmaca, M., Akdemir, D., Schwartz, B., & Hutchins, B. T. (2019). Description of a new tribe Cabralcandonini (Candonidae,Ostracoda) from karst aquifers in central Texas, U.S.A. Journal of Cave and Karst Studies, 81(2), 136–151. https://doi.org/10.4311/2019lsc0101

Lewis, J. J., & Reid, J. W. (2007). Patterns and processes of groundwater invasion by copepods in the interior low plateaus of the United States. Acta Carsologica, 36(2), 279–289. https://doi.org/10.3986/ac.v36i2.197

Longley, G. (1981). The Edwards Aquifer: Earth's most diverse groundwater ecosystem? International Journal of Speleology, 11(1/2), 123–128. https://doi.org/10.5038/1827-806x.11.1.12

McFatter, M. M., Meyer, H. A., & Hinton, J. G. (2007). Nearctic freshwater tardigrades: A review. Journal of Limnology, 66(SUPPL. 1), 84–89. https://doi.org/10.4081/jlimnol.2007.s1.84

Mitchell, J. R. (2011). Traps Designed to Document the Occurrence of Groundwater Stygofauna at the Savoy Experimental Watershed, Washington County, Arkansas. In E. L. Kuniansky (Ed.), U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Arkansas, April 26–29, 2011 (pp. 142–148). U.S. Geological Survey.

Niemiller, M. L., Porter, M. L., Keany, J., Gilbert, H., Fong, D. W., Culver, D. C., Hobson, C. S., Kendall, K. D., Davis, M. A., & Taylor, S. J. (2018). Evaluation of eDNA for groundwater invertebrate detection and monitoring: a case study with endangered Stygobromus (Amphipoda: Crangonyctidae). Conservation Genetics Resources, 10(2), 247–257. https://doi.org/10.1007/s12686-017-0785-2

Reid, J. W. (1995). Redescription of Parastenocaris brevipes Kessler and description of a new species of Parastenocaris (Copepoda: Harpacticoida: Parastenocarididae) from the U.S.A. Canadian Journal of Zoology, 73, 173–187.

Rivera, M. A. J., Howarth, F. G., Taiti, S., & Roderick, G. K. (2002). Evolution in Hawaiian cave-adapted isopods (Oniscidea: Philosciidae): Vicariant speciation or adaptive shifts? Molecular Phylogenetics and Evolution, 25(1), 1–9. https://doi.org/10.1016/S1055-7903(02)00353-6

Schneider, K., & Culver, D. C. (2004). Estimating subterranean species richness using intensive sampling and rarefaction curves in a high density cave region in West Virginia. Journal of Cave and Karst Studies, 66(2), 39– 45.

Spicer, J. I. (1998). Is the reduced metabolism of hypogean amphipods solely a result of food limitation? Hydrobiologia, 377(1–3), 201–204. https://doi.org/10.1023/a:1003264807500

Stamm, J. F., Poteet, M. F., Symstad, A. J., Musgrove, M., Long, A. J., Mahler, B. J., & Norton, P. A. (2015). Historical and Projected Climate (1901– 2050) and Hydrologic Response of Karst Aquifers, and Species Vulnerability in South-Central Texas and Western South Dakota. In U.S. Geological Survey Scientific Investigations Report 2014–5089. https://doi.org/10.3133/sir20145089

Strayer, D. L., May, S. E., Nielsen, P., Wollheim, W., & Hausam, S. (1995). An endemic groundwater fauna in unglaciated eastern North America. Canadian Journal of Zoology, 73(3), 502–508. https://doi.org/10.1139/z95057

Strayer, D. L., Nelson, D. R., & O'Donnell, E. B. (1994). Tardigrades from Shallow Groundwaters in Southeastern New York, with the First Record of Thulinia from North America. Transactions of the American Microscopical Society, 113(3), 325–332. https://doi.org/10.2307/3226626

Thorp, J. H., & Covich, A. P. (2001). Ecology and Classification of North American Freshwater Invertebrates (Vol. 2). Academic Press. https://doi.org/10.2307/1467674

Ward, J. V., Voelz, N. J., & Harvey, J. H. (1989). Groundwater faunas as indicators of groundwater quality: the South Platte River System (Issue 150).

Wetzel, M. J., Oberlin, G. E., & Blinn, D. W. (1999). The aquatic oligochaeta (Annelida: Clitellata) of Montezuma Well, Arizona: A near thermally constant limnocrene. Southwestern Naturalist, 44(4), 514–518. https://doi.org/10.2307/3672352

Wilhelm, F. M., Taylor, S. J., & Adams, G. L. (2006). Comparison of routine metabolic rates of the stygobite, Gammarus acherondytes (Amphipoda: Gammaridae) andthe stygophile, Gammarus troglophilus. Freshwater Biology, 51, 1162–1174. https://doi.org/doi:10.1111/j.1365-2427.2006.01564.x

Central America	Angyal, D., Simões, N., & Mascaró, M. (2020). Uptaded checklist, historical overview and illustrated guide to the stygobiont Malacostraca (Arthropoda: Crustacea) species of Yucatan (Mexico). Subterranean Biology, 36, 83– 108. https://doi.org/10.3897/SUBTBIOL.36.53558 Botosaneanu, L. (1973). Observations sur la faune aquatique souterraine de Cuba. International Journal of Speleology, 5, 209–218. https://doi.org/10.5038/1827-806x.5.3.2 Noodt, W. (1961). Limnisch-subterrane Copepoden der Gattung Parastenocaris Kessler aus Mittelamerika. Beitrage Zur Neotropischen Fauna, 2(3), 223–248. https://doi.org/10.1080/01650526109380628 Rodríguez, P. (2002). Benthic and subterranean aquatic oligochaete fauna (Annelida, Oligochaeta) from Coiba Island (Panamá) and Cuba. Graellsia, 58(2), 3–19. https://doi.org/10.3989/graellsia.2002.v58.i2.275 Ruffo, S., & Vigna Taglianti, A. (1973). Three New Subterranean Bogidiella from Mexico and Guatemala (Crustacea, Amphipoda). In Subterranean Fauna of Mexico. Quaderni Accademia Xazionale Dei Lincei, 171(2), 105–133. Ruffo, S., & Vigna Taglianti, A. (1977). Secondo contributo alia conoscenza del genere Bogidiella in Messico e Guatemala (Crustacea, Amphipoda, Gammaridae). Subterranean fauna of Mexico, part 3. Accademia Nazionale Dei Lincei, 171(3), 125–172. Stock, J. H. (1983). The stygobiont Jamaica. Bijdragen Tot de Dierkunde, 53(2), 267–286. Stock, J. H. (1985). Bogidiellidae (Amphipoda) from Haiti and some general rules on the occurrence of crustacea Malacostraca in inland groundwaters of the West Indies. Stygologia, 1(2), 208–223. Stock, J. H. (1994). Biogeographic synthesis of the insular groundwater faunas of the (sub)tropical Atlantic. Hydrobiologia, 287(1), 105–117. https://doi.org/10.1007/BF00006900 Stock, J. H., Holsinger, J. R., Sket, B., & Iliffe, T. M. (1986). Two new species of Pseudoniphargus (Amphipoda), in Bermudian groundwaters. Zoologica Scripta, 15(3), 237–249. https://doi.org/10.1111/j.1463-6409.1986.tb00226.x

South America	Bertelli Simões, L., Dos Santos Ferreira, T. C., & Bichuette, M. E. (2013). Aquatic biota of different karst habitats in epigean and subterranean systems of Central Brazil - visibility versus relevance of taxa. Subterranean Biology, 11, 55–74. https://doi.org/10.3897/subtbiol.11.5981
	Davalo Centurião, T., Marcos da Silva, W., & Garcia Gabas, S. (2020). Is groundwater fauna impacted by swine effluent fertigation? Ciência e Natura, 42(34), 11. https://doi.org/10.5902/2179460x42327
	De Los Ríos-Escalante, P., Parra-Coloma, L., Peralta, M. A., Pérez-Schultheiss, J., & Rudolph, E. H. (2016). A checklist of subterranean water crustaceans from Chile (South America). Proceedings of the Biological Society of Washington, 129(1), 114–128. https://doi.org/10.2988/0006-324X-129.Q2.114
	Grosso, L. E., & Ringuelet, R. A. (1979). Subterranean fresh water fauna of Argentina. I. Two new species of amphipod genus Bogidiella. Limnobios, 1(9), 381–394.
	Leal-Zanchet, A. M., Teles de Souza, S., & Lopes Ferreira, R. (2014). A new genus and species for the first recorded cave-dwelling Cavernicola (Platyhelminthes) from South America. ZooKeys, 15(442), 1–15. https://doi.org/10.3897/zookeys.442.8199
	Pérez-Schultheiss, J. (2013). First species of the family Bogidiellidae Hertzog, 1936 (Crustacea: Amphipoda) in Chilean groundwaters: Patagongidiella wefkoi n. Sp. Zootaxa, 3694(2), 185–195. https://doi.org/10.11646/zootaxa.3694.2.8
	Platvoet, D. (1983). Bogidiella (B.) Neotropica Ruffo, 1952 (Crustacea, Amphipoda) rediscovered in Venezuela. Bijdragen Tot de Dierkunde, 53(1), 109–114.
	Ruffo, S. (1952). Bogidiella neotropica n. sp., nuovo Anfipodo dell' Amazonia. Schweizer Zeitschrift Für Hydrologie, 14, 129–134.
	Tione, M. L., Bedano, J. C., & Blarasin, M. (2016a). Land Use and Hydrogeological Characteristics Influence Groundwater Invertebrate Communities. Water Environment Research, 88(8), 756–767. https://doi.org/10.2175/106143016x14609975747162
	Tione, M. L., Bedano, J. C., & Blarasin, M. (2016b). Relationships among invertebrate communities and groundwater properties in an unconfined aquifer in Argentina. International Journal of Environmental Studies, 73(5), 760–777. https://doi.org/10.1080/00207233.2016.1160650

Europe	Altermatt, F., Alther, R., Fišer, C., Jokela, J., Konec, M., Küry, D., Mächler, E., Stucki, P., & Westram, A. M. (2014). Diversity and distribution of freshwater amphipod species in Switzerland (Crustacea: Amphipoda). PLoS ONE, 9(10), 12. https://doi.org/10.1371/journal.pone.0110328 Alther, R. (2018). Diversity and distribution of Amphipods in Switzerland. Universität Zürich. Alther, R., & Altermatt, F. (2018). Fluvial network topology shapes communities of native and non-native amphipods. Ecosphere, 9(2), 14. https://doi.org/10.1002/ecs2.2102 Alther, R., Bongni, N., Borko, Š., Fišer, C., & Altermatt, F. (2020). Reiche Grundwasser-Fauna. Aqua & Gas, 7(8), 36– 42. Alther, R., Bongni, N., Borko, Š., Fišer, C., & Altermatt, F. (2021). Citizen Science Approach Reveals Groundwater Fauna In Switzerland And A New Species Of Niphargus (Amphipoda, Niphargidae). Subterranean Biology, 39, 1–31. https://doi.org/10.3897/SUBTBIOL.39.66755 Alther, R., Fišer, C., Konec, M., Svara, V., & Altermatt, F. (2017). Das Hölloch: Ein Flohkrebs-Hotspot in der Schweiz. Stalactite, 67(1), 18–24. Apostolov, A. M., & Pesce, G. L. (1989). Copepodes Harpacticoides stygobies de Bulgarie. Riv. Idrobiologie, 28(1–2), 113–149. Artheau, M., & Giani, N. (2006). A checklist of the groundfreshwater Oligochaeta and polychaeta in France: an overview. Bulletin de l'Institut Royal Des Sciences Naturelles de Belgique, Biologie, 76, 229–255. Bachura, B., Blatterer, H., Müller, G., & Schay, G. (1993). Gewässerschutz Bericht 4/1993. Amt der Oberösterreichischen Landesregierung. Berezina, N. A. (2003). Tolerance of freshwater invertebrates to changes in water salinity. Russian Journal of Ecology, 34(4), 261–266. https://doi.org/10.1023/A:1024597832095 Boettger, C. (1939). Die subterrane Molluskenfauna Belgiens. Memoirs of the Royal Belgian Museum of Natural Sciences, 88, 5–67. Bou, C., & Ruffo, S. (1979). Contributo alla conoscenza delle Bogidiella di Grecia. Natura - Rivista Di Scienze Naturali, 70(4), 295–309. Boulton, A. J., Dole-Olivier, M.-J., & Marmonier, P. (2003). Optimizing a sampling strategy for assessing hyporheic invertebrate biodiversity using the Bou-Rouch method: Within-site replication and sample volume. Archiv Fur Hydrobiologie, 156(4), 431–456. https://doi.org/10.1127/0003-9136/2003/0156-0431

Boulton, A. J., Dole-Olivier, M.-J., & Marmonier, P. (2004). Effects of sample volume and taxonomic resolution on assessment of hyporheic assemblage composition sampled using a Bou-Rouch pump. In Archiv für Hydrobiologie (Vol. 159, Issue 3, pp. 327–355). Schwarzbart'sche Verlagsbuchhandlung. https://doi.org/10.1127/000391304773124583

Bozkurt, A., & Bozça, M. (2019). Investigation of zooplankton fauna in water wells of Yayladağı District (Hatay, Turkey). Turkish Journal of Zoology, 43(4), 356–366. https://doi.org/10.3906/zoo-1903-33

Brad, T., Fišer, C., Flot, J.-F., & Sarbu, S. M. (2015). Niphargus dancaui sp. nov. (Amphipoda, Niphargidae) - A new species thriving in sulfidic groundwaters in southeastern Romania. European Journal of Taxonomy, 164, 1–28. https://doi.org/10.5852/ejt.2015.164

Brancelj, A. (2011). Copepoda from a deep-groundwater porous aquifer in contact with Karst: Description of a new species, Paramorariopsis Brigitae N. Sp. (Copepoda, Harpacticoida). Studies on Freshwater Copepoda, CRM 016, 85–104.

Brancelj, A., Mori, N., Treu, F., & Stoch, F. (2020). The groundwater fauna of the Classical Karst: hydrogeological indicators and descriptors. Aquatic Ecology, 54(1), 205–224. https://doi.org/10.1007/s10452-019-09737-w

Brancelj, A., Žibrat, U., & Jamnik, B. (2016). Differences between groundwater fauna in shallow and in deep intergranular aquifers as an indication of different characteristics of habitats and hydraulic connections. Journal of Limnology, 75(2), 248–261. https://doi.org/10.4081/jlimnol.2016.1294

Brehm, V. (1954). Bemerkenswerte Entomostracken aus der Salzburger Brunnenfauna. Österreichische Zoologische Zeitschrift, 4, 9–18.

Brinck, P., Dahl, E., & Wieser, W. (1955). On the littoral subsoil fauna of the Simrishamn Beach in Eastern Scania. Kungliga Fysiografiska Sallskapets i Lund Forhandlingar, 25(14), 109–129.

Camacho, A. I. (1989). Iberobathynella notenboomi, spec. nov. from a well in Alicante, South-East Spain. SPIXIANA, 12(2), 105–113.

Camacho, A. I. (2003). An overview of the distribution of the Parabathynellidae (Crustacea, Syncarida Bathynellacea) on the Iberian Peninsula and Balearic Islands. Graellsia, 59(1), 63–78. https://doi.org/10.3989/graellsia.2003.v59.i1.224

Camacho, A. I., & Puch, C. (2006). La fauna acuática subterránea de andalucía. MUSEO NACIONAL DE CIENCIAS NATURALES DE MADRID (CSIC), 67–74.

Castellarini, F., Dole-Olivier, M.-J., Malard, F., & Gibert, J. (2004). Improving the assessment of groundwater biodiversity by exploring environmental heterogeneity at a regional scale. In J. Gibert (Ed.), World Subterranean Biodiversity (pp. 83–88).

Chertoprud, E. S., Palatov, D. M., Borisov, R. R., Marinskiy, V. V., Bizin, M. S., & Dbar, R. S. (2016). Distribution and a comparative analysis of the aquatic invertebrate fauna in caves of the western Caucasus. Subterranean Biology, 18, 49–70. https://doi.org/10.3897/SUBTBIOL.18.8648

Christian, E., & Spötl, C. (2010). Karst geology and cave fauna of Austria: A concise review. International Journal of Speleology, 39(2), 71–90. https://doi.org/10.5038/1827-806X.39.2.3

Claret, C., Marmonier, P., Dole-Olivier, M.-J., Creuzé Des Châtelliers, M., Boulton, A. J., & Castella, E. (1999). A functional classification of interstitial invertebrates: Supplementing measures of biodiversity using species traits and habitat affinities. Archiv Fur Hydrobiologie, 145(4), 385–403. https://doi.org/10.1127/archivhydrobiol/145/1999/385

Colson-Proch, C., Morales, A., Hervant, F., Konecny, L., Moulin, C., & Douady, C. J. (2010). First cellular approach of the effects of global warming on groundwater organisms: A study of the HSP70 gene expression. Cell Stress and Chaperones, 15(3), 259–270. https://doi.org/10.1007/s12192-009-0139-4

Cottarelli, V., & Bruno, M. C. (1996). First record of Parastenocarididae (Crustacea, Copepoda, Harpacticoida) from subterranean freshwater of insular Greece and description of two new species. International Journal of Speleology, 25(1/2), 43–57. https://doi.org/10.5038/1827-806x.25.1.4

Cottarelli, V., Bruno, M. C., & Berera, R. (2007). Interstitial harpacticoids from groundwater in Tuscany (Central Italy): Parastenocaris reidae sp. nov., Nitocrella ensifera sp. nov., and notes on the morphology of Parastenocaris cf. glacialis Noodt (Crustacea: Copepoda). Italian Journal of Zoology, 74(1), 83–99. https://doi.org/10.1080/11250000601022605

Creuzé Des Châtelliers, M., Juget, J., Lafont, M., & Martin, P. (2009). Subterranean aquatic Oligochaeta. Freshwater Biology, 54(4), 678–690. https://doi.org/10.1111/j.1365-2427.2009.02173.x

Crişan, C. D., Battes, K. P., & Cîmpean, M. (2016). First record of Bryocamptus (Bryocamptus) mrazeki (Minkiewicz , 1916) in the Romanian harpacticoid fauna (Copepoda , Harpacticoida). Studia Universitatis Babes-Bolyai Biologia, LXI(2), 205–212.

Culver, D. C., Christman, M. C., Sket, B., & Trontelj, P. (2004). Sampling adequacy in an extreme environment: species richness patterns in Slovenian caves. Biodiversity and Conservation, 13, 1209–1229. https://doi.org/10.1023/B:BIOC.0000018153.49280.89

Culver, D. C., Pipan, T., & Schneider, K. (2009). Vicariance, dispersal and scale in the aquatic subterranean fauna of karst regions. Freshwater Biology, 54(4), 918–929. https://doi.org/10.1111/j.1365-2427.2007.01856.x

Danielopol, D. L. (1989). Groundwater Fauna Associated with riverine aquifers. Journal of the North American Benthological Society, 8(1), 18–35. https://doi.org/29.13.72.197

Danielopol, D. L., Drozdowski, G., Mindl, B., Neudorfer, W., Pospisil, P., Reiff, N., Schabetsberger, R., Stichler, W., & Griebler, C. (2006). Invertebrate animals and microbial assemblages as useful indicators for evaluation of the sustainability and optimisation of an artificial groundwater-recharge system (Stallingerfeld, Deutsch-Wagram, Lower Austria). HydroEco, 6, 149–156.

Danielopol, D. L., & Marmonier, P. (1992). Aspects of research on groundwater along the Rhone, Rhine and Danube. Regulated Rivers: Research & Management, 7, 5–16.

Danielopol, D. L., & Pospisil, P. (2001). Hidden biodiversity in the groundwater of the Danube Flood Plain National Park (Austria). Biodiversity and Conservation, 10(10), 1711–1721. https://doi.org/10.1023/A:1012098706986

Danielopol, D. L., Rouch, R., & Baltanás, A. (2002). Taxonomic diversity of groundwater harpacticoida (Copepoda, crustacea) in southern France. A contribution to characterise Hotspot Diversity Sites. Vie et Milieu, 52(1), 1–15.

Datry, T., Malard, F., & Gibert, J. (2005). Response of invertebrate assemblages to increased groundwater recharge rates in a phreatic aquifer. Journal of the North American Benthological Society, 24(3), 461–477. https://doi.org/10.1899/04-140.1

Deharveng, L., Stoch, F., Gibert, J., Bedos, A., Galassi, D. M. P., Zagmajster, M., Brancelj, A., Camacho, A. I., Fiers, F., Martin, P., Giani, N., Magniez, G. J., & Marmonier, P. (2009). Groundwater biodiversity in Europe. Freshwater Biology, 54(4), 709–726. https://doi.org/10.1111/j.1365-2427.2008.01972.x

Delić, T., Švara, V., Coleman, C. O., Trontelj, P., & Fišer, C. (2017). The giant cryptic amphipod species of the subterranean genus Niphargus (Crustacea, Amphipoda). Zoologica Scripta, 46(6), 740–752. https://doi.org/10.1111/zsc.12252

Delić, T., Trontelj, P., Rendoš, M., & Fišer, C. (2017). The importance of naming cryptic species and the conservation of endemic subterranean amphipods. Scientific Reports, 7(1), 1–12. https://doi.org/10.1038/s41598-017-02938-z

Delmare Debouteville, C., & Ruffo, S. (1952). Deux nouveaux amphipodes souterrains de France, Salentinella angelieri n.sp. et Bogidiella chappuisi n.sp. In Comptes Rendus (Vol. 33, Issue 4, pp. 1636–1638). Academie des Sciences de Paris. https://doi.org/10.1163/157181965X00304 di Lorenzo, T., Cifoni, M., Lombardo, P., Fiasca, B., & Galassi, D. M. P. (2015). Ammonium threshold values for groundwater quality in the EU may not protect groundwater fauna: evidence from an alluvial aquifer in Italy. Hydrobiologia, 743(1), 139–150. https://doi.org/10.1007/s10750-014-2018-y

di Lorenzo, T., Fiasca, B., di Camillo Tabilio, A., Murolo, A., di Cicco, M., & Galassi, D. M. P. (2020). The weighted Groundwater Health Index (wGHI) by Korbel and Hose (2017) in European groundwater bodies in nitrate vulnerable zones. Ecological Indicators, 116(106525), 11. https://doi.org/10.1016/j.ecolind.2020.106525

di Lorenzo, T., Fiasca, B., di Cicco, M., & Galassi, D. M. P. (2020). The impact of nitrate on the groundwater assemblages of European unconsolidated aquifers is likely less severe than expected. Environmental Science and Pollution Research, 28, 11518–11527. https://doi.org/10.1007/s11356-020-11408-5

di Lorenzo, T., & Galassi, D. M. P. (2013). Agricultural impact on Mediterranean alluvial aquifers: Do groundwater communities respond? Fundamental and Applied Limnology, 182(4), 271–282. https://doi.org/10.1127/18639135/2013/0398

di Lorenzo, T., & Galassi, D. M. P. (2017). Effect of temperature rising on the stygobitic crustacean species Diacyclops belgicus: Does global warming affect groundwater populations? Water (Switzerland), 9(951), 12. https://doi.org/10.3390/w9120951

Dole-Olivier, M. J., Castellarini, F., Coineau, N., Galassi, D. M. P., Martin, P., Mori, N., Valdecasas, A., & Gibert, J. (2009). Towards an optimal sampling strategy to assess groundwater biodiversity: Comparison across six European regions. Freshwater Biology, 54(4), 777–796. https://doi.org/10.1111/j.1365-2427.2008.02133.x

Dole-Olivier, M.-J. (1998). Surface water–groundwater exchanges in three dimensions on a backwater of the Rhône River. Freshwater Biology, 40, 93–109.

Dole-Olivier, M.-J., Maazouzi, C., Cellot, B., Fiers, F., Galassi, D. M. P., Claret, C., Martin, D., Mérigoux, S., & Marmonier, P. (2014). Assessing invertebrate assemblages in the subsurface zone of stream sediments (0-15 cm deep) using a hyporheic sampler. Water Resources Research, 50(1), 453–465. https://doi.org/10.1002/2012WR013207

Dole-Olivier, M.-J., Malard, F., Martin, D., Lefébure, T., & Gibert, J. (2009). Relationships between environmental variables and groundwater biodiversity at the regional scale. Freshwater Biology, 54(4), 797–813. https://doi.org/10.1111/j.1365-2427.2009.02184.x

Dumas, P., Bou, C., & Gibert, J. (2001). Groundwater macrocrustaceans as natural indicators of the Ariège alluvial aquifer. International Review of Hydrobiology, 86(6), 619–633. https://doi.org/10.1002/1522-2632(200110)86:6<619::AID-IROH619>3.0.CO;2-P

Dumnicka, E. (2014). Stygobitic oligochaetes (Annelida, Clitellata) in Poland with remarks on their distribution in Central Europe. Subterranean Biology, 14(1), 15–24. https://doi.org/10.3897/subtbiol.14.7700

Dumnicka, E., & Galas, J. (2017). An overview of stygobiontic invertebrates of Poland based on published data. Subterranean Biology, 23(1), 1–18. https://doi.org/10.3897/subtbiol.23.11877

Dumnicka, E., Galas, J., & Krodkiewska, M. (2017). Patterns of Benthic Fauna Distribution in Wells: The Role of Anthropogenic Impact and Geology. Vadose Zone Journal, 16(5), vzj2016.07.0057. https://doi.org/10.2136/vzj2016.07.0057

Dumnicka, E., Galas, J., Krodkiewska, M., & Pociecha, A. (2020). The diversity of annelids in subterranean waters: A case study from Poland. Knowledge and Management of Aquatic Ecosystems, 421(16), 11. https://doi.org/10.1051/kmae/2020007

Eder, V. R. (1975). Zwei neue Funde von Stenonchulus troglodytes SCHNEIDER 1940 (Onchulidae, Nematoda). Carinthia, 2, 291–294.

Ercoli, F., Lefebvre, F., Delangle, M., Godé, N., Caillon, M., Raimond, R., & Souty-Grosset, C. (2019). Differing trophic niches of three French stygobionts and their implications for conservation of endemic stygofauna. Aquatic Conservation: Marine and Freshwater Ecosystems, 29(12), 2193–2203. https://doi.org/10.1002/aqc.3227

Erséus, C. (1992). Groundwater and marine intertidal Tubificidae (Oligochaeta) from the Canary and Cabo Verde Islands, with descriptions of two new species. Bijdragen Tot de Dierkunde, 62(2), 63–70.

Esmaeili-Rineh, S., Sari, A., Delić, T., Moškrič, A., & Fišer, C. (2015). Molecular phylogeny of the subterranean genus Niphargus (Crustacea: Amphipoda) in the Middle East: A comparison with European Niphargids. Zoological Journal of the Linnean Society, 175(4), 812–826. https://doi.org/10.1111/zoj.12296

Evtimova, V., Pandourski, I. S., & Benderev, A. D. (2009). Stygofauna of karstic ecosystem in Ponor Mountains, Western Bulgaria: present knowledge and research challenges. Acta Zoologica Bulgarica, 61(2), 161–168.

Falniowski, A., Grego, J., Rysiewska, A., Osikowski, A., & Hofman, S. (2021). Two new stygobiotic species of Horatia Bourguignat, 1887 (Hydrobiidae) from Croatia. Subterranean Biology, 37, 89–104. https://doi.org/10.3897/subtbiol.37.61573

Fattorini, S., Di Lorenzo, T., & Galassi, D. M. P. (2018). Earthquake impacts on microcrustacean communities inhabiting groundwater-fed springs alter species-abundance distribution patterns. Scientific Reports, 8(1), 1–12. https://doi.org/10.1038/s41598-018-20011-1

Ferreira, D., Dole-Olivier, M.-J., Malard, F., Deharveng, L., Gibert, J., Bou, C., Brancelj, A., Coineau, N., Falkner, M., Falkner, G., Galassi, D. M. P., Giani, N., Ginet, R., Henry, J.-P., Jouin-Toulmond, C., Juget, J., Lescher-Moutoué, F., Magniez, G. J., Marmonier, P., . . . Turquin, M.-J. (2003). Faune aquatique souterraine de France: base de données et éléments de biogéographie. Karstologia: Revue de Karstologie et de Spéléologie Physique, 42(2), 15– 22. https://doi.org/10.3406/karst.2003.2528

Ferreira, D., Malard, F., Dole-Olivier, M.-J., & Gibert, J. (2007). Obligate groundwater fauna of France: Diversity patterns and conservation implications. Biodiversity and Conservation, 16(3), 567–596. https://doi.org/10.1007/s10531-005-0305-7

Fiasca, B., Stoch, F., Dole-Olivier, M.-J., Maazouzi, C., Petitta, M., Di Cioccio, A., & Galassi, D. M. P. (2014). The dark side of springs: What drives small-scale spatial patterns of subsurface meiofaunal assemblages? Journal of Limnology, 73(1), 71–80. https://doi.org/10.4081/jlimnol.2014.848

Fišer, C., Alther, R., Zakšek, V., Borko, Š., Fuchs, A., & Altermatt, F. (2018). Translating Niphargus barcodes from Switzerland into taxonomy with a description of two new species (Amphipoda, Niphargidae). ZooKeys, 760, 113– 141. https://doi.org/10.3897/zookeys.760.24978

Fišer, C., Konec, M., Alther, R., Švara, V., & Altermatt, F. (2017). Taxonomic, phylogenetic and ecological diversity of Niphargus (Amphipoda: Crustacea) in the Hölloch cave system (Switzerland). Systematics and Biodiversity, 15(3), 218–237. https://doi.org/10.1080/14772000.2016.1249112

Flot, J.-F., Wörheide, G., & Dattagupta, S. (2010). Unsuspected diversity of Niphargus amphipods in the chemoautotrophic cave ecosystem of Frasassi, central Italy. BMC Evolutionary Biology, 10(171), 13. https://doi.org/10.1186/1471-2148-10-171

Foulquier, A., Malard, F., Mermillod-Blondin, F., Montuelle, B., Dolédec, S., Volat, B., & Gibert, J. (2011). Surface Water Linkages Regulate Trophic Interactions in a Groundwater Food Web. Ecosystems, 14(8), 1339–1353. https://doi.org/10.1007/s10021-011-9484-0

Galassi, D. M. P., Lombardo, P., Fiasca, B., Di Cioccio, A., Di Lorenzo, T., Petitta, M., & Di Carlo, P. (2014). Earthquakes trigger the loss of groundwater biodiversity. Scientific Reports, 4(6273), 1–8. https://doi.org/10.1038/srep06273

Galassi, D. M. P., Stoch, F., Fiasca, B., Di Lorenzo, T., & Gattone, E. (2009). Groundwater biodiversity patterns in the Lessinian Massif of northern Italy. Freshwater Biology, 54(4), 830–847. https://doi.org/10.1111/j.13652427.2009.02203.x

Gaviria, S. (1998). Checklist and distribution of the free-living copepods (Arthropoda: Crustacea) from Austria. Ann. Naturhist. Mus. Wien, 100(B), 539–594.

Gaviria-Melo, S., Forró, L., Jersabek, C., & Schabetsberger, R. (2005). Checklist and distribution of cladocerans and leptodorans (Crustacea: Branchiopoda) from Austria. Ann. Naturhist. Mus. Wien, 106, 145–216.

Gerecke, R., Stoch, F., Meisch, C., & Schrankel, I. (2005). Die Fauna der Quellen und des hyporheischen Interstitials in Luxemburg Unter besonderer Berücksichtigung der Milben (Acari), Muschelkrebse (Ostracoda) und Ruderfusskrebse (Copepoda). Ferrantia, 41, 140.

Giani, N., Sambugar, B., Martínez-Ansemil, E., Martin, P., & Schmelz, R. M. (2011). The groundwater oligochaetes (Annelida, Clitellata) of Slovenia. Subterranean Biology, 9(1), 85–102. https://doi.org/10.3897/subtbiol.9.2512

Gibert, J., Culver, D. C., Dole-Olivier, M.-J., Malard, F., Christman, M. C., & Deharveng, L. (2009). Assessing and conserving groundwater biodiversity: Synthesis and perspectives. Freshwater Biology, 54(4), 930–941. https://doi.org/10.1111/j.1365-2427.2009.02201.x

Gibert, J., & Deharveng, L. (2002). Subterranean Ecosystems: A Truncated Functional Biodiversity. BioScience, 52(6), 473. https://doi.org/10.1641/0006-3568(2002)052[0473:seatfb]2.0.co;

Glöer, P., & Pešic, V. (2014). New subterranean freshwater gastropods of Montenegro (Mollusca: Gastropoda: Hydrobiidae), with description of one new genus and two new species. Ecologica Montenegrina, 1(4), 244–248. https://doi.org/10.37828/em.2014.1.32

Golovatch, S. I., Palatov, D. M., Turbanov, I. S., Kniss, V. A., Gazaryan, S., Snit'ko, V. P., Decu, V., Juberthie, C., & Nazareanu, G. (2018). Subterranean biota of the european part of russia: A review. Invertebrate Zoology, 15(2), 153–213. https://doi.org/10.15298/invertzool.15.2.01

Gorički, Š., Stanković, D., Snoj, A., Kuntner, M., Jeffery, W. R., Trontelj, P., Pavićević, M., Grizelj, Z., NăpăruşAljančič, M., & Aljančič, G. (2017). Environmental DNA in subterranean biology: Range extension and taxonomic implications for Proteus. Scientific Reports, 7(45054), 1–11. https://doi.org/10.1038/srep45054

Graeter, A., & Chappuis, P. A. (1913). Cyclops sensitivus n. sp. Zoologischer Anzeiger, 43, 507–510.

Green, J. (1959). Haemoglobin and the Habitat of the Harpacticoid Copepod Elaphoidella gracilis (Sars). Nature, 183, 1834.

Haase, M. (1992). A new, stygobiont, valvatiform, hydrobiid gastropod from Austria (caenogastropoda: Hydrobiidae). Journal of Molluscan Studies, 58(2), 207–214. https://doi.org/10.1093/mollus/58.2.207

Haase, M. (1993). Belgrandiella ganslmayri, a new hydrobiid species from Upper Austria (Caenogastropoda). Annalen Des Naturhistorischen Museums in Wien, 94/95(B), 181–186.

Haase, M. (1994). Differentiation of selected species of Belgrandiella and the redefined genus Graziana (Gastropoda: Hydrobiidae). Zoological Journal of the Linnean Society, 111(3), 219–246. https://doi.org/10.1111/j.10963642.1994.tb01484.x

Haase, M., Weigand, E., & Haseke, H. (2000). Two new species of the family Hydrobiidae (Mollusca: Caenogastropoda) from Austria. The Veliger, 43(2), 179–189.

Haase, M., Wilke, T., & Mildner, P. (2007). Identifying species of Bythinella (Caenogastropoda: Rissooidea): A plea for an integrative approach. Zootaxa, 16(1563), 1–16. https://doi.org/10.11646/zootaxa.1563.1.1

Hänfling, B., Douterelo-Soler, I., Knight, L. R. F. D., & Proudlove, G. S. (2009). Molecular studies on the Niphargus kochianus group (Crustacea: Amphipoda: Niphargidae) in Great Britain and Ireland. Cave and Karst Science, 35(1–2), 35–40.

Hertzog, L. (1933). Bogidiella albertimagni sp. nov., ein neuer Grundwasseramphipode aus der Rheinebene bei Strassburg. Zoologischer Anzeiger, 102(9/10), 225–227.

Hertzog, L. (1935). Amphipoden aus dem Grundwasser von Skoplje. Bogidiella albertimagni mihi und Ingolfiella acherontis (Karaman). Zoologischer Anzeiger, 11(1–2), 50–52.

Hilberg, S., & Eisendle-Flöckner, U. (2016). About faunal life in Austrian aquifers – historical background and current developments. Austrian Journal of Earth Sciences, 109(1), 119–134. https://doi.org/10.17738/ajes.2016.0009

Hoffsten, P.-O., & Malmqvist, B. (2000). The macroinvertebrate fauna and hydrogeology of springs in central Sweden. Hydrobiologia, 436, 91–104. https://doi.org/10.1023/A:1026550207764

Iepure, S., Feurdean, A., Bădăluță, C., Nagavciuc, V., & Perşoiu, A. (2015). Pattern of richness and distribution of groundwater Copepoda (Cyclopoida: Harpacticoida) and Ostracoda in Romania: an evolutionary perspective. Biological Journal of the Linnean Society, 119(3), 593–608. https://doi.org/10.1111/bij.12686

Iepure, S., Martinez-Hernandez, V., Herrera, S., Rasines-Ladero, R., & De Bustamante, I. (2013). Response of microcrustacean communities from the surface-groundwater interface to water contamination in urban river system of the Jarama basin (central Spain). Environmental Science and Pollution Research, 20(8), 5813–5826. https://doi.org/10.1007/s11356-013-1529-9

Iepure, S., Rasines-Ladero, R., Meffe, R., Carreño, F., Mostaza Colado, D., Sundberg, A., Di Lorenzo, T., & Barroso, J. L. (2017). Exploring the distribution of groundwater Crustacea (Copepoda and Ostracoda) to disentangle aquifer type features—A case study in the upper Tajo basin (Central Spain). Ecohydrology, 10(7), 1–13. https://doi.org/10.1002/eco.1876

Iglikowska, A., & Namiotko, T. (2012). The non-marine Ostracoda of Lapland: Changes over the past century. Journal of Limnology, 71(2), 237–244. https://doi.org/10.4081/jlimnol.2012.e26

Issartel, J., Hervant, F., Voituron, Y., Renault, D., & Vernon, P. (2005). Behavioural, ventilatory and respiratory responses of epigean and hypogean crustaceans to different temperatures. Comparative Biochemistry and Physiology Part A, 141(1), 1–7. https://doi.org/10.1016/j.cbpb.2005.02.013

Issartel, J., Renault, D., Voituron, Y., Bouchereau, A., Vernon, P., & Hervant, F. (2005). Metabolic responses to cold in subterranean crustaceans. Journal of Experimental Biology, 208(15), 2923–2929. https://doi.org/10.1242/jeb.01737

Jaworowski, A. (1895). Neue Arten der Brunnenfauna von Krakau und Lemberg. Archiv Für Naturgeschichte, 61(1), 319–345.

Johns, T., & Dunscombe, M. (2011). The Groundwater Animals Project - An investigation into the diversity and distribution of groundwater fauna in England.

Johns, T., Jones, J. I., Knight, L. R. F. D., Maurice, L., Wood, P. J., & Robertson, A. L. (2014). Regional-scale drivers of groundwater faunal distributions. Freshwater Science, 34(1), 316–328. https://doi.org/10.1086/678460

Karaman, G. S. (1973). Contribution to the knowledge of the Amphipoda. On the genus Bogidiella Hert. (fam. Gammaridae) in Yugoslavia. Poljoprivreda I Sumarstvo, 19(4), 21–53.

Karaman, G. S. (1987). Contribution to the Knowledge of the Amphipoda 183. New species of the family Bogidiellidae (Gammaridea) from Yugoslavia, Bogidiella serbica, n. sp. Bulletin of Natural History Museum, Belgrade, Ser. B., 42, 37–50.

Karaman, G. S. (1988). Contribution to the knowledge of Amphipoda 180. Two new species of genus Bogidiella Hert. from Sardinia and France, with remarks to B. vandeli Coineau 1968 (Gammaridea, Fam. Bogidiellidae). Poljoprivreda i Sumarstvo, Titograd, 34(4), 25–41.

Karaman, G. S. (1989). Contribution to the knowledge of the Amphipoda 190. Bogidiella cypria, new species of the family Bogidiellidae from Cyprus Island in the Mediterranean Sea. Glasnik of the Section of Natural Sciences, Montenegrin Academy of Sciences and Arts, 7, 7–23.

Karaman, G. S. (1990). Contribution to the knowledge of the Amphipoda 192. One new species of the family Bogidiellidae from Creta Island, Greece, Bogidiella (Medigidiella) aquatica, n. sp. Bulletin of Natural History Museum, Belgrade, Ser. B., 45, 27-39.

Karaman, G. S. (2012). Further studies on genus Niphargus Schiödte, 1849 (Fam. Niphargidae) from the Near East (Contribution to the knowledge of the Amphipoda 260). Agriculture & Forestry, 55(9), 49–74.

Karaman, S. L. (1933). Über zwei neue Amphipoden, Balcanella und Jugocrangonyx aus dem Grundwasser von Skopje. Zoologischer Anzeiger, 103, 41–47.

Karaman, S. L. (1953). Über subterrane Amphipoden und Isopoden des Karstes von Dubrovnik und seines Hinterlandes. Acta Musei Macedonici Scientiarum Naturalium, 7, 137–167.

Karaman, S. L. (1959). Über eine neue Art und Unterart der Gattung Bogidiella (Crust. Amphipoda) aus Jugoslawien. Acta Zoologica Academiae Scientiearum Hungaricae, 4, 339–348.

Karanovic, T. (2001). Description of Allocyclops montenegrinus, spec. nov. and a revision of the genus Allocyclops Kiefer, 1932. Spixiana, 24(1), 19–27.

Khmeleva, N., Nesterovich, A., & Czachorowski, S. (1994). The macroinvertebrate fauna of some Byeloussian, Karelian and Altaian springs and its relation with certain factors. Acta Hydrobiologica, 36(1), 75–90.

Kiefer, F. (1964). Zur Kenntnis der subterranen Copepoden (Crustacea) Österreichs. Annalen Des Naturhistorischen Museums in Wien, 67(September), 477–485.

Klie, W. (1936). Neue Candoninae (Ostr.) aus dem Grundwasser von Belgien (1). Bulletin Du Musée Royal d ' Histoire Naturelle de Belgique, XII(13), 16.

Klie, W. (1937). Weitere Ostracoden aus dem Grundwasser von Belgien. Bulletin Du Musée Royal d ' Histoire Naturelle de Belgique, XIII(4), 8.

Klinth, M. J., Kreiling, A.-K., & Erséus, C. (2019). Investigating the clitellata (Annelida) of icelandic springs with alternative barcodes. Fauna Norvegica, 39, 119–132. https://doi.org/10.5324/fn.v39i0.3043

Knight, L. R. F. D. (2008). The Biodiversity Action Plan (BAP) for niphargus glenniei (Crustacea: Amphipoda: Niphargidae): The first British troglobite to be listed. Cave and Karst Science, 35(1–2), 13–18.

Knight, L. R. F. D., Brancelj, A., Hänfling, B., & Cheney, C. (2015). The groundwater invertebrate fauna of the Channel Islands. Subterranean Biology, 15(1), 69–94. https://doi.org/10.3897/subtbiol.15.4792

Knight, L. R. F. D., & Gledhill, T. (2010). The discovery of Microniphargus leruthi Schellenberg, 1934 (Crustacea: Amphipoda: Niphargidae) in Britain and its distribution in the British Isles. Zootaxa, 2655, 52–56. https://doi.org/10.11646/zootaxa.2655.1.3

Koenemann, S., Vonk, R., & Schram, F. R. (1998). Cladistic analysis of 37 Mediterranean Bogidiellidae (Amphipoda), including Bogidiella arista, new species, from Turkey. Journal of Crustacean Biology, 18(2), 383–404. https://doi.org/10.2307/1549332

Kornobis, E. (2011). Groundwater amphipods in Iceland: Population structure and phylogenetics. University of Iceland.

Kristjánsson, B. K., & Svavarsson, J. (2007). Subglacial Refugia in Iceland Enabled Groundwater Amphipods to Survive Glaciations. The American Naturalist, 170(2), 292–296. https://doi.org/10.2307/4541082

Lafont, M., & Vivier, A. (2006). Oligochaete assemblages in the hyporheic zone and coarse surface sediments: their importance for understanding of ecological functioning of watercourses. Hydrobiologia, 564, 171–181. https://doi.org/10.1007/s10750-005-1717-9

Lefébure, T., Douady, C. J., Gouy, M., Trontelj, P., Briolay, J., & Gibert, J. (2006). Phylogeography of a subterranean amphipod reveals cryptic diversity and dynamic evolution in extreme environments. Molecular Ecology, 15(7), 1797–1806. https://doi.org/10.1111/j.1365-294X.2006.02888.x

Leruth, R. (1938). La faune de la nappe phrèatique du Gravier de la Meuse a Hermalle-Sous-Argenteau. Bulletin de l'Institut Royal Des Sciences Naturelles de Belgique, 14(14), 37.

Löffler, H. (1960a). 2. Beitrag zur Kenntnis der Entomostrakenfauna Burgenländischer Brunnen und Quellen. Wissenschaftliche, 26, 17.

Löffler, H. (1960b). Die Entomostrakenfauna der Ziehbrunnen und einiger Quellen des nördlichen Burgenlandes.

Löffler, H. (1964). 3. Beitrag zu Kenntnis der Entomostrakenfauna Gurgenländischer Brunnen und Quellen (Südliches Birgenland). Wissenschaftliche Arbeiten Aus Dem Burgenland, 31, 156–169.

Malard, F., Boutin, C., Camacho, A. I., Ferreira, D., Michel, G., Sket, B., & Stoch, F. (2009). Diversity patterns of stygobiotic crustaceans across multiple spatial scales in Europe. Freshwater Biology, 54(4), 756–776. https://doi.org/10.1111/j.1365-2427.2009.02180.x

Malard, F., Gibert, J., & Laurent, R. (1997). L'aquifère de la source du Lez: un réservoir d'eau... et de biodiversité. Karstologia: Revue de Karstologie et de Spéléologie Physique, 30(1), 49–54. https://doi.org/10.3406/karst.1997.2402

Malard, F., Plénet, S., & Gibert, J. (1996). The use of Invertebrates in groundwater monitoring: A rising research field. Groundwater Monitoring & Remediation, 16(2), 103–113.

Manenti, R., & Pezzoli, E. (2019). Think of what lies below, not only of what is visible above, or: a comprehensive zoological study of invertebrate communities of spring habitats. European Zoological Journal, 86(1), 272–279. https://doi.org/10.1080/24750263.2019.1634769

Manganelli, G., Bodon, M., Cianfanelli, S., Talenti, E., & Giusti, F. (1998). New hydrobiids from subterranean waters of eastern Sardinia, Italy (Gastropoda Prosobranchia: Hydrobiidae). Basteria, 62, 43–67.

Marmonier, P., Maazouzi, C., Baran, N., Blanchet, S., Ritter, A., Saplairoles, M., Dole-Olivier, M.-J., Galassi, D. M. P., Eme, D., Dolédec, S., & Piscart, C. (2018). Ecology-based evaluation of groundwater ecosystems under intensive agriculture: A combination of community analysis and sentinel exposure. Science of the Total Environment, 613– 614, 1353–1366. https://doi.org/10.1016/j.scitotenv.2017.09.191

Marmonier, P., Vervier, P., Gibert, J., & Dole-Olivier, M.-J. (1993). Biodiversity in ground waters. Trends in Ecology and Evolution, 8(11), 392–395. https://doi.org/10.1016/0169-5347(93)90039-R

Martin, P., De Broyer, C., Fiers, F., Michel, G., Sablon, R., & Wouters, K. (2009). Biodiversity of Belgian groundwater fauna in relation to environmental conditions. Freshwater Biology, 54(4), 814–829. https://doi.org/10.1111/j.13652427.2008.01993.x

Martin, P., Schmelz, R. M., & Dole-Olivier, M.-J. (2015). Groundwater oligochaetes (Annelida, Clitellata) the Mercantour National Park (France), with the descriptions of one new genus and two new stygobiont species. Zoosystema, 37(4), 551–569. https://doi.org/10.5252/z2015n4a2

Mateus, A., & De Lourdes Magiel, M. (1967). Description d'une nouvelle espece de Bogidiella (Crustacea, Amphipoda) du psammon du Portugal et quelques notes sur son genre. Publicações Do Instituto de Zoologia "Dr. Augusto Nobre", Faculdade de Ciências Do Porto, 100, 11–47.

Maurice, L. (2009). Groundwater Ecology Literature: Review. In British Geological Survey Open Report: Vol. OR/09/061.

Maurice, L., Robertson, A. L., White, D., Knight, L. R. F. D., Johns, T., Edwards, F. K., Arietti, M., Sorensen, J. P. R., Weitowitz, D., Marchant, B. P., & Bloomfield, J. (2016). The invertebrate ecology of the Chalk aquifer in England (UK). Hydrogeology Journal, 24(2), 459–474. https://doi.org/10.1007/s10040-015-1334-2

McInerney, C. E., Maurice, L., Robertson, A. L., Knight, L. R. F. D., Arnscheidt, J., Venditti, C., Dooley, J. S. G., Mathers, T., Matthijs, S., Eriksson, K., Proudlove, G. S., & Hänfling, B. (2014). The ancient Britons: Groundwater fauna survived extreme climate change over tens of millions of years across NW Europe. Molecular Ecology, 23(5), 1153–1166. https://doi.org/10.1111/mec.12664

Meleg, I. N., Moldovan, O. T., Iepure, S., Fiers, F., & Brad, T. (2011). Diversity patterns of fauna in dripping water of caves from Transylvania. Annales de Limnologie, 47(2), 185–197. https://doi.org/10.1051/limn/2011014

Mermillod-Blondin, F., Lefour, C., Lalouette, L., Renault, D., Malard, F., Simon, L., & Douady, C. J. (2013). Thermal tolerance breadths among groundwater crustaceans living in a thermally constant environment. Journal of Experimental Biology, 216(9), 1683–1694. https://doi.org/10.1242/jeb.081232

Messouli, M., Coineau, N., & Boutin, C. (2002). Revision, phylogeny and biogeography of the groundwater amphipods Salentinellidae. I. Description of Salentinella anae nov. sp. from Spain with remarks on the genera Salentinella and Parasalentinella. Zoological Science, 19(10), 1147–1154. https://doi.org/10.2108/zsj.19.1147

Messouli, M., Messana, G., & Yacoubi-khebiza, M. (2006). Three new species of Pseudoniphargus (Amphipoda), from the groundwater of three Mediterranean islands, with notes on the Ps . adriaticus. Subterranean Biology, 4, 79– 101.
Moniez, R. (1889). du Department du Nord et en particulier de la ville de Lille. Extrait de La Revue Biologique Du Nord de La France, 1, 70.
Moog, O. (2002). Fauna Aquatica Austriaca Katalog zur autökologischen Einstufung aquatischer Organismen Österreichs.
Mösslacher, F. (1998). Subsurface Dwelling Crustaceans as Indicators of Hydrological Conditions, Oxygen Concentrations, and Sediment Structure in an Alluvial Aquifer. International Review of Hydrobiology, 83(4), 349– 364.
Motas, C., & Capuse, I. (1965). Beiträge zur Kenntnis der Brunnenfauna im Tal des Flusses Bela Reca (Rumänien). International Journal of Speleology, 1(4), 461–478. https://doi.org/10.5038/1827-806x.1.4.4
Muehlberger, C. (1954). Über die Verbreitung subterraner Amphipoden im Gebiet der Lausitzer Hauptverwerfung. Die Naturwissenschaften, 17(Jg. 41), 407–408.
Namiotko, T., Marmonier, P., & Danielopol, D. L. (2005). Cryptocandona kieferi (Crustacea, Ostracoda): Redescription, morphological variability, geographical distribution. Vie et Milieu, 55(2), 91–108.
Notenboom, J. (1986). The species of the genus Pseudoniphargus Chevreux, 1901 (Amphipoda) from northern Spain. Bijdragen Tot de Dierkunde, 56(1), 75–122.
Notenboom, J. (1987). Species of the genus Pseudoniphargus Chevreux, 1901 (Amphipoda) from the Betic Cordillera of southern Spain. Bijdragen Tot de Dierkunde, 57(1), 87–150.
Notenboom, J. (1988). Biogeographical Observations on the Genera of Iberian Stygobiont Amphipoda. Crustaceana. Supplement., 13, 122–133.
Notenboom, J., Cruys, K., Hoekstra, J., & Van Beelen, P. (1992). Effect of ambient oxygen concentration upon the acute toxicity of chlorophenols and heavy metals to the groundwater copepod Parastenocaris germanica (crustacea). Ecotoxicology and Environmental Safety, 24(2), 131–143. https://doi.org/10.1016/01476513(92)90041-Z
Notenboom, J., & Meijers, I. (1985). Investigaciones sobre la fauna de las aguas subterráneas de España: Lista de estaciones y primeros resultados.

Notenboom, J., Serrano, R., Morell, I., & Hernández, F. (1995). The phreatic aquifer of the "Plana de Castellón" (Spain): relationships between animal assemblages and groundwater pollution. Hydrobiologia, 297(3), 241–249. https://doi.org/10.1007/BF00019288

Núñez, J., Glasby, C. J., & Naranjo, M. (2020). Groundwater annelids from Gran Canaria and Fuerteventura (Canary Islands), with the description of two new species of Namanereis (Namanereidinae, Nereididae, Polychaeta). Subterranean Biology, 36, 35–49. https://doi.org/10.3897/subtbiol.36.55090

Opalički Slabe, M. (2015). Patterns in invertebrate drift from an alpine karst Aquifer over an one year period. Acta Carsologica, 44(2), 265–278. https://doi.org/10.3986/ac.v44i2.1513

Paran, F., Malard, F., Mathieu, J., Lafont, M., Galassi, D. M. P., & Marmonier, P. (2004). Distribution of groundwater invertebrates along an environmental gradient in a shallow water-table aquifer. In J. Gibert (Ed.), Symposium on World Subterranean Biodiversity (p. 7). Equipe Hydrobiologie et Ecologie Souterraines.

Pesce, G. L. (1980). Bogidiella aprutina n. sp., a new subterranean amphipod from phreatic waters of central Italy. Crustaceana, 38(2), 139–144.

Pesce, G. L. (1981). A new phreatic Bogidiella from subterranean waters of Sardinia (Crustacea Amphipoda, Gammaridae). Revue Suisse de Zoologie., 88(1), 157–162. https://doi.org/10.5962/bhl.part.82362

Pesce, G. L., & Galassi, D. M. P. (1987). Arpacticoidi di acque sotterranee del Friuli-Venezia Giulia (Crustacea: Copepoda). Biogeographia, 13, 587–593.

Pesce, G. L., & Galassi, D. M. P. (1994). Elaphoidella plesai n. sp. from groundwaters of Austria (Copepoda Harpacticoida: Canthocamptidae). Annales de Limnologie, 30(2), 91–94. https://doi.org/10.1051/limn/1994011

Petitta, M., Caschetto, M., Galassi, D. M. P., & Aravena, R. (2015). Dual-flow in karst aquifers toward a steady discharge spring (Presciano, Central Italy): influences on a subsurface groundwater dependent ecosystem and on changes related to post-earthquake hydrodynamics. Environmental Earth Sciences, 73(6), 2609–2625. https://doi.org/10.1007/s12665-014-3440-1

Pipan, T., & Culver, D. C. (2007). Copepod distribution as an indicator of epikarst system connectivity. Hydrogeology Journal, 15(4), 817–822. https://doi.org/10.1007/s10040-006-0114-4

Pociecha, A., Karpowicz, M., Namiotko, T., Dumnicka, E., & Galas, J. (2021). Diversity of groundwater crustaceans in wells in various geologic formations of Southern Poland. Water (Switzerland), 13(16), 1–14. https://doi.org/10.3390/w13162193

Pospisil, P. (1994). The groundwater fauna of a Danube aquifer in the “Lobau” wetland in Vienna, Austria. In J. Gibert, D. L. Danielopol, & J. A. Stanford (Eds.), Groundwater Ecology (pp. 346–366). Academic Press.

Pospisil, P. (1999a). Acanthocyclops sensitivus (Graeter & Chappuis , 1914) (Copepoda: Cyclopoida) in Austria. Annales de Limnologie, 35(1), 49–55.

Pospisil, P. (1999b). The Composition of Cyclopoid Assemblages in Ecologically Different Groundwater Habitats of a Danube Riverine Wetland in Austria. Crustaceana, 72(8), 883–892.

Pospisil, P., & Stoch, F. (1999). Two new species of the Diacyclops languidoides-group (Copepoda, Cyclopoida) from groundwaters of Austria. Hydrobiologia, 412, 165–176. https://doi.org/10.1023/A

Proudlove, G. S., Wood, P. J., Harding, P. T., Horne, D. J., Gledhill, T., & Knight, L. R. F. D. (2003). A review of the status and distribution of the subterranean aquatic Crustacea of Britain and Ireland. Cave and Karst Science, 30(2), 53–74.

Reboleira, A. S. P. S., Abrantes, N., Oromí, P., & Gonçalves, F. (2013). Acute toxicity of copper sulfate and potassium dichromate on stygobiont proasellus: General aspects of groundwater ecotoxicology and future perspectives. Water, Air, and Soil Pollution, 224(1550), 1–9. https://doi.org/10.1007/s11270-013-1550-0

Reboleira, A. S. P. S., Borges, P. A. V., Gonçalves, F., Serrano, A. R. M., & Oromí, P. (2011). The subterranean fauna of a biodiversity hotspot region - Portugal: an overview and its conservation. International Journal of Speleology, 40(1), 23–37.

Ressl, F. (1983). Die Tierwelt des Bezirks Scheibbs (2nd ed.). Naturkundliche Arbeitsgemeinschaft des Bezirkes Scheibbs.

Ribera, I., & Reboleira, A. S. P. S. (2019). The first stygobiont species of Coleoptera from Portugal, with a molecular phylogeny of the Siettitia group of genera (Dytiscidae, Hydroporinae, Hydroporini, Siettitiina). ZooKeys, 813, 21– 38. https://doi.org/10.3897/zookeys.813.29765

Robertson, A. L., Johns, T., Smith, J., & Proudlove, G. S. (2008). A review of the subterranean aquatic ecology of England and Wales. In Science Reports.

Robertson, A. L., Smith, J., Johns, T., & Proudlove, G. S. (2009). The distribution and diversity of stygobites Great Britain: An analysis to inform groundwater management. Quarterly Journal of Engineering Geology and Hydrogeology, 42(3), 359–368. https://doi.org/10.1144/1470-9236/08-046

Rogulj, B., & Danielopol, D. L. (1980). Three new Mixtacandona (Ostracoda) species from Croatia, Austria and France. Vie et Milieu, 43(2), 145–154.

Rouch, R., & Danielopol, D. L. (1997). Species Richness of Microcrustacea in Subterranean Freshwater Habitats. Comparative Analysis and Approximate Evaluation. Internationale Revue Der Gesamten Hydrobiologie Und Hydrographie, 82(2), 121–145.

Ruffo, S. (1953). Anfipodi di acque interstiziali raccolti dal Dr. C. Delamare Deboutteville in Francia, Spagna e Algeria. Vie et Milieu (France), 4(4), 669–681.

Ruffo, S., & Schiecke, U. (1976). Una nuova Bogidiella di Creta. Bollettino Del Museo Civico Di Storia Naturale Di Verona, 3, 147–155.

Ruffo, S., & Vigna Taglianti, A. (1975). Una nuova Bogidiella della Sardegna (Crustacea Amphipoda, Gammaridae). Fragmenta Entomologica, 11(1), 73–82.

Sánchez, E. L. (1990). A new species of Pseudoniphargus (Crustacea, Amphipoda) from subterranean waters in Tenerife (Canary Islands). Hydrobiologia, 196(1), 51–63. https://doi.org/10.1007/BF00008892

Sanchez, E. L. (1991). Stygofauna of the Canary Islands 22. Bogidiella (Stygogidiella) atlantica n. sp. (Amphipoda) from interstitial waters on the western Canary Islands. Crustaceana, 61(2), 113–124.

Sarbu, S. M., Galsenzi, S., Menichetti, M., & Gentile, G. (2000). Geology and biology of the Frasassi Caves in Central Italy: An ecological multi-disciplinary study of a hypogenic underground karst system. In H. Wilkens, D. C. Culver, & W. F. Humphreys (Eds.), Subterranean Ecosystems (pp. 359–378). Elsevir.

Särkkä, J., Levonen, L., & Mäkelä, J. (1998). Harpacticoid and cyclopoid fauna of groundwater and springs in southern Finland. Journal of Marine Systems, 15(1–4), 155–161. https://doi.org/10.1016/S0924-7963(97)00075-4

Särkkä, J., & Mäkelä, J. (1998). Troglochaetus beranecki Delachaux (Polychaeta, Archiannelida) in esker groundwaters of Finland: A new class of limnic animals for northern Europe. Hydrobiologia, 379(1–3), 17–21. https://doi.org/10.1023/a:1003292202048

Schnitter, H., & Chappuis, P. A. (1914). 2. Parastenocaris fontinalis nov. spec, ein neuer Süßwasserharpacticide. Zoologischer Anzeiger, 45, 290–302.

Senz, W. (1996). Prostoma communopore sp. n., eine neue Nemertine aus dem Grundwasser in Österreich (Nemertini: Hoplonemertini: Monostilifera). Annalen Des Naturhistorischen Museums in Wien Serie B Botanik Und Zoologie, 98B, 23–30.

Shapouri, M., Cancela da Fonseca, L., Iepure, S., Stigter, T. Y., Ribeiro, L., & Silva, A. (2016). The variation of stygofauna along a gradient of salinization in a coastal aquifer. Hydrology Research, 47(1), 89–103. https://doi.org/10.2166/nh.2015.153

Sidorov, D. A., & Gontcharov, A. A. (2013). Studies on subterranean amphipod crustaceans of Primory, Russia. Part 1. Three new species of the genus Pseudocrangonyx from springs and other groundwater habitats in far eastern Russia. Zootaxa, 3693(4), 547–567. https://doi.org/10.11646/zootaxa.3693.4.8

Skalski, A. W. (1976). Groundwater Inhabitants in Poland. International Journal of Speleology, 8, 217–228.

Sket, B. (1999). The nature of biodiversity in hypogean waters and how it is endangered. Biodiversity and Conservation, 8(10), 1319–1338. https://doi.org/10.1023/A:1008916601121

Smit, H., & Van der Hammen, H. (2000). Atlas van de Nederlandse Watermijten (aAcari: Hydrachnidia). In Nederlandse faunistische Mededelingen.

Sorensen, J. P. R., Maurice, L., Edwards, F. K., Lapworth, D. J., Read, D. S., Allen, D., Butcher, A. S., Newbold, L. K., Townsend, B. R., & Williams, P. J. (2013). Using Boreholes as Windows into Groundwater Ecosystems. PLoS ONE, 8(7), 13. https://doi.org/10.1371/journal.pone.0070264

Stocchino, G. A., Sluys, R., Kawakatsu, M., Sarbu, S. M., & Manconi, R. (2017). A new species of freshwater flatworm (Platyhelminthes, tricladida, dendrocoelidae) inhabiting a chemoautotrophic groundwater ecosystem in Romania. European Journal of Taxonomy, 342, 1–21. https://doi.org/10.5852/ejt.2017.342

Stoch, F., Artheau, M., Brancelj, A., Galassi, D. M. P., & Malard, F. (2009). Biodiversity indicators in European ground waters: Towards a predictive model of stygobiotic species richness. Freshwater Biology, 54(4), 745–755. https://doi.org/10.1111/j.1365-2427.2008.02143.x

Stoch, F., Fiasca, B., Di Lorenzo, T., Porfirio, S., Petitta, M., & Galassi, D. M. P. (2016). Exploring copepod distribution patterns at three nested spatial scales in a spring system: Habitat partitioning and potential for hydrological bioindication. Journal of Limnology, 75(1), 1–13. https://doi.org/10.4081/jlimnol.2015.1209

Stoch, F., Pieri, V., Sambugar, B., & Zullini, A. (2009). La fauna delle acque sotterranee dell' Alta Val di Secchia (Appennino Reggiano). Il Progetto Trias - Memorie Dell'Istituto Italiano Di Speleologia, 22, 145–163.

Stoch, F., & Pospisil, P. (2000a). Redescription of diacyclops disjunctus (Thallwitz, 1927) from Austria, with remarks on the diacyclops languidus-group in Europe (Copepoda, Cyclopoida, Cyclopidae). Crustaceana, 73(4), 469–478. https://doi.org/10.1163/156854000504552

Stoch, F., & Pospisil, P. (2000b). The Diacyclops languidoides - group (Copepoda: Cyclopoida) in Austria, with redescription of Diacyclops cohabitatus Monchenko 1980. Annales de Limnologie, 36(1), 21–29. https://doi.org/10.1051/limn/2000002

Stock, J. H. (1978). Bogidiella martini, un nouvel Amphipode souterrain de l'Ile Saint-Martin (Antilles) et la zoogéographie des Bogidiellidae. International Journal of Speleology, 9, 103–113. https://doi.org/10.5038/1827806x.9.2.3

Stock, J. H. (1988). Stygofauna of the Canary Islands 8. Amphipoda (Crustacea) from inland groundwaters of Fuerteventura. Bulletin Zoölogisch Museum, Universiteit van Amsterdam, 11(12), 105–112.

Stock, J. H., & Abreu, A. D. (1992). Three New Species of Pseudoniphargus (Crustacea: Amphipoda) From the Madeira Archipelago. Boletim Do Museu Municipal Do Funchal, 44(241), 131–155.

Stock, J. H., & Notenboom, J. (1988). Five new bogidiellid Amphipoda from Spain - the first freshwater records in the Iberian Peninsula. Hydrobiologia, 164(1), 75–95. https://doi.org/10.1007/BF00014351

Stock, J. H., & Rondé-Broekhuizen, B. L. M. (1987). Stygofauna of the Canary Islands, 3. The genus Bogidiella (Crustacea, Amphipoda). Revue de Zoologie Africaine, 101(4), 439–461.

Stock, J. H., & Vonk, R. (1990). Stygofauna of the Canary Islands, 15 marine interstitial isopoda asellota of the superfamily Gnathostenetroidoidea. Cahiers De Biologie Marine, 31(1), 5–24.

Stubbington, R., Wood, P. J., & Boulton, A. J. (2009). Low flow controls on benthic and hyporheic macroinvertebrate assemblages during supra-seasonal drought. Hydrological Processes, 23, 2252–2263. https://doi.org/10.1002/hyp.7290

Svavarsson, J., & Kristjánsson, B. K. (2006). Crangonyx islandicus sp. nov., a subterranean freshwater amphipod (Crustacea, Amphipoda, Crangonyctidae) from springs in lava fields in Iceland. Zootaxa, 1365, 1–17. https://doi.org/10.11646/zootaxa.1365.1.1

Takhteev, V. V., Galimzyanova, A. V., Ambrosova, E. V., Kravtsova, L. S., Rozhkova, N. A., Okuneva, G. L., Semernoi, V. P., Pomazkova, G. I., & Lopatovskaya, O. G. (2010). Zoobenthos communities and their seasonal dynamics in nonfreezing springs of Baikal region. Biology Bulletin, 37(6), 638–646. https://doi.org/10.1134/S1062359010060129

Turbanov, I. S., Palatov, D. M., & Golovatch, S. I. (2016). The state of the art of biospeleology in Russia and other countries of the former Soviet Union: a review of the cave (endogean) invertebrate fauna. 1. Introduction— crustacea. Entomological Review, 96(7), 926–963. https://doi.org/10.1134/S0013873816070162

Vanek, V. (1982). Fauna of groundwaters of Bohemian Karst (Barrandium). Methodology and preliminary results. Polskie Archiwum Hydrobii, 29(2), 415–424.

Vejdovský, F. (1881). Thierische Organismen der Brunnenwässer von Prag. Denskschriften Der Mathem-Naturw. Abhandlungen von Nichtmitgliedern, 43, 33–90.

Verdonschot, P. F. M. (2007). Spatial and temporal re-distribution of Naididae (tubificoid naidids and naidids s . str ., Annelida , Clitellata) in Europe due to climate change: a review based on observational data. Acta Hydrobiologica Sinica, 31, 116–138.

Vila-Farré, M., Sluys, R., Almagro, Í., Handberg-Thorsager, M., & Romero, R. (2011). Freshwater planarians (Platyhelminthes, Tricladida) from the Iberian Peninsula and Greece: Diversity and notes on ecology. Zootaxa, 2779, 1–38. https://doi.org/10.11646/zootaxa.2779.1.1

Walther, A. (2002). Comparison of the groundwater fauna of two contrasting reaches of the Upper Rhone River. In Travail de diplôme à l 'EPF Zurich/ . . . (Issue 97). ETH Zürich.

	Weber, M. (1881). Über einige neue Isopoden der Niederländischen Fauna. Tijdschrift Der Nederlandsche Dierkundige Vereenging, 167–196. Weitowitz, D. (2016). An investigation into the distribution of obligate groundwater animals (stygobites) in England and Wales. University of Roehampton London. Więcek, M., Martin, P., & Gąbka, M. (2013). Distribution patterns and environmental correlates of water mites (Hydrachnidia, Acari) in peatland microhabitats. In Experimental and Applied Acarology (Vol. 61, Issue 2, pp. 147–160). https://doi.org/10.1007/s10493-013-9692-8 Wrzesniowski, A. (1890). Über drei unterirdische Gammariden. Zeitschrift Für Wissenschaftliche Zoologie, 50, 600– 724. Zhai, M., Hřívová, D., & Peterka, T. (2015). The harpacticoid assemblages (Copepoda: Harpacticoida) in the Western Carpathian spring fens in relation to environmental variables and habitat age. Limnologica, 53, 84–94. https://doi.org/10.1016/j.limno.2015.07.001 Zollhöfer, J. M. (1999). Spring biotopes in Northern Switzerland Habitat heterogeneity, zoobenthic communities and colonization dynamics. ETH Zürich.
Germany	Alqaragholi, S. A., Kanoua, W., & Göbel, P. (2021). Comparative investigation of aquatic invertebrates in springs in area (Western Germany). Water (Switzerland), 13(3), 1–18. https://doi.org/10.3390/w13030359 Avramov, M., Schmidt, S. I., & Griebler, C. (2013). A new bioassay for the ecotoxicological testing of VOCs on groundwater invertebrates and the effects of toluene on Niphargus inopinatus. Aquatic Toxicology, 130–131, 1–8. https://doi.org/10.1016/j.aquatox.2012.12.023 Barufke, K.-P. (2010). Langjährige Erfahrungen mit Grundwasser - Fauna - Projekten in Baden - Württemberg. Tagung Grundwasserökosysteme Entdecken, Bewerten, Erhalten, 59. Bellstedt, R. (2001). Ein aktueller Fund von Proasellus cavaticus Leydig, 1871 in Thüringen (Crustacea, Isopoda, Asellidae). Thüringer Faunistische Abhandlungen, 8, 277–278. Berkhoff, S. E. (2010). Die Meiofauna des Interstitials und Grundwassers als Indikator für OberflächenwasserGrundwasser-Interaktionen im Bereich einer Uferfiltrationsanlage. University Koblenz-Landau. Beyer, H. (1932). Die Tierwelt der Quellen und Bäche des Baumbergegebietes. In H. Reichling (Ed.), Abhandlung aus dem westfälischen Provinzial-Museum für Naturkunde (3rd ed., pp. 9–188).

Brandis, D., Hollert, H., & Storch, V. (2005). Artenvielfalt in Heidelberg (2. Auflage). Selbstverlag Zoologisches Institut der Universität Heidelberg.

Brielmann, H., Griebler, C., Schmidt, S. I., Michel, R., & Lueders, T. (2009). Effects of thermal energy discharge on shallow groundwater ecosystems. FEMS Microbiology Ecology, 68(3), 273–286. https://doi.org/10.1111/j.15746941.2009.00674.x

Buder, L. (2019). Untersuchungen zur Grundwasserfauna im Stadtgebiet von München. Technische Universität München.

Feest, J., Briesemann, C., Greune, B., & Penassa, J. (1976). Zum Artenbestand von vier Quellregionen der Baumberge verglichen mit faunistischen Untersuchungen aus den Jahren 1926-30. Natur Und Heimat, 36(2), 32–39.

Fišer, C., Sket, B., & Trontelj, P. (2008). A phylogenetic perspective on 160 years of troubled taxonomy of Niphargus (Crustacea: Amphipoda). Zoologica Scripta, 37(6), 665–680. https://doi.org/10.1111/j.1463-6409.2008.00347.x

Flot, J.-F. (2010). Vers une taxonomie moléculaire des amphipodes du genre Niphargus: exemples d'utilisation de séquences d'ADN pour l'identification des espèces. Bulletin de La Société
Des Sciences Naturelles de l'Ouest de La France, 32(2), 62–68.

Fries, S. (1878). Mittheilungen aus dem Gebiete der Dunkel-Fauna. Zoologischer Anzeiger, 56–60.

Fuchs, A. (2007). Erhebung und Beschreibung der Grundwasserfauna in Baden-Württemberg. 1–109. https://kola.opus.hbz-nrw.de/frontdoor/index/index/docId/175

Fuchs, A., Hahn, H. J., & Barufke, K.-P. (2006). Grundwasser-Überwachungsprogramm - Erhebung und Beschreibung der Grundwasserfauna in Baden-Württemberg. https://pudi.lubw.de/detailseite/-/publication/77258

Gaviria, S., & Defaye, D. (2017). A new species of Moraria (Copepoda, Harpacticoida, Canthocamptidae) from groundwaters of Germany, including a key for the identification of the species of the Western Palaearctic Region. Crustaceana, 90(13), 1537–1561. https://doi.org/10.1163/15685403-00003706

Griebler, C., Stein, H., Hahn, H. J., Steube, C., Kellermann, C., Fuchs, A., Berkhoff, S. E., & Brielmann, H. (2014). Entwicklung biologischer Bewertungsmethoden und -kriterien für Grundwasserökosysteme. Umweltbundesamt.

Gutjahr, S., Bork, J., & Hahn, H. J. (2013). Grundwasserfauna als Indikator für komplexe hydrogeologische Verhältnisse am westlichen Kaiserstuhl. Grundwasser, 18(3), 173–184. https://doi.org/10.1007/s00767-013-02273

Gutjahr, S., Schmidt, S. I., & Hahn, H. J. (2014). A proposal for a groundwater habitat classification at local scale. Subterranean Biology, 14(1), 25–49. https://doi.org/10.3897/subtbiol.14.5429

Hahn, H. J., & Fuchs, A. (2009). Distribution patterns of groundwater communities across aquifer types in southwestern Germany. Freshwater Biology, 54(4), 848–860. https://doi.org/10.1111/j.1365-2427.2008.02132.x Hahn, H. J., Fuchs, A., & Berkhoff, S. E. (2020). Biomonitoring Nitrat 2020 in Sachsen-Anhalt.

Hahn, H. J., & Matzke, D. (2005). A comparison of stygofauna communities inside and outside groundwater bores. Limologica, 35, 31–44.

Hahn, H. J., Matzke, D., Kolberg, A., & Limberg, A. (2013). Untersuchung zur Fauna des Berliner Grundwassers – erste Ergebnisse. Brandenburgische Geowissenschaftliche Beiträge, 20, 85–92.

Hartke, T. R., Fišer, C., Hohagen, J., Kleber, S., Hartmann, R., & Koenemann, S. (2011). Morphological and molecular analyses of closely related species in the stygobiontic genus niphargus (Amphipoda). Journal of Crustacean Biology, 31(4), 701–709. https://doi.org/10.1651/10-3434.1

Heynig, H. (1977). Organismen im Leitungswasser der Stadt Halle (Saale) unter besonderer Berucksichtigung von Testacea und Crustacea. Acta Hydrochimica. Hydrobiologica., 5(2), 179–183.

Husmann, S. (1964). Studien zur Ökologie und Verbreitung der Gattung Chappuisius Kiefer, 1938 (Copepoda, Harpacticoida); Mitteilung über Neufunde aus den Grundwasserströmen von Lahn, Niederrhein, Ruhr, Leine und Unterweser. Crustaceana, 6(3), 179–194. https://doi.org/10.1163/156854064X00588

Husmann, S. (1976). Studies on subterranean drift of stygobiont Crustaceans (Niphargus, Crangonyx, Graeteriella). International Journal of Speleology, 8(1/2), 81–92. https://doi.org/10.5038/1827-806x.8.1.7

Jäger, N., Kempf, K., Lanfervoß, A., Lüke, J., Niederle-Bilitza, A.-L., & Schils, W. (2015). Aktualisierte Umwelterklärung 2015.

Kappes, H., Zaenker, S., & Cölln, K. (2002). Vorkommen von Niphargus schellenbergi KARAMAN, 1932 (Crustacea: Amphipoda) in der Eifel. 9(4), 1203–1210.

Kiefer, F. (1957a). Die Grundwasserfauna des Oberrheingebietes mit besonderer Berücksichtigung der Crustaceen. Beitr.Naturk.Forsch.Südwestdeutsch., 16(2), 65–90.

Kiefer, F. (1957b). Ruderfusskrebse (Crustacea Copepoda) aus dem Grundwasser des südlichen Oberrheingebietes. Mitt. Bad. Landesver. Naturkunde u. Naturschutz, 7(1), 53–68.

Klie, W. (1950). Entomostraken aus Unterfranken. Mitteilungen Des Naturwissenschaftlichen Museums Der Stadt Aschaffenburg, 4, 15–28.

Koch, F., Menberg, K., Schweikert, S., Spengler, C., Hahn, H. J., & Blum, P. (2021). Groundwater fauna in an urban area - Natural or affected? Hydrology and Earth System Sciences, 25(6), 3053–3070. https://doi.org/10.5194/hess25-3053-2021

Kunz, H. (1978). Beitrag zur Kenntnis der Ruderfußkrebse (Copepoda) des Saarlandes und benachbarter Gebiete. Abhandlung Der Arbeitsgemeinschaft Tier-Und Pflanzengeographischen Heimatforschung Saarland, 137–154.

Lais, R. (1936). Beiträge zur Kenntnis der badischen Molluskenfauna. Mitteilungen Des Badischen Landesvereins Für Naturkunde Und Naturschutz e.V. Freiburg i. Breisgau, 3(21), 291–297. Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg. (2011). Grundwasserüberwachungsprogramm.

Löffler, H. (1961). Grundwasser- und Brunnenostracoden aus Südwestdeutschland und den Vogesen. Beitrag Zur Naturkundlichen Forschung in Südwestdeutschland, 20(1), 31–42.

Matzke, D., Fuchs, A., Berkhoff, S. E., Bork, J., & Hahn, H. J. (2009). Erhebung und Bewertung der Grundwasserfauna Sachsen-Anhalts.

Matzke, D., Fuchs, A., Berkhoff, S. E., & Hahn, H. J. (2012). Erhebung und Beschreibung der Grundwasserfauna Sachsen-Anhalts - Monitoring Referenzmessstellen Grundwasserfauna 2010-2012 Untersuchungsbericht.

Matzke, D., Hahn, H. J., Ramstöck, A., & Rother, K. (2005). Bewertung von Altlasten im Grundwasser anhand der Meiofaunagemeinschaften - Erste Ergebnisse. Grundwasser, 10(1), 25–34. https://doi.org/10.1007/s00767-0050067-x

Meisch, C., Stoch, F., & Gerecke, R. (2006). Krebstiere (Crustacea: Copepoda, Ostracoda, Amphipoda et Isopoda) im Kalkquellmoor “Benninger Ried” bei Memmingen, Bayern. Lauterbornia, 57(1–2), 95–105.

Noll, W. (1939). Die Grundwasserfauna des Maingebietes. Mitt.Naturwiss.Mus.Aschaffenburg, 1, 3–25.

Noll, W., & Stammer, H.-J. (1953). Die Grundwasserfauna des Untermaingebietes von Hanau bis Würzburg mit Einschluss des Spessarts. https://www.zobodat.at/pdf/MittNaturwissMusStadtAschaffenburg_NF_6_1953_00010077.pdf

Noodt, W. (1952). Neue unterirdische Copepoden aus Schleswig-Holstein. Faunastisch-Ökologische Mitteilungen, 1_1, 2–3.

Preuß, G., & Vincent, L. (2010). Mikrobiologie im Grund- und Quellwasser der Baumberge (Kreis Coesfeld, Nordrhein-Westfalen) - Charakterisierung der Bakterienbesiedlung und der Grundwasserfauna. Abhandlungen Aus Dem Westfälischen Museum Für Naturkunde, 72(3/4), 75–86.

Rehberg, H. (1880). Zwei neue Crustaceen aus einem Brunnen auf Helgoland. Zoologischer Anzeiger, 3, 301–303.

Reid, N. (2011). European hare (Lepus europaeus) invasion ecology: Implication for the conservation of the endemic Irish hare (Lepus timidus hibernicus). Biological Invasions, 13(3), 559–569. https://doi.org/10.1007/s10530-0109849-x

Remane, A., & Schuöz, E. (1933). Die Tierwelt des Kustengrundwassers bei Schilksee (Kieler Bucht) I-Vil. 1. Das Kustengrundwasser. Schriften Des Naturwissenschaftlichen Vereins Für Schleswig-Holstein, 20, 399–408.

Rumm, P. (1999). Untersuchungen zum Abbau partikulärer organischer Substanzen in einem Langsamsandfilter durch Metazoen am Beispiel von Niphargus fontanus. University Oldenburg.

Schäfers, C., Wenzel, A., Lukow, T., & Sehr, I. (2001). Ökotoxikologische Prüfung von Pflanzenschutzmitteln hinsichtlich ihres Potenzials zur Grundwassergefährdung: Vol. 298 28 415. https://doi.org/10.13140/RG.2.1.4865.0329

Schulz, H., & Roskam, A. (2011). Untersuchungen zur Fauna im Grundwasser Ostfrieslands.

Schulz, I., Pelzer, G., Riedel, T., & Weitzel, I. (2018). Kommunales Grundwassermonitoring.

Schwoerbel, J. (1959a). Graeteriella unisetiger (E. Graeter 1908), ein seltener Cyclopide (Crustacea, Copepoda) aus dem Grundwasser der versickernden Donau bei Möhringen. Mitt. Bad. Landesver. Naturkunde u. Naturschutz, 7(5), 321–322.

Schwoerbel, J. (1959b). Zur Kenntnis der Wassermilbenfauna des südlichen Schwarzwaldes (Hydrachnellae, Acari). 5. Beitrag: Wassermilben aus dem Grundwasser (Hydrachnellae, Porohalacaridae, Stygothrombiidae). Mitteilungen Des Badischen Landesvereins Für Naturkunde Und Naturschutz, 7(5), 323–330.

Schwoerbel, J. (1961). Neue und wenig bekannte Atractides-Arten aus dem hyporheischen Grundwasser (Acari: Hygrobatidae). Mitteilungen Des Badischen Landesvereins Für Naturkunde Und Naturschutz, 8(1), 41–63.

Schwoerbel, J. (1962). Zur Kenntnis der Wassermilbenfauna des südlichen Schwarzwaldes 6. Beitrag: Weitere Arten aus dem hyporhe ischen Grundwasser und aus Fließgewässern (mit Berücksichtigung der südlichen Vogesen). Mitteilungen Des Badischen Landesvereins Für Naturkunde Und Naturschutz, 2, 251–260.

Spangenberg, H.-J. (1973a). Beitrag zur Faunistik von Höhlengewässern im Zechstein des Südharzes und Kyffhäusers. Hercynia N.F., 10(2), 143–160.

Spangenberg, H.-J. (1973b). Faunistisch-okologische Untersuchungen an Gewassern von Gipshöhlen und im Grundwasser des Südharzes und Kyffhäusers. Internationale Revue Der Gesamten Hydrobiologie Und Hydrographie, 58(4), 501–542.

Spengler, C. (2017). Die Auswirkungen von anthropogenen Temperaturerhöhungen auf die Crustaceagemeinschaften im Grundwasser. Universität Koblenz-Landau.

Steenken, B. (1990). Die Grundwasserfauna. In Handbuch Angewandte Limnologie (7th ed., pp. 3–49).
Stein, H., Griebler, C., Berkhoff, S., Matzke, D., Fuchs, A., & Hahn, H. J. (2012). Stygoregions-a promising approach to a bioregional classification of groundwater systems. Scientific Reports, 2, 1–9. https://doi.org/10.1038/srep00673
Steube, C., Richter, S., & Griebler, C. (2009). First attempts towards an integrative concept for the ecological assessment of groundwater ecosystems. Hydrogeology Journal, 17(1), 23–35. https://doi.org/10.1007/s10040-0080346-6
Thiemann, K. (2007). Protokoll eines Praktikums beim Landesamt für Natur und Umwelt, Schleswig-Holstein.
Trontelj, P., Douady, C. J., Fišer, C., Gibert, J., Gorički, Š., Lefébure, T., Sket, B., & Zakšek, V. (2009). A molecular test for cryptic diversity in ground water: How large are the ranges of macro-stygobionts? Freshwater Biology, 54(4), 727–744. https://doi.org/10.1111/j.1365-2427.2007.01877.x
Viets, K. (1918). Ein neuer Fundort des blinden Brunnen-Flohkrebses bei Bremen. Abhandlung Des Naturwissenschaftlichen Vereins Zu Bremen, 24, 551.
Weckwert, N., Hahn, H. J., & Göbel, P. (2014). Grundwasserfauna in den Baumbergen, zentrales Münsterland, NRW. In S. Holzheu, R. Kaufmann-Knoke, & B. Thies (Eds.), Grundwasser trifft Boden und Energie. FH-DGG.
Wegelin, R. (1966). Beitrag zur Kenntnis der Grundwasserfauna des Saale-Elbe-Einzugsgebietes. Referate Einschlägiger Literaur Landesbibliothek Sachsen-Anhalt, 93, 416–419.
Zaenker, S., & Reiss, M. (2016). Quellkartierung im Vogelsberg - Teil 1 - Unveröffentlichter Untersuchungsbericht im Auftrag des Naturschutzgroßprojekts Vogelsberg.
Zaenker, S., & Reiss, M. (2017). Quellenkartierung südlich und südöstlich von Ulrichstein.

Appendix Study 2

This Appendix refers to Study 2 (Chapter 3). The content was published in the journal Hydrology and Earth System Sciences as a supplement and is available online.

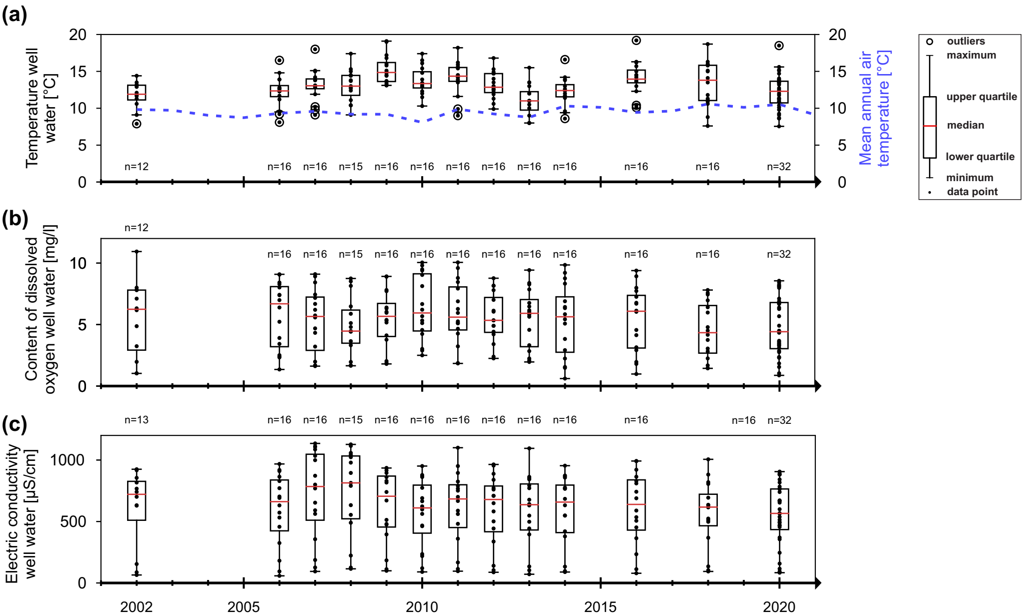

Figure A2.1: Boxplots of important abiotic parameters between 2022 and 2020: (a) temperature of the well water; (b) content of dissolved oxygen of the well water and (c) electric conductivity of the well water. For comparability of results, only data from June to September were used for 2002 and 2020, and the same monitoring sites as in subsequent years. "n" indicates the number of measuring points. No sampling was conducted in years with no boxplot.

Table A2.1: List of all parameters of the LUBW annual catalogue used in this study (Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg, 2022)

Parameter	Unit	Parameter	Unit	Parameter	Unit	Parameter	Unit
Physical-chemical complete analysis		**Heavy metals**		**Pesticides**		**Hydrocarbons**	
acid capacity up to pH 4.3	[mmol/l]	arsenic	[mg/l]	atrazine	[µg/l]	benzene	[µg/l]
calcium	[mg/l]	barium	[mg/l]	bromacil	[µg/l]		
chloride	[mg/l]	beryllium	[mg/l]				
dissolved oxygen concentration	[-]	boron	[mg/l]				
dissolved oxygen saturation	[mg/l]	cadmium	[mg/l]				
DOC (dissolved organic carbon)	[mg/l]	cobalt	[mg/l]				
electric conductivity	[%]	cooper	[mg/l]				
fluoride	[mg/l]	lead	[mg/l]				
iron	[mg/l]	lithium	[mg/l]				
magnesium	[mg/l]	molybdenum	[mg/l]				
manganese	[mg/l]	nickel	[mg/l]				
nitrate	[mg/l]	mercury	[mg/l]				
ortho-phosphate	[mg/l]	selenium	[mg/l]				
pH-value	[-]	silicate	[mg/l]				
phosphorous	[mg/l]	strontium	[mg/l]				
potassium	[mg/l]	thallium	[mg/l]				
sodium	[mg/l]	uranium	[mg/l]				
spectral absorption coefficient at 436nm	[1/m]	zinc	[mg/l]				
sulphate	[mg/l]						
sum alkali metals	[mmol/l]						
temperature	[°C]						

Table A2.2: Parameters of the PHATE-analysis.

Parameters	**Unit**
Physical	
temperature well water	[°C]
detritus content (classes with estimated values)	[-]
amount of sediment	[ml]
Biotical	
number of taxa	[-]
total abundance	[-]
proportion of Crustaceans (acc. to Griebler et al., 2014)	[%]
proportion of Oligochaetes (acc. to Griebler et al., 2014)	[%]
proportion of stygobiont to non-stygobiont individuals	[-]
abundance Amphipods	[-]
abundance Cyclopoids	[-]
abundance Harpacticoids	[-]
abundance Nematodes	[-]
(Hydro-)geological	
geological unit	[-]
well depth	[m]
Assessment scheme	
Groundwater-Fauna-Index (GFI)	[-]

Table A2.3: Standard deviation of different faunistic and hydro-chemical parameters over time of each well. Wells with an asterisk * show stable hydro-chemical and faunistic conditions and a variance of less than 13.

	Standard deviation of the:							
Location of the well	**Temperature well water [°C]**	**Content of dissolved oxygen well water [mg/l]**	**Electric conductivity well water [µS/cm]**	**Total abundance [-]**	**Number of species [-]**	**Proportion of Crustaceans [%]**	**Proportion of Oligochaetes [%]**	**Proportion of stygobionts to no-stygobionts [-]**
Dahenfeld*	1.08	0.51	90.41	3.33	1.06	35.73	14.92	1.98
Zienken	1.41	2.61	53.47	77.32	1.49	0.62	0.62	1.12
Efringen-Kirchen	1.11	0.74	124.08	192.46	1.67	5.39	5.39	0.37
Kadelburg*	2	0.55	57.88	11.4	2.17	16.25	16.25	0.29
Schwäbisch Hall	1.56	1.45	97.23	115.85	2.12	22.26	22.26	4.01
Rohrdorf*	1.41	0.93	54.38	31.53	2.19	23.38	23.38	1.16
Furtwangen*	2.07	0.5	37.81	30.66	1.79	4.86	4.86	0.89
Riedlingen*	1.14	0.86	114.06	8.96	1.33	1.48	1.48	1.16
Weingarten	1.27	1.13	98.01	9.34	1.08	44.71	29	1.55
Hausen*	1.53	0.7	81.65	19.61	1.4	2.05	2.05	0.92
Balgheim*	0.87	1.16	107.63	21.25	1.02	2.77	2.77	0.75
Sankt Leon	1.25	0.78	47.08	46.23	2.25	35.38	35.38	3.55
Neckargartach	1.3	1.02	86.41	2.6	0.96	45.42	43.06	0.59
Todtnau*	1.41	0.54	12.2	3.42	1.6	34.77	4.29	2.64
Gaggenau	1.51	1.6	41.63	37.73	1.6	13.01	13.01	3.51
Brenden*	1.93	0.93	16.6	10.29	1.76	2.11	2.11	3.12

Neckargartach

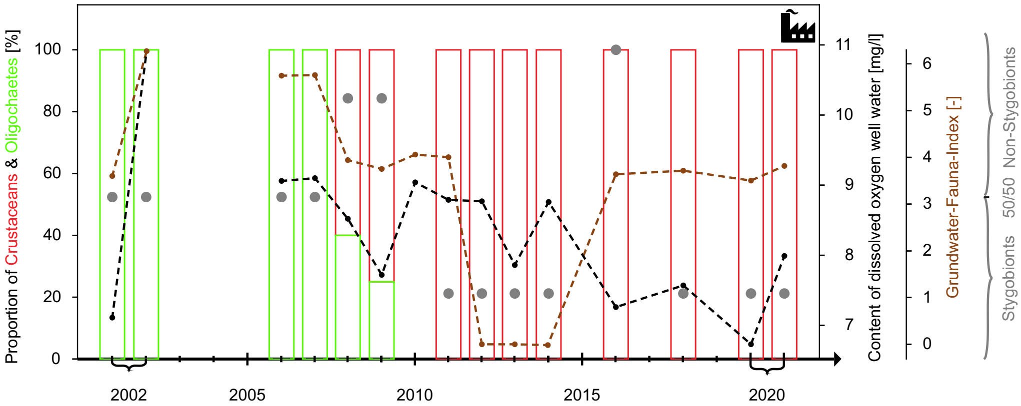

Figure A2.2: Temporal change of abiotic and faunal parameters over time in Neckargartach. The Groundwater-Faun-Index (GFI) changes from 6.3 in 2002 to 5.8 in 2007 and finally to 3.4 in 2020, which can be due to a decrease in the surface influence. This shows a clear connection between changes in GFI and land development. No sampling was conducted in years with no bar.

Figure A2.3: Aerial image of the location of the monitoring well in Sankt Leon (a) and Todtnau (b) (Source: Google Earth Pro (Google LLC., 2022)). The surrounding of the wells has not changed over the investigation period (2002 - 2020).

Appendix Study 3

This Appendix refers to Study 3 (Chapter 4). The content was published in the journal Hydrology and Earth System Sciences as a supplement and is available online at: `https://doi.org/10.5194/hess-25-3053-2021-supplement`.

Groundwater Fauna Index (GFI)

The Groundwater-Fauna-Index (GFI), introduced by Hahn (2006), quantifies the ecological relevant conditions in the groundwater as a result of hydrological exchange between surface and groundwater. It incorporates ecologically important groundwater parameters such as relative amount of detritus, variation of groundwater temperature and concentration of dissolved oxygen (Hahn, 2006) and is calculated by using this equation:

$$GWFaunaIndex = \sqrt{\textit{Dissolved Oxygen}\left(\frac{mg}{l}\right)} \times \sqrt{\textit{Relative Amount of Detritus}} \times \textit{Standard deviation of Temperature} \tag{A3.1}$$

The determined average GFI of all sampled wells is 6.0 ± 2.8 with a total variation between 0 and 14 and a heterogeneous distribution of the GFI-values. High GFI values (> 10, Type III), indicating hydrological exchange with the surface (Hahn, 2006), were only found in three wells which share a high standard deviation of GWT (2.6 to 3.5 °C), higher dissolved oxygen (5.5 to 5.8 mg/l) as well as nitrate concentrations (7.7 up to 12 mg/l). These specific well locations have mainly no or minor sealed surfaces. Overall, 82 % of the measurement wells showed meso-alimonic conditions (GFI > 2 - 10, Type II) and therefore indicate a medium level of surface influence, at diverse urban and forested locations. Only four wells in this study were well insulated from surface influences (GFI < 2), with three wells located in densely built-up surroundings with sealed surfaces. Moreover, the average GFI in the forested area is 4.5 ± 1.9 and in the urban area 6.2 ± 2.7.

Shannon diversity index

The Shannon-Index, introduced by Shannon and Weaver (1949) is an established standard method to quantify the ecological diversity of e.g. bacterial or faunal communities. The index describes the diversity by including the number of species and the relative frequency of individuals. The sampled wells in the forested area show the highest balance (median Shannon Equitability/Evenness Index (EH) = 0.47) and Shannon diversity index (median Shannon Diversity Index (HS) = 0.74).

The maximum diversity (median Shannon Index $(H)_{max}$ = 1.58) is the same in both the forested and the urban area. The balance (median EH = 0.42) and Shannon diversity index (median HS = 0.52) are only a little bit lower in the urban area. These results are comparable with the study of Brielmann et al. (2009), where the Shannon diversity index of an anthropogenically influenced groundwater of an aquifer downstream of an industrial facility varies between 0.20 and 1.45. Nevertheless, no clear distribution pattern according to faunal diversity is recognizable. Thus, the Shannon diversity index was not considered further.

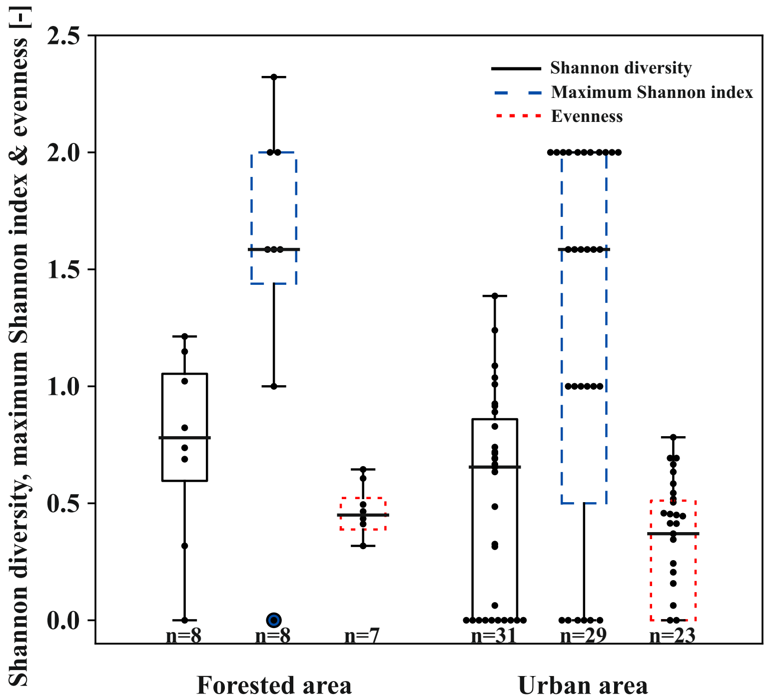

Figure A3.1: Boxplots of the Shannon diversity index, maximum Shannon index and evenness, divided in forested and urban area (*n* = number of wells, or number of wells at which the evaluation is applicable).

Urban impacts on groundwater quality

Urban impacts on groundwater systems can be manifold, such as increasing temperatures (urban heat islands (Menberg et al., 2013b)), contaminants (Kuroda and Fukushi, 2008), changes in the precipitation discharge due to sealing, falling water levels due to groundwater withdrawal (Foster, 1990). In our study, we intend to provide a first impression of the situation in Karlsruhe and therefore focus on the standard parameters. A first overview is given by the LUBW continuous monitoring program of groundwater wells (Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg, 2020), which provides profound groundwater analysis in Karlsruhe. Some of the considered measurement wells are close to the measurement wells of this study. Assessing the evaluation period of this study (2011 - 2014), most of the wells of the monitoring program show values within the range of the local background or below the thresholds of the drinking water ordinance of Germany and therefore no contamination.

One exception is a measurement well in the Kapellen-Street (next to T105), which shows higher ammonium (average: 0.55 mg/l, threshold drinking water ordinance: 0.5 mg/l), iron (5.1 mg/l, threshold value of the German drinking water ordinance: 0.2 mg/l) and manganese concentrations (0.55 mg/l), threshold drinking water ordinance: 0.05 mg/l). Moreover, this well has a noticeable concentration of arsenic (8.7 μg/l, threshold drinking water ordinance: 10 μg/l) and of the herbizide CGA 369873 (0.1 μg/l, threshold: 0.1 μg/l). This well is at the margin of one of the largest contaminated sites in Karlsruhe, the former gas plant.

Three other wells, which contain contaminants are in the Kaiserallee, Mathy-Street (next to T124) and near the municipal hospital. They showed noticeable concentrations of volatile hydrocarbons of up to 13 μg/l during the evaluation period (in detail at the hospital: 3 - 6 μg/l; Kaiserallee: 5 - 8 μg/l; Mathy Street: about 3 μg/l). In comparison, the German threshold value of the drinking water ordinance is 20 μg/l.

The groundwater of one measurement well in the Hardtwald (next to SWM-005/SOM- 020) has a different chemical composition than the wells in the urban area. It shows lower concentrations of boron (30 - 45 μg/l, compared to the other wells: 50 - 98 μg/l), calcium (100 - 110 mg/l, compared to the other wells of up to 150 mg/l), chloride (25.5 mg/l in 2014 compared to the other wells: > 50 mg/l), potassium (3.2 mg/l) and sodium (11.3 mg/l). Furthermore, the content of dissolved oxygen is higher than in the wells of the urban area (average with 4.8 mg/l).

This overview indicates that beside one larger and two smaller contaminations, the groundwater beneath Karlsruhe contains only minor pollution. Groundwater fauna can usually cope well with short-term changes of chemical-physical parameters (Griebler et al., 2016). Previous studies showed that some species can even benefit from pollutants (Matzke, 2006; Zuurbier et al., 2013). Thus, the main documented impacts on groundwater quality in the study area are related to GWT, oxygen and nitrate concentration.

Table A3.1: Estimation of the relative amounts of sediment per sample (modified after Hahn (2006).

Scale	Description	Characterisation
0	Absent	No sediments in the sampling vessel
1	Little	Bottom of the sampling vessel ($\varnothing \frac{1}{4}$ 7.6 cm) slightly covered by sediment
2	Much	Bottom of the sampling vessel covered by several millimetres of sediment
3	Very much	Bottom of the sampling vessel covered by one or more centimetres of sediment

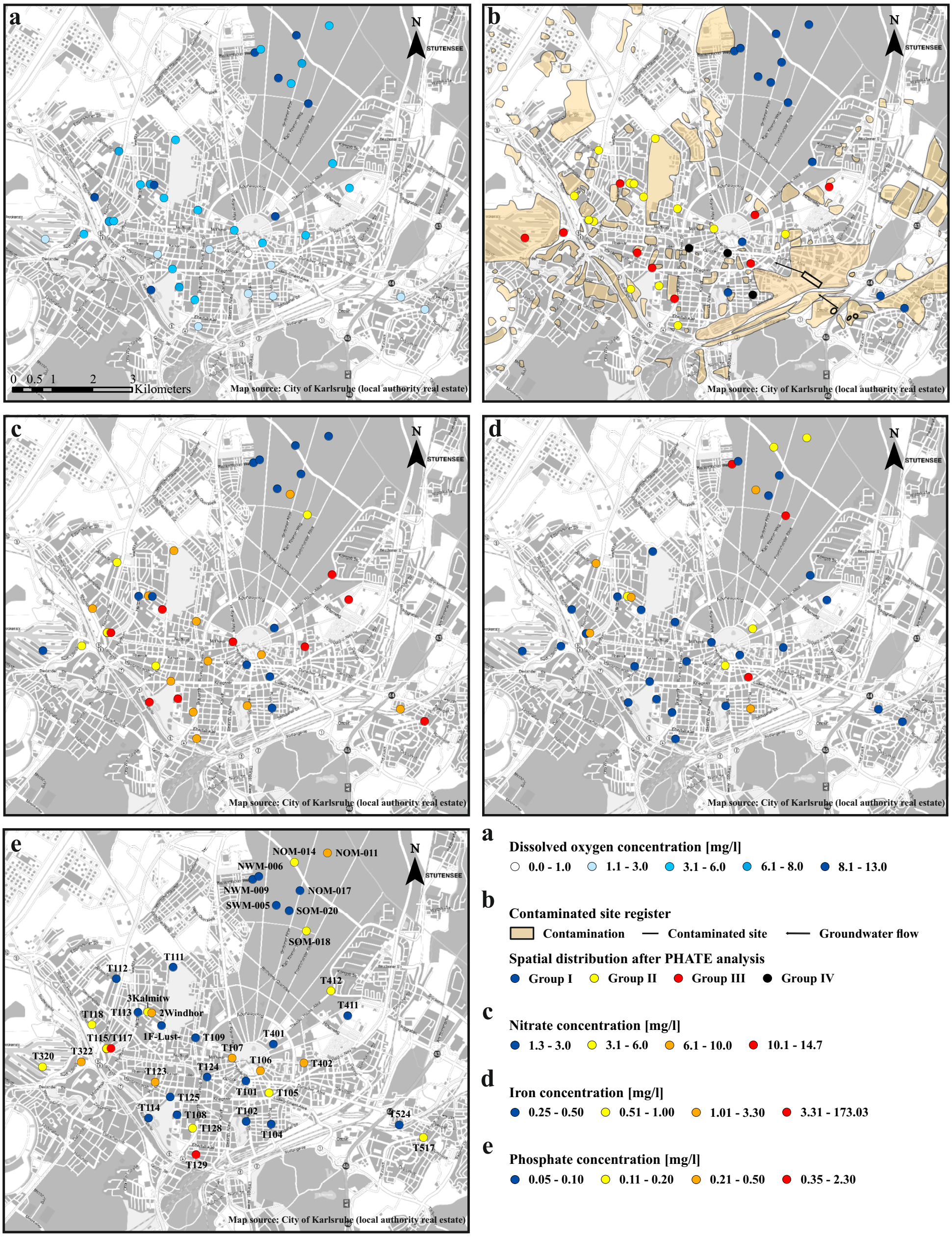

Figure A3.2: Overview map of Karlsruhe: (a) the average content of dissolved oxygen of the multiple measurements [mg/l]; (b) contaminated sites of the soil protection and contaminated site register (Bodenschutz- und Altlastenkataster) of Karlsruhe (modified after Kühlers et al. (2012), Stadt Karlsruhe (2006), and Wickert et al. (2006)) and the spatial distribution after the PHATE analysis; (c) average nitrate concentration [mg/l] of the repeated measurements; (d) iron concentration [mg/l] of the repeated 5 measurements and (e) the phosphate concentration [mg/l] of the repeated measurements at the bottom of the measurement wells.

Table A3.2: Well locations, information, sampled properties and result of the evaluation (GWT=groundwater temperature, *sampling 2011-2012: 6 times, † sampling 2014: 3 times).

Measur-ing point	Location		Area classi-fication	Depth [m]	Average GWT [°C]	SD GWT [-]	Relative amount of detritus [-]	Average dissolved oxygen [mg/l]	Average GFI [-]	Amount crustaceans (acc. to Griebler et al. (2014)) [%]	Amount oligochaetes (acc. to Griebler et al. (2014)) [%]	Total amount of indi-viduals [-]	Numbers of taxa [-]	Ecological condition (acc. to Griebler et al. (2014))
T101	Lammstr. No.7	*	Urban area	39	14.4	0.05	3	0.97	0	0	0	0	0	Faunistic evaluation not possible
T102	Tulla Bad	*	Urban area	10	14	2.99	2	1.45	5	100	0	4	2	Natural
T104	Arbeitsamt - Rankestr.	*	Urban area	15.8	12.5	1.28	3	1.07	2	0	0	0	0	Faunistic evaluation not possible
T105	Fritz-Erler-Str. No.21	*	Urban area	9.3	14.4	3.29	3	1.29	6	0	100	1	1	Faunistic evaluation not possible
T106	Schloßplatz / Schloßbezirk	*	Urban area	11	14.2	2.6	3	4.02	9	86	14	7	3	Natural
T123	Sophienstr. - Grillparzerstr.	*	Urban area	14	12.8	1.65	1	2.18	2	0	100	3	2	Affected
T124	Kaiserplatz	*	Urban area	13	14.9	1.95	3	1.97	5	0	0	2	1	Affected
T125	Kriegsstr. No.141	*	Urban area	11.8	15	2.32	1	3.64	4	0	100	103	3	Affected
T128	Södendstr. - Brauerstr.	*	Urban area	9.5	13.2	3.21	2	5.5	11	0	100	13	2	Affected

Measuring point	Location		Area classification	Depth [m]	Average GWT [°C]	SD GWT [-]	Relative amount of detritus [-]	Average dissolved oxygen [mg/l]	Average GFI [-]	Amount crustaceans (acc. to Griebler et al. (2014)) [%]	Amount oligochaetes (acc. to Griebler et al. (2014)) [%]	Total amount of individuals [-]	Numbers of taxa [-]	Ecological condition (acc. to Griebler et al. (2014))
T129	Schule Beiertheim	*	Urban area	8.5	12.2	3.67	1	2.31	6	91	9	124	4	Natural
T320	Südbeckenstr. No.16	*	Urban area	9	12.6	3.43	1	2.62	6	0	100	252	1	Affected
T322	Rheinhafenbad	*	Urban area	10	15.9	2.99	2	3.45	8	0	100	6	2	Affected
T402	Am Fasanengarten - Parkstraße	*	Urban area	9	12.4	3.43	2	3.68	9	50	50	4	4	Affected
T411	Gewann Blüsse	*	Urban area	10.9	11.3	2.64	3	5.74	11	0	100	34	2	Affected
T412	Theodor- Heuss - Allee	*	Urban area	10	11.4	2.99	1	4.47	6	100	0	6	4	Natural
T517	Auer Str. - Reichenbachstr.	*	Urban area	9	12.8	3.43	2	2.84	8	100	0	5	1	Natural
T524	Dornwaldstr.	*	Urban area	9	11.5	3.43	2	1.77	6	99	1	275	2	Natural
T401	Area next to the Wildpark-Stadion	†	Urban area	11	14.2	2.6	2	8.9	10	0	100	8	1	Affected
T109	Erzbergerstr.	†	Urban area	13.7	14.1	1.76	1	4.86	4	92	8	38	4	Natural
T108	Edgar-von-Gierke/ Siegfried-Kühn-Straße	†	Urban area	12	14.9	2.26	2	6.12	8	79	21	25	4	Affected
T114	Allotment garden at the Alb	†	Urban area	12.8	15.4	2.01	1	8.25	6	13	88	171	4	Affected

Measur-ing point	Location		Area classi-fication	Depth [m]	Average GWT [°C]	SD GWT [-]	Relative amount of detritus [-]	Average dissolved oxygen [mg/l]	Average GFI [-]	Amount crustaceans (acc. to Griebler et al. (2014)) [%]	Amount oligochaetes (acc. to Griebler et al. (2014)) [%]	Total amount of indi-viduals [-]	Numbers of taxa [-]	Ecological condition (acc. to Griebler et al. (2014))
T115	Sonnenstr. – Zietenstr.	†	Urban area	13.5	14.8	1.81	1	4.83	4	89	11	23	4	Natural
T117	Sonnenstr. – Zietenstr.	†	Urban area	13	17	1.95	3	6.24	8	92	8	76	5	Natural
T118	Schoemperlenstr.	†	Urban area	13.7	16.1	1.76	1	8.45	6	38	63	11	4	Affected
T112	Wattstr. – Annweilerstr.	†	Urban area	12	14.5	2.26	2	6.87	8	100	0	204	4	Natural
T111	Field near Kaiserslauterner-Straße	†	Urban area	8.9	13.4	3.48	3	5.75	14	77	23	96	4	Affected
T113	Hertzstr. – St. Barbara-Weg	†	Urban area	11	17.5	2.6	1	3.35	5	0	100	1	1	Affected
3Kalmit-weg	Kalmitweg No.3	†	Urban area	15.5	15.3	1.34	1	6.44	3	77	23	13	3	Affected
2Wind-hor	Wilhelm-Windhorst-Straße Schänzle	†	Urban area	15.2	15.8	1.34	2	8.64	6	20	80	353	4	Affected
1F-Lust	Franz-Lust-Str. – Kußmaulstr.	†	Urban area	15.2	17.3	1.34	2	5.95	5	65	35	630	3	Affected
T107	Molkestr. -Willy-Brandt-Allee	†	Urban area	10.1	16.2	2.95	1	4.9	7	66	34	130	3	Affected

Measur-ing point	Location		Area classi-fication	Depth [m]	Average GWT [°C]	SD GWT [-]	Relative amount of detritus [-]	Average dissolved oxygen [mg/l]	Average GFI [-]	Amount crustaceans (acc. to Griebler et al. (2014)) [%]	Amount oligochaetes (acc. to Griebler et al. (2014)) [%]	Total amount of indi-viduals [-]	Numbers of taxa [-]	Ecological condition (acc. to Griebler et al. (2014))
NOM-011		†	Forested area	14.9	10.7	1.47	1	3.42	3	100	0	15	1	Natural
NOM-017		†	Forested area	15	10.9	1.45	3	7.2	7	97	3	506	6	Natural
SOM-020		†	Forested area	15	10.7	1.45	1	5.81	3	50	50	9	4	Affected
SOM-018		†	Forested area	27	10.3	0.26	3	12.75	2	90	10	31	2	Natural
SWM-005	Hardtwald	†	Forested area	15.5	10.5	1.34	2	8.72	6	26	74	358	3	Affected
NWM-009		†	Forested area	15	10.8	1.45	2	10.69	7	43	57	90	4	Affected
NWM-006		†	Forested area	14.8	10.7	1.49	1	5	3	86	14	16	3	Natural
NOM-014		†	Forested area	15	10.5	1.45	1	9.92	5	67	33	23	3	Affected

Table A3.3: Taxa-site matrix of the invertebrate fauna of each water gauge.

Official designation of the water gauges	**T101**	**T102**	**T104**	**T105**	**T106**	**T123**	**T124**	**T125**	**T128**	**T129**	**T320**	**T322**	**T402**	**T411**	**T412**	**T517**	**T524**	**Number of indi-viduals**	**Percen-tage**
Amphipoda	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0
Cyclopoida	0	0	0	0	5	0	0	0	0	76	0	0	1	0	0	5	0	87	10
Harpacticoida	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parastenocaris	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Bathynelleacea	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	272	274	33
Nauplia	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	2	0
Amount Crustacea	0	2	0	0	6	0	0	0	0	77	0	0	1	0	3	5	272	366	44
Amount Crustacea %	0	50	0	0	86	0	0	0	0	62	0	0	25	0	50	100	99		
Amount Amphipoda %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33.3	0	0		
Amount Cyclopoida %	0	0	0	0	71.4	0	0	0	0	61.3	0	0	25	0	0	100	0		
Amount Harpacticoida %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Amount Parastenocaris %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16.7	0	0		
Amount Bathynellacea %	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	98.9		
Amount Nauplia %	0	0	0	0	14.3	0	0	0	0	0.8	0	0	0	0	0	0	0		
Nematoda	0	2	0	0	0	0	2	65	5	0	0	0	1	0	1	0	0	76	9
Oligochaeta	0	0	0	1	1	2	0	37	8	8	252	3	1	33	0	0	3	349	42
Acari	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	2	0
Mikturbellaria	0	0	0	0	0	0	0	1	0	39	0	3	0	1	2	0	0	46	5
Amount others	0	2	0	1	1	3	2	103	13	47	252	6	3	34	3	0	3	473	56
Total amount	0	4	0	1	7	3	2	103	13	124	252	6	4	34	6	5	275	839	100
Amount Oligochaeta %	0	0	0	100	14.3	66.7	0	35.9	61.5	6.5	100	50	25	97.1	0	0	1.1		
Amount Nematoda %	0	50	0	0	0	0	100	63.1	38.5	0	0	0	25	0	16.7	0	0		
Amount Acari %	0	0	0	0	0	33.3	0	0	0	0	0	0	25	0	0	0	0		
Amount Microturbellaria %	0	0	0	0	0	0	0	1	0	31.5	0	50	0	2.9	33.3	0	0		

Official designation of the water gauges	T401	T109	T108	T114	T115	T117	T118	T112	T111	T113	3Kalmitw	2Windhor	1F - Lust-	T107	NOM - 011	NOM - 017	SOM - 020
Amphipoda	0	6	0	2	0	0	0	0	0	0	0	0	10	0	0	41	3
Cyclopoida	0	27	14	6	15	64	2	171	0	0	8	19	0	84	15	299	1
Harpacticoida	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	30	0
Parastenocaris	0	0	0	0	0	0	0	0	11	0	2	48	402	0	0	119	0
Bathynelleacea	0	0	1	0	2	1	0	31	62	0	0	0	0	0	0	0	0
Nauplia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amount Crustacea	0	33	15	8	17	67	3	202	73	0	10	67	412	84	15	489	4
Amount Crustacea %	0	87	60	5	74	88	27	99	76	0	77	19	65	65	100	97	44
Amount Amphipoda %	0	15.8	0	1.2	0	0	0	0	0	0	0	0	1.6	0	0	8.1	33.3
Amount Cyclopoida %	0	71.1	56	3.5	65.2	84.2	18.2	83.8	0	0	61.5	5.4	0	64.6	100	59.1	11.1
Amount Harpacticoida %	0	0	0	0	0	2.6	9.1	0	0	0	0	0	0	0	0	5.9	0
Amount Parastenocaris %	0	0	0	0	0	0	0	0	11.5	0	15.4	13.6	63.8	0	0	23.5	0
Amount Bathynellacea %	0	0	4	0	8.7	13	0	15.2	64.6	0	0	0	0	0	0	0	0
Amount Nauplia %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nematoda	0	2	6	107	4	3	3	1	1	0	0	12	0	2	0	2	1
Oligochaeta	8	3	4	56	2	6	5	1	22	1	3	274	218	44	0	15	4
Acari	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mikturbellaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amount others	8	5	10	163	6	9	8	2	23	1	3	286	218	46	0	17	5
Total amount	8	38	25	171	23	76	11	204	96	1	13	353	630	130	15	506	9
Amount Oligochaeta %	100	7.9	16	32.7	8.7	7.9	45.5	0.5	22.9	100	23.1	77.6	34.6	33.8	0	3	44.4
Amount Nematoda %	0	5.3	24	62.6	17.4	3.9	27.3	0.5	1	0	0	3.4	0	1.5	0	0.4	11.1
Amount Acari %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amount Microturbellaria %	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Official designation of the water gauges	**SOM-018**	**SWM-005**	**NWM-009**	**NWM-006**	**NOM-014**	**Number of indi-viduals**	**Percen-tage**	**Number of all indi-viduals**	**Percen-tage of all**
Amphipoda	0	0	2	0	0	64	2.3	66	1.8
Cyclopoida	28	76	36	12	12	889	31.4	976	26.6
Harpacticoida	0	0	0	0	0	33	1.2	33	0.9
Parastenocaris	0	16	0	0	0	598	21.2	599	16.3
Bathynelleacea	0	0	0	0	0	97	3.4	371	10.1
Nauplia	0	0	0	0	0	0	0	2	0.1
Amount Crustacea	28	92	38	12	12	1681	59.5	2047	55.8
Amount Crustacea %	90	26	42	75	52				
Amount Amphipoda %	0	0	2.2	0	0				
Amount Cyclopoida %	90.3	21.2	40	75	52.2				
Amount Harpacticoida %	0	0	0	0	0				
Amount Parastenocaris %	0	4.5	0	0	0				
Amount Bathynellacea %	0	0	0	0	0				
Amount Nauplia %	0	0	0	0	0				
Nematoda	0	0	1	2	5	152	5.4	228	6.2
Oligochaeta	3	266	51	2	6	994	35.2	1343	36.6
Acari	0	0	0	0	0	0	0	2	0.1
Mikturbellaria	0	0	0	0	0	0	0	46	1.3
Amount others	3	266	52	4	11	1146	40.5	1619	44.2
Total amount	31	358	90	16	23	2827	100	3666	100
Amount Oligochaeta %	9.7	74.3	56.7	12.5	26.1				
Amount Nematoda %	0	0	1.1	12.5	21.7				
Amount Acari %	0	0	0	0	0				
Amount Microturbellaria %	0	0	0	0	0				

Table A3.4: Average and standard deviation of faunistic, chemical and physical parameters with regard to the four groups (result of the PHATE analysis).

	Average amount crustaceans (acc. to Griebler et al. (2014)) [%]	**Average amount oligochaetes (acc. to Griebler et al. (2014)) [%]**	**Average numbers of taxa [-]**	**Average total amount of individuals [-]**	**Average Shannon diversity [-]**	**Average abundance Amphipoda [-]**	**Average abundance Cyclopoida [-]**	**Average abundance Parastenocaris [-]**	**Average abundance Bathynellacea [-]**
Group I (n = 13)	80.3 (± 24.5)	19.7 (± 24.5)	2.9 (± 1.3)	103.5 (± 159.6)	0.6 (± 0.4)	3.7 (± 10.8)	37.6 (± 78.2)	10.5 (± 31.6)	21.1 (± 72.4)
Group II (n = 14)	67.8 (± 26.7)	32.4 (± 26.9)	3.9 (± 0.5)	135.6 (± 165.9)	0.9 (± 0.3)	1.3 (± 2.9)	34.8 (± 46.9)	33.1 (± 103.1)	6.9 (± 17.2)
Group III (n = 9)	0.0 (± 0.0)	100.0 (± 0.0)	1.7 (± 0.7)	46.8 (± 78.8)	0.2 (± 0.3)	0.0 (± 0.0)	0.0 (± 0.0)	0.0 (± 0.0)	0.0 (± 0.0)
Group IV(n = 3)	0.0 (± 0.0)	0.0 (± 0.0)	0.3 (± 0.5)	0.7 (± 0.9)	0.0 (± 0.0)	0.0 (± 0.0)	0.0 (± 0.0)	0.0 (± 0.0)	0.0 (± 0.0)

	Average geological unit [-]	**Average GWT [°C]**	**Average phosphate concentration [mg/l]**	**Average nitrate concentration [mg/l]**	**Average relative amount of detritus [-]**	**Average depth [m]**
Group I (n = 13)	2 (± 1)	11.5 (± 1.3)	0.1 (± 0.1)	5.4 (± 3.9)	1.8 (± 0.8)	13.9 (± 4.5)
Group II (n = 14)	3 (± 1)	15.0 (± 1.5)	0.3 (± 0.6)	9.1 (± 3.7)	1.7 (± 0.7)	12.4 (± 2.3)
Group III (n = 9)	3 (± 1)	14.1 (± 1.8)	0.1 (± 0.1)	4.9 (± 3.9)	1.8 (± 0.8)	10.7 (± 1.5)
Group IV(n = 3)	2 (± 1)	13.9 (± 1.0)	0.1 (± 0.0)	3.9 (± 3.4)	3.0 (± 0.0)	22.6 (± 11.7)

Table A3.5: Results of the Mann-Whitney-Tests from the four groups of the PHATE analysis.

	Amount crustaceans (acc. to Griebler et al. (2014)) [%]	Amount oligochaetes (acc. to Griebler et al. (2014)) [%]	Numbers of taxa [-]	Total amount of individuals [-]	Shannon diversity [-]	Abundance Amphipoda [-]	Abundance Cyclopoida [-]	Abundance Parastenocaris [-]	Abundance Bathynellacea [-]
Group I vs. II (n = 13;14)	1.3×10-1	1.3×10-1	1.5×10-2	2.0×10-1	3.2×10-1	7.4×10-1	5.6×10-1	7.2×10-1	4.0×10-1
Group I vs. III (n = 13;9)	4.0×10-6	4.0×10-6	2.7×10-2	2.4×10-1	3.9×10-1	2.0×10-1	8.9×10-4	3.7×10-1	6.8×10-1
Group IV vs. I (n = 3;13)	3.6×10-3	1.3×10-1	1.1×10-2	3.6×10-3	2.0×10-1	7.9×10-1	7.1×10-2	1	1
Group II vs. III (n = 14;9)	2.5×10-6	2.5×10-6	9.8×10-7	3.4×10-2	3.3×10-2	4.1×10-1	1.4×10-4	2.3×10-1	1.2×10-1
Group IV vs. II (n = 3;14)	2.9×10-3	1.2×10-2	2.9×10-3	2.9×10-3	2.9×10-2	1	2.9×10-2	8.4×10-1	6.5×10-1
Group IV vs. III (n = 3;9)	1	9.1×10-3	4.6×10-2	2.7×10-2	7.6×10-1	1	1	1	1

	Geological unit [-]	GWT [°C]	Phosphate concentration [mg/l]	Nitrate concentration [mg/l]	Relative amount of detritus [-]	Depth [m]
Group I vs. II (n = 13;14)	8.2×10-3	2.0×10-5	5.2×10-1	1.2×10-2	6.1×10-1	2.8×10-1
Group I vs. III (n = 13;9)	1.5×10-1	3.8×10-3	1	9.9×10-1	9.7×10-1	7.4×10-2
Group IV vs. I (n = 3;13)	4.8×10-1	2.1×10-2	3.6×10-3	6.1×10-1	7.1×10-1	2.2×10-1
Group II vs. III (n = 14;9)	4.4×10-1	3.2×10-1	7.2×10-1	4.5×10-2	8.5×10-1	9.4×10-2
Group IV vs. II (n = 3;14)	3.5×10-1	2.8×10-1	2.9×10-2	9.1×10-2	2.9×10-2	1.1×10-1
Group IV vs. III (n = 3;9)	8.4×10-1	9.6×10-1	9.1×10-3	1.7×10-1	9.1×10-2	1.8×10-2

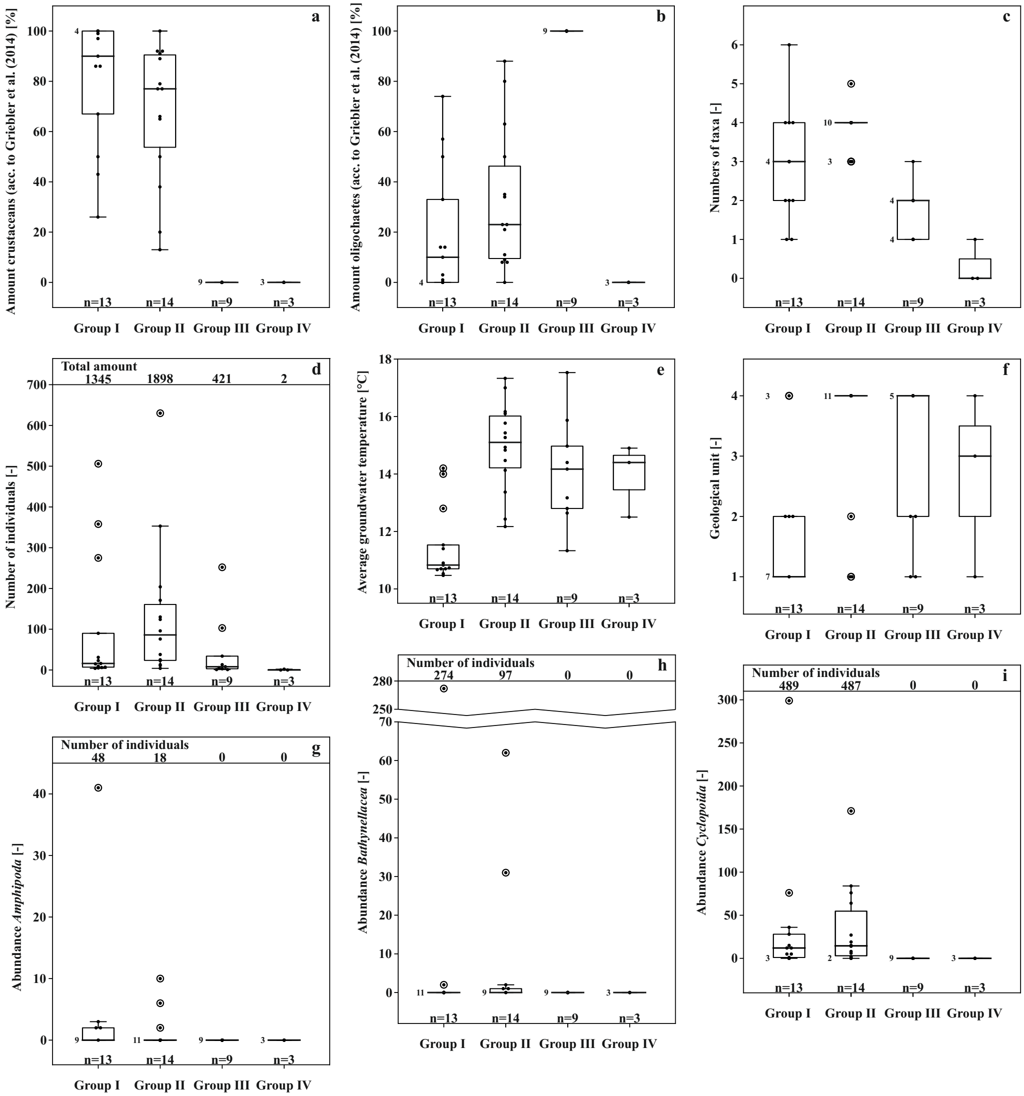

Figure A3.3: Boxplots of: (a) Amount of crustaceans [%] and (b) oligochaetes [%] according to the scheme of Griebler et al. (2014b); (c) numbers of Taxa [-]; (d) number of individuals [-]; (e) average GWT of the repeated measurements at the bottom of the measurement wells [%] and (f) geological unit [-]; (g) Abundance of the order *Amphipoda* [-]; (h) of the order *Bathynellacea* [-] and (i) of the order *Cyclopoida* [-], divided into four groups according to the PHATE visualization (n = number of wells).

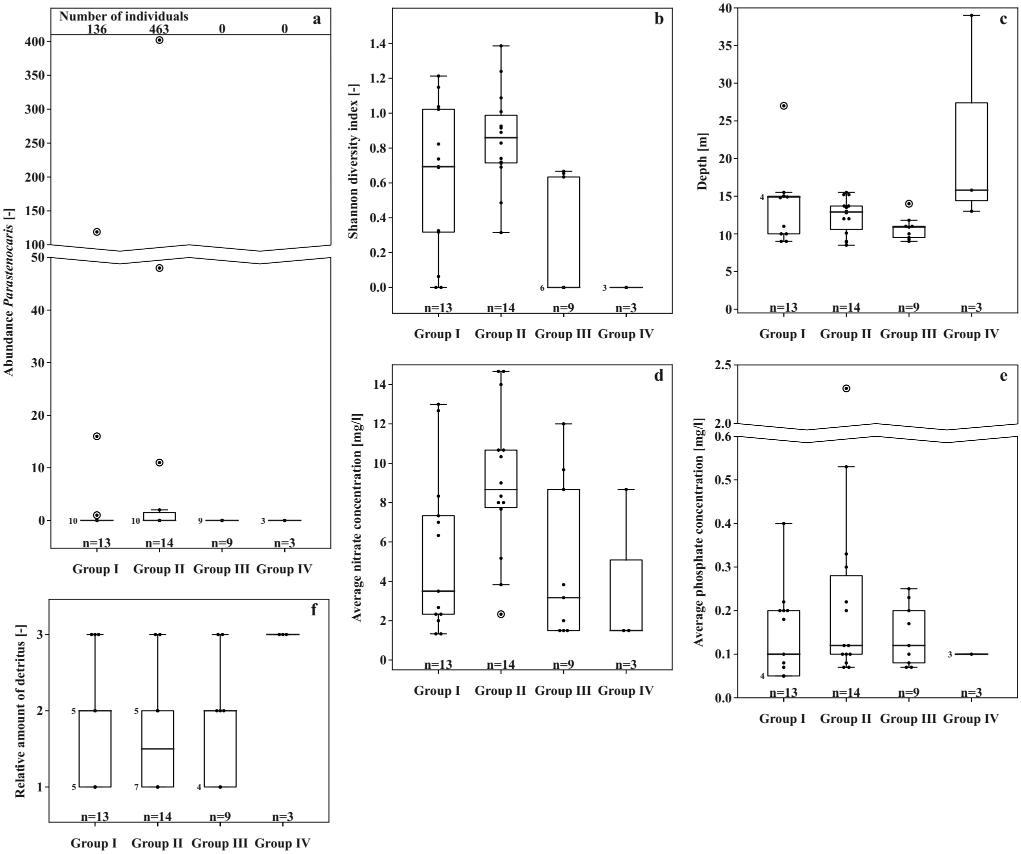

Figure A3.4: Boxplots of: (a) Abundance of the genus *Parastenocaris* [-]; (b) Shannon diversity index [-]; (c) depth of the measurement wells [m]; (d) of the average nitrate concentration [mg/l]; (e) average phosphate concentration [mg/l] of the repeated measurements at the bottom of the measurement wells and (f) of the relative amount of detritus [-], divided into four groups according to the PHATE visualization (n = number of wells).

BACKMATTER

References

Aber, John, William Mcdowell, Knute Nadelhoffer, Alison Magill, Glenn Berntson, Steven Mcnulty, William Currie, Lindsey Rustad, and Ivan Fernandez (1998). “Nitrogen saturation in temperate forest ecosystems – Hypotheses revisited”. In: *BioScience* 48.11, pp. 921–934.

Aidaoui, Samy Charaf Eddine (2019). “Recherches phréatobiologiques dans la région du Nord-Constantinois”. PhD thesis. Université Larbi Ben M’hidi Oum El Bouaghi, p. 125. URL: http://bib.univ-oeb.dz:8080/jspui/bitstream/123456789/9125/1/These%20AIDAOUI.pdf.

Alfreider, Albin, Carsten Vogt, and Wolfgang Babel (2002). “Microbial diversity in an in situ reactor system treating monochlorobenzene contaminated groundwater as revealed by 16S ribosomal DNA analysis”. In: *Systematic and Applied Microbiology* 25.2, pp. 232–240. ISSN: 07232020. DOI: 10.1078/0723-2020-00111.

Allford, Adam, Steven John Baynard Cooper, William F. Humphreys, and Andrew D. Austin (2008). “Diversity and distribution of groundwater fauna in a calcrete aquifer: Does sampling method influence the story?” In: *Invertebrate Systematics* 22.2, pp. 127–138. ISSN: 14455226. DOI: 10.1071/IS07058.

Amanambu, Amobichukwu C., Omon A. Obarein, Joann Mossa, Lanhai Li, Shamusideen S. Ayeni, Olalekan Balogun, Abiola Oyebamiji, and Friday U. Ochege (2020). “Groundwater system and climate change: Present status and future considerations”. In: *Journal of Hydrology* 589, p. 125163. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2020.125163. URL: https://doi.org/10.1016/j.jhydrol.2020.125163.

Amt für Stadtentwicklung - Statistikstelle (2018). *Statistic Atlas Karlsruhe*. URL: https://web3.karlsruhe.de/Stadtentwicklung/statistik/atlas/?select=005 (visited on 02/27/2019).

Asmyhr, Maria G. and Steven John Baynard Cooper (2012). “Difficulties barcoding in the dark: The case of crustacean stygofauna from eastern Australia”. In: *Invertebrate Systematics* 26.5-6, pp. 583–591. ISSN: 14455226. DOI: 10.1071/IS12032.

Avramov, Maria, Susanne I. Schmidt, and Christian Griebler (2013). “A new bioassay for the ecotoxicological testing of VOCs on groundwater invertebrates and the effects of toluene on Niphargus inopinatus”. In: *Aquatic Toxicology* 130-131, pp. 1–8. ISSN: 0166445X. DOI: 10.1016/j.aquatox.2012.12.023. URL: http://dx.doi.org/10.1016/j.aquatox.2012.12.023.

Avramov, Maria, Susanne I. Schmidt, Christian Griebler, Hans Jürgen Hahn, and Sven E. Berkhoff (2010). “Dienstleistungen der Grundwasserökosysteme”. In: *KW - Korrespondenz Wasserwirtschaft* 3.2, pp. 74–81. DOI: 10.3243/kwe2010.02.001.

Bandari, Elia, Shabuddin Shaik, and Yenumula Ranga Reddy (2017). “A phylogenetic review of the genus Atopobathynella Schminke, 1973 (Crustacea, Malacostraca, Bathynellacea) with three new species from southeastern India”. In: *Journal of Natural History* 51.35-36, pp. 2143–2184. ISSN: 14645262. DOI: 10.1080/00222933.2017.1360528. URL: https://doi.org/10.1080/00222933.2017.1360528.

Bargrizaneh, Zeinab, Cene Fišer, and Somayeh Esmaeili-Rineh (2021). “Groundwater amphipods of the genus Niphargus Schiødte, 1834 in Boyer-Ahmad region (Iran) with description of two new species”. In: *Zoosystema* 43.7, pp. 127–144. DOI: https://doi.org/10.5252/zoosystema2021v43a7.

Barton, Hazel A., Michael R. Taylor, and Norman R. Pace (2004). “Molecular phylogenetic analysis of a bacterial community in an oligotrophic cave environment”. In: *Geomicrobiology Journal* 21.1, pp. 11–20. ISSN: 01490451. DOI: 10.1080/01490450490253428. URL: https://doi.org/10.1080/01490450490253428.

Batzer, Darold and Dani Boix (2016). *Invertebrates in Freswater Wetlands: An International Perspective on their Ecology*. Heidelberg: Springer International Publishing, p. 647. ISBN: 978-3-319-24976-6. DOI: 10.1007/978-3-319-24978-0_9. URL: http://link.springer.com/10.1007/978-3-319-24978-0.

Becher, Julia, Constanze Englisch, Christian Griebler, and Peter Bayer (2022). “Groundwater fauna downtown – Drivers, impacts and implications for subsurface ecosystems in urban areas”. In: *Journal of Contaminant Hydrology*. ISSN: 0048-9697. DOI: 10.1016/j.jconhyd.2022.104021. URL: https://doi.org/10.1016/j.jconhyd.2022.104021.

Benz, Susanne A., Peter Bayer, Frank M. Goettsche, Folke S. Olesen, and Philipp Blum (2016). “Linking Surface Urban Heat Islands with Groundwater Temperatures”. In: *Environmental Science and Technology* 50.1, pp. 70–78. ISSN: 15205851. DOI: 10.1021/acs.est.5b03672.

Benz, Susanne A., Peter Bayer, Kathrin Menberg, and Philipp Blum (2014). "Comparison of local and regional heat transport processes into the subsurface urban heat island of Karlsruhe , Germany". In: *Geophysical Research Abstract EGU General Assembly*. Vol. 16, p. 11252.

Benz, Susanne A., S. Bayer, and Philipp Blum (2017). "Identifying anthropogenic anomalies in air, surface and groundwater temperatures in Germany". In: *Science of the Total Environment* 584-584, pp. 145–153.

Berkhoff, Sven E. (2010). "Die Meiofauna des Interstitials und Grundwassers als Indikator für Oberflächenwasser-Grundwasser-Interaktionen im Bereich einer Uferfiltrationsanlage". PhD thesis. University Koblenz-Landau, p. 209. URL: `https://kola.opus.hbz-nrw.de/frontdoor/index/index/year/2010/docId/388`.

Berkhoff, Sven E., Hans Jürgen Hahn, Joo-Lae Cho, and Hyoung-Soo Kim (2003). "Development of regional models of groundwater fauna in South Korea". In: *Proceedings of the Korean Society of Soil and Groundwater Environment Conference*. Korean Society of Soil and Groundwater Environment, pp. 240–243. URL: `http://www.koreascience.or.kr/article/CFKO200311922146241.view`.

Beyer, Helmut (1932). "Die Tierwelt der Quellen und Bäche des Baumbergegebietes". In: *Abhandlung aus dem westfälischen Provinzial-Museum für Naturkunde*. Ed. by Hermann Reichling. 3rd ed. Münster: Westfälischen Provinzial-Museums für Naturkunde, pp. 9–188.

Blum, Philipp, Kathrin Menberg, Fabien Koch, Susanne A. Benz, Carolin Tissen, Hannes Hemmerle, and Peter Bayer (2021). "Is thermal use of groundwater a pollution?" In: *Journal of Contaminant Hydrology* 239, p. 103791. ISSN: 01697722. DOI: `10.1016/j.jconhyd.2021.103791`. URL: `https://linkinghub.elsevier.com/retrieve/pii/S0169772221000309`.

Borgonie, Gaetan, Aantonio García-Moyano, Derek Litthauer, Wim Bert, Phillip Armand Bester, Esta Van Heerden, C. Möller, Mariana Erasmus, and T. C. Onstott (2011). "Nematoda from the terrestrial deep subsurface of South Africa". In: *Nature* 474.7349, pp. 79–82. ISSN: 00280836. DOI: `10.1038/nature09974`.

Bork, Jörg, Sven E. Berkhoff, Sabine Bork, and Hans Jürgen Hahn (2009). "Using subsurface metazoan fauna to indicate groundwater-surface water interactions in the Nakdong River floodplain, South Korea". In: *Hydrogeology Journal* 17.1, pp. 61–75. ISSN: 14312174. DOI: `10.1007/s10040-008-0374-2`.

Botosaneanu, L. (1986). *Stygofauna mundi: a faunistic, distributional, and ecological synthesis of the world fauna inhabiting subterranean waters (including the marine interstitial)*. Leiden The Netherlands, p. 740. ISBN: 9004075712.

Bou, Claude and Raymond Rouch (1967). "Un nouveau champ de recherches sur la faune aquatique souterraine". In: *Communication yearbook: an annual review* 265.4, pp. 369–370.

Boughrous, Ali Aït (2007). "Biodiversité, écologie et qualité des eaux souterraines de deux régions arides du Maroc : le Tafilalet et la région de Marrakech". PhD thesis. Université Cadi Ayyad Marrakech, p. 207.

Boughrous, Ali Aït, Mohammed Yacoubi-Khebiza, Mohamed Boulanouar, Claude Boutin, and Giuseppe Messana (2007). "Groundwater quality in two arid areas of Morocco: Impact of pollution on biodiversity and paleogeographic implications". In: *Environmental Technology* 28.11, pp. 1299–1315. ISSN: 09593330. DOI: 10.1080/09593332808618887. URL: http://dx.doi.org/10.1080/09593332808618887.

Boulaassafer, Khadija, Mohamed Ghamizi, Annie Machordom, Christian Albrecht, and Diana Delicado (2021). "Hidden species diversity of Corrosella Boeters, 1970 (Caenogastropoda: Truncatelloidea) in the Moroccan Atlas reveals the ancient biogeographic link between North Africa and Iberia". In: *Organisms Diversity and Evolution* 21, pp. 393–420. ISSN: 16181077. DOI: 10.1007/s13127-021-00490-3.

Boulal, Mokhtar, Mohamed Boulanouar, Mohamed Ghamizi, and Claude Boutin (2017). "Qualité de l'eau et faune aquatique des puits dans la région de Tiznit (Anti-Atlas occidental, Maroc)". In: *Bulletin de la Société d'histoire naturelle de Toulouse* 153, pp. 25–41.

Boulton, Andrew J., Maria Elina Bichuette, Kathryn L. Korbel, Fabio Stoch, Matthew L. Niemiller, Grant C. Hose, and Simon Linke (2023). "Recent concepts and approaches for conserving groundwater biodiversity". In: *Groundwater Ecology and Evolution*. Ed. by Pierre Marmonier, Christian Griebler, and Sylvie Rétaux. 2nd ed. Elsevier. Chap. 23, pp. 525–550. ISBN: 978-0-12-819119-4.

Boulton, Andrew J., Marie-José Dole-Olivier, and Pierre Marmonier (2003a). "Optimizing a sampling strategy for assessing hyporheic invertebrate biodiversity using the Bou-Rouch method: Within-site replication and sample volume". In: *Archiv für Hydrobiologie* 156.4, pp. 431–456. ISSN: 00039136. DOI: 10.1127/0003-9136/2003/0156-0431.

Boulton, Andrew J., Graham D. Fenwick, Peter J. Hancock, and Mark S. Harvey (2008). "Biodiversity, functional roles and ecosystem services of groundwater invertebrates". In: *Invertebrate Systematics* 22.2, pp. 103–116. ISSN: 14455226. DOI: 10.1071/IS07024.

Boulton, Andrew J., Stuart Findlay, Pierre Marmonier, Emily H. Stanley, and H. Maurice Valett (1998). "The Functional Significance of the Hyporheic Zone in Streams and Rivers". In: *Annual Review of Ecology and Systematics* 29, pp. 59–81.

Boulton, Andrew J., William F. Humphreys, and Stefan M. Eberhard (2003b). "Imperilled subsurface waters in Australia: Biodiversity, threatening processes and conservation". In: *Aquatic Ecosystem Health and Management* 6.1, pp. 41–54. ISSN: 14634988. DOI: 10.1080/14634980301475.

Boulton, Andrew J., Mike R. Scarsbrook, John M. Quinn, and Greg P. Burrell (1997). "Land-use effects on the hyporheic ecology of five small streams near Hamilton, New Zealand". In: *New*

Zealand Journal of Marine and Freshwater Research 31.5, pp. 609–622. ISSN: 11758805. DOI: 10.1080/00288330.1997.9516793.

Boutin, Claude and Mohamed Boulanouar (1983). “Méthodes de capture de la faune stygobie: Expérimentation de différents types de pièges appâtés dans les puits de Marrakech”. In: *Bulletin Faculty of Sciences Marrakech* 2, pp. 5–21.

Boutin, Claude, Mohamed Boulanouar, and Mohammed Yacoubi-Khebiza (1995). “Un test biologique simple pour apprécier la toxicité de I’eau et des sédiments d’un puits. Toxicité comparée, in vitro, de quelques métaux lourds et de I’ammonium, vis-à-vis de trois genres de crustacés de la zoocénose des puits”. In: *Hydroécologie Appliquée* 7, pp. 91–109. ISSN: 1147-9213. DOI: 10.1051/hydro:1995006.

Boutin, Claude and B. Idbennacer (1989). “Faune stygobie du sud de l’Anti-Atlas Marocain: Premiers résultats”. In: *Revue des Sciences de l’Eau* 2.4, pp. 891–904. ISSN: 00927158. DOI: 10.7202/705061ar.

Boxshall, Geoffrey A., Terue C. Kihara, and Rony Huys (2016). “Collecting and processing non-planktonic copepods”. In: *Journal of Crustacean Biology* 36.4, pp. 576–583. ISSN: 1937240X. DOI: 10.1163/1937240X-00002438.

Bradbury, John H. and Stefan M. Eberhard (2000). “A new stygobiont melitid amphipod from the Nullarbor Plain”. In: *Records of the Western Australian Museum* 20.1, pp. 39–50. ISSN: 0312-3162.

Bradford, Tessa, Mark Adams, Michelle T. Guzik, William F. Humphreys, Andrew D. Austin, and Steven John Baynard Cooper (2013). “Patterns of population genetic variation in sympatric chiltoniid amphipods within a calcrete aquifer reveal a dynamic subterranean environment”. In: *Heredity* 111.1, pp. 77–85. ISSN: 0018067X. DOI: 10.1038/hdy.2013.22.

Bradford, Tessa, Mark Adams, William F. Humphreys, Andrew D. Austin, and Steven John Baynard Cooper (2010). “DNA barcoding of stygofauna uncovers cryptic amphipod diversity in a calcrete aquifer in Western Australia’s arid zone”. In: *Molecular Ecology Resources* 10.1, pp. 41–50. ISSN: 1755098X. DOI: 10.1111/j.1755-0998.2009.02706.x.

Brancelj, Anton, Chaichat Boonyanusith, Santi Watiroyram, and La-orsri Sanoamuang (2013). “The groundwater-dwelling fauna of South East Asia”. In: *Journal of Limnology* 72.S2, pp. 327–344. ISSN: 11295767. DOI: 10.4081/jlimnol.2013.s2.e16.

Brehm, Vinzenz (1930). *Einführung in die Limnologie*. 1st ed. Berlin: Springer-Verlag Berlin Heidelberg, p. 261. DOI: 10.1007/978-3-642-48595-4.

Brielmann, Heike, Christian Griebler, Susanne I. Schmidt, Rainer Michel, and Tillmann Lueders (2009). “Effects of thermal energy discharge on shallow groundwater ecosystems”. In: *FEMS Microbiology Ecology* 68.3, pp. 273–286. ISSN: 01686496. DOI: 10.1111/j.1574-6941.2009.00674.x.

Brielmann, Heike, Tillmann Lueders, Kathrin Schreglmann, Francesco Ferraro, Maria Avramov, Verena Hammerl, Philipp Blum, Peter Bayer, and Christian Griebler (2011). “Oberflächennahe

Geothermie und ihre potenziellen Auswirkungen auf Grundwasserökosysteme”. In: *Grundwasser* 16.2, pp. 77–91. ISSN: 1430483X. DOI: 10.1007/s00767-011-0166-9.

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) (2019). *Hydrogeologie von Deutschland 1:1.000.000 – Klassifikation gemäß der Standardlegende für Hydrogeologische Karten (HY1000–SLHyM)*. URL: https://produktcenter.bgr.de/terraCatalog/DetailResult.do?fileIdentifier=f0b8086e-9dc1-402c-9f38-15b9933b5b77 (visited on 10/18/2022).

Burri, Nicole M., Robin Weatherl, Christian Moeck, and Mario Schirmer (2019). “A review of threats to groundwater quality in the anthropocene”. In: *Science of the Total Environment* 684, pp. 136–154. ISSN: 18791026. DOI: 10.1016/j.scitotenv.2019.05.236.

Burrows, Ryan M., Helen Rutlidge, Nick R. Bond, Stefan M. Eberhard, Alexandra Auhl, Martin S. Andersen, Dominic G. Valdez, and Mark J. Kennard (2017). “High rates of organic carbon processing in the hyporheic zone of intermittent streams”. In: *Scientific Reports* 7.1, pp. 1–11. ISSN: 20452322. DOI: 10.1038/s41598-017-12957-5. URL: http://dx.doi.org/10.1038/s41598-017-12957-5.

Busch, Erica L., Jessie Huang, Andrew Benz, Tom Wallenstein, Guillaume Lajoie, Guy Wolf, Smita Krishnaswamy, and Nicholas B Turk-Browne (2022). “Temporal PHATE: A multi-view manifold learning method for brain state trajectories”. In: *bioRxiv*, p. 2022.05.03.490534. URL: https://www.biorxiv.org/content/10.1101/2022.05.03.490534v1%0Ahttps://www.biorxiv.org/content/10.1101/2022.05.03.490534v1.abstract.

Camacho, Ana Isabel (1989). “Iberobathynella notenboomi, spec. nov. from a well in Alicante, South-East Spain”. In: *SPIXIANA* 12.2, pp. 105–113.

– (2006). “An annotated checklist of the Syncarida (Crustacea, Malacostraca) of the world”. In: *Zootaxa* 1374, pp. 1–54.

Carpenter, Stephen R, Ruth Defries, Thomas Dietz, Harold A Mooney, Stephen Polasky, Walter V Reid, and Robert J Scholes (2006). “Millennium Ecosystem Assessment: Research Needs”. In: *Science* 314, pp. 257–259. DOI: 10.1126/science.1131946.

Castaño-Sánchez, Andrea, Grant C. Hose, and Ana Sofia P.S. Reboleira (2020a). “Ecotoxicological effects of anthropogenic stressors in subterranean organisms: A review”. In: *Chemosphere* 244. ISSN: 18791298. DOI: 10.1016/j.chemosphere.2019.125422. URL: https://doi.org/10.1016/j.chemosphere.2019.125422.

– (2020b). “Salinity and temperature increase impact groundwater crustaceans”. In: *Scientific Reports* 10.12328, pp. 1–9. ISSN: 20452322. DOI: 10.1038/s41598-020-69050-7. URL: https://doi.org/10.1038/s41598-020-69050-7.

Castellarini, Fabiana, Marie-José Dole-Olivier, Florian Malard, and Janine Gibert (2004). “Improving the assessment of groundwater biodiversity by exploring environmental heterogeneity at a regional scale”. In: *World Subterranean Biodiversity*. Ed. by Janine Gibert, pp. 83–88.

Chilton, Charles (1882). “On some subterranean Crustacea: Art. III.—Notes on, and a new Species of Subterranean Crustacea”. In: *Transactions and Proceedings of the New Zealand Institute* 15, pp. 87–94.

Close, Murray, Rod Dann, Andrew Ball, Ruth Pirie, Marion Savill, and Zella Smith (2008). “Microbial groundwater quality and its health implications for a border-strip irrigated dairy farm catchment, South Island, New Zealand”. In: *Journal of Water and Health* 6.1, pp. 83–98. ISSN: 14778920. DOI: 10.2166/wh.2007.020.

Colson-Proch, Céline, David Renault, Antoine Gravot, Christophe J. Douady, and Frédéric Hervant (2009). “Do current environmental conditions explain physiological and metabolic responses of subterranean crustaceans to cold?” In: *Journal of Experimental Biology* 212.12, pp. 1859–1868. ISSN: 00220949. DOI: 10.1242/jeb.027987.

Conti, M E (2008). *Biomonitoring of freshwater environment*. Vol. 30, pp. 47–79. ISBN: 9781845640026. DOI: 10.2495/978184564002603.

Cook, B. D., K. M. Abrams, Jonathan C. Marshall, C. N. Perna, Satish Choy, Michelle T. Guzik, and Steven John Baynard Cooper (2012). “Species diversity and genetic differentiation of stygofauna (Syncarida: Bathynellacea) across an alluvial aquifer in north-eastern Australia”. In: *Australian Journal of Zoology* 60.3, pp. 152–158. ISSN: 0004959X. DOI: 10.1071/ZO12061.

Cooper, Steven John Baynard, John H. Bradbury, Kathleen M. Saint, Remko Leys, Andrew D. Austin, and William F. Humphreys (2007). “Subterranean archipelago in the Australian arid zone: Mitochondrial DNA phylogeography of amphipods from central Western Australia”. In: *Molecular Ecology* 16.7, pp. 1533–1544. ISSN: 09621083. DOI: 10.1111/j.1365-294X.2007.03261.x.

Cooper, Steven John Baynard, Cene Fišer, Valerija Zakšek, Teo Delić, Špela Borko, Arnaud Faille, and William F. Humphreys (2023). “Phylogenies reveal speciation dynamics: case studies from groundwater”. In: *Groundwater Ecology and Evolution*. Ed. by Florian Malard, Christian Griebler, and Sylvie Rétaux. 2nd ed. Academic Press. Chap. 7, pp. 165–183. ISBN: 9780128191194. URL: https://shop.elsevier.com/books/groundwater-ecology-and-evolution/malard/978-0-12-819119-4.

Cooper, Steven John Baynard, S. Hinze, Remko Leys, Chris H.S. Watts, and William F. Humphreys (2002). “Islands under the desert: Molecular systematics and evolutionary origins of stygobitic water beetles (Coleoptera: Dytiscidae) from central Western Australia”. In: *Invertebrate Systematics* 16.4, pp. 589–598. ISSN: 14455226. DOI: 10.1071/IT01039.

Cornu, Jean François, David Eme, and Florian Malard (2013). “The distribution of groundwater habitats in Europe”. In: *Hydrogeology Journal* 21.5, pp. 949–960. ISSN: 14312174. DOI: 10.1007/s10040-013-0984-1.

Culver, David C., Louis Deharveng, Anne Bedos, Julian J. Lewis, Molly K. Madden, James R. Reddell, Boris Sket, Peter Trontelj, and Denis White (2006). “The mid-latitude biodiversity ridge in terrestrial cave fauna”. In: *Ecography* 29, pp. 120–128.

Culver, David C. and John R. Holsinger (1992). “How many species of troglobites are there?” In: *Journal of Caves and Karst Studies*. Ed. by Andrew J. Flurkey. Vol. 54. 2. Lake Mills: The National Speleological Society, pp. 79–80. ISBN: 0146-9517.

Culver, David C. and Tanja Pipan (2013). “Subterranean Ecosystems”. In: *Encyclopedia of Biodiversity: Second Edition* 7, pp. 49–62. DOI: 10.1016/B978-0-12-384719-5.00224-0. URL: http://dx.doi.org/10.1016/B978-0-12-384719-5.00224-0.

Culver, David C. and Boris Sket (2000). “Hotspots of subterranean biodiversity in caves and wells”. In: *Journal of Cave and Karst Studies* 62.1, pp. 11–17. ISSN: 10906924.

Danielopol, Dan Luca, Janine Gibert, Christian Griebler, Amara Gunatilaka, Hans Jürgen Hahn, Giuseppe Messana, Jos Notenboom, and Boris Sket (2004). “Incorporating ecological perspectives in European groundwater management policy”. In: *Environmental Conservation* 31.3, pp. 185–189. ISSN: 03768929. DOI: 10.1017/S0376892904001444.

Danielopol, Dan Luca and Christian Griebler (2008). “Changing paradigms in groundwater ecology - From the ’living fossils’ tradition to the ’new groundwater ecology’”. In: *International Review of Hydrobiology* 93.4-5, pp. 565–577. ISSN: 14342944. DOI: 10.1002/iroh.200711045.

Danielopol, Dan Luca, Christian Griebler, Amara Gunatilaka, and Jos Notenboom (2003). “Present state and future prospects for groundwater ecosystems”. In: *Environmental Conservation* 30.2, pp. 104–130. ISSN: 03768929. DOI: 10.1017/S0376892903000109.

Danielopol, Dan Luca and Pierre Marmonier (1992). “Aspects of research on groundwater along the Rhône, Rhine and Danube”. In: *Regulated Rivers: Research Management* 7, pp. 5–16.

Danielopol, Dan Luca and Richard Niederreiter (1987). “A sampling device for groundwater organisms and oxygen measurement in multi-level monitoring wells”. In: *Stygologia* 3, pp. 252–263.

Danielopol, Dan Luca, Peter Pospisil, and Raymond Rouch (2000). “Biodiversity in groundwater: A large-scale view”. In: *Trends in Ecology and Evolution* 15.6, pp. 223–224. ISSN: 01695347. DOI: 10.1016/S0169-5347(00)01868-1.

Datry, Thibault, Florian Malard, and Janine Gibert (2005). “Response of invertebrate assemblages to increased groundwater recharge rates in a phreatic aquifer”. In: *Journal of the North American Benthological Society* 24.3, pp. 461–477. ISSN: 08873593. DOI: 10.1899/04-140.1.

Datry, Thibault, Florian Malard, Richard Niederreiter, and Janine Gibert (2003). “Video-logging for examining biogenic structures in deep heterogenous subsurface sediments”. In: *Comptes Rendus - Biologies* 326.6, pp. 589–597. ISSN: 16310691. DOI: 10.1016/S1631-0691(03)00147-1.

Davalo Centurião, Thaynara, William Marcos da Silva, and Sandra Garcia Gabas (2020). "Is groundwater fauna impacted by swine effluent fertigation?" In: *Ciência e Natura* 42.34, p. 11. ISSN: 0100-8307. DOI: 10.5902/2179460x42327.

De Laurentiis, Pierpaolo, Guiseppe Lucio Pesce, and William F. Humphreys (1999). "Copepods from ground waters of Western Australia, IV. Cyclopids from basin and craton aquifers (Crustacea: Copepoda: Cyclopidae)". In: *Records of the Western Australian Museum* 19, pp. 243–257. ISSN: 0312-3162.

– (2001). "Copepods from ground waters of Western Australia, VI. Cyclopidae (Crustacea: Copepoda) from the Yilgarn Region and the Swan Coastal Plain". In: *Records of the Western Australian Museum, Supplement* 64.1, pp. 115–131. ISSN: 0313-122X. DOI: 10.18195/issn.0313-122x.64.2001.115-131.

Deharveng, Louis, Fabio Stoch, Janine Gibert, Anne Bedos, Diana Maria Paola Galassi, Maja Zagmajster, Anton Brancelj, Ana Isabel Camacho, Frank Fiers, Peter Martin, Narcisse Giani, Guy J. Magniez, and Pierre Marmonier (2009). "Groundwater biodiversity in Europe". In: *Freshwater Biology* 54.4, pp. 709–726. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2008.01972.x.

Deiner, Kristy, Holly M. Bik, Elvira Mächler, Mathew Seymour, Anaïs Lacoursière-Roussel, Florian Altermatt, Simon Creer, Iliana Bista, David M. Lodge, Natasha de Vere, Michael E. Pfrender, and Louis Bernatchez (2017). "Environmental DNA metabarcoding: Transforming how we survey animal and plant communities". In: *Molecular Ecology* 26.21, pp. 5872–5895. ISSN: 1365294X. DOI: 10.1111/mec.14350.

Di Lorenzo, Tiziana, Marco Cifoni, Paola Lombardo, Barbara Fiasca, and Diana Maria Paola Galassi (2015). "Ammonium threshold values for groundwater quality in the EU may not protect groundwater fauna: evidence from an alluvial aquifer in Italy". In: *Hydrobiologia* 743.1, pp. 139–150. ISSN: 15735117. DOI: 10.1007/s10750-014-2018-y.

Di Lorenzo, Tiziana, Walter Dario Di Marzio, Barbara Fiasca, Diana Maria Paola Galassi, Kathryn L. Korbel, Sanda Iepure, Joana Luísa Pereira, Ana Sofia P.S. Reboleira, Susanne I. Schmidt, and Grant C. Hose (2019). "Recommendations for ecotoxicity testing with stygobiotic species in the framework of groundwater environmental risk assessment". In: *Science of the Total Environment* 681, pp. 292–304. ISSN: 18791026. DOI: 10.1016/j.scitotenv.2019.05.030.

Di Lorenzo, Tiziana, Barbara Fiasca, Agostina Di Camillo Tabilio, Alessandro Murolo, Mattia Di Cicco, and Diana Maria Paola Galassi (2020a). "The weighted Groundwater Health Index (wGHI) by Korbel and Hose (2017) in European groundwater bodies in nitrate vulnerable zones". In: *Ecological Indicators* 116.106525, p. 11. URL: https://doi.org/10.1016/j.ecolind.2020.106525.

Di Lorenzo, Tiziana, Barbara Fiasca, Mattia Di Cicco, and Diana Maria Paola Galassi (2020b). "The impact of nitrate on the groundwater assemblages of European unconsolidated aquifers is likely less severe than expected". In: *Environmental Science and Pollution Research* 28, pp. 11518–11527. ISSN: 16147499. DOI: 10.1007/s11356-020-11408-5.

Di Lorenzo, Tiziana and Diana Maria Paola Galassi (2013). "Agricultural impact on Mediterranean alluvial aquifers: Do groundwater communities respond?" In: *Fundamental and Applied Limnology* 182.4, pp. 271–282. ISSN: 18639135. DOI: 10.1127/1863-9135/2013/0398.

– (2017). "Effect of temperature rising on the stygobitic crustacean species Diacyclops belgicus: Does global warming affect groundwater populations?" In: *Water* 8.12. ISSN: 20734441. DOI: 10.3390/w9120951.

Di Sabatino, Antonio, Reinhard Gerecke, and Peter Martin (2000). "The biology and ecology of lotic water mites (Hydrachnidia)". In: *Freshwater Biology* 44.1, pp. 47–62.

Dole-Olivier, Marie José, Florian Malard, Dominique Martin, Tristan Lefébure, and Janine Gibert (2009). "Relationships between environmental variables and groundwater biodiversity at the regional scale". In: *Freshwater Biology* 54.4, pp. 797–813. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2009.02184.x.

Dole-Olivier, Marie-José (1998). "Surface water–groundwater exchanges in three dimensions on a backwater of the Rhône River". In: *Freshwater Biology* 40, pp. 93–109.

Dole-Olivier, Marie-José, Fabiana Castellarini, Nicole Coineau, Diana Maria Paola Galassi, Peter Martin, Nataša Mori, Antonio G. Valdecasas, and Janine Gibert (2009). "Towards an optimal sampling strategy to assess groundwater biodiversity: Comparison across six European regions". In: *Freshwater Biology* 54.4, pp. 777–796. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2008.02133.x.

Dumnicka, Elzbieta, Joanna Galas, and Mariola Krodkiewska (2017). "Patterns of Benthic Fauna Distribution in Wells: The Role of Anthropogenic Impact and Geology". In: *Vadose Zone Journal* 16.5, vzj2016.07.0057. ISSN: 1539-1663. DOI: 10.2136/vzj2016.07.0057.

Dumnicka, Elzbieta, Tanja Pipan, and David C. Culver (2020). "Habitats and diversity of subterranean macroscopic freshwater invertebrates: Main gaps and future trends". In: *Water (Switzerland)* 12.8, p. 15. ISSN: 20734441. DOI: 10.3390/w12082170.

DWD Climate Data Center (CDC) (2022). *Raster der Monatsmittel der Lufttemperaturminima (2m) für Deutschland, Version v19.3*. (Visited on 05/23/2022).

Eamus, Derek and Ray Froend (2006). "Groundwater-dependent ecosystems: The where, what and why of GDEs". In: *Australian Journal of Botany* 54.2, pp. 91–96. ISSN: 00671924. DOI: 10.1071/BT06029.

Eberhard, Stefan M. (1992). "The invertebrate cave fauna of Tasmania: ecology and conservation biology". PhD thesis. University of Tasmania, p. 214.

– (2001). "Cave fauna monitoring and management at Ida Bay, Tasmania". In: *Records of the Western Australian Museum, Supplement* 64.1, p. 97. ISSN: 0313-122X. DOI: 10.18195/issn.0313-122x.64.2001.097-104.

Eberhard, Stefan M., Martin Anderson, and Helen Rutlidge (2017). “Impact of groundwater drawdown on stygofauna in the hyporheic zone”. In: *Australian Groundwater Conference ’Groundwater Futures Science to Practice’*. Ed. by Book of Abstracts by the National Centre for Groundwater Research and Training. Sydney, p. 195.

Eberhard, Stefan M., Stuart A. Halse, Michael D. Scanlon, James Cocking, and Harley J. Barron (2004). “Assessment and conservation of aquatic life in the subsurface of the Pilbara region, Western Australia”. In: *Symposium on World Subterranean Biodiversity*. Ed. by Janine Gibert. Villeurbanne: Subterranean Ecology, Scientific Environmental Services, pp. 61–68.

Eberhard, Stefan M., Stuart A. Halse, Matthew R. Williams, Michael D. Scanlon, James Cocking, and Harley J. Barron (2009). “Exploring the relationship between sampling efficiency and short-range endemism for groundwater fauna in the Pilbara region, Western Australia”. In: *Freshwater Biology* 54.4, pp. 885–901. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2007.01863.x.

Eberhard, Stefan M., Remko Leys, and Mark Adams (2005). “Conservation of subterranean biodiversity in Western Australia: using molecular genetics to define spatial and temporal relationships in two species of cave-dwelling Amphipoda”. In: *Subterranean Biology* 3, pp. 13–27.

Eberhard, Stefan M. and Andy Spate (1995). *Cave invertebrate survey: towards an atlas of NSW cave fauna*. Tech. rep. Canberra: Department of Urban Affairs, Planning, and the Australian Heritage Commissio Report prepared under the NSW Heritage Assistance Programn.

Eckert, J., K. T. Friedhoff, H. Zahner, and P. Deplazes (2008). *Lehrbuch der Parasitologie für die Tiermedizin Teil II Parasiten und Parasitosen: 3 Metazoa*. 2nd ed. Stuttgart: Thieme Verlagsgruppe Stuttgart/ Enke Verlag, p. 632. DOI: 10.1055/-001-3188.

Edler, C. and W. K. Dodds (1996). “The ecology of a subterranean isopod, Caecidotea tridentata”. In: *Freshwater Biology* 35.2, pp. 249–259. ISSN: 00465070. DOI: 10.1046/j.1365-2427.1996.00497.x.

Einsle, U. (1993). *Crustacea: Copepoda, Calanoida and Cyclopoida – Süßwasserfauna von Mitteleuropa*. 8/4-1. Stuttgart: Gustav Fischer Verlag Stuttgart, p. 208. ISBN: 3437306316.

El Adnani, Mariam, Ali Aït Boughrous, Mohammed Yacoubi-Khebiza, A. El Gharmali, M. L. Sbai, A. Sadik Errouane, Leila Loukili Idrissi, and A. Nejmeddine (2007). “Impact of mining wastes on the physicochemical and biological characteristics of groundwater in a mining area in Marrakech (Morocco)”. In: *Environmental Technology* 28.1, pp. 71–82. ISSN: 09593330. DOI: 10.1080/09593332808618762.

El Adnani, Mariam, Ali Aït Boughrous, Mohammed Yacoubi-Khebiza, M. L. Sbai, and A. Nejmeddine (2006). “Mine tailings impact on the physico-chemical and biological characteristics of underground waters in Marrakech mining area (Morocco)”. In: *2006 1st International Symposium on Environment Identities and Mediterranean Area, ISEIM*, pp. 287–293. DOI: 10.1109/ISEIMA.2006.344970.

El Moustaine, Radouane, Abdelkader Chahlaoui, and El Habib Rour (2013). "Groundwater fauna can be used as indicators of anthropogenic impacts on aquifers: A case study from Meknes area, Morocco". In: *International Journal of Biosciences (IJB)* 3.10, pp. 139–152. ISSN: 22206655. DOI: 10.12692/ijb/3.10.139-152. URL: Wells,%20stygobiontic%20fauna,%20water%20quality,%20indicators%20of%20water%20quality.

– (2014). "Relationships between the physico-chemical variables and groundwater biodiversity: a case study from Meknes area, Morocco". In: *International Journal of Conservation Science* 5.2, pp. 203–214.

Environmental Protection Authority (EPA) (2016). *Technical Guidance Sampling methods for Subterranean fauna*. Tech. rep. Perth: Environmental Protection Authority Western Australia, p. 37.

Ercoli, Fabio, François Lefebvre, Marjorie Delangle, Nil Godé, Michel Caillon, Roland Raimond, and Catherine Souty-Grosset (2019). "Differing trophic niches of three French stygobionts and their implications for conservation of endemic stygofauna". In: *Aquatic Conservation: Marine and Freshwater Ecosystems* 29.12, pp. 2193–2203. ISSN: 10990755. DOI: 10.1002/aqc.3227.

Esmaeili-Rineh, Somayeh, Firoozeh Heidari, Cene Fišer, and Vahid Akmali (2016). "Description of new endemic species of the genus Niphargus Schiodte, 1849 (Amphipoda: Niphargidae) from a karst spring in Zagros Mountains in Iran". In: *Zootaxa* 4126.3, pp. 338–350. ISSN: 11755334. DOI: 10.11646/zootaxa.4126.3.2.

Esmaeili-Rineh, Somayeh, Mahmoud Mamaghani-Shishvan, Cene Fišer, Vahid Akmali, and Nargess Najafi (2020). "Range sizes of groundwater amphipods (Crustacea) are not smaller than range sizes of surface amphipods: A case study from Iran". In: *Contributions to Zoology* 89.1, pp. 1–13. ISSN: 18759866. DOI: 10.1163/18759866-20191418.

Esmaeili-Rineh, Somayeh, Seyyed Ahmad Mirghaffari, and Mozafar Sharifi (2017a). "The description of a new species of Niphargus from Iran based on morphological and molecular data". In: *Subterranean Biology* 58.22, pp. 43–58. ISSN: 13142615. DOI: 10.3897/subtbiol.22.11286.

Esmaeili-Rineh, Somayeh, Ali Mohammad-Niakan, and Vahid Akmali (2018). "Niphargus Sarii Sp. N., A new subterranean Niphargid (Crustacea: Amphipoda) from Iran based on molecular and morphological characters". In: *Acta Zoologica Academiae Scientiarum Hungaricae* 64.2, pp. 113–132. ISSN: 12178837. DOI: 10.17109/AZH.64.2.113.2018.

Esmaeili-Rineh, Somayeh, Alireza Sari, Teo Delić, Ajda Moškrič, and Cene Fišer (2015). "Molecular phylogeny of the subterranean genus Niphargus (Crustacea: Amphipoda) in the Middle East: A comparison with European Niphargids". In: *Zoological Journal of the Linnean Society* 175.4, pp. 812–826. ISSN: 10963642. DOI: 10.1111/zoj.12296.

Esmaeili-Rineh, Somayeh, Alireza Sari, Cene Fišer, and Zeinab Bargrizaneh (2017b). "Completion of molecular taxonomy: description of four amphipod species (Crustacea:

Amphipoda: Niphargidae) from Iran and release of database for morphological taxonomy”. In: *Zoologischer Anzeiger* 271, pp. 57–79. ISSN: 00445231. DOI: 10.1016/j.jcz.2017.04.009.

European Environment Agency (2016). *Corine Land Cover (CLC) European seamless vector database*. Kopenhagen. URL: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download.

European Parliament (2023). **** I Report on the proposal for a directive of the European Parliament and of the Council amending Directive 2000/60/EC establishing a framework for Community action in the field of water policy, Directive 2006/118/EC on the protection of groundwater aga*. Tech. rep. Committee on the Environment, Public Health and Food Safety, p. 148.

European Union (2006). “Directive 2006/118/EC of the European Parliament and of the council of 12 December 2006 on the protection of groundwater against pollution and deterioration”. In: *Official Journal of the European Union* 19.L372, pp. 19–31. ISSN: 0144-557X. DOI: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32006L0118. arXiv: CELEX:32006L0118.

– (2020). *European Groundwater Crustacea Database*.

Fakher el Abiari, Abdelmoumen, Zineba Oulbaz, Mohammed Yacoubi-Khebiza, Nicole Coineau, and Claude Boutin (1998). “Etude expérimentale de la sensibilité comparée de trois crustacés stygobies vis-à-vis de diverses substances toxiques pouvant se rencontrer dans les eaux souterraines”. In: *Mémoires de Biospéologie* 25, pp. 167–181.

Fenwick, Graham D. (2001). “The freshwater amphipoda (Crustacea) of New Zealand: A review”. In: *Journal of the Royal Society of New Zealand* 31.2, pp. 341–363. ISSN: 03036758. DOI: 10.1080/03014223.2001.9517658.

Fenwick, Graham D., Michelle J. Greenwood, Ian D. Hogg, and Stacey J. Meyer (2021). “High diversity and local endemism in Aotearoa New Zealand’s groundwater crustacean fauna”. In: *Ecology and Evolution* 11.22, pp. 15664–15682. ISSN: 20457758. DOI: 10.1002/ece3.8220.

Fenwick, Graham D. and Mike R. Scarsbrook (2004). “Lightless, not lifeless: New Zealand’s subterranean biodiversity”. In: *Water and Atmosphere* 12.3, p. 2.

Ferguson, Grant, Jennifer C. McIntosh, Oliver Warr, Barbara Sherwood Lollar, Christopher J. Ballentine, James S. Famiglietti, Ji Hyun Kim, Joseph R. Michalski, John F. Mustard, Jesse Tarnas, and Jeffrey J. McDonnell (2021). “Crustal Groundwater Volumes Greater Than Previously Thought”. In: *Geophysical Research Letters* 48.16, pp. 1–9. ISSN: 19448007. DOI: 10.1029/2021GL093549.

Figura, Simon, David M. Livingstone, Eduard Hoehn, and Rolf Kipfer (2011). “Regime shift in groundwater temperature triggered by the Arctic Oscillation”. In: *Geophysical Research Letters* 38.23, pp. 1–5. ISSN: 00948276. DOI: 10.1029/2011GL049749.

Fillinger, Lucas, Katrin Hug, Anne Madeleine Trimbach, He Wang, Claudia Kellermann, Astrid Meyer, Bernd Bendinger, and Christian Griebler (2019). "The D-A-(C) index: A practical approach towards the microbiological-ecological monitoring of groundwater ecosystems". In: *Water Research* 163, p. 114902. ISSN: 18792448. DOI: 10.1016/j.watres.2019.114902. URL: https://doi.org/10.1016/j.watres.2019.114902.

Fišer, Cene, Teo Delić, Roman Luštrik, Maja Zagmajster, and Florian Altermatt (2019). "Niches within a niche: ecological differentiation of subterranean amphipods across Europe's interstitial waters". In: *Ecography* 42.6, pp. 1212–1223. ISSN: 16000587. DOI: 10.1111/ecog.03983.

Food and Agriculture Organization of the United Nations (FAO) (2023). *AQUASTAT Dissemination system*. URL: https://data.apps.fao.org/aquastat/?lang=en.

Foster, S.S.D. (1990). "Impacts of urbanization on groundwater". In: *Hydrological Processes and Water Management in Urban Areas (Proceedings of the Duisberg Symposium, 1988)* 198, pp. 209–216. URL: https://www.researchgate.net/profile/Stephen_Foster11/publication/237480481_Impacts_of_urbanisation_on_groundwater/links/55b4d97508ae092e96557248/Impacts-of-urbanisation-on-groundwater.pdf.

Foulquier, Arnaud, Florian Malard, Florian Mermillod-Blondin, Bernard Montuelle, Sylvain Dolédec, Bernadette Volat, and Janine Gibert (2011). "Surface Water Linkages Regulate Trophic Interactions in a Groundwater Food Web". In: *Ecosystems* 14.8, pp. 1339–1353. ISSN: 14350629. DOI: 10.1007/s10021-011-9484-0.

Freiherr von Valvasor, Johann Weichard (1689). *Die Ehre des Herzogthums Crain*. Ed. by W. Endtner. Vol. 9 - 11. Nürnberg: Laybach: Endter, p. 134.

Friberg, Nikolai, Núria Bonada, David C. Bradley, Michael J. Dunbar, Francois K. Edwards, Jonathan Grey, Richard B. Hayes, Alan G. Hildrew, Nicolas Lamouroux, Mark Trimmer, and Guy Woodward (2011). *Biomonitoring of Human Impacts in Freshwater Ecosystems. The Good, the Bad and the Ugly*. Vol. 44, pp. 1–68. ISBN: 9780123747945. DOI: 10.1016/B978-0-12-374794-5.00001-8.

Fuchs, Andreas (2007). "Erhebung und Beschreibung der Grundwasserfauna in Baden-Württemberg". In: pp. 1–109. URL: https://kola.opus.hbz-nrw.de/frontdoor/index/index/docId/175.

Fuchs, Andreas, Hans Jürgen Hahn, and Klaus-Peter Barufke (2006). *Grundwasser-Überwachungsprogramm - Erhebung und Beschreibung der Grundwasserfauna in Baden-Württemberg*. Tech. rep. Karlsruhe: LUBW Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg, p. 76. URL: https://pudi.lubw.de/detailseite/-/publication/77258.

Galassi, Diana Maria Paola (2001). "Groundwater copepods: Diversity patterns over ecological and evolutionary scales". In: *Hydrobiologia* 453-454.1997, pp. 227–253. ISSN: 00188158. DOI: 10.1023/A:1013100924948.

Galassi, Diana Maria Paola, Rony Huys, and Janet W. Reid (2009). “Diversity, ecology and evolution of groundwater copepods”. In: *Freshwater Biology* 54.4, pp. 691–708. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2009.02185.x.

Galassi, Diana Maria Paola, Paola Lombardo, Barbara Fiasca, Alessia Di Cioccio, Tiziana Di Lorenzo, Marco Petitta, and Piero Di Carlo (2014). “Earthquakes trigger the loss of groundwater biodiversity”. In: *Scientific Reports* 4.6273, pp. 1–8. ISSN: 20452322. DOI: 10.1038/srep06273.

Geets, J., J. Vangronsveld, B. Borremans, L. Diels, and D. van der Lelie (2001). “Development of molecular monitoring methods for the evaluation of the activity of sulfate-and metal reducing bacteria (SMRBS) as an indication of the in situ immobilisation of heavy metals and metalloids”. In: *Mededelingen (Rijksuniversiteit te Gent. Fakulteit van de Landbouwkundige en Toegepaste Biologische Wetenschappen)* 66.3a, pp. 41–48.

German Environment Agency (2018). *Bericht des Bundesministeriums für Gesundheit und des Umweltbundesamtes an die Verbraucherinnen und Verbraucher über die Qualität von Wasser für den menschlichen Gebrauch (Trinkwasser) in Deutschland 2014 – 2016*. Tech. rep. Dessau-Roßlau: German Federal Ministry of Health, German Environment Agency (UBA), p. 74. URL: https://www.umweltbundesamt.de/publikationen/bericht-des-bundesministeriums-fuer-gesundheit-des-3.

Geyer, O. F., M. P. Gwinner, E. Nitsch, and T. Simon (2011). *Geologie von Baden-Württemberg*. 5. Schweizerbart Stuttgart. ISBN: 3510652673.

Gibert, Janine and David C. Culver (2009). “Assessing and conserving groundwater biodiversity: An introduction”. In: *Freshwater Biology* 54.4, pp. 639–648. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2009.02202.x.

Gibert, Janine, David C. Culver, Marie-José Dole-Olivier, Florian Malard, Mary C. Christman, and Louis Deharveng (2009). “Assessing and conserving groundwater biodiversity: Synthesis and perspectives”. In: *Freshwater Biology* 54.4, pp. 930–941. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2009.02201.x.

Gibert, Janine, Dan Luca Danielopol, and Jack A. Stanford (1994). *Groundwater ecology*. Academic Press, p. 571. ISBN: 978-0-08-050762-0.

Gibert, Janine and Louis Deharveng (2002). “Subterranean Ecosystems: A Truncated Functional Biodiversity”. In: *BioScience* 52.6, p. 473. ISSN: 0006-3568. DOI: 10.1641/0006-3568(2002)052[0473:seatfb]2.0.co;2.

Ginet, René and Vasile Decou (1977). “Initiation à la Biologie et à l’Ecologie souterraines”. In: *Publications de la Société Linnéenne de Lyon* 47.4, pp. 195–196. URL: https://www.persee.fr/doc/linly_0366-1326_1978_num_47_4_14275_t1_0195_0000_7.

Glanville, Katharine, Cameron Schulz, Moya Tomlinson, and Don Butler (2016). “Biodiversity and biogeography of groundwater invertebrates in Queensland, Australia”. In: *Subterranean Biology* 17, pp. 55–76. ISSN: 13142615. DOI: 10.3897/SUBTBIOL.17.7542.

Glatzel, T. (1990). “On the biology of Parastenocaris phyllura Kiefer 1938 (Copepoda: Harpacticoida)”. In: *Stygologia* 5, pp. 131–136.

Goater, Sarah Elizabeth (2009). “Are Stygofauna Really Protected In Western Australia?” PhD thesis. The University of Western Australia, p. 186.

Goldscheider, Nico, Daniel Hunkeler, and Pierre Rossi (2006). “Review: Microbial biocenoses in pristine aquifers and an assessment of investigative methods”. In: *Hydrogeology Journal* 14.6, pp. 926–941. ISSN: 14312174. DOI: 10.1007/s10040-005-0009-9.

Google LLC. (2022). *Google Earth Pro*.

Gorički, Špela, David Stanković, Aleš Snoj, Matjaž Kuntner, William R. Jeffery, Peter Trontelj, Miloš Pavićević, Zlatko Grizelj, Magdalena Năpăruş-Aljančič, and Gregor Aljančič (2017). “Environmental DNA in subterranean biology: Range extension and taxonomic implications for Proteus”. In: *Scientific Reports* 7.45054, pp. 1–11. ISSN: 20452322. DOI: 10.1038/srep45054. URL: http://dx.doi.org/10.1038/srep45054.

Graeter, A. and P. A. Chappuis (1913). “Cyclops sensitivus n. sp.” In: *Zoologischer Anzeiger* 43, pp. 507–510.

Greenwood, Michelle J. and Graham D. Fenwick (2019). *Suitability of invertebrate data for assessing groundwater ecosystem health*. Tech. rep. December. Christchurch: National Institute of Water Atmospheric Research Ltd.

Griebler, C. and T. Lueders (2009). “Microbial biodiversity in groundwater ecosystems”. In: *Freshwater Biology* 54.4, pp. 649–677. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2008.02013.x.

Griebler, Christian (2001). “Microbial ecology of subsurface ecosystems”. In: *Groundwater ecology; A tool for management of water resources*. Ed. by Christian Griebler, Dan Luca Danielopol, Janine Gibert, Hans Peter Nachtnebel, and Jos Notenboom. Luxemburg: Official Publication of the European Communities, pp. 81–108.

Griebler, Christian and Maria Avramov (2015). “Groundwater ecosystem services: A review”. In: *Freshwater Science* 34.1, pp. 355–367. ISSN: 21619565. DOI: 10.1086/679903.

Griebler, Christian, Heike Brielmann, Christina M. Haberer, Sigrid Kaschuba, Claudia Kellermann, Christine Stumpp, Florian Hegler, David Kuntz, Simone Walker-Hertkorn, and Tillmann Lueders (2016). “Potential impacts of geothermal energy use and storage of heat on groundwater quality, biodiversity, and ecosystem processes”. In: *Environmental Earth Sciences* 75.20, pp. 1–18. ISSN: 18666299. DOI: 10.1007/s12665-016-6207-z.

Griebler, Christian, Hans Jürgen Hahn, Stefano Mammola, Matthew L. Niemiller, Louise Weaver, Mattia Saccò, Maria Elina Bichuette, and Grant C. Hose (2023). “Legal frameworks for the conservation and sustainable management of groundwater ecosystems”. In: *Groundwater Ecology and Evolution*. Ed. by Florian Malard, Christian Griebler, and Sylvie Rétaux. 2nd ed. Elsevier. Chap. 24, pp. 551–571. ISBN: 9780128191194. URL:

https://shop.elsevier.com/books/groundwater-ecology-and-evolution/malard/978-0-12-819119-4.

Griebler, Christian, Florian Malard, and Tristan Lefébure (2014a). "Current developments in groundwater ecology - from biodiversity to ecosystem function and services". In: *Current Opinion in Biotechnology* 27, pp. 159–167. ISSN: 18790429. DOI: 10.1016/j.copbio.2014.01.018.

Griebler, Christian, Birgit Mindl, Doris Slezak, and Margot Geiger-Kaiser (2002). "Distribution patterns of attached and suspended bacteria in pristine and contaminated shallow aquifers studied with an in situ sediment exposure microcosm". In: *Aquatic Microbial Ecology* 28.2, pp. 117–129. ISSN: 09483055. DOI: 10.3354/ame028117.

Griebler, Christian, Heide Stein, Hans Jürgen Hahn, Christian Steube, Claudia Kellermann, Andreas Fuchs, Sven E. Berkhoff, and Heike Brielmann (2014b). *Entwicklung biologischer Bewertungsmethoden und -kriterien für Grundwasserökosysteme*. Dessau: Umweltbundesamt, p. 153. ISBN: 1862-4804.

Griebler, Christian, Heide Stein, Claudia Kellermann, Sven E. Berkhoff, Heike Brielmann, Susanne I. Schmidt, Drazenka Selesi, Christian Steube, Andreas Fuchs, and Hans Jürgen Hahn (2010). "Ecological assessment of groundwater ecosystems - Vision or illusion?" In: *Ecological Engineering* 36.9, pp. 1174–1190. ISSN: 09258574. DOI: 10.1016/j.ecoleng.2010.01.010. URL: http://dx.doi.org/10.1016/j.ecoleng.2010.01.010.

Grzybowska, Urszula and Marek Karwański (2022). "Archetypal Analysis and DEA Model, Their Application on Financial Data and Visualization with PHATE". In: *Entropy* 24.1. ISSN: 10994300. DOI: 10.3390/e24010088.

Gutjahr, Simon (2013). "Grundwasserlebensräume in der Landschaft - Untersuchungen zur Bedeutung von Hydrologie und Hydrogeologie für Grundwasserlebensgemeinschaften". PhD thesis. Universität Koblenz-Landau.

Gutjahr, Simon, Susanne I. Schmidt, and Hans Jürgen Hahn (2014). "A proposal for a groundwater habitat classification at local scale". In: *Subterranean Biology* 14.1, pp. 25–49. ISSN: 13142615. DOI: 10.3897/subtbiol.14.5429.

Haase, Peter, Diana E. Bowler, Nathan J. Baker, Núria Bonada, Sami Domisch, Jaime R. Garcia Marquez, Jani Heino, Daniel Hering, Sonja C. Jähnig, Astrid Schmidt-Kloiber, Rachel Stubbington, Florian Altermatt, Mario Álvarez-Cabria, Giuseppe Amatulli, David G. Angeler, Gaït Archambaud-Suard, Iñaki Arrate Jorrín, Thomas Aspin, Iker Azpiroz, Iñaki Bañares, José Barquín Ortiz, Christian L. Bodin, Luca Bonacina, Roberta Bottarin, Miguel Cañedo-Argüelles, Zoltán Csabai, Thibault Datry, Elvira de Eyto, Alain Dohet, Gerald Dörflinger, Emma Drohan, Knut A. Eikland, Judy England, Tor E. Eriksen, Vesela Evtimova, Maria J. Feio, Martial Ferréol, Mathieu Floury, Maxence Forcellini, Marie Anne Eurie Forio, Riccardo Fornaroli, Nikolai Friberg, Jean François Fruget, Galia Georgieva, Peter Goethals, Manuel A.S. Graça, Wolfram Graf, Andy House, Kaisa Leena Huttunen, Thomas C. Jensen, Richard K. Johnson, J. Iwan Jones, Jens Kiesel, Lenka Kuglerová, Aitor Larrañaga, Patrick Leitner, Lionel L'Hoste, Marie Helène Lizée, Armin W. Lorenz, Anthony Maire, Jesús Alberto Manzanos Arnaiz, Brendan G. McKie, Andrés Millán, Don Monteith, Timo Muotka, John F. Murphy, Davis Ozolins, Riku Paavola, Petr Paril, Francisco J. Peñas, Francesca Pilotto, Marek Polášek, Jes Jessen Rasmussen, Manu Rubio, David Sánchez-Fernández, Leonard Sandin, Ralf B. Schäfer, Alberto Scotti, Longzhu Q. Shen, Agnija Skuja, Stefan Stoll, Michal Straka, Henn Timm, Violeta G. Tyufekchieva, Iakovos Tziortzis, Yordan Uzunov, Gea H. van der Lee, Rudy Vannevel, Emilia Varadinova, Gábor Várbíró, Gaute Velle, Piet F.M. Verdonschot, Ralf C.M. Verdonschot, Yanka Vidinova, Peter Wiberg-Larsen, and Ellen A.R. Welti (2023). "The recovery of European freshwater biodiversity has come to a halt". In: *Nature* 620.7974, pp. 582–588. ISSN: 14764687. DOI: 10.1038/s41586-023-06400-1.

Hach Lang GmbH (2022). *Intellical LDO101 lumineszenzbasierte/optische Sonde für gelösten Sauerstoff, für das Labor, 1 m Kabel Intellical PHC101 gelgefüllte pH-Elektrode für das Labor, geringer Wartungsbedarf, 1 m Kabel*. URL: https://de.hach.com/intellical-ldo101-lumineszenzbasierte-optische-sonde-fur-gelosten-sauerstoff-fur-das-labor-1-m-kabel/product-details?id=23358342977&callback=qs%20https://de.hach.com/intellical-phc101-gelgefullte-ph-elektrode-fur-das-labor-geringer-wartu (visited on 05/23/2022).

Hahn, Hans Jürgen (1996). *Die Ökologie der Sedimente eines Buntsandsteinbaches im Pfälzerwald unter besonderer Berücksichtigung der Ostracoden und Harpacticoiden (Crustacea)*. 62nd ed. Marburg: Tectum-Verlag, p. 264. ISBN: 3-89608-362-7.

– (2002). "Methods of sampling stygofauna". In: *Field Screening Europe 2001*. Ed. by Wolfgang Breh, Johannes Gottlieb, Heinz Hötzl, Frieder Kern, Tanja Liesch, and Reinhard Niessner. 1st ed. Kluwer Academic Publishers, pp. 201–205. ISBN: 978-94-010-0564-7. DOI: https://doi.org/10.1007/978-94-010-0564-7.

– (2005). "Unbaited phreatic traps: A new method of sampling stygofauna". In: *Limnologica* 35.4, pp. 248–261. ISSN: 00759511. DOI: 10.1016/j.limno.2005.04.004.

– (2006). "A first approach to a quantitative ecological assessment of groundwater habitats: The GW-Fauna-Index". In: *Limnologica* 36.2, pp. 119–137.

– (2015). "Grundwasser - die Tiefsee des Festlandes". In: *Wissenschaftsgesellschaft Pfalz 90 Jahre Pfälzische Gesellschaft zur Förderung der Wissenschaft*. Ed. by Alexa Strittmatter. Ubstadt-Weiher/Heidelberg/Neustadt a. d. W./Basel: Verlag Regionalkultur, pp. 119–131. ISBN: 9783897359031.

Hahn, Hans Jürgen and Andreas Fuchs (2009). "Distribution patterns of groundwater communities across aquifer types in south-western Germany". In: *Freshwater Biology* 54.4, pp. 848–860. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2008.02132.x.

Hahn, Hans Jürgen, Andreas Fuchs, and Sven E. Berkhoff (2020). *Biomonitoring Nitrat 2020 in Sachsen-Anhalt*. Tech. rep. Landau in der Pfalz: Landesbetriebes für Hochwasserschutz und Wasserwirtschaft Sachsen-Anhalt, p. 71.

Hahn, Hans Jürgen and Simon Gutjahr (2014). "Bioindikation im Grundwasser funktioniert – Erwiderung zum Kommentar von T. Scheytt zum Beitrag „Grundwasserfauna als Indikator für komplexe hydrogeologische Verhältnisse am westlichen Kaiserstuhl“ von Gutjahr, S., Bork, J. Hahn, H.J. in Grundwasser 18 ". In: *Grundwasser* 19.3, pp. 215–218. ISSN: 1430483X. DOI: 10.1007/s00767-014-0266-4.

Hahn, Hans Jürgen and Dirk Matzke (2005). "A comparison of stygofauna communities inside and outside groundwater bores". In: *Limologica* 35, pp. 31–44.

Hahn, Hans Jürgen, Dirk Matzke, Annette Kolberg, and Alexander Limberg (2013). "Untersuchung zur Fauna des Berliner Grundwassers – erste Ergebnisse". In: *Brandenburgische Geowissenschaftliche Beiträge* 20, pp. 85–92.

Hahn, Hans Jürgen, Christian Schweer, and Christian Griebler (2018). "Grundwasserökosysteme im Recht?" In: *Grundwasser* 23.3, pp. 209–218. ISSN: 1430483X. DOI: 10.1007/s00767-018-0394-3.

Hähnlein, Stefanie, Peter Bayer, and Philipp Blum (2010). "International legal status of the use of shallow geothermal energy". In: *Renewable and Sustainable Energy Reviews* 14.9, pp. 2611–2625. ISSN: 13640321. DOI: 10.1016/j.rser.2010.07.069. URL: http://dx.doi.org/10.1016/j.rser.2010.07.069.

Hähnlein, Stefanie, Peter Bayer, Grant Ferguson, and Philipp Blum (2013). "Sustainability and policy for the thermal use of shallow geothermal energy". In: *Energy Policy* 59, pp. 914–925. ISSN: 03014215. DOI: 10.1016/j.enpol.2013.04.040. URL: http://dx.doi.org/10.1016/j.enpol.2013.04.040.

Hallam, F., Mohammed Yacoubi-Khebiza, Khalid Oufdou, and Mohamed Boulanouar (2008). "Groundwater quality in an arid area of Morocco: Impact of pollution on the biodiversity and relationships between crustaceans and bacteria of health interest". In: *Environmental Technology* 29.11, pp. 1179–1189. ISSN: 1479487X. DOI: 10.1080/09593330802180237.

Hancock, Peter J. (2002). "Human impacts on the stream-groundwater exchange zone". In: *Environmental Management* 29.6, pp. 763–781. ISSN: 0364152X. DOI: 10.1007/s00267-001-0064-5.

Hancock, Peter J. and Andrew J. Boulton (2008). "Stygofauna biodiversity and endemism in four alluvial aquifers in eastern Australia". In: *Invertebrate Systematics* 22.2, pp. 117–126. ISSN: 14455226. DOI: 10.1071/IS07023.

Hancock, Peter J., Andrew J. Boulton, and William F. Humphreys (2005). “Aquifers and hyporheic zones: Towards an ecological understanding of groundwater”. In: *Hydrogeology Journal* 13.1, pp. 98–111. ISSN: 14312174. DOI: 10.1007/s10040-004-0421-6.

Hartland, Adam, Graham D. Fenwick, and Sarah J. Bury (2011). “Tracing sewage-derived organic matter into a shallow groundwater food web using stable isotope and fluorescence signatures”. In: *Marine and Freshwater Research* 62.2, pp. 119–129. ISSN: 13231650. DOI: 10.1071/MF10110.

Harvey, Mark S. (2002). “Short-range endemism among the Australian fauna: some examples from non-marine environments”. In: *Invertebrate Systematics* 16.4, pp. 555–570. DOI: https://doi.org/10.1071/IS02009.

Hatton, Thomas J. and R. Evans (1998). *Dependence of Ecosystems on Groundwater and its Significance to Australia*. Tech. rep. Canberra: Land, Water Resources Research, and Development Corporation.

Hebert, Paul D.N., Sujeevan Ratnasingham, and Jeremy R. De Waard (2003). “Barcoding animal life: Cytochrome c oxidase subunit 1 divergences among closely related species”. In: *Proceedings of the Royal Society B: Biological Sciences* 270.SUPPL. 1, pp. 96–99. ISSN: 14712970. DOI: 10.1098/rsbl.2003.0025.

Hekmatara, M., Valerija Zakšek, M. Heidari Baladehi, and Cene Fišer (2013). “Two new species of Niphargus (Crustacea: Amphipoda) from Iran”. In: *Journal of Natural History* 47.21-22, pp. 1421–1449. ISSN: 00222933. DOI: 10.1080/00222933.2012.743616.

Herrmann, Jan (1985). “Temperature dependence of reproduction in Dendrocoelum lacteum (Turbellaria): an experimental approach”. In: *Oikos* 44.2, pp. 268–272.

Hertzog, L. (1933). “Bogidiella albertimagni sp. nov., ein neuer Grundwasseramphipode aus der Rheinebene bei Strassburg”. In: *Zoologischer Anzeiger* 102.9/10, pp. 225–227.

Hervant, Frédéric and Florian Malard (1999). “Oxygen supply and the adaptations of animals in groundwater”. In: *Freshwater Biology* 41.1, pp. 1–30. ISSN: 00465070. DOI: 10.1046/j.1365-2427.1999.00379.x.

Heyde, Mieke van der, Nicole E. White, Paul Nevill, Andrew D. Austin, Nicholas Stevens, Matt Jones, and Michelle T. Guzik (2023). “Taking eDNA underground: Factors affecting eDNA detection of subterranean fauna in groundwater”. In: *Molecular Ecology Resources* 23, pp. 1257–1274. ISSN: 17550998. DOI: 10.1111/1755-0998.13792.

Hichem, Khammar, Hadjab Ramzi, and Merzoug Djemoi (2019). “Biodiversity and distribution of groundwater fauna in the oum-el-bouaghi region (Northeast of Algeria)”. In: *Biodiversitas* 20.12, pp. 3553–3558. ISSN: 20854722. DOI: 10.13057/biodiv/d201213.

Holsinger, John R. and Glenn Longley (1980). *The subterranean amphipod crustacean fauna of an artesian well in Texas*. 308. Washington: Smithsonian Institution Press, p. 72. DOI: 10.5479/si.00810282.308.

Hose, Grant C., Maria G. Asmyhr, Steven John Baynard Cooper, and William F. Humphreys (2014). “Down under down under: Austral groundwater life”. In: *Austral Ark: The State of Wildlife in Australia and New Zealand*. Ed. by Adam Stow, Norman Maclean, and Gregory I. Holwell. Cambridge: Cambridge University Press. Chap. 24, pp. 512–536. ISBN: 9781139519960. DOI: 10.1017/CBO9781139519960.026. URL: https://www.cambridge.org/core/books/austral-ark/down-under-down-under-austral-groundwater-life/9A76DD71E4B5B99831D355227516AE83.

Hose, Grant C., Anthony A. Chariton, Michiel A. Daam, Tiziana Di Lorenzo, Diana Maria Paola Galassi, Stuart A. Halse, Ana Sofia P.S. Reboleira, Anne L. Robertson, Susanne I. Schmidt, and Kathryn L. Korbel (2022). “Invertebrate traits, diversity and the vulnerability of groundwater ecosystems”. In: *Functional Ecology* 36, pp. 2200–2214. ISSN: 13652435. DOI: 10.1111/1365-2435.14125.

Hose, Grant C. and M. J. Lategan (2012). *Sampling strategies for biological assessment of groundwater ecosystems - CRC CARE Technical Report*. Tech. rep. 21. Adelaide: Cooperative Research Centre for Contamination Assessment and Remediation of the Environment, p. 32.

Hose, Grant C., Janardhanan Sreekanth, Olga Barron, and Carmel Pollino (2015). *Stygofauna in Australian groundwater systems: Extent of knowledge*. CSIRO, p. 71.

Hose, Grant C. and Christine Stumpp (2019). “Architects of the underworld: bioturbation by groundwater invertebrates influences aquifer hydraulic properties”. In: *Aquatic Sciences* 81.1, pp. 1–9. ISSN: 14209055. DOI: 10.1007/s00027-018-0613-0. URL: http://dx.doi.org/10.1007/s00027-018-0613-0.

Humphreys, William F. (2001). “Groundwater calcrete aquifers in the Australian arid zone: the context to an unfolding plethora of stygal biodiversity”. In: *Records of the Western Australian Museum Supplement* 64.1, pp. 63–83. ISSN: 0313-122X. DOI: 10.18195/issn.0313-122x.64.2001.063-083.

– (2006). “Aquifers: The ultimate groundwater-dependent ecosystems”. In: *Australian Journal of Botany* 54.2, pp. 115–132. ISSN: 00671924. DOI: 10.1071/BT04151.

– (2009). “Hydrogeology and groundwater ecology: Does each inform the other?” In: *Hydrogeology Journal* 17.1, pp. 5–21. ISSN: 14312174. DOI: 10.1007/s10040-008-0349-3.

Hunkeler, Daniel, Nico Goldscheider, Pierre Rossi, and Christine Burn (2006). *Biozönosen im Grundwasser - Grundlagen und Methoden der Charakterisierung von mikrobiellen Gemeinschaften*. Umwelt-Wis. Bern: Bundesamt für Umwelt (BAFU), p. 113.

Husana, Daniel Edison and Masumi Yamamuro (2013). “Groundwater quality in karst regions in the Philippines”. In: *Limnology* 14.3, pp. 293–299. ISSN: 14398621. DOI: 10.1007/s10201-013-0398-8.

Issartel, Julien, Frédéric Hervant, Yann Voituron, David Renault, and Philippe Vernon (2005). “Behavioural, ventilatory and respiratory responses of epigean and hypogean crustaceans to different temperatures”. In: *Comparative Biochemistry and Physiology Part A* 141.1, pp. 1–7. DOI: 10.1016/j.cbpb.2005.02.013.

Janetzka, W., R. Enderle, and W. Noodt (1996). *Crustacea: Copepoda: Gelyelloida and Harpacticoida – Süßwasserfauna von Mitteleuropa*. 8/4-2. Stuttgart: Gustav Fischer Verlag Stuttgart, p. 228. ISBN: 3-437-30741-X.

Job, Charles A. (2022). *Production, Use, and Sustainability of Groundwater: Groundwater Economics*. 2nd ed. Vol. 1. CRC Press, p. 435. ISBN: 9780429552793.

Jones, Clive G., John H. Lawron, and Moshe Shachak (1997). “Positive and negative effects of organisms as physical ecosystem engineers”. In: *Ecology* 78.7, pp. 1946–1957. ISSN: 00129658. DOI: 10.1890/0012-9658(1997)078[1946:PANEOO]2.0.CO;2.

Juberthie, Christian (2000). “The diversity of the karstic and pseudokarstic hypogean habitats in the world”. In: *Ecosystems of the World 30. Subterranean Ecosystems*. Ed. by H. Wilkens, David C. Culver, and William F. Humphreys. Amsterdam: Elsevier, pp. 17–39.

Karaman, Stanko L. (1933). “Über zwei neue Amphipoden, Balcanella und Jugocrangonyx aus dem Grundwasser von Skopje”. In: *Zoologischer Anzeiger* 103, pp. 41–47.

Karanovic, Ivana and Pierre Marmonier (2003). “Three new genera and nine new species of the subfamily Candoninae (Crustacea, Ostracoda, Podocopida) from the Pilbara region (Western Australia)”. In: *Beaufortia* 53.1, pp. 1–51. ISSN: 0067-4745. URL: http://www.repository.naturalis.nl/record/505207%5Cnhttp://www.repository.naturalis.nl/document/548864.

Karanovic, Tomislav (2006). “Subterranean copepods (Crustacea, Copepoda) from the Pilbara region in Western Australia”. In: *Records of the Western Australian Museum, Supplement* 70.1, p. 239. ISSN: 0313-122X. DOI: 10.18195/issn.0313-122x.70.2006.001-239.

– (2020). “Four new cyclopina (Copepoda, cyclopinidae) from South Korea”. In: *ZooKeys* 992, pp. 59–104. ISSN: 13132970. DOI: 10.3897/zookeys.992.54856. URL: http://zoobank.org/E604D905-F161-482D-9944-75496EEFF427.

Karanovic, Tomislav, Mark J. Grygier, and Wonchoel Lee (2013). *Endemism of subterranean Diacyclops in Korea and Japan, with descriptions of seven new species of the languidoides-group and redescriptions of D. brevifurcus Ishida, 2006 and D. suoensis Ito, 1954 (Crustacea, Copepoda, Cyclopoida)*. Vol. 267, pp. 1–76. ISBN: 8950757680. DOI: 10.3897/zookeys.267.3935.

Karanovic, Tomislav, Kichoon Kim, and Mark J. Grygier (2015). “A new species of Schizopera (Copepoda: Harpacticoida) from Japan, its phylogeny based on the mtCOI gene and comments on the genus Schizoperopsis”. In: *Journal of Natural History* 49.41-42, pp. 2493–2526. ISSN: 14645262. DOI: 10.1080/00222933.2015.1028112. URL: http://dx.doi.org/10.1080/00222933.2015.1028112.

Karanovic, Tomislav and Wonchoel Lee (2012). “A new species of Parastenocaris from Korea, with a redescription of the closely related P. biwae from Japan (Copepoda: Harpacticoida:

Parastenocarididae)”. In: *Journal of Species Research* 1.1, pp. 4–34. ISSN: 2234-7909. DOI: 10.12651/jsr.2012.1.1.004.

Karanovic, Tomislav and Y. Ranga Ready (2004). “A new genus and species of the family diosaccidae (Copepoda: Harpacticoida) from the groundwaters of India”. In: *Journal of Crustacean Biology* 24.2, pp. 246–260. ISSN: 02780372. DOI: 10.1651/C-2433.

Karanovic, Tomislav, Hyunsu Yoo, and Wonchoel Lee (2012). “A new cyclopoid copepod from Korean subterranean waters reveals an interesting connection with the Central Asian fauna (Crustacea: Copepoda: Cyclopoida)”. In: *Journal of Species Research* 1.2, pp. 156–174. ISSN: 2234-7909. DOI: 10.12651/jsr.2012.1.2.156.

Kiefer, Friedrich (1957). “Die Grundwasserfauna des Oberrheingebietes mit besonderer Berücksichtigung der Crustaceen”. In: *Beitr.Naturk.Forsch.Südwestdeutsch.* 16.2, pp. 65–90.

Kinsey, Jennifer, Timothy J. Cooney, and Kevin S. Simon (2007). “A comparison of the leaf shredding ability and influence on microbial films of surface and cave forms of Gammarus minus Say”. In: *Hydrobiologia* 589.1, pp. 199–205. ISSN: 00188158. DOI: 10.1007/s10750-007-0739-x.

Knight, Lee R.F.D. and Marcin R. Penk (2010). “Groundwater crustacea of Ireland: A survey of the stygobitic Malacostraca in caves and springs”. In: *Biology and Environment* 110.3, pp. 211–235. ISSN: 07917945. DOI: 10.3318/BIOE.2010.110.3.211.

Koch, Fabien, Philipp Blum, Kathryn L. Korbel, and Kathrin Menberg (2022). “Global overview on groundwater fauna”. In: *Ecohydrology* 17.1, pp. 1–28. DOI: 10.1002/eco.2607. URL: https://onlinelibrary.wiley.com/doi/epdf/10.1002/eco.2607.

Koch, Fabien, Kathrin Menberg, Svenja Schweikert, Cornelia Spengler, Hans Jürgen Hahn, and Philipp Blum (2021). “Groundwater fauna in an urban area - Natural or affected?” In: *Hydrology and Earth System Sciences* 25.6, pp. 3053–3070. ISSN: 16077938. DOI: 10.5194/hess-25-3053-2021.

Korbel, Kathryn L., Anthony Chariton, Sarah Stephenson, Paul Greenfield, and Grant C. Hose (2017). “Wells provide a distorted view of life in the aquifer: Implications for sampling, monitoring and assessment of groundwater ecosystems”. In: *Scientific Reports* 7.40702, pp. 1–14. ISSN: 20452322. DOI: 10.1038/srep40702. URL: http://dx.doi.org/10.1038/srep40702.

Korbel, Kathryn L., Anthony A. Chariton, and Grant C. Hose (2018). “Biotic distribution within groundwater- is it really unpredictable?” In: *ARPHA Conference Abstracts* 1, pp. 1–2. DOI: 10.3897/aca.1.e29806.

Korbel, Kathryn L., Paul Greenfield, and Grant C. Hose (2022a). “Agricultural practices linked to shifts in groundwater microbial structure and denitrifying bacteria”. In: *Science of the Total Environment* 807, p. 150870.

Korbel, Kathryn L., Peter J. Hancock, P. Serov, R. P. Lim, and Grant C. Hose (2013a). “Groundwater Ecosystems Vary with Land Use across a Mixed Agricultural Landscape”. In:

Journal of Environmental Quality 42.2, pp. 380–390. ISSN: 00472425. DOI: 10.2134/jeq2012.0018.

Korbel, Kathryn L. and Grant C. Hose (2011). "A tiered framework for assessing groundwater ecosystem health". In: *Hydrobiologia* 661.1, pp. 329–349. ISSN: 00188158. DOI: 10.1007/s10750-010-0541-z.

– (2015). "Habitat, water quality, seasonality, or site? Identifying environmental correlates of the distribution of groundwater biota". In: *Freshwater Science* 34.1, pp. 329–342. ISSN: 21619565. DOI: 10.1086/680038.

– (2017). "The weighted groundwater health index: Improving the monitoring and management of groundwater resources". In: *Ecological Indicators* 75, pp. 164–181. ISSN: 1470160X. DOI: 10.1016/j.ecolind.2016.11.039. URL: http://dx.doi.org/10.1016/j.ecolind.2016.11.039.

Korbel, Kathryn L., R. P. Lim, and Grant C. Hose (2013b). "An inter-catchment comparison of groundwater biota in the cotton-growing region of north-western New South Wales". In: *Crop and Pasture Science* 64.11-12, pp. 1195–1208. ISSN: 18360947. DOI: 10.1071/CP13176.

Korbel, Kathryn L., Kitty McKnight, Paul Greenfield, Brad Angel, Mark Adams, Anthony A. Chariton, and Grant C. Hose (2022b). *Bioassessment of groundwater ecosystems I. Sampling methods and analysis of eDNA for microbes and stygofauna in shallow alluvial aquifers*. Tech. rep. Canberra: Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas, Large Coal Mining Development through the Department of Climate Change, Energy, the Environment, and Water, p. 116.

Korbel, Kathryn L., Helen Rutlidge, Grant C. Hose, Stefan M. Eberhard, and Martin S. Andersen (2022c). "Dynamics of microbiotic patterns reveal surface water groundwater interactions in intermittent and perennial streams". In: *Science of The Total Environment* 811, p. 152380.

Korbel, Kathryn L., Sarah Stephenson, and Grant C. Hose (2019). "Sediment size influences habitat selection and use by groundwater macrofauna and meiofauna". In: *Aquatic Sciences* 81.39, p. 10. ISSN: 14209055. DOI: 10.1007/s00027-019-0636-1. URL: https://doi.org/10.1007/s00027-019-0636-1.

Kristensen, Peter, Caroline Whalley, Fernanda Néry Nihat Zal, and Trine Christiansen (2018). *European waters: Assessment of status and pressures 2018*. Tech. rep. 7. Copenhagen: European Union, European Environment Agency, pp. 1–373.

Kuchroo, Manik et al. (2022). "Multiscale PHATE identifies multimodal signatures of COVID-19". In: *Nature Biotechnology* 40.5, pp. 681–691. ISSN: 15461696. DOI: 10.1038/s41587-021-01186-x.

Kühlers, Dirk, Matthias Maier, and Karl Roth (2012). "Sanierung im Verborgenen". In: *TerraTech Sanierungspraxis* 3, pp. 14–16.

Kunkel, R, F Wendland, and S Hannappel (2004). *Die natürliche, ubiquitär überprägte Grundwasserbeschaffenheit in Deutschland*. 47th ed. Jülich: Schriften des Forschungszentrums Jülich (Forschungszentrum Jülich GmbH). ISBN: 3-89336-353-X.

Kuroda, Keisuke and Tetsuo Fukushi (2008). "Groundwater Management in Asian Cities". In: *Groundwater Management in Asian Cities*, pp. 125–149. DOI: 10.1007/978-4-431-78399-2. URL: http://books.google.com/books?id=GOn5dWDRtL4C&pgis=1.

Laid, Louze and Bendaira Zouheir (2018). "Diversite benthique et qualite des eaux souterraine de la region D'Ain M'Lila". PhD thesis. Universite de Larbi Bn M'Hidi, p. 81.

Landesanstalt für Umwelt Messungen und Naturschutz Baden-Württemberg (2013). *Leitfaden Grundwasserprobennahme*. Tech. rep. LUBW, p. 52. URL: http://www.lubw.baden-wuerttemberg.de/servlet/is/6638/.

– (2020). *Jahresdatenkatalog Grundwasser*. URL: http://jdkgw.lubw.baden-wuerttemberg.de/servlet/is/200/.

– (2022). *Jahresdatenkatalog Grundwasser*. URL: http://jdkgw.lubw.baden-wuerttemberg.de/servlet/is/200/?csrt=11385035495993194480 (visited on 10/18/2022).

Lang, Ulrich, Randolf Rausch, and Thomas Gudera (2004). "Modellierung der großräumigen Grundwasserströmungsverhältnisse im Bereich der Heilbronner Mulde". In: URL: https://www.researchgate.net/publication/329542726.

Larned, Scott T. (2012). "Phreatic groundwater ecosystems: Research frontiers for freshwater ecology". In: *Freshwater Biology* 57.5, pp. 885–906. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2012.02769.x.

Larned, Scott T., Thibault Datry, and Christopher T. Robinson (2007). "Invertebrate and microbial responses to inundation in an ephemeral river reach in New Zealand: Effects of preceding dry periods". In: *Aquatic Sciences* 69.4, pp. 554–567. ISSN: 10151621. DOI: 10.1007/s00027-007-0930-1.

Lefébure, Tristan, Christophe J. Douady, M. Gouy, Peter Trontelj, Jérôme Briolay, and Janine Gibert (2006). "Phylogeography of a subterranean amphipod reveals cryptic diversity and dynamic evolution in extreme environments". In: *Molecular Ecology* 15.7, pp. 1797–1806. ISSN: 09621083. DOI: 10.1111/j.1365-294X.2006.02888.x.

Lennon, Jayme (2019). "Inter catchment comparisons of groundwater communities from the Lower Murray Darling Basin". PhD thesis. Maquarie University, p. 70. ISBN: 9781119130536.

Lewis, Julian J. and Janet W. Reid (2007). "Patterns and processes of groundwater invasion by copepods in the interior low plateaus of the United States". In: *Acta Carsologica* 36.2, pp. 279–289. ISSN: 15802612. DOI: 10.3986/ac.v36i2.197.

Leys, Remko, Ben Roudnew, and Chris H.S. Watts (2010). "Paroster extraordinarius sp. nov., a new groundwater diving beetle from the Flinders Ranges, with notes on other diving beetles from gravels in South Australia (Coleoptera: Dytiscidae)”. In: *Australian Journal of Entomology* 49.1, pp. 66–72. ISSN: 13266756. DOI: 10.1111/j.1440-6055.2009.00738.x.

Leys, Remko, Chris H.S. Watts, Steven John Baynard Cooper, and William F. Humphreys (2003). “Evolution of subterranean diving beetles (Coleoptera: Dytiscidae: Hydroporini, Bidessini) in the arid zone of Australia”. In: *Evolution* 57.12, pp. 2819–2834. ISSN: 00143820. DOI: 10.1111/j.0014-3820.2003.tb01523.x.

Little, John, Daniel J. Schmidt, Benjamin D. Cook, Timothy J. Page, and Jane M. Hughes (2016). “Diversity and phylogeny of south-east Queensland Bathynellacea”. In: *Australian Journal of Zoology* 64.1, pp. 36–47. ISSN: 14465698. DOI: 10.1071/ZO16005.

MacDonald, F. (2017). “Assessment of the salinity/ stygofauna relationship and determinative elements of stygofauna habitats”. PhD thesis. Macquarie University.

Magbanua, Francis S. (2022). *Personal communication.*

Malard, Florian, Claude Boutin, Ana Isabel Camacho, David Ferreira, Georges Michel, Boris Sket, and Fabio Stoch (2009). “Diversity patterns of stygobiotic crustaceans across multiple spatial scales in Europe”. In: *Freshwater Biology* 54.4, pp. 756–776. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2009.02180.x.

Malard, Florian, Marie-José Dole-Olivier, Julien Mathieu, Fabio Stoch, Claude Boutin, Anton Brancelj, Ana Isabel Camacho, Frank Fiers, Diana Maria Paola Galassi, Janine Gibert, Tristan Lefébure, Peter Martin, Boris Sket, and Antonio G. Valdecasas (2002). *Sampling Manual for the Assessment of Regional Groundwater Biodiversity*. Tech. rep., p. 111. URL: www.eugris.info/displayresource.aspx?r=5247.

Malard, Florian, Christian Griebler, and Sylvie Rétaux (2023). *Groundwater Ecology and Evolution*. Ed. by Florian Malard, Christian Griebler, and Sylvie Rétaux. 2nd ed. Elsevier, p. 640. ISBN: 9780128191194. URL: https://shop.elsevier.com/books/groundwater-ecology-and-evolution/malard/978-0-12-819119-4.

Malard, Florian, Sandrine Plénet, and Janine Gibert (1996). “The use of Invertebrates in groundwater monitoring: A rising research field”. In: *Groundwater Monitoring Remediation* 16.2, pp. 103–113.

Malard, Florian, J. L. Reygrobellet, Jacques Mathieu, and Michel Lafont (1994). “The use of invertebrate communities to describe groundwater flow and contaminant transport in a fractured rock aquifer”. In: *Archiv für Hydrobiologie* 131.1, pp. 93–110.

Mamaghani-Shishvan, Mahmoud and Somayeh Esmaeili-Rineh (2019). “Two new species of groundwater amphipods of the genus Niphargus Schiödte, 1849 from northwestern Iran”. In: *European Journal of Taxonomy* 546, pp. 1–23. ISSN: 21189773. DOI: 10.5852/ejt.2019.546.

Margat, Jean and Jac van der Gun (2013). *Groundwater around the World: A Geographical Synopsis*. Boca Raton: CRC Press, Taylor Francis, p. 372. ISBN: 978-0-203-77214-0. URL:

https://www.un-igrac.org/sites/default/files/resources/files/Groundwater_around_world.pdf.

Marmonier, Pierre, Cécile Claret, and Marie-José Dole-Olivier (2000). "Interstitial fauna in newly-created floodplain canals of a large regulated river". In: *Regulated Rivers: Research Management* 16, pp. 23–36.

Marmonier, Pierre, Diana Maria Paola Galassi, Kathryn L. Korbel, Murray Close, Thibault Datry, and Clemens Karwautz (2023). "Groundwater biodiversity and constraints to biological distribution". In: *Groundwater Ecology and Evolution*. Ed. by Florian Malard, Christian Griebler, and Sylvie Rétaux. 2nd ed. Elsevier. Chap. 5, pp. 113–140. ISBN: 978-0-12-819119-4.

Marmonier, Pierre, Chafik Maazouzi, Nicole Baran, Simon Blanchet, Amy Ritter, Maritxu Saplairoles, Marie-José Dole-Olivier, Diana Maria Paola Galassi, David Eme, Sylvain Dolédec, and Christophe Piscart (2018). "Ecology-based evaluation of groundwater ecosystems under intensive agriculture: A combination of community analysis and sentinel exposure". In: *Science of the Total Environment* 613-614, pp. 1353–1366. ISSN: 18791026. DOI: 10.1016/j.scitotenv.2017.09.191.

Marmonier, Pierre, Philippe Vervier, Janine Gibert, and Marie-José Dole-Olivier (1993). "Biodiversity in ground waters". In: *Trends in Ecology and Evolution* 8.11, pp. 392–395. ISSN: 01695347. DOI: 10.1016/0169-5347(93)90039-R.

Martin, Patrick, Claude De Broyer, Frank Fiers, Georges Michel, Rose Sablon, and Karel Wouters (2009). "Biodiversity of Belgian groundwater fauna in relation to environmental conditions". In: *Freshwater Biology* 54.4, pp. 814–829. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2008.01993.x.

Martinez, Alejandro, Nikoleta Anicic, Salvatore Calvaruso, Nuria Sanchez, Laura Puppieni, Tommaso Sforzi, Silvia Zaupa, Fernando Alvarez, Dávid Brankovits, Ludwik Gasiorowski, Vasilis Gerovasileiou, Brett Gonzalez, William F. Humphreys, Thomas Iliffe, Katrine Worsaae, Nicolas Bailly, and Diego Fontaneto (2018). "A new insight into the Stygofauna Mundi: assembling a global dataset for aquatic fauna in subterranean environments". In: *ARPHA Conference Abstracts*. Vol. 1. Pensoft Publishers, e29514. DOI: 10.3897/aca.1.e29514.

Matsumoto, Kôichi (1976). "An introduction to the Japanese groundwater animals with reference to their ecology and hygienic significance". In: *International Journal of Speleology* 8, pp. 141–155. ISSN: 0392-6672. DOI: 10.5038/1827-806x.8.1.13.

Matzke, Dirk (2006). "Untersuchungen zum Verhalten von Grundwasserfauna in Altlastflächen mit vorangegangenem Vergleich unterschiedlicher Sammeltechniken." PhD thesis. Universität Koblenz-Landau, p. 229.

Matzke, Dirk, Andreas Fuchs, Sven E. Berkhoff, Jörg Bork, and Hans Jürgen Hahn (2009). *Erhebung und Bewertung der Grundwasserfauna Sachsen-Anhalts*. Tech. rep. Landau in der Pfalz: Institut für Grundwasserökologie GbR, p. 100.

Maurice, Louise (2009). *Groundwater Ecology Literature: Review*. Tech. rep., p. 37. URL: http://nora.nerc.ac.uk/id/eprint/14751.

Meisch, C. (2000). *Freshwater Ostracoda of Western and Central Europe - Süßwasserfauna von Mitteleuropa*. 8/3. Heidelberg: Spektrum Akademischer Verlag. ISBN: 3827410010.

Meissner, Richard and P.M. Mampane (2009). "Global freshwater quantity, quality and distribution". In: *Future Challenges of Providing High-Quality Water*. Ed. by Jo-Ansie van Wyk, Richard Meissner, and Hannatjie Jacobs. 2nd ed. EOLSS Publications, p. 268. ISBN: 1848262302.

Menberg, Kathrin, Peter Bayer, Kai Zosseder, Sven Rumohr, and Philipp Blum (2013a). "Subsurface urban heat islands in German cities". In: *Science of the Total Environment* 442, pp. 123–133. ISSN: 00489697. DOI: 10.1016/j.scitotenv.2012.10.043. URL: http://dx.doi.org/10.1016/j.scitotenv.2012.10.043.

Menberg, Kathrin, Philipp Blum, B. L. Kurylyk, and Peter Bayer (2014). "Observed groundwater temperature response to recent climate change". In: *Hydrology and Earth System Sciences* 18.11, pp. 4453–4466. ISSN: 16077938. DOI: 10.5194/hess-18-4453-2014.

Menberg, Kathrin, Philipp Blum, Axel Schaffitel, and Peter Bayer (2013b). "Long-term evolution of anthropogenic heat fluxes into a subsurface urban heat island". In: *Environmental Science and Technology* 47.17, pp. 9747–9755. ISSN: 0013936X. DOI: 10.1021/es401546u.

Menció, Anna, Kathryn L. Korbel, and Grant C. Hose (2014). "River-aquifer interactions and their relationship to stygofauna assemblages: A case study of the Gwydir River alluvial aquifer (New South Wales, Australia)". In: *Science of the Total Environment* 479-480.1, pp. 292–305. ISSN: 00489697. DOI: 10.1016/j.scitotenv.2014.02.009. URL: http://dx.doi.org/10.1016/j.scitotenv.2014.02.009.

Mermillod-Blondin, Florian, Magali Gérino, Michel Creuzé Des Châtelliers, and Valérie Degrange (2002). "Functional diversity among 3 detritivorous hyporheic invertebrates: An experimental study in microcosms". In: *Journal of the North American Benthological Society* 21.1, pp. 132–149. ISSN: 08873593. DOI: 10.2307/1468305.

Mermillod-Blondin, Florian, Grant C. Hose, Kevin S. Simon, Kathryn L. Korbel, Maria Avramov, and R. Vander Vorste (2023). "Role of invertebrates in groundwater ecosystem processes and services". In: *Groundwater Ecology and Evolution*. Ed. by Florian Malard, Christian Griebler, and Sylvie Rétaux. 2nd ed. Elsevir. Chap. 11, pp. 263–281. ISBN: 978-0-12-819119-4.

Mermillod-Blondin, Florian and Rutger Rosenberg (2006). "Ecosystem engineering: The impact of bioturbation on biogeochemical processes in marine and freshwater benthic habitats". In: *Aquatic Sciences* 68.4, pp. 434–442. ISSN: 10151621. DOI: 10.1007/s00027-006-0858-x.

Merzoug, Djémoi, A. Khiari, Ali Aït Boughrous, and Claude Boutin (2011). "Faune aquatique et qualité de l'eau des puits et sources de la région d'Oum-El-Bouaghi (Nord-Est algérien)". In: *Hydroecologie Appliquee* 17, pp. 77–97. ISSN: 1958556X. DOI: 10.1051/hydro/2010001.

Merzoug, Djémoi, A. Khiari, Lahbib Tamrabet, and M. Saheb (2014). “Bio-Evaluation de la qualite des eaux souterraines: Cas de la nappe phreatique Mechta Lehteb region d’Oum-El-Bouaghi (Nord-Est de l’Algerie) Bio-evaluation Of The Groundwater Quality : Case Of Mechta Lehteb (oum Ebouaghi, Neast Algeria)”. In: *Le Journal de l’Eau et de l’Environnement* 7.13, pp. 92–104. URL: https://www.asjp.cerist.dz/en/article/39413.

Millennium Ecosystem Assessment (2005). *Millennium Ecosystem Assessment: Ecosystem and Human Well-Being: Wetlands and Water Synthesis*. Washington, D.C.: World Reesources Institute, p. 80. ISBN: 1-56973-597-2.

Moniez, R. (1889). “Faune des eaux souterraines du Department du Nord et en particulier de la ville de Lille”. In: *Extrait de la Revue Biologique du Nord de la France* 1, p. 70.

Moog, Otto (2002). *Fauna Aquatica Austriaca Katalog zur autökologischen Einstufung aquatischer Organismen Österreichs*. Tech. rep. Wien: Wasserwirtschaftskataster, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft. Wien, Österreich, p. 670.

Moon, Kevin R., David van Dijk, Zheng Wang, Scott Gigante, Daniel B. Burkhardt, William S. Chen, Kristina Yim, Antonia van den Elzen, Matthew J. Hirn, Ronald R. Coifman, Natalia B. Ivanova, Guy Wolf, and Smita Krishnaswamy (2019). “Visualizing structure and transitions in high-dimensional biological data”. In: *Nature Biotechnology* 37.12, pp. 1482–1492. ISSN: 15461696. DOI: 10.1038/s41587-019-0336-3. URL: http://dx.doi.org/10.1038/s41587-019-0336-3.

Moore, Willard S. (1999). “The subterranean estuary: A reaction zone of ground water and sea water”. In: *Marine Chemistry* 65.1-2, pp. 111–125. ISSN: 03044203. DOI: 10.1016/S0304-4203(99)00014-6.

Mösslacher, F. and J. Notenboom (2000). “Groundwater biomonitoring”. In: *Biomonitoring of polluted water*. Ed. by A. Gerhardt. Zurich-Uetikon: Trans Tech Publications Ltd, pp. 119–139. ISBN: 0878498451.

Mösslacher, Friederike (1998). “Subsurface Dwelling Crustaceans as Indicators of Hydrological Conditions, Oxygen Concentrations, and Sediment Structure in an Alluvial Aquifer”. In: *International Review of Hydrobiology* 83.4, pp. 349–364.

Mösslacher, Friederike, Christian Griebler, and Jos Notenboom (2001). “Biomonitoring of groundwater systems: Methods, applications and possible indicators among the groundwater biota.” In: *Groundwater ecology: A tool for management of water resources*. Ed. by Christian Griebler, Dan Luca Danielopol, Janine Gibert, Hans Peter Nachtnebel, and Jos Notenboom. European Communities, pp. 132–170.

Mösslacher, Friederike and Jos Notenboom (1999). “Groundwater biomonitoring”. In: *Environmental Science Forum* 96, pp. 119–140.

Motas, Constantin (1958). “Freatobiologia, o noura ramura a limnologiei [Phreatobiology, a new field of limnology]”. In: *Natura* 10, pp. 95–105.

Murphy, Nicholas P., Mark Adams, and Andrew D. Austin (2009). “Independent colonization and extensive cryptic speciation of freshwater amphipods in the isolated groundwater springs of Australia’s Great Artesian Basin”. In: *Molecular Ecology* 18.1, pp. 109–122. ISSN: 09621083. DOI: 10.1111/j.1365-294X.2008.04007.x.

Mylroie, John (2004). “Biospheleologists”. In: *Encyclopedia of Caves and Karst Science*. Ed. by John Gunn. Routledge, pp. 313–322. ISBN: 9781579583996.

Nelson, Tess (2020). “Factors influencing groundwater microbial communities across an intensive agricultural landscape”. PhD thesis. Macquarie University.

NGC (2004). *Improved management and protection of groundwater dependent ecosystems*. Tech. rep. Department of Environment and Heritage, Commonwealth of Australia.

Niemiller, Matthew L., Megan L. Porter, Jenna Keany, Heather Gilbert, Daniel W. Fong, David C. Culver, Christopher S. Hobson, K. Denise Kendall, Mark A. Davis, and Steven J. Taylor (2018). “Evaluation of eDNA for groundwater invertebrate detection and monitoring: a case study with endangered Stygobromus (Amphipoda: Crangonyctidae)”. In: *Conservation Genetics Resources* 10.2, pp. 247–257. ISSN: 18777260. DOI: 10.1007/s12686-017-0785-2.

Nogaro, Geraldine, Florian Mermillod-Blondin, Frederique François-Carcaillet, Jean Paul Gaudet, Michel Lafont, and Janine Gibert (2006). “Invertebrate bioturbation can reduce the clogging of sediment: An experimental study using infiltration sediment columns”. In: *Freshwater Biology* 51.8, pp. 1458–1473. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2006.01577.x.

Noll, Wilhelm (1939). “Die Grundwasserfauna des Maingebietes”. In: *Mitt.Naturwiss.Mus.Aschaffenburg* 1, pp. 3–25.

Notenboom, Jos (1991). “Marine regressions and the evolution of groundwater dwelling amphipods (Crustacea)”. In: *Journal of Biogeography* 18, pp. 437–454.

Notenboom, Jos and Ine Meijers (1985). *Investigaciones sobre la fauna de las aguas subterráneas de España: Lista de estaciones y primeros resultados*. Tech. rep. Amsterdam: Instituut voor Taxonomische Zoölogie Verslagen en Technische Gegevens., p. 94.

Notenboom, Jos, Roque Serrano, Ignacio Morell, and Felix Hernández (1995). “The phreatic aquifer of the ’Plana de Castellón’ (Spain):relationships between animal assemblages and groundwater pollution”. In: *Hydrobiologia* 297.3, pp. 241–249. ISSN: 00188158. DOI: 10.1007/BF00019288.

NSW Department of Planning and Environment (2022). *Draft Regional Water Strategy: Gwydir Strategy*. Tech. rep. NSW Department of Planning and Environment, p. 122. URL: https://www.industry.nsw.gov.au/__data/assets/pdf_file/0019/324514/draft-rws-lachlan.pdf.

Oberprieler, Stefanie, Gavin Rees, Daryl Nielsen, Michael Shackleton, Garth Watson, Lisa Chandler, and Jenny Davis (2021). “Connectivity, not short-range endemism, characterises the groundwater biota of a northern Australian karst system”. In: *Science of the Total Environment* 796, p. 148955. ISSN: 18791026. DOI: 10.1016/j.scitotenv.2021.148955. URL: https://doi.org/10.1016/j.scitotenv.2021.148955.

Patel, Meghana P., Bharat Gami, Akash Patel, Pankaj Patel, and Beena Patel (2020). “Climatic and anthropogenic impact on groundwater quality of agriculture dominated areas of southern and central Gujarat, India”. In: *Groundwater for Sustainable Development* 10, p. 100306. ISSN: 2352801X. DOI: 10.1016/j.gsd.2019.100306. URL: https://doi.org/10.1016/j.gsd.2019.100306.

Pesce, Guiseppe Lucio (1980). “Bogidiella aprutina n. sp., a new subterranean amphipod from phreatic waters of central Italy”. In: *Crustaceana* 38.2, pp. 139–144.

Pipan, Tanja and David C. Culver (2007). “Copepod distribution as an indicator of epikarst system connectivity”. In: *Hydrogeology Journal* 15.4, pp. 817–822. ISSN: 14312174. DOI: 10.1007/s10040-006-0114-4.

Pipan, Tanja, Louis Deharveng, and David C. Culver (2020). “Hotspots of subterranean biodiversity”. In: *Diversity* 12.209, pp. 1–5. ISSN: 14242818. DOI: 10.3390/D12050209.

Playford, P.E. (2001). *Subterranean biotas in Western Australia. Report for the EPA*. Tech. rep. Perth: Environmental Protection Authority.

Poore, Gary C. B. and William F. Humphreys (1998). “First record of Spelaeogriphacea from Australasia: a new genus and species from an aquifer in the arid Pilbara of Western Australia”. In: *Crustaceana* 71.7, pp. 721–742. DOI: 10.1163/156854098X00013.

Pospisil, Peter (1992). “Sampling methods for groundwater animals of unconsolidated sediments”. In: *Natural History of Biospeology*. Ed. by Ana I. Camacho. Volume 7 M. Madrid: CSIC Press, pp. 107–134. ISBN: 9788400072803.

– (1999). “The Composition of Cyclopoid Assemblages in Ecologically Different Groundwater Habitats of a Danube Riverine Wetland in Austria”. In: *Crustaceana* 72.8, pp. 883–892.

Preuß, Gudrun and Horst Kurt Schminke (2004). “Ein globales Ökosystem: Grundwasser lebt!” In: *Chemie in Unserer Zeit* 38.5, pp. 340–347. ISSN: 00092851. DOI: 10.1002/ciuz.200400307.

Price, Michael and A. Williams (1993). “A pumped double-packer system for use in aquifer evaluation and groundwater sampling”. In: *Proceedings of the Institution of Civil Engineers: Water, Maritime and Energy* 101.2, pp. 85–92. ISSN: 17537819. DOI: 10.1680/iwtme.1993.23589.

Proudlove, Graham S., Paul J. Wood, Paul T. Harding, David J. Horne, Terry Gledhill, and Lee R.F.D. Knight (2003). “A review of the status and distribution of the subterranean aquatic Crustacea of Britain and Ireland”. In: *Cave and Karst Science* 30.2, pp. 53–74. ISSN: 1356191X.

Racovitza, Emile G. (1907). *Essai sur les problèmes biospéologiques*. Schleicher frères, p. 18.

Ramzi, Hadjab, Khammar Hichem, Redjaimia Lylia, Merzoug Djemoi, and Saheb Menouar (2020). "Impact of Anthropic Pressure on the Quality and Diversity of Groundwater in the Region of Sighus Oum-El-Bouaghi and El Rahmounia, Algeria." In: *Journal of Bioresource Management* 7.3, pp. 85–105. ISSN: 2309-3854. DOI: 10.35691/jbm.0202.0142.

Rapoport, Eduardo H. (1982). *Areography Geographical Stategies of Species*. Oxford: Pergamon, p. 286. ISBN: 9781483152776.

Reboleira, Ana Sofia P.S., Nelson Abrantes, Pedro Oromí, and Fernando Gonçalves (2013). "Acute toxicity of copper sulfate and potassium dichromate on stygobiont proasellus: General aspects of groundwater ecotoxicology and future perspectives". In: *Water, Air, and Soil Pollution* 224.1550, pp. 1–9. ISSN: 15732932. DOI: 10.1007/s11270-013-1550-0.

Rees, Gavin, Stefanie Oberprieler, Daryl Nielsen, Garth Watson, Michael Shackleton, and Jenny Davis (2020). *Characterisation of the stygofauna and microbial assemblages of the Beetaloo Sub-Basin, Northern Territory*. Tech. rep. CSIRO, p. 67.

Regierungspräsidium Freiburg (2019). *LGRB-Kartenviewer – Layer GK50: Geologische Einheiten (Flächen)*. URL: https://maps.lgrb-bw.de/ (visited on 07/06/2020).

Rétaux, Sylvie and William R. Jeffery (2023). "Voices from the underground: animal models for the study of trait evolution during groundwater colonization and adaption". In: *Groundwater Ecology and Evolution*. Ed. by Florian Malard, Christian Griebler, and Sylvie Rétaux. 2nd ed. Academic Press Inc. London. Chap. 12, pp. 285–328. ISBN: 9780128191194. URL: https://shop.elsevier.com/books/groundwater-ecology-and-evolution/malard/978-0-12-819119-4.

Romano, Nicholas and Chaoshu Zeng (2013). "Toxic Effects of Ammonia, Nitrite, and Nitrate to Decapod Crustaceans: A Review on Factors Influencing their Toxicity, Physiological Consequences, and Coping Mechanisms". In: *Reviews in Fisheries Science* 21.1, pp. 1–21. ISSN: 10641262. DOI: 10.1080/10641262.2012.753404.

Romero, Aldemaro (2001). "Scientists prefer them blind: The history of hypogean fish research". In: *Environmental Biology of Fishes* 62.1-3, pp. 43–71. ISSN: 03781909. DOI: 10.1023/A:1011830329016.

Ross, Nathalie, Richard Villemur, Louise Deschênes, and Réjean Samson (2001). "Clogging of a limestone fracture by stimulating groundwater microbes". In: *Water Research* 35.8, pp. 2029–2037. ISSN: 00431354. DOI: 10.1016/S0043-1354(00)00476-0.

Rouch, Raymond (1986). "Sur l'écologie des eaux souterraines dans le karst". In: *Stygologia* 2, pp. 352–398.

Roudnew, Ben, Trish J. Lavery, Justin R. Seymour, Thomas C. Jeffries, and James G. Mitchell (2014). "Variability in bacteria and virus-like particle abundances during purging of unconfined aquifers". In: *Groundwater* 52.1, pp. 118–124.

Saccò, Mattia, Alison Blyth, Philip W. Bateman, Quan Hua, Debashish Mazumder, Nicole White, William F. Humphreys, Alex Laini, Christian Griebler, and Kliti Grice (2019). "New light in the dark - a proposed multidisciplinary framework for studying functional ecology of groundwater fauna". In: *Science of the Total Environment* 662, pp. 963–977. ISSN: 18791026. DOI: 10.1016/j.scitotenv.2019.01.296. URL: https://doi.org/10.1016/j.scitotenv.2019.01.296.

Saccò, Mattia, Alison J. Blyth, Grant Douglas, William F. Humphreys, Grant C. Hose, Jenny Davis, Michelle T. Guzik, Alejandro Martínez, Stefan M. Eberhard, and Stuart A. Halse (2022a). "Stygofaunal diversity and ecological sustainability of coastal groundwater ecosystems in a changing climate : The Australian paradigm". In: *Freshwater Biology* August, pp. 1–17. DOI: 10.1111/fwb.13987.

Saccò, Mattia, Alison J. Blyth, William F. Humphreys, Steven John Baynard Cooper, Nicole E. White, Matthew Campbell, Mahsa Mousavi-Derazmahalleh, Quan Hua, Debashish Mazumder, Colin Smith, Christian Griebler, and Kliti Grice (2021). "Rainfall as a trigger of ecological cascade effects in an Australian groundwater ecosystem". In: *Scientific Reports* 11.1, pp. 1–15. ISSN: 20452322. DOI: 10.1038/s41598-021-83286-x. URL: https://doi.org/10.1038/s41598-021-83286-x.

Saccò, Mattia, Alison J. Blyth, William F. Humphreys, Stéphane Karasiewicz, Karina T. Meredith, Alex Laini, Steven J.B. Cooper, Philip W. Bateman, and Kliti Grice (2020). "Stygofaunal community trends along varied rainfall conditions: Deciphering ecological niche dynamics of a shallow calcrete in Western Australia". In: *Ecohydrology* 13.1, pp. 1–19. ISSN: 19360592. DOI: 10.1002/eco.2150.

Saccò, Mattia, Alison J. Blyth, Michael Venarsky, and William F. Humphreys (2022b). "Trophic interactions in subterranean environments in reference module in earth systems and environmental sciences". In: *Encyclopedia of Inland Waters, Second Edition*. 3rd ed. Elsevier, pp. 537–547. ISBN: 978-012822041-2, 978-012819166-8. DOI: https://doi.org/10.1016/B978-0-12-819166-8.00064-5.

Saccò, Mattia, Michelle T. Guzik, Mieke Van der Heyde, Paul Nevill, Steven John Baynard Cooper, Andrew D. Austin, Peterson J. Coates, Morten E. Allentoft, and Nicole E. White (2022c). "eDNA in subterranean ecosystems: Applications, technical aspects, and future prospects". In: *Science of The Total Environment* 820, p. 153223. ISSN: 00489697. DOI: 10.1016/j.scitotenv.2022.153223.

Saccò, Mattia, William F. Humphreys, Nicholas Stevens, Matthew R. Jones, Fiona Taukulis, Erin Thomas, and Alison J. Blyth (2022d). "Subterranean carbon flows from source to stygofauna: a case study on the atyid shrimp Stygiocaris stylifera (Holthuis, 1960) from Barrow Island (WA)". In: *Isotopes in Environmental and Health Studies* 58.3, pp. 247–257. ISSN: 14772639. DOI: 10.1080/10256016.2022.2071873. URL: https://doi.org/10.1080/10256016.2022.2071873.

Sampat, Payal (2000). *Deep trouble: the hidden threat of groundwater pollution. W*. Washington DC.: Worldwatch Institute, p. 55.

Särkkä, Jukka, Leena Levonen, and Jorma Mäkelä (1998). "Harpacticoid and cyclopoid fauna of groundwater and springs in southern Finland". In: *Journal of Marine Systems* 15.1-4, pp. 155–161. ISSN: 09247963. DOI: 10.1016/S0924-7963(97)00075-4.

Särkkä, Jukka and Jorma Mäkelä (1998). "Troglochaetus beranecki Delachaux (Polychaeta, Archiannelida) in esker groundwaters of Finland: A new class of limnic animals for northern Europe". In: *Hydrobiologia* 379.1-3, pp. 17–21. ISSN: 00188158. DOI: 10.1023/a:1003292202048.

Sauermost, R. and D. Freudig (1999a). *Bathynellacea*. URL: https://www.spektrum.de/lexikon/biologie/bathynellacea/7445 (visited on 02/27/2019).

– (1999b). *Oligochaeta*. URL: https://www.spektrum.de/lexikon/biologie/oligochaeta/47593 (visited on 02/27/2019).

– (1999c). *Strudelwürmer*. URL: https://www.spektrum.de/lexikon/biologie/strudelwuermer/64369 (visited on 02/27/2019).

Sbordoni, Valerio, Giuliana Allegrucci, and Donatella Cesaroni (2000). "Population genetic structure, speciation and evolutionary rates in cave-dwelling organisms". In: *Subterranean Ecosystems*. Ed. by H Wilkens, David C Culver, and William F Humphreys. Elsivier. Chap. 24, pp. 459–483.

Scarsbrook, M. R. and G. D. Fenwick (2003). "Preliminary assessment of crustacean distribution patterns in New Zealand groundwater aquifers". In: *New Zealand Journal of Marine and Freshwater Research* 37.2, pp. 405–413. ISSN: 11758805. DOI: 10.1080/00288330.2003.9517176.

Scarsbrook, Mike R., Graham D. Fenwick, and John Radford (2000). "Living groundwater: studying the fauna beneath our feet". In: *Water and Atmosphere* 8.3, pp. 15–17.

Schellenberg, A. (1942). "Krebstiere oder Crustace, IV: Flohkebs oder Amphipoda". In: *Die Tierwelt Deutschlands und der angrenzenden Meeresteile nach ihren Merkmalen und nach ihrer Lebensweise*. Gustav Fischer Verlag Jena, p. 252.

Scheytt, Traugott (2014). "Kommentar zur Veröffentlichung von Gutjahr, S., Bork, J. und Hahn, H.J.: Grundwasserfauna als Indikator für komplexe hydrogeologische Verhältnisse am westlichen Kaiserstuhl in Grundwasser 18 (3), 173–184 (2013)". In: *Grundwasser* 19.3, pp. 211–213. ISSN: 1430483X. DOI: 10.1007/s00767-014-0267-3.

Schmidt, Susanne I., Hans Jürgen Hahn, Thomas J. Hatton, and William F. Humphreys (2007). "Do faunal assemblages reflect the exchange intensity in groundwater zones?" In: *Hydrobiologia* 583.1, pp. 1–19. ISSN: 00188158. DOI: 10.1007/s10750-006-0405-8.

Schmidt, Susanne I., Miroslava Svátková, Vit Kodeš, and Tanja Shabarova (2023). "Direct and indirect effects of the increase in atmospheric CO_2 and temperature on groundwater organisms". In: *bioRxiv*, p. 51. DOI: 10.1101/2023.09.13.557665. URL: https://doi.org/10.1101/2023.09.13.557665.

Schminke, Horst Kurt, G. Grad, W. Ahlrichs, I. Bartsch, H. Christl, R. Gerecke, P. Martin, P. Rumm, and J. W. Wägele (2007). *Grundwasserfauna Deutschlands - Ein Bestimmungswerk: DWA-Themen*. 1st ed. Hennef: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall, p. 628. ISBN: 3939057444.

Schnitter, Helmut and P. A. Chappuis (1914). "2. Parastenocaris fontinalis nov. spec, ein neuer Süßwasserharpacticide". In: *Zoologischer Anzeiger* 45, pp. 290–302.

Schönborn, Wilfried (2003). *Lehrbuch der Limnologie*. Stuttgart: Schwarzbart'sche Verlagsbuchhandlung, p. 588. ISBN: 3-510-65204-5.

Schönthaler, Konstanze and Stefan von Adrian-Werburg (2008). *Erster integrierter Umweltbericht für das länderübergreifende UNESCO-Biosphärenreservat Rhön*. Tech. rep. Oberrelsbach.

Schulz, Cameron, Alisha L. Steward, and Andrea Prior (2013). "Stygofauna presence within fresh and highly saline aquifers of the Border Rivers region in Southern Queensland". In: *Proceedings of the Royal Society of Queensland* 118, pp. 27–35. ISSN: 0080469X. DOI: 10.5962/p.357777.

Schweizerischer Bundesrat (1998). *Gewässerschutzverordnung*.

Schwoerbel, Jürgen (1961). "Subterrane Wassermilben (Acari: Hydrachnellae, Porohalacaridae und Stygothrombiidae), ihre Ökologie und Bedeutung für die Abgrenzung eines aquatischen Lebensraums zwischen Oberfläche und Grundwasser". In: *Archiv für Hydrobiologie* 25.42-3, pp. 242–306.

Shannon, C.E. and W. Weaver (1949). *The mathematical theory of communication*. The University of Illinois Press, p. 117.

Shiklomanov, I. A. and John C Rodda (2003). *World water resources at the beginning of the twenty-first century*. Cambridge: Cambridge University Press, p. 25. ISBN: 0521820855.

Siebert, Stefan, Jacob Burke, Jean Marc Faures, Karen Frenken, Jippe Hoogeveen, Petra Döll, and Felix T. Portmann (2010). "Groundwater use for irrigation - A global inventory". In: *Hydrology and Earth System Sciences* 14.10, pp. 1863–1880. ISSN: 10275606. DOI: 10.5194/hess-14-1863-2010.

Simon, K. S. and E. F. Benfield (2001). "Leaf and wood breakdown in cave streams". In: *Journal of the North American Benthological Society* 20, pp. 550–563.

Sinclair, J. L., D. H. Kampbell, M. L. Cook, and J. T. Wilson (1993). "Protozoa in subsurface sediments from sites contaminated with aviation gasoline or jet fuel". In: *Applied and Environmental Microbiology* 59.2, pp. 467–472. ISSN: 00992240. DOI: 10.1128/aem.59.2.467-472.1993.

Sinton, Lester W. (1984). "The Microinvertebrates in a sewage polluted aquifer". In: *Hydrobiologia* 119, pp. 161–169.

Sket, Boris (1999). "The nature of biodiversity in hypogean waters and how it is endangered". In: *Biodiversity and Conservation* 8.10, pp. 1319–1338. ISSN: 09603115. DOI: 10.1023/A:1008916601121.

– (2018). "Collecting and processing crustaceans of subterranean habitats". In: *Journal of Crustacean Biology* 38.3, pp. 380–384. ISSN: 1937240X. DOI: 10.1093/jcbiol/rux125.

Smith, Renee J., James S. Paterson, Elise Launer, Shanan S. Tobe, Eliesa Morello, Remko Leijs, Shashikanth Marri, and James G. Mitchell (2016). "Stygofauna enhance prokaryotic transport in groundwater ecosystems". In: *Scientific Reports* 6.Article No. 32738, pp. 1–7. ISSN: 20452322. DOI: 10.1038/srep32738.

Sorensen, James P.R., Louise Maurice, François K. Edwards, Daniel J. Lapworth, Daniel S. Read, Debbie Allen, Andrew S. Butcher, Lindsay K. Newbold, Barry R. Townsend, and Peter J. Williams (2013). "Using Boreholes as Windows into Groundwater Ecosystems". In: *PLoS ONE* 8.7, p. 13. ISSN: 19326203. DOI: 10.1371/journal.pone.0070264.

Spandl, Hermann (1926). *Die Tierwelt der unterirdischen Gewässer*. Wien: Speläologisches Institut Wien, p. 235.

Spengler, Cornelia (2017). "Die Auswirkungen von anthropogenen Temperaturerhöhungen auf die Crustaceagemeinschaften im Grundwasser". PhD thesis. Universität Koblenz-Landau, p. 226.

Spengler, Cornelia, A. Gerhardt, N. Rütz, S. van der Berg-Stein, Maria Avramov, V. Wolters, J. Marxen, Christian Griebler, and Hans Jürgen Hahn (2017). "Faunistische Grundwasserbewertung: Neue Verfahren und Möglichkeiten". In: *ReWaM: Regionales Wasserressourcen-Management* 15.5, pp. 272–279. DOI: 10.3243/kwe2017.05.001.

Spengler, Cornelia and Jürgen Hahn (2018). "Thermostress : Ökologisch begründete , thermische Schwellenwerte und Bewertungsansätze für das Grundwasser". In: *Korrespondenz Wasserwirtschaft: Fachbeiträge Gewässer und Böden* 11.9, pp. 521–525. DOI: 10.3243/kwe2018.09.001.

Stadt Karlsruhe (2006). *Bodenschutz- und Altlastenkataster der Stadt Karlsruhe*. URL: https://www.karlsruhe.de/b3/natur_und_umwelt/umweltschutz/altlasten.de (visited on 10/23/2019).

Stauffer, Fritz, Peter Bayer, Philipp Blum, Nelson Giraldo Molina, and Wolfgang Kinzelbach (2013). *Thermal use of shallow groundwater*. 1 st. Boca Raton: CRC Press, p. 287. ISBN: 978-1-4665-6019-2. DOI: https://doi.org/10.1201/b16239.

Stein, Heide, Sven Berkhoff, Andreas Fuchs, and Hans Jürgen Hahn (2015). *Ökologisches Dauermonitoring an ausgewählten Grundwassermessstellen in Baden-Württemberg*. Tech. rep. Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), p. 181.

Stein, Heide, Christian Griebler, Sven Berkhoff, Dirk Matzke, Andreas Fuchs, and Hans Jürgen Hahn (2012). "Stygoregions- a promising approach to a bioregional classification of groundwater systems". In: *Scientific Reports* 2, pp. 1–9. ISSN: 20452322. DOI: 10.1038/srep00673.

Stein, Heide, Claudia Kellermann, Susanne I. Schmidt, Heike Brielmann, Christian Steube, Sven E. Berkhoff, Andreas Fuchs, Hans Jürgen Hahn, Barbara Thulin, and Christian Griebler (2010). "The potential use of fauna and bacteria as ecological indicators for the assessment of groundwater quality". In: *Journal of Environmental Monitoring* 12.1, pp. 242–254. ISSN: 14640325. DOI: 10.1039/b913484k.

Steube, Christian, Simone Richter, and Christian Griebler (2009). "First attempts towards an integrative concept for the ecological assessment of groundwater ecosystems". In: *Hydrogeology Journal* 17.1, pp. 23–35. ISSN: 14312174. DOI: 10.1007/s10040-008-0346-6.

Stoch, Fabio, Malvina Artheau, Anton Brancelj, Diana Maria Paola Galassi, and Florian Malard (2009). "Biodiversity indicators in European ground waters: Towards a predictive model of stygobiotic species richness". In: *Freshwater Biology* 54.4, pp. 745–755. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2008.02143.x.

Stoch, Fabio and Diana Maria Paola Galassi (2010). "Stygobiotic crustacean species richness: A question of numbers, a matter of scale". In: *Hydrobiologia* 653.1, pp. 217–234. ISSN: 00188158. DOI: 10.1007/s10750-010-0356-y.

Stocker, Z. S. J. and D. Dudley Williams (1972). "A freezing core method for describing the vertical distribution of sediments in a streambed". In: *Limnology and Oceanography* 17.1, pp. 136–138.

Strayer, David L., Sarah E. May, Pamela Nielsen, Wilfried Wollheim, and Sharon Hausam (1995). "An endemic groundwater fauna in unglaciated eastern North America". In: *Canadian Journal of Zoology* 73.3, pp. 502–508. ISSN: 00084301. DOI: 10.1139/z95-057.

Stubbington, Rachel, Marie-José Dole-Olivier, Diana Maria Paola Galassi, John Paul Hogan, and Paul J. Wood (2016). "Characterization of macroinvertebrate communities in the hyporheic zone of river ecosystems reflects the pump-sampling technique used". In: *PLoS ONE* 11.10, pp. 1–27. ISSN: 19326203. DOI: 10.1371/journal.pone.0164372.

Stumpp, Christine and Grant C. Hose (2013). "The Impact of water table drawdown and drying on subterranean aquatic fauna in in-vitro experiments". In: *PLoS ONE* 8.11, p. 10. ISSN: 19326203. DOI: 10.1371/journal.pone.0078502.

– (2017). "Groundwater amphipods alter aquifer sediment structure". In: *Hydrological Processes* 31.19, pp. 3452–3454. ISSN: 10991085. DOI: 10.1002/hyp.11252.

Subterranean Ecology (2012). *Elmatta Project Stygofauna Survey*. Tech. rep. Perth: Report prepared for Taroom Coal Pty Ltd.

Taylor, Craig A. and Heinz G. Stefan (2009). "Shallow groundwater temperature response to climate change and urbanization". In: *Journal of Hydrology* 375.3-4, pp. 601–612. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.07.009. URL: http://dx.doi.org/10.1016/j.jhydrol.2009.07.009.

Technologiezentrum Wasser (2018). *Grundwasserdatenbank Wasserversorgung: Regionale Auswertung - Region Mittlerer Oberrhein*. URL: http://www.grundwasserdatenbank.de/regionmo.htm (visited on 02/27/2019).

Terramin (2018). *Bird in Hand Gold Project*. Tech. rep. Fullarton: Terramin Exploration Pty Ltd, p. 22.

Thulin, Barbara and Hans Jürgen Hahn (2008). *Ecology and living conditions of groundwater fauna*. Tech. rep. Svensk Kärnbränslehantering AB, p. 51.

Tione, María Laura, José Camilo Bedano, and Mónica Blarasin (2016). "Land Use and Hydrogeological Characteristics Influence Groundwater Invertebrate Communities". In: *Water Environment Research* 88.8, pp. 756–767. ISSN: 10614303. DOI: 10.2175/106143016x14609975747162.

Tissen, Carolin, Susanne A. Benz, Kathrin Menberg, Peter Bayer, and Philipp Blum (2019). "Groundwater temperature anomalies in central Europe". In: *Environmental Research Letters* 14.10, p. 104012. ISSN: 1748-9326. DOI: 10.1088/1748-9326/ab4240.

Tissen, Carolin, Kathrin Menberg, Peter Bayer, and Philipp Blum (2018). "Heat supply by shallow geothermal energy in Karlsruhe". In: *Groundwater in the surrounding of mining, energy and urban space*. Bochum: Conference of the professional division Hydrogeology in the DGGV.

Tomlinson, Moya, Andrew J. Boulton, Peter J. Hancock, and Peter G. Cook (2007). "Deliberate omission or unfortunate oversight: Should stygofaunal surveys be included in routine groundwater monitoring programs?" In: *Hydrogeology Journal* 15.7, pp. 1317–1320. ISSN: 14312174. DOI: 10.1007/s10040-007-0211-z.

Totakura, Venkateswara Rao and Yenumula Ranga Reddy (2015). *Groundwater cyclopoid copepods of peninsular India, with description of eight new species*. Vol. 3945. Auckland: Magnolia Press, p. 93. ISBN: 9781775576792. DOI: 10.11646/zootaxa.3963.3.9.

Trimbos, Krijn B., Ellen Cieraad, Maarten Schrama, Aagje I. Saarloos, Kees J. M. Musters, Laura D. Bertola, and Peter M. van Bodegom (2021). "Stirring up the relationship between quantified environmental DNA concentrations and exoskeleton-shedding invertebrate densities". In: *Environmental DNA* 3, pp. 605–618.

Trontelj, Peter, Christophe J. Douady, Cene Fišer, Janine Gibert, Špela Gorički, Tristan Lefébure, Boris Sket, and Valerija Zakšek (2009). "A molecular test for cryptic diversity in ground water: How large are the ranges of macro-stygobionts?" In: *Freshwater Biology* 54.4, pp. 727–744. ISSN: 00465070. DOI: 10.1111/j.1365-2427.2007.01877.x.

Tuékam Kayo, Par Raoul, Pierre Marmonier, Claude Boutin, Moïse Nola, Serge H. Zébazé Togouet, Serge Hubert, and Christophe Piscart (2012). "Les crustacés aquatiques souterrains d'Afrique et de Madagascar: bilan et enjeux". In: *Spelunca* 128, pp. 43–46.

Uhl, Anke, Hans Jürgen Hahn, Anne Jäger, Teresa Luftensteiner, Tobias Siemensmeyer, Petra Döll, Markus Noack, Klaus Schwenk, Sven Berkhoff, Markus Weiler, Clemens Karwautz, and Christian Griebler (2022). "Making waves: Pulling the plug—Climate change effects will turn gaining into losing streams with detrimental effects on groundwater quality”. In: *Water Research* 220.May. ISSN: 18792448. DOI: 10.1016/j.watres.2022.118649.

Underwood, A. J. (1997). *Experiments in ecology and management: Their logical design and interpretation using analysis of variance*. Cambridge University Press, p. 524. ISBN: 9780521556965.

United Nations (2022). *The United Nations World Water Development Report 2022: Groundwater: Making the invisible visible*. Tech. rep. Paris: UNESCO, p. 246.

Verein Deutscher Ingenieure e.V. (VDI) (1994). *DIN 4049-3 Hydrologie Teil 3: Begriffe zur quantitativen Hydrologie*.

– (2018). *VDI 4230 Biological procedures to determine environmental impact (bioindication)*. Tech. rep. Part 5. Berlin, p. 88.

Vörös, Judit, Orsolya Márton, Benedikt R. Schmidt, Júlia Tünde Gál, and Dušan Jelić (2017). “Surveying Europe’s only cave-dwelling chordate species (proteus anguinus) using environmental DNA”. In: *PLoS ONE* 12.1, pp. 12–14. ISSN: 19326203. DOI: 10.1371/journal.pone.0170945.

Vörösmarty, Charles J., Pamela Green, Joseph Salisbury, and Richard B. Lammers (2000). “Global water resources: Vulnerability from climate change and population growth”. In: *Science* 289.5477, pp. 284–288. ISSN: 00368075. DOI: 10.1126/science.289.5477.284.

Wada, Yoshihide, Ludovicus P.H. Van Beek, Cheryl M. Van Kempen, Josef W.T.M. Reckman, Slavek Vasak, and Marc F.P. Bierkens (2010). “Global depletion of groundwater resources”. In: *Geophysical Research Letters* 37.20, pp. 1–5. ISSN: 00948276. DOI: 10.1029/2010GL044571.

Wada, Yoshihide, Dominik Wisser, and Marc F.P. Bierkens (2014). “Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources”. In: *Earth System Dynamics* 5.1, pp. 15–40. ISSN: 21904979. DOI: 10.5194/esd-5-15-2014.

Ward, J. V. and K. Tockner (2001). “Biodiversity: Towards a unifying theme for river ecology”. In: *Freshwater Biology* 46.6, pp. 807–819. ISSN: 00465070. DOI: 10.1046/j.1365-2427.2001.00713.x.

Watiroyram, Santi, La-orsri Sanoamuang, and Anton Brancelj (2017). “Two new species of Elaphoidella (Copepoda, Harpacticoida) from caves in southern Thailand and a key to the species of Southeast Asia”. In: *Zootaxa* 4282.3, pp. 501–525. ISSN: 11755334. DOI: 10.11646/zootaxa.4282.3.5.

Watts, Chris H.S., Peter J. Hancock, and Remko Leys (2007). “A stygobitic Carabhydrus Watts (Dytiscidae, Coleoptera) from the Hunter Valley in New South Wales, Australia”. In: *Australian Journal of Entomology* 46.1, pp. 56–59. ISSN: 13266756. DOI: 10.1111/j.1440-6055.2007.00585.x.

Weaver, L., N. Karki, M. Mackenzie, L. Sinton, D. Wood, M. Flintoft, P. Havelaar, and M. Close (2016). “Microbial transport into groundwater from irrigation: Comparison of two irrigation practices in New Zealand". In: *Science of the Total Environment* 543, pp. 83–94. ISSN: 18791026. DOI: 10.1016/j.scitotenv.2015.09.075. URL: http://dx.doi.org/10.1016/j.scitotenv.2015.09.075.

West, Katrina M., Zoe T. Richards, Euan S. Harvey, Robert Susac, Alicia Grealy, and Michael Bunce (2020). "Under the karst: detecting hidden subterranean assemblages using eDNA metabarcoding in the caves of Christmas Island, Australia". In: *Scientific Reports* 10.1, pp. 1–15. ISSN: 20452322. DOI: 10.1038/s41598-020-78525-6. URL: https://doi.org/10.1038/s41598-020-78525-6.

Wickert, F., A. Müller, W. Schäfer, and A. Tiehm (2006). "Vergleich hochauflösender Grundwasserprobennahmeverfahren zur Charakterisierung der vertikalen LCKW-Verteilung im Grundwasserleiter". In: *Altlastenspektrum* 01, pp. 29–35.

Wiecek, Mariusz, Peter Martin, and Maciej Gabka (2013). *Distribution patterns and environmental correlates of water mites (Hydrachnidia, Acari) in peatland microhabitats*. DOI: 10.1007/s10493-013-9692-8.

Wilhelm, Frank M., Steven J. Taylor, and Ginny L. Adams (2006). "Comparison of routine metabolic rates of the stygobite, Gammarus acherondytes (Amphipoda: Gammaridae) and the stygophile, Gammarus troglophilus". In: *Freshwater Biology* 51, pp. 1162–1174. DOI: doi:10.1111/j.1365-2427.2006.01564.x.

Williams, D. Dudley and Holly B. N. Hynes (1974). "The occurrence of benthos deep in the substratum of a stream". In: *Freshwater Biology* 4.3, pp. 233–256. ISSN: 13652427. DOI: 10.1111/j.1365-2427.1974.tb00094.x.

Wilson, George D.F. and Graham D. Fenwick (1999). "Taxonomy and ecology of Phreatoicus typicus Chilton, 1883 (Crustacea, Isopoda, Phreatoicidae)". In: *Journal of the Royal Society of New Zealand* 29.1, pp. 41–64. ISSN: 03036758. DOI: 10.1080/03014223.1999.9517582.

Wirsing, Gunther and Alex Luz (2007). *Hydrogeologischer Bau und Aquifereigenschaften der Lockergesteine im Oberrheingraben (Baden-Württemberg)*. Tech. rep. Freiburg: Regierungspräsidium Freiburg, p. 130.

Zaenker, Stefan, Klaus Bogon, and Alexander Weigand (2020). *Die Höhlentiere Deutschlands*. Wiebelsheim: Quelle Meyer Verlag, p. 448. ISBN: 9783494018317.

Zagmajster, Maja, David Eme, Cene Fišer, Diana Maria Paola Galassi, Pierre Marmonier, Fabio Stoch, Jean François Cornu, and Florian Malard (2014). "Geographic variation in range size and beta diversity of groundwater crustaceans: Insights from habitats with low thermal seasonality". In: *Global Ecology and Biogeography* 23.10, pp. 1135–1145. ISSN: 14668238. DOI: 10.1111/geb.12200. URL: http://wileyonlinelibrary.com/journal/geb.

Zagmajster, Maja, Rodrigo Lopes Ferreira, William F. Humphreys, Matthew L. Niemiller, and Florian Malard (2023). "Patterns and determinants of richness and composition of the groundwater fauna". In: *Groundwater Ecology and Evolution*. Ed. by Florian Malard, Christian Griebler, and Sylvie Rétaux. 2nd ed. Academic Press. Chap. 6, pp. 141–164. ISBN:

9780128191194. URL: https://shop.elsevier.com/books/groundwater-ecology-and-evolution/malard/978-0-12-819119-4.

Zakšek, Valerija, Boris Sket, and Peter Trontelj (2007). “Phylogeny of the cave shrimp Troglocaris: Evidence of a young connection between Balkans and Caucasus”. In: *Molecular Phylogenetics and Evolution* 42.1, pp. 223–235. ISSN: 10557903. DOI: 10.1016/j.ympev.2006.07.009.

Zeidler, Wolfgang (1985). “A new species of Crustacean (Syncarida: Anaspidacea: Koonungidae), from sinkholes and caves in the south-east of South Australia”. In: *Transactions of the Royal Society of South Australia* 109.3, pp. 63–75.

Zhu, Ke, Philipp Blum, Grant Ferguson, Klaus Dieter Balke, and Peter Bayer (2010). “The geothermal potential of urban heat Islands”. In: *Environmental Research Letters* 5.Article No. 044002, pp. 1–6. ISSN: 17489326. DOI: 10.1088/1748-9326/6/1/019501.

Zuurbier, Koen G., Niels Hartog, Johan Valstar, Vincent E.A. Post, and Boris M. Van Breukelen (2013). “The impact of low-temperature seasonal aquifer thermal energy storage (SATES) systems on chlorinated solvent contaminated groundwater: Modeling of spreading and degradation”. In: *Journal of Contaminant Hydrology* 147, pp. 1–13. ISSN: 01697722. DOI: 10.1016/j.jconhyd.2013.01.002. URL: http://dx.doi.org/10.1016/j.jconhyd.2013.01.002.

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Declaration of authorship

Study 1 (Chapter 2)

Koch, F., Blum, P., Korbel, K., Menberg, K., (2023) Global overview on groundwater fauna. Ecohydrology 17 (1). 28. https://doi.org/10.1002/eco.2607

Fabien Koch (FK) did all the literature search and data analysis. Kathryn Korbel (KK) provided critical feedback and contributed to the interpretation of the results. Kathrin Menberg (KM) and Philipp Blum supervised the work. FK wrote the initial draft and all authors (FK, PB, KK, KM) discussed and interpreted the results and substantially contributed to editing and reviewing the manuscript.

Study 2 (Chapter 3)

Koch, F., Blum, P., Stein, H., Fuchs, A., Hahn, H. J., Menberg, K., (2024) Temporal shift of groundwater fauna in South-West Germany. Hydrology and Earth System Sciences (submitted)

Andreas Fuchs (AF) and one time also Fabien Koch (FK) executed the fieldwork and AF evaluated the fauna samples. FK evaluated the collected data, interpreted and visualised the results. Philipp Blum (PB) and Hans Jürgen Hahn (HJH) provided the topic and supervised the work, together with Kathrin Menberg (KM). FK and wrote the initial draft of the paper. All authors (KM, AF, HS, HJH and PB) discussed and interpreted the results and substantially contributed to editing and reviewing the manuscript.

Study 3 (Chapter 4)

Koch, F., Menberg, K., Schweikert, S., Spengler, C., Hahn, H.J., Blum, P. (2021) Groundwater fauna in an urban area - natural or affected?. Hydrology and Earth System Sciences 25. 3053-3070. https://doi.org/10.5194/hess-25-3053-2021

Svenja Schweikert (SS) and Cornelia Spengler (CS) executed the fieldwork. Fabien Koch (FK) evaluated the collected data, interpreted and visualised the results with support from CS. Philipp Blum (PB) and Hans Jürgen Hahn (HJH) provided the topic and scientifically supervised the work, together with Kathrin Menberg (KM). FK wrote the initial draft and all authors (FK, CS, HJH, KM and PB) discussed the results and substantially contributed to editing and reviewing the manuscript.

Publications and contributions

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Koch, F., Blum, P., Korbel, K., Menberg, K., (2023) Global overview on groundwater fauna. Ecohydrology 17 (1). 28. https://doi.org/10.1002/eco.2607.

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Blum, P., Menberg, K., **Koch, F.**, Benz, S. A., Tissen, C., Hemmerle, H., Bayer, P. (2021) Is thermal use of groundwater a pollution?. Journal of Contaminant Hydrogeology. 239. 10379. 10.1016/j.jconhyd.2021.103791.

Jaeger, N., Besaury, L., Röhling, A. N., **Koch, F.**, Delort, A.-M., Gasc, C., Greule, M., Kolb, S., Nadalig, T., Peyret, P., Vuilleumier, S., Amato, P., Bringel, F., Keppler, F. (2018) Chloromethane formation and degradation in the fern phyllosphere. Science of the Total Environment. 634. 1278-1287. 10.1016/j.scitotenv.2018.03.316.

Conference contributions (as first author)

Koch, F., Menberg, K., Spengler, C., Stein, H., Fuchs, A., Hahn, H. J., Blum, P. (2023) Groundwater biomonitoring as a tool for identifying environmental trends. Conference: Transforming towards a sustainable society – challenges and solutions. 12. October 2023. Karlsruhe. https://indico.scc.kit.edu/event/3604/attachments/6805/10699/231009__BookofAbstracts_A5_09102023.pdf (presentation).

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Koch, F., Menberg, K., Schweikert, S., Hengel, J., Spengler, C., Hahn, H.J., Blum, P. (2023) Urban groundwater fauna – natural or anthropogenically influenced?. EGU23. The 25th EGU General Assembly. 24-28 April. 2023 in Vienna and online. id. EGU23-5773. 10.5194/egusphere-egu23-5773 (presentation).

Koch, F., Menberg, K., Schweikert, S., Spengler, C., Hahn, H.J., Blum, P. (2022) Urbane Grundwasserfauna: natürlich oder anthropogen beeinflusst?. FH-DGGV Jahrestagung. 23. March 2022. online (presentation).

Eidesstattliche Versicherung

Eidesstattliche Versicherung gemäß § 13 Absatz 2 Satz 1 Ziffer 4 der Promotionsordnung des Karlsruher Instituts für Technologie (KIT) für die KIT-Fakultät für Bauingenieur-, Geo- und Umweltwissenschaften

1. Bei der eingereichten Dissertation zu dem Thema „Spatial and temporal analysis on groundwater ecosystems“ handelt es sich um meine eigenständig erbrachte Leistung.
2. Ich habe nur die angegebenen Quellen und Hilfsmittel benutzt und mich keiner unzulässigen Hilfe Dritter bedient. Insbesondere habe ich wörtlich oder sinngemäß aus anderen Werken über-nommene Inhalte als solche kenntlich gemacht.
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5. Die Bedeutung der eidesstattlichen Versicherung und die strafrechtlichen Folgen einer unrichtigen oder unvollständigen eidesstattlichen Versicherung sind mir bekannt.

Ich versichere an Eides statt, dass ich nach bestem Wissen die reine Wahrheit erklärt und nichts verschwiegen habe.

Karlsruhe, 08.02.2024 M.Sc. Fabien Koch