FIELDING FLOODS FOR FARMS AND (LOW) FLOWS:

The Potential Benefit of Repurposing Small Flood Reservoirs for Drought Protection

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FIELDING FLOODS FOR FARMS AND (LOW) FLOWS

THE POTENTIAL BENEFIT OF REPURPOSING SMALL FLOOD RESERVOIRS FOR DROUGHT PROTECTION

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For all the versions of me who came before,

all the versions who could have been,

and all the versions still to come.

"What am I going to find if I get through this?"

"I don't know. But wouldn't it be interesting to find out?"

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ABSTRACT

Droughts have long been recognized as significant natural hazards that impose severe impacts on multiple sectors worldwide. Under climate change, these impacts will likely become more severe and more frequent in the future, prompting a need for increased water resources resilience in even temperate and water rich regions. At the same time, temperate regions have often contended with flooding as the primary hydrological hazard. Over 600 flood reservoirs have been built in the German state of Baden-Württemberg alone, with many of them fitting under the criteria of small reservoirs. Small reservoirs– those with a dam height of $\leq$ 15 m, a surface area of $<$ 0.1 km^2, and / or a storage volume of up to 1-2 million m^3– have been proposed as decentralized solutions to water scarcity in arid regions, though their potential in temperate regions is still unexplored. This dissertation aimed to explore the potential water supply benefits of repurposing flood reservoirs as small reservoirs in temperate regions in addition to preserving their flood protection functions. To this end, a variety of models were built to represent the operation of repurposed flood reservoirs for two purposes– streamflow supplementation and irrigation demand– and tested them first in perfect-knowledge conditions and then under uncertain forecasts.

In chapter 2, the benefit to streamflow supplementation was measured under perfect-knowledge conditions using a function to determine the value of the quantity and timing of water delivered by the modeled reservoirs in relation to low-flow conditions. The reservoirs stored water when water was plenty and released water such that the downstream conditions would meet or exceed the 70^{th} percentile exceedance flow, and emptied in time for a flood event. Under the perfect-knowledge conditions, it was shown that 12 of the 30 reservoirs tested could alleviate at least 70% of drought conditions, and that none of the reservoirs experienced an increase in flooding as a result of the new operating rules. However, there were no strong relationships between how much water was available to the reservoir and performance.

In chapter 3, the benefit to irrigation demand was measured under perfect-knowledge conditions by modelling the agricultural irrigation demand around each reservoir individually and determining how much of this demand the reservoirs could fulfill. Similar to chapter 2, the reservoirs stored water when water was plenty, but instead of releasing water, scheduled withdrawals when irrigation demand occurred. This analysis focused on the years 2017-2020, which include the landmark 2018-2020 drought years that caused massive increases in agricultural irrigation demand in the region. Of the 30 tested reservoirs, 20 could provide at least 70% of the needed water during the drought years without increasing flooding conditions. While some of these reservoirs also performed well in chapter 2, the timing of demand is different enough that the two use cases should be considered distinctly.

In chapter 4, the main assumption in the previous two studies was challenged: the assumption of perfect-knowledge conditions. Instead, the models in this chapter make a decision based on the current inflow and the forecast available to them at each point in time. If a flood was occurring, that took priority; else, the reservoir could either

pre-release in anticipation of a flood in its forecast, store water when water was plenty and no flood was forecasted, release or allow withdrawal upon demand, or simply pass water through. The results demonstrated that most reservoirs were still able to provide tangible benefits ($> 40\%$) when optimized for either use case. The performance decay from perfect-knowledge to forecasted conditions (which in several cases was quite considerable) was explained less by common forecast quality metrics and more by flood incidence, but the timing of flood predictions (i.e. if a forecast caused emptying before demand occurred) was most influential. The most successful operating rules mimicked the rules under perfect-knowledge scenarios, allowing aggressive storage and holding onto the water as long as is safe.

Overall, the potential water supply benefits of repurposing flood reservoirs for drought protection can be quite high, particularly for agriculture, and can be operated without increasing flood risk. While calculated metrics were largely unable to identify unsuitable or especially suitable reservoirs, categorization by size and use are possible first filters; however, the sample size remains too small to determine this conclusively. Future investigations of utilization potential in small reservoirs should thus be conducted for each reservoir individually, and with consideration for additional factors such as water quality, river ecology, and any potential long-term effects on water supply and drought, including as a potential mitigation strategy for flash drought. This dissertation has provided the basic tools for such analyses, and in doing so, contributes to informed conversations about ways to increase water supply resilience in a warming world.

ZUSAMMENFASSUNG

Dürren gelten seit langer Zeit als bedeutende Naturgefahr, die weltweit in mehreren Sektoren schwerwiegende Auswirkungen haben. Als Folge des Klimawandels werden diese Auswirkungen voraussichtlich stärker und häufiger auftreten, sodass selbst in feuchten und wasserreichen Regionen eine gesteigerte Resilienz der Wasserressourcen erforderlich sein wird. Zugleich haben diese gemäßigten Regionen oft mit Überschwemmungen als primäre hydrologischer Gefahr zu kämpfen. Im Rahmen von Schutzmaßnahmen gegen Überschwemmungen wurden allein in Baden-Württemberg über 600 Hochwasserrückhaltebecken gebaut, von denen viele in die Kategorie der kleinen Stauanlagen fallen. Kleine Stauanlagen werden durch eine Dammhöhe von $\leq$ 15 m, eine maximale Oberfläche von $<$ 0,1 km² und/oder einen Speichervolumen von bis zu 1–2 Mio. m³ charakterisiert und wurden als dezentrale Lösungen gegen Wasserknappheit in ariden Regionen vorgeschlagen. Doch ihr Potenzial in gemäßigten Regionen ist noch unerforscht. Ziel dieser Dissertation war es, die potenziellen Vorteile einer Umnutzung von Hochwasserrückhaltebecken zu kleinen Stauanlagen für die Wasserversorgung in gemäßigten Regionen zu untersuchen, unter der Prämisse des Erhalts ihrer Funktion im Hochwasserschutz. Hierzu wurden verschiedene Modelle entwickelt, die die Betriebsregeln der umfunktionierten Hochwasserrückhaltebecken sowohl zur Niedrigwassererhöhung als auch zur Deckung des landwirtschaftlichen Bewässerungsbedarf darstellen. Diese Modelle wurden zunächst unter idealisierten Bedingungen mit perfektem Wissen und anschließend unter unsicheren Prognosen getestet.

In Kapitel 2 wurde der Nutzen der Niedrigwassererhöhung unter der Bedingung perfekter Kenntnis quantifiziert. Hierfür wurde eine Funktion verwendet, mit der sowohl die Menge als auch der Zeitpunkt des von der modellierten Stauanlage gelieferten Wassers in Relation zu Niedrigwasserbedingungen bestimmt wird. Bei ausreichend vorhandenem Wasser, wurde das Wasser im Becken gespeichert, und wieder abgegeben, sodass die Abflussbedingungen im Flussunterlauf den 70. Perzentilwert erreichten. Im Falle eines Hochwasserereignisses wurde die Stauanlage rechtzeitig geleert. Unter der Bedingung perfekter Kenntnis zeigte sich, dass 12 von 30 getesteten Stauanlagen mindestens 70% der Dürrezustände lindern konnten und dass keine der Stauanlagen durch die neuen Betriebsregeln von Hochwasser betroffen waren . Es gab jedoch keine eindeutigen Zusammenhänge zwischen dem verfügbaren Wasserdargebot und der erreichten Leistungsfähigkeit.

In Kapitel 3 wurde der Nutzen für den landwirtschaftlichen Bewässerungsbedarf unter der Bedingung perfekter Kenntnis quantifiziert. Dazu wurde der Bewässerungsbedarf in einer Region von 5 km2 rund um jede Stauanlage individuell modelliert, und bestimmt, wie viel Bewässerungsbedarf die Stauanlagen jeweils decken konnten. Wie schon in Kapitel 2 speicherten die Becken nur dann Wasser ein, wenn es in ausreichender Menge zur Verfügung stand. Wenn jedoch Bewässerungsbedarf bestand, wurden planmäßige Entnahmen vorgenommen, anstatt Wasser abzulassen. Diese Analyse konzentrierte sich auf die Jahre 2017–2020, zu denen die markanten Dürrejahre 2018–2020

zu erheblichen Anstiegen in der landwirtschaftlichen Bewässerungsnachfrage in der Region führten. Von den 30 getesteten Becken konnten 20 mindestens 70% des benötigten Wassers während der Dürrejahre bereitstellen, ohne dass die Hochwasserschutzfunktion beeinträchtigt wurde. Während einige dieser Becken auch in Kapitel 2 gut abschnitten, unterscheidet sich die zeitliche Nachfrage so deutlich, dass beide Anwendungsfälle getrennt betrachtet werden sollten.

In Kapitel 4 wurde die zentrale Annahme der beiden vorangegangenen Studien in Frage gestellt: die Bedingung perfekte Kenntnis. Anstatt von idealen Kenntnisbedingungen auszugehen, treffen die Modelle in diesem Kapitel Entscheidungen basierend auf dem aktuellen Zufluss und der Prognose, die ihnen zu jedem Zeitpunkt vorliegt. Tritt ein Hochwasser auf, hatte die Hochwasserschutzfunktion Vorrang; andernfalls konnte das Becken entweder vorab entleert werden, um einem in der Prognose erkennbaren Hochwasser zuvorzukommen; Wasser speichern, wenn ausreichend Wasser vorhanden war und kein Hochwasser prognostiziert wurde; Wasser bei Bedarf abgeben oder den Zufluss ungehindert durchleiten. Diese Betriebsregeln wurden für jede Stauanlage und jeden Anwendungsfall optimiert. Die Ergebnisse zeigten, dass die meisten Stauseen bei Optimierung für einen der beiden Anwendungsfälle weiterhin greifbare Vorteile (>40 %) bieten konnten. Der Leistungsabfall von Szenarien mit perfekter Kenntnis zu Prognosebedingungen ließ sich weniger durch gängige Metriken zur Prognosequalität erklären als vielmehr durch die Häufigkeit von Hochwasserereignissen, wobei jedoch der Zeitpunkt der Hochwasservorhersagen (d. h. ob eine Prognose zu einer Entleerung führte, bevor Bedarf entstand) den größten Einfluss hatte. Die erfolgreichsten Betriebsregeln aus der Optimierung ähnelten denen aus der Perfekt-Kenntnis-Szenarien, die eine aggressive Speicherung und das Vorhalten des Wassers ermöglichen.

Insgesamt können die potenziellen Vorteile einer Umnutzung von Hochwasserrückhaltebecken zum Schutz vor Dürre, insbesondere für die Landwirtschaft, erheblich sein, ohne dass dadurch das Hochwasserrisiko erhöht wird. Während berechnete Kennzahlen nicht in der Lage waren Muster für ungeeignete oder besonders geeignete Becken weitgehend zu identifizieren, deuten Größen- und Nutzungskategorien auf erste mögliche Filter hin. Es ist jedoch zu beachten, dass die Stichprobengröße zu gering ist, um dies abschließend zu beurteilen. Zukünftige Untersuchungen des Potenzials in kleinen Becken sollten daher für jedes Stauanlagen individuell erfolgen und weitere Faktoren wie Wasserqualität, Flussökologie und Langzeitwirkungen auf Wasserversorgung und Dürrerisiken (insbesondere sogenannte Flash-Droughts) berücksichtigen. Diese Dissertation hat die grundlegenden Werkzeuge für eine solche Analyse bereitgestellt und trägt damit zu fundierten Diskussionen über Möglichkeiten zur Erhöhung der Resilienz der Wasserversorgung in einer sich erwärmenden Welt bei.

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Part I

INTRODUCTION

1 INTRODUCTION

1.1 PERSONAL MOTIVATION

The first flood that I ever witnessed was, funnily enough, not even a real flood at all.

On July 29, 2014, a 76 cm-diameter main water pipe broke, causing massive flooding on the campus of the University of California, Los Angeles, where I earned my Bachelor's degree. Within a few hours, enough water had gushed out of the pipe to submerge the nearby underground parking lot, cover my path to campus in 10 cm of water, and flood the newly renovated basketball stadium. Carefree undergrads took advantage of the currents to boogie board, swim, and paddleboard on campus during a summer of record high heat. University employees clamored to claim damage settlements for their ruined cars, and university administrators clutched their pearls over the damage to the stadium. As I stood at the edge of the current, watching the water struggle to disappear down the storm drains clogged from disuse, it seemed as if the water would never end.

On campus, we jokingly called this water main break "the Great UCLA Flood of 2014."

That could not have been further from the truth. In January of 2014, six months before the pipe broke, the state governor signed a state of emergency declaring that California was in one of its driest three-year periods in recent history. Wildfires raged in the absence of suppressing rainfall. Record low precipitation and high temperatures caused water shortages in critical watersheds, causing farmers to rely on groundwater aquifers to prevent critical crop failures. The rate of withdrawal was so extreme that in some areas, groundwater removal caused the soil surface to sink up to 5 centimeters per month. Just two months after the UCLA "flood", in September of 2014, the state governor signed the historic Sustainable Groundwater Management Act, the first of its kind in California to regulate the withdrawal of groundwater. It was official: California was neck deep in a megadrought.

This was, of course, entirely lost on me in my undergraduate naïveté– growing up in sunny southern California, lack of rain was nothing new to me. I figured it would blow over soon when it rained next. The impacts of the drought only became clear when I began an internship at the very utility responsible for the UCLA flood. As I visited near-empty local surface water reservoirs, attended meetings dealing with the fallout of the UCLA main break, and read reports on the restoration of lakes dried entirely by Los Angeles demand, it became abundantly clear to me that there was, in fact, an end to our water.

Yet at the end of 2016, the tides turned– literally and metaphorically. The weather and ocean currents driving the drought shifted, bringing well-needed rain. The farms were watered, the reservoirs were filled, and the rivers rose.

And rose.

And rose.

Suddenly, reports of flooding gushed in from all over the state. Onslaughts of rain destabilized dry hillslopes, causing landslides. Power was cut off to hundreds of thousands of households. Hundreds were evacuated from the agricultural regions of the Central Valley. Thousands more were evacuated in the wake of the Oroville Dam failure. California swung clumsily from one hydrological crisis to the other, wholly unprepared for both.

In between scathing articles condemning the dam failures and grateful news bits highlighting brave first responders, one question seemed to underpin the news cycle: is there any way we could have saved this flood water for the next drought? Can we somehow turn this excess of water into reserves for the next time our water runs dry?

As an undergrad, the answer seemed simple– why not just try? As a masters student studying drought, I realized it could be a bit more complicated than that when I saw the aftermath of the Ahr Valley flood on the news. The public would need assurance that this kind of flooding disaster wouldn't happen again while trying to avert drought-related disaster. And as a doctoral candidate, I was excited to realize that this was something I could investigate.

It has been my pleasure to spend the last three years attempting to solve this problem.

1.2 SCIENTIFIC MOTIVATION

1.2.1 *Drought*

Droughts have many consequences, but in this dissertation I focus on effects to streamflow (which is a proxy for many other sectors) and agriculture.

Droughts have long been recognized as significant natural hazards that impose severe impacts on multiple sectors worldwide. Shortages in water, coupled with higher temperatures, reduce crop yields and can even impact livestock mortality, ultimately resulting in massive economic losses (Caretta et al., 2022; Matiu et al., 2017). The increasing frequency and severity of droughts due to climate change exacerbate these challenges (Spinoni et al., 2017), posing substantial threats to food security as agricultural droughts become a major driver of yield reduction worldwide (Lesk et al., 2016; Naumann et al., 2021). Prolonged lower river levels as a result of hydrological drought can affect river ecology—for example, low flow indices are commonly part of an assessment of flows for ecological protection (Poff et al., 2017; Vigiak et al., 2018; Yarnell et al., 2020). Lower river levels can also limit or reduce riverine transport, which may have significant effects on the economy (Christodoulou et al., 2020; Jonkeren et al., 2007), and have significant impacts on surface water quality (Mosley, 2015). In Central Europe, droughts have become more recurrent and intense over the past decades (Boeing et al., 2022; Cai et al., 2015).

The 2018-2020 drought years in Germany drew attention to drought mitigation strategies.

The 2018-2020 and 2022 droughts were among some of the most devastating in Germany's recent history (Baden-Württemberg, 2019b, 2020, 2021; Erfurt et al., 2020; Tijdeman et al., 2022). Anomalies in precipitation, along with higher temperatures, created soil moisture deficits that challenged various sectors across the typically humid and temperate country, including agriculture (Shyrokaya et al., 2024), likely contributing to the increase in demand for irrigation. By 2022, the area of irrigated cropland in the southwestern state of Baden-Württemberg had increased by 61% from 2009 levels. The demand for irrigation will likely continue to increase with persistent drought conditions (Bernhardt et al., 2022; Fliß et al., 2021; Hirschfeld, 2015; McNamara et al., 2024). Anthropogenic influences, such as heavy groundwater withdrawals and structural changes in the landscape, exacerbated issues of water insecurity (KLIWA, 2021; Umwelt, 2022b). Recent research has suggested that, under climate change, the intensity of this landmark drought event will become more common in the future, emphasizing the urgent need for additional strategies against drought (Rakovec et al., 2022). Strong decreases in crop productivity (Naumann et al., 2021; Thober et al., 2018) and strong increases in surface water stress (Forzieri et al., 2014) can be expected in central and southern Europe in the absence of adaptation measures as a result of anthropogenic climate change. The threat of further water stress has prompted many local governments in Germany, such as Baden-Württemberg, to begin strategic planning for water scarcity (Bundesamt, 2021; Stölzle et al., 2018; Umwelt, 2022a,b), including ways to store water for drought.

1.2.2 *Small Reservoirs*

Small reservoirs have often been named as a potential decentralized solution to water scarcity in semi-arid and arid regions (Casadei et al., 2019; Jurík et al., 2018; Liebe et al., 2007; Wisser et al., 2010). These are reservoirs typically defined as having a dam height of $\leq$15 m, a surface area of $<$ 0.1 km², and / or a storage volume of up to 1-2 million m³ (Casadei et al., 2019; Jurík et al., 2018). Because they are smaller, they are cheaper to construct and maintain, and can be implemented in otherwise remote locations (Qadir et al., 2007). They can also be much more easily adapted to local conditions and can be managed locally (Venot et al., 2011). While they have a plethora of benefits, such as flood retention, ecosystem protection, and recreation (Jurik et al., 2015; Liebe et al., 2007; Ogilvie et al., 2019), the most common usage is to capture rainwater for supplementing agriculture. Research in Thuringia, Germany, has suggested that recommissioning small reservoirs could maintain or even increase crop yields in an uncertain future (Heinzel et al., 2022). In a global-scale analysis of their potential impact, small reservoirs in certain regions were estimated to potentially increase green water flow—in other words, agricultural water—by up to 1,100 km³ per year, with an estimated ~35% increase in cereal production (Wisser et al., 2010). As climate change impacts destabilize traditional water availability patterns, decentralized small-scale solutions such as small reservoirs may play a role in mitigating these effects.

Small reservoirs could become a part of an integrated drought management program.

However, small reservoirs are not without their challenges. Small reservoirs may release water of reduced quality due to eutrophication within the reservoir (Jurík et al., 2018) and may even worsen water shortages in the long term by unsustainably increasing demand (Di Baldassarre et al., 2018). According to one study, managers across Ethiopia, Ghana, Burkina Faso, and Zambia consider many (anywhere from 25-70%) of their small reservoirs to be performing poorly (Venot et al., 2012). For example, implementations in Ghana—while overall well-received by the local farmers for their plethora of benefits—were found to have no statistically significant increase in the income of vegetable farmers (Acheampong et al., 2018). An analysis of 56 small reservoirs in Tunisia similarly showed that 16 of the reservoirs showed negligible benefits to the local agriculture (Ogilvie et al., 2019). Proposed reasons for the suboptimal operation of these reservoirs include insufficient inflow to the reservoir (Berhane et al., 2016); siltation, seepage, and evaporation losses (Acheampong et al., 2018; Mady et al., 2020); structural damage due to lack of maintenance (Berhane et al., 2016; Casadei et al., 2019; Jurík et al., 2018); and mismanagement due to poor organizational capacity at the local management level (Acheampong et al., 2018; Venot et al., 2011). Despite these

Of course, they are not without their issues; however, they have not yet been tested in water-rich countries like Germany yet.

challenges, the potential additional water provided by small reservoirs is still extremely valuable for enhancing the resilience of local water resources in drought, especially in the context of rainwater harvesting via flood retention (Qadir et al., 2007); however, the potential benefits of these strategies in water-rich countries like Germany remains underresearched.

The lack of knowledge is a limiting factor in regional analyses of small reservoirs.

One of the main challenges in incorporating small reservoirs into regional analyses of water availability is the lack of data available to catalogue them (Habets et al., 2018). Even large global databases of reservoirs, such as HydroLAKES (Messager et al., 2016) and the Global Reservoir and Dam database (GRanD) (Lehner et al., 2011), do not include them. Existing studies have sought to identify small reservoirs and their potential impacts on the water balance using higher resolution remote sensing data to drive physically based models (Aminzadeh et al., 2024; Casadei et al., 2019; Mady et al., 2020). However, the lack of knowledge about a region's small reservoirs and their capacities seems to be a limiting factor in investigating their operating rules.

1.2.3 *Reservoir Operation*

Reservoirs employ hedging rules to increase water available for drought.

Reservoirs and their operation are a critical part of drought resilience infrastructure. The ability of such reservoirs and rulesets to enhance low flows and therefore reduce drought conditions has been demonstrated by many studies (Chang et al., 2019; Huang and Chou, 2005; Karamouz and Araghinejad, 2008; Padiyedath Gopalan et al., 2020; Shih and ReVelle, 1994, 1995; You and Cai, 2008a,b). While reservoir operation and optimization for drought and irrigation has been researched throughout the years (Cañón et al., 2009; Chang et al., 2019; Chang et al., 1995; Consoli et al., 2007; Ding et al., 2017; Draper and Lund, 2004), these studies mainly focus on the impacts of large reservoirs and rely on machine learning methods to derive operating rules. Research on optimal reservoir operation rules for drought have often focused on the concept of hedging rules. Hedging rules assume that by storing water and creating a small deficit of water now, we can use that water to mitigate the consequences of a heavy deficit later (Shih and ReVelle, 1994). While several types of hedging rules exist, Draper and Lund (2004) found that, for most cases, a two-point hedging rule (where hedging storage begins at one point and ends at another) is optimal. Hedging rules have been applied for not only drought hedging operations (Chang et al., 2019; You and Cai, 2008a), but also for environmental benefits (Adams et al., 2017) and flood operation (Hui et al., 2016).

Flood operation is the main purpose of many reservoirs in Germany.

After all, in many temperate regions around the globe, the primary hydrological hazard has long been floods. The disastrous floods in Germany, Belgium, and the Netherlands in 2021 (Ludwig et al., 2023; Mohr et al., 2023) remain heavy on the public conscience, and many flood reservoirs across the country have been built specifically for this purpose. The general principle of flood operation (Figure 1.1) is that a reservoir will begin to store water once the inflow (Q_{in}) reaches the downstream flooding limit (Q_{crit}). Once this flow rate is exceeded, the reservoir limits the outflow (Q_{out}) to Q_{crit} and stores the remaining water. If the reservoir's flood retention capacity is reached, the reservoir will release extra water through emergency channels. The reservoir spills and fails if even the emergency volume is exceeded. Once the flood wave has passed, the reservoir will then continue to release water at the maximum rate allowed (i.e. at

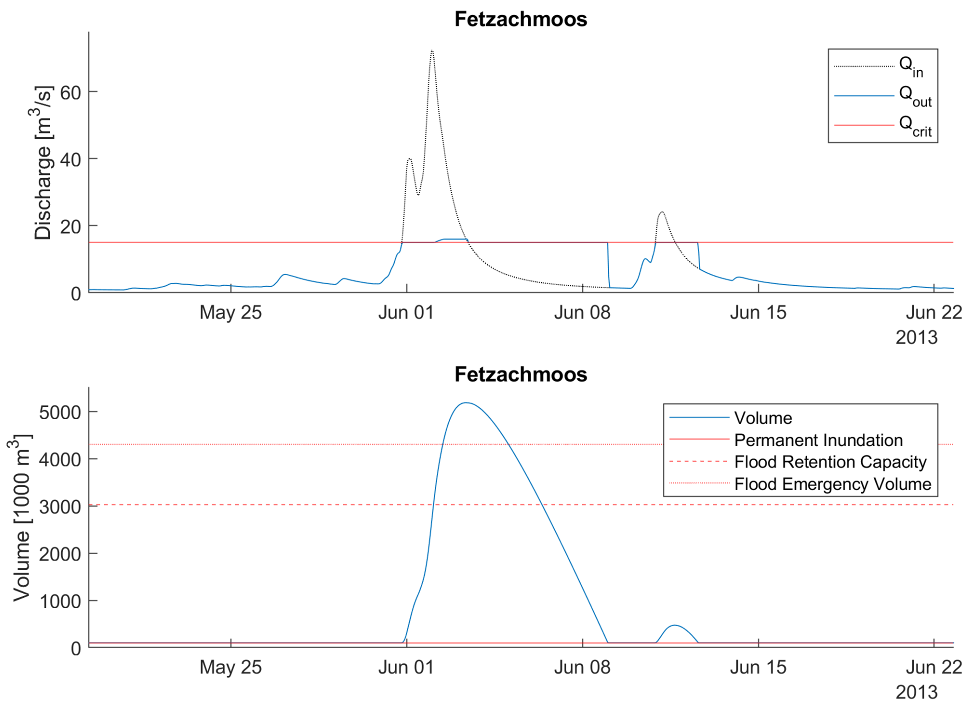

Figure 1.1: An example of flood reservoir operation featuring an event where the reservoir's emergency volume was exceeded, causing failure.

Q_{crit}) in order to empty the reservoir for the next flood. If the reservoir has a permanent inundation requirement, this is respected in the emptying phase.

Bartholomeus et al., 2023 argue, however, that over-preparing for floods may have left temperate countries underprepared for drought, and call for resilience measures that enable an integrated approach for managing both floods and droughts. Research has demonstrated that flood hedging is similar to that of hedging for water supply (Zhao et al., 2014), indicating that this should be possible. Indeed, studies have found that the combination of the two objectives—storing water for drought and maintaining retention capacity for flood retention—is difficult due to their inherently competing nature, but can be more effective when the trigger rules for hedging are variable throughout the year rather than a single fixed value (Balley, 1997; Chang et al., 1995). However, the majority of these studies focus on large drinking water reservoirs with capacities on the scale of 100 million to 1 billion m³—whether such conclusions would hold for small reservoirs is uncertain.

Studies combining flood and drought operation have been in large reservoirs–could small reservoirs also be useful?

The impact of forecasts in reservoir hedging and optimization has been an active topic. Many studies report that reservoir operations benefit from (or at the very least, are not negatively affected by) operation under forecasts in comparison to the case where no future information is available (Chen et al., 2016; Delaney et al., 2020; Mostaghimzadeh et al., 2022; Schwanenberg et al., 2015). The value of these forecasts are affected by two factors: forecast uncertainty and forecast horizon (the time into the future which is forecasted). Zhao et al. (2011) found that reservoir performance generally decreases with increasing uncertainty, but that the magnitude of this decrease depends on the type of forecasting product used (probabilistic, deterministic, or semi-probabilistic forecasts).

Forecasts and their uncertainty are a huge challenge in reservoir operation.

Forecast uncertainty tends to increase with increasing forecast horizon; however, studies have shown that a balance between forecast uncertainty and horizon can be achieved to benefit performance (Zhao et al., 2019; Zhao et al., 2012). Turner et al. (2017) argued that, when operating for demands for water, this relationship breaks down—high forecast accuracy no longer necessitates improvement. Further research suggests that the value of the forecasts may decrease or disappear altogether, depending on the specific objectives and constraints (Doering et al., 2021). These results, however, are primarily in the context of large reservoirs. Given the potential benefits of small repurposed flood reservoirs for drought resilience under perfect knowledge, the value of forecasts in the operation of these reservoirs should be investigated.

1.2.4 *Flood Reservoirs in Baden-Württemberg as Small Reservoirs: Potential for Increased Water Resources Resilience*

The state government of Baden-Württemberg, Germany, is beginning investigation into drought mitigation strategies alongside flood prevention.

Baden-Württemberg, located in the temperate regions of southern Germany, is accustomed to floods as the main hydrological hazard in the region. Flood prevention and management systems such as a flood forecasting system, flood risk maps, and emergency plans have already been established (Baden-Württemberg, 2014). At the same time, drought events in Germany have been increasing in severity and frequency, including extreme events in 2018 and 2020 (Bundesamt, 2021; Erfurt et al., 2020). The potential shift in annual water availability in the near- and far-future due to both climate and anthropogenic influences (Bundesamt, 2021) is the primary motivator for the state government's development of a 12-point plan for water shortages (Umwelt, 2022b). The 12 actionable points fall under one of five categories: improving monitoring and information, managing and accounting of water uses, strengthening the resilience of existing water resources, improving awareness and protection incentives, and emergency planning. The potential reuse of flood reservoirs in this state for drought protection could contribute to improved resilience of water resources—provided, of course, that their flood retention capabilities are not impacted.

A rich database of flood reservoirs exist in this region that could be retrofitted as small reservoirs.

More than 800 reservoirs in Baden-Württemberg exist today, with total capacities ranging from as small as 200 m^3 to almost 43 million m^3, and a rich database of reservoirs in various sizes already exists (Baden-Württemberg, 2019a). Over 650 of the existing reservoirs are built for flood retention, while other uses include nature conservation, energy production, recreation, agricultural water supply, and drinking water supply. 90% of these reservoirs have dams less than 15 meters in height. The German reservoir design standard DIN 19700 (LUBW, 2007) categorizes these reservoirs by dam height and capacity into large, medium, small, and very small reservoirs. In the global context, the majority of these "small" and "medium" would be small reservoirs. Many of the "large" reservoirs in Baden-Württemberg are just above the cutoff and remain quite small in comparison to typical large dams in the literature, which often have capacities that are at least an order of magnitude larger, generally 100 million to 1 billion m^3 (Cañón et al., 2009; Consoli et al., 2007; Liu et al., 2020). Should these flood reservoirs be repurposed for drought protection, they could be operated and researched as small reservoirs.

In recent years, river renaturalization efforts in line with the European Water Framework Directive have called into question if some of these reservoirs should be destroyed.

The usage of reservoirs have also been shown to aggravate drought conditions during wet seasons or extend drought duration (Brunner, 2021; Van Loon et al., 2022). The existence of water supply reservoirs could even create a water-supply version of the flood protection levee effect, where the availability of water enables higher water demand, making critical shortages even more cost intensive (Di Baldassarre et al., 2018). However, given that drought conditions across Europe are expected to increase (and that we have already seen the immense impacts of recent drought events), the storage volume presented by these decentralized small flood reservoirs could serve to increase water resources resilience in the region. Indeed, reservoirs have been shown to be able to substantially modulate both floods and droughts, regardless of what the primary purpose is (Brunner, 2021), and there have been calls for a joint management of drought and floods in neighboring countries (Bartholomeus et al., 2023). The primary physical challenges to the ability of small reservoirs to fulfill their potential—namely losses to evaporation and low inflows—may not be as important in a temperate region, where evaporation may no longer be a dominant process and river levels are generally higher.

Despite challenges associated with the use of reservoirs, their potential should still be explored.

I argue that, despite the known challenges surrounding reservoirs (both large and small) and their operation, an investigation of the potential water supply benefits of reusing flood reservoirs for drought protection is needed to help water managers determine if the risks presented by the reservoirs are worth the rewards they can provide. Baden-Württemberg, with its temperate climate and and dense informational network on its flood reservoirs, enables a reliable analysis of the potential benefits that such reservoirs could bring. Because reservoirs' purposes can be quite regionally-dependent, I focus here on two use cases that are applicable in nearly all regions across the globe: streamflow supplementation, which raises river levels when they are low; and irrigation demand, which serves to provide water to local agriculture. Finally, this investigation of repurposed benefit should be constrained by the reservoirs' original function: the flooding conditions downstream as a result of the combined usage should never increase.

Knowing the potential benefits of a solution can better inform conversations around its use.

1.3 OBJECTIVES

The main objective of this work is to determine the potential water supply benefits of small flood reservoirs when additionally providing drought protection, and without impacting their flood protection capabilities. 30 reservoirs of various sizes and characteristics are modeled. Their operating rules are modified to allow for storage of above-average flow, then optimized under both perfect knowledge and uncertain forecasts to maximize the benefit of two use cases– streamflow and irrigation supplementation– to evaluate potential benefits. Operational setups that result in any worsening of flood outcomes (i.e. the flood outcome under the new operation was worse than what the current operation provided) were discarded. The potential study consists of three sub-objectives:

- Establish a benchmark performance for each of the two use cases using perfect-knowledge conditions. This allows a (relatively) low-data approach to getting a first understanding of the potential benefits;

- Determine the degree of performance decay of reservoirs operating under forecasts compared to perfect-knowledge conditions. This brings the operation into a more realistic setting; and
- Determine if any indicators can easily filter out unsuitable reservoirs or identify especially suitable reservoirs. Identification of such characteristics can help water managers filter through potential candidates for further study.

In meeting these objectives, I present novel information regarding the potential water supply benefits of repurposing flood reservoirs for water storage. Such an approach has, thus far, been seldom explicitly discussed in the literature. Quantitative discussions of the potential water supply benefits of small reservoirs have been limited due to lack of data restricting the detail of modeling, and the transferability of results from large reservoirs are questionable due to the sheer difference in volume.

1.3.1 *Overarching Assumptions*

For the purposes of this dissertation, I simplify a few elements of the reservoir's operation. First, rather than considering all elements of the flood reservoirs' operation such as the permanent inundation volume and the flood emergency volume, I only consider the reservoir's operation within its operating capacity– in other words, the volume between the flood retention capacity and the permanent inundation (Figure 1.2). Once the operating capacity is reached, any additional outflow above Q_{crit} is considered failure. Moreover, I assume that the reservoir has been retrofitted with the constructional aspects necessary for the usage (such as remotely controllable outflow gates, reservoir walls that can withstand both suspended volume and rapid emptying, and an impermeable floor to prevent infiltration losses). I do not model the losses due to evaporation (as this is not a dominant process in the region; see appendix B.1), infiltration (as I assume the reservoir is watertight), or siltation (as I assume that regular maintenance can be done). I also do not seek to improve the flood performance, as I assume the current operation is already flood-optimized: rather, I consider a model to have successfully preserved its flood protection function if it results in no further increases of flooding volume than the simplified operation. And finally, I focus here on only the potential water supply benefits of this combined use– though the impacts to water quality, ecology, and human society that reservoirs can have are certainly important, they are also extremely context-dependent and rely on an in-depth analysis of each reservoir individually. Thus, the potential consequences are out of the scope of this work.

1.4 DOCUMENT STRUCTURE

Chapter 2 establishes the baseline (perfect knowledge) performance of selected reservoirs for streamflow supplementation to reduce streamflow drought conditions. An objective function based on the reservoir's ability to improve fulfillment of the 70th percentile exceedance flow (i.e. reduce streamflow drought conditions) is defined and the reservoir's operating rules are optimized to maximize the benefit. In particular, this study seeks to answer the following questions:

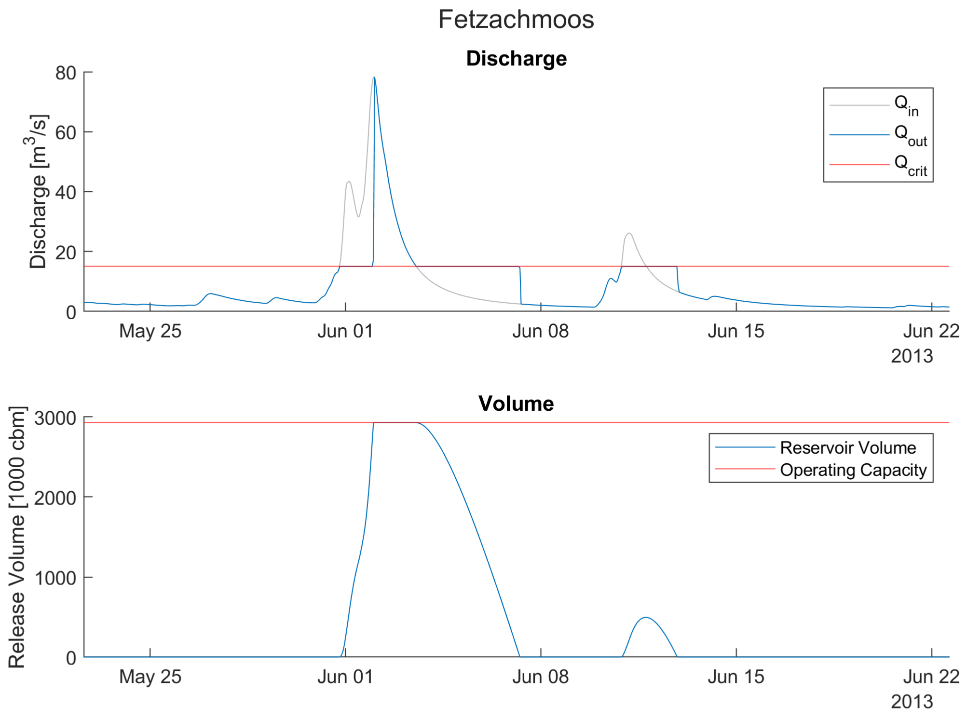

Figure 1.2: An example of how the reservoir's operation has been simplified for the modelling done in this dissertation. Note that the failure is preserved; under these assumptions, the failure occurs sooner and with a larger impact.

- Q2.1: Is the simultaneous operation of small reservoirs for both protection against streamflow drought conditions and against floods possible across a range of different reservoir sizes?
- Q2.2: Is there a relationship between characteristics of water availability and reservoir performance in reducing streamflow drought conditions?

Chapter 3 establishes the baseline (perfect knowledge) performance of the same reservoirs for agricultural irrigation benefit during known drought years. Irrigation demand time series are estimated for each reservoir in a 5 km^2 area, which are used as withdrawal schedules for the reservoirs. The reservoirs are evaluated based on the percentage of irrigation demand that they can fulfill. In particular, this study seeks to answer the following questions:

- Q3.1: Can small flood reservoirs be repurposed via operation rules based on hedging rules to simultaneously provide water for irrigation while maintaining flood protection?
- Q3.2: Could repurposed flood reservoirs in Baden-Württemberg have supplied the necessary irrigation demand in their local areas during the 2018-2020 drought without compromising flood protection?
- Q3.3: Do reservoirs that potentially provide water supply benefit to agriculture also have the ability to benefit streamflow supplementation?

Chapter 4 models the same reservoirs under the same use cases as the previous chapters but under uncertain forecasts. Rather than knowing exactly when to empty the reservoir to prepare for a flood (as was done in the perfect knowledge scenarios), the reservoirs instead operate based on the most recent forecast available. This simulates a more realistic operation. The reservoirs were re-optimized for both use cases, and the impact of the forecasts on the baseline performance was analyzed. In particular, this study seeks to answer the following questions:

- Q4.1: Does the uncertainty introduced by using forecasts for decision-making significantly decrease the performance of repurposed small reservoirs' operation such that it is no longer beneficial?
- Q4.2: What is the relationship between forecast accuracy and decrease in optimal performance between the perfect-knowledge and forecasting operations?
- Q4.3: What operating rules are most likely to be optimal, and how do these differ from current operation rules?

Chapter 5 summarizes the key findings and presents the conclusions drawn from the studies.

Part II

FIELDING FLOODS FOR (LOW) FLOWS

This chapter is a reprint of the following study that was published in the scientific journal Hydrological and Earth System Sciences (HESS):

Ho, Sarah Quynh-Giang and Uwe Ehret (2025). "Is drought protection possible without compromising flood protection? Estimating the potential dual-use benefit of small flood reservoirs in Southern Germany." In: Hydrological and Earth System Sciences 29.13, pp. 2785–2810. doi: 10.5194/hess-29-2785-2025.

2

FIELDING FLOODS FOR (LOW) FLOWS

ABSTRACT

As climate change drives intensification and increased frequency of hydrological extremes, the need to balance drought resilience and flood protection becomes critical for proper water resources management. Recent extreme droughts in the last decade in Germany have caused significant damages to ecosystems and human society, prompting renewed interest in sustainable water resources management. At the same time, protection from floods such as the catastrophic 2021 event in the Ahr Valley remain heavy in the public conscience. In the state of Baden-Württemberg in southwestern Germany alone, over 600 small (< 1 million m^3) to medium-sized (1-10 million m^3) reservoirs are currently operated for flood protection. In this study, we investigate the potential of different reservoirs for a dual flood-drought protection scheme that introduces a retention flow to store excess water for release in drought conditions, with the assumption that locations with more water available for storage will be better able to mitigate downstream streamflow drought. 30 reservoirs in Baden-Württemberg are selected based on their size according to the German design standard DIN19700 (where small reservoirs have capacities of roughly 50,000-100,000 m^3, medium have 100,000-1,000,000 m^3, and large have more than 1,00,000 m^3), their purpose (flood-only or multipurpose), and their relative water availability (expressed as the number of times the reservoir can be filled by the difference between the mean inflow and mean low flow). These reservoirs, despite their DIN19700 sizing categories, remain small in the context of global reservoir studies. Daily target releases for drought protection are proposed based on the 70^{th} percentile exceedance of modeled inflows from the calibrated hydrological model LARSIM. The retention flow is optimized to maximize penalty reduction in a scenario of perfect knowledge of flooding by using meteorological observations as artificial weather forecasts in LARSIM. The results of different retention flows are then evaluated based on their adherence to the target releases and flood protection performance. Reservoirs were required to maintain the same level of flood protection under these modified rules. The optimized results were varied: there are reservoirs that can release up to 80 times their capacity with limited benefit for streamflow drought prevention; others that can reduce streamflow drought conditions and water deficits by almost 95% over a 24-year simulation period; and others that have potential but are limited by either the capacity or by constraints for flood protection. There seems to be a trade-off between relative water availability to the reservoir and ability to alleviate drought conditions. We find that relative water availability at the reservoir has a strong relation to the amount of water a reservoir can release for drought protection, but fails to summarily describe the reservoir's potential impact on drought conditions downstream.

2.1 INTRODUCTION

Reservoirs and their operation are a critical part of drought resilience infrastructure. The ability of reservoirs to enhance low flows and therefore reduce drought conditions has been demonstrated by many studies (Chang et al., 2019; Huang and Chou, 2005; Karamouz and Araghinejad, 2008; Padiyedath Gopalan et al., 2020; Shih and ReVelle, 1994, 1995; You and Cai, 2008a,b). Research on optimal reservoir operation rules for drought have often focused on the concept of hedging rules. Hedging rules assume that by storing water and creating a small deficit of water now, we can use that water mitigate the consequences of a heavy deficit later (Shih and ReVelle, 1994). While several types of hedging rules exist, Draper and Lund (2004) found that, for most cases, a two-point hedging rule (where hedging storage begins at one point and ends at another) is optimal. Hedging rules have been applied for not only drought hedging operations (Chang et al., 2019; You and Cai, 2008b), but also for environmental benefits (Adams et al., 2017) and flood operation (Hui et al., 2016). Further research has also demonstrated that flood hedging is similar to that of hedging for water supply (Zhao et al., 2014). The combination of the two objectives—storing water for drought and maintaining retention capacity for flood retention—is difficult due to their inherently competing nature, but is more effective when the trigger rules are variable throughout the year (Balley, 1997; Chang et al., 1995). However, the majority of these studies focus on large drinking water reservoirs with capacities on the scale of 100 million to 1 billion m^3—whether such conclusions would hold for small reservoirs is uncertain.

Small reservoirs have often been named as a potential decentralized solution to water scarcity in semi-arid and arid regions (Casadei et al., 2019; Jurík et al., 2018; Liebe et al., 2007; Wisser et al., 2010). These are reservoirs typically defined as having a dam height of $\leq$ 15 m, a surface area of $<$ 0.1 km^2, and / or a storage volume of up to 1-2 million m^3 (Casadei et al., 2019; Jurík et al., 2018). Because they are smaller, they are cheaper to construct and maintain, and can be implemented in otherwise remote locations (Qadir et al., 2007). They can also be much more easily adapted to local conditions and can be managed locally (Venot et al., 2011). While they have a plethora of benefits, such as flood retention, ecosystem protection, and recreation (Jurik et al., 2015; Liebe et al., 2007; Ogilvie et al., 2019), the most common usage is to capture rainwater for supplementing agriculture. Research in Thuringia, Germany, has suggested that recommissioning small reservoirs could maintain or even increase crop yields in an uncertain future (Heinzel et al., 2022). In a global-scale analysis of their potential impact, small reservoirs in certain regions were estimated to potentially increase green water flow—in other words, agricultural water—by up to 1,100 km^3 per year, with an estimated ~35% increase in cereal production (Wisser et al., 2010). As climate change impacts destabilize traditional water availability patterns, decentralized small-scale solutions such as small reservoirs may play a role in mitigating these effects.

However, small reservoirs are not without their challenges. Small reservoirs may release water of reduced quality due to eutrophication within the reservoir (Jurík et al., 2018) and may even worsen water shortages in the long term by unsustainably increasing demand (Di Baldassarre et al., 2018). According to one study, managers across Ethiopia, Ghana, Burkina Faso, and Zambia consider many (anywhere from 25-70%) of their small reservoirs to be performing poorly (Venot et al., 2012). For example, implementations in Ghana—while overall well-received by the local farmers for their plethora of benefits—were found to have no statistically significant increase in the income of vegetable farmers (Acheampong et al., 2018). An analysis of 56 small reservoirs in Tunisia similarly showed that 16 of the reservoirs showed negligible benefits to the local agriculture (Ogilvie et al., 2019). Proposed reasons for the suboptimal operation of these reservoirs include insufficient inflow to the reservoir (Berhane et al., 2016); siltation, seepage, and evaporation losses (Acheampong et al., 2018; Mady et al., 2020); structural damage due to lack of maintenance (Berhane et al., 2016; Casadei et al., 2019; Jurík et al., 2018); and mismanagement due to poor organizational capacity at the local management level (Acheampong et al., 2018; Venot and Krishnan, 2011). Despite these challenges, the potential additional water provided by small reservoirs is still extremely valuable for enhancing the resilience of local water resources in drought, especially in the context of rainwater harvesting via flood retention (Qadir et al., 2007); however, the potential benefits of these strategies in water-rich countries like Germany remains underresearched.

More than 800 reservoirs in the German southwestern state of Baden-Württemberg exist today, with total capacities ranging from as small as 200 m^3 to almost 43 million m^3. 90% of these reservoirs have dams less than 15 meters in height. The German reservoir design standard DIN 19700 (LUBW, 2007) categorizes these reservoirs by dam height and capacity into large, medium, small, and very small reservoirs (see Table 2.1). In the global context, the majority of these "small" and "medium" would be small reservoirs. Many of the "large" reservoirs in Baden-Württemberg are just above the cutoff and remain quite small in comparison to typical large dams in the literature, which often have capacities that are at least an order of magnitude larger, generally 100 million to 1 billion m^3 (Cañón et al., 2009; Consoli et al., 2007; Liu et al., 2020). Henceforth we adopt the DIN 19700 size definitions as descriptors for reservoir sizes with the understanding that these refer to small and, at most, mid-size reservoirs on the global scale. Historically, flooding has been the major hydrological problem in the region: over 650 of the existing reservoirs are built for flood retention. Other uses include nature conservation, energy production, recreation, agricultural water supply, and drinking water supply. Flood prevention and management systems such as a flood forecasting system, flood risk maps, and emergency plans have already been established (Baden-Württemberg, 2014). In recent years, river renaturalization efforts in line with the European Water Framework Directive have called into question if some of these reservoirs should be destroyed.

At the same time, drought events in Germany have been increasing in severity and frequency, including extreme events in 2018 and 2020 (Bundesamt, 2021; Erfurt et al., 2020). The potential shift in annual water availability in the near- and far-future due to both climate and anthropogenic influences (Bundesamt, 2021) is the primary motivator for the state government's development of a 12-point plan for water shortages (Umwelt, 2022b). The 12 actionable points fall under one of five categories: improving monitoring and information, managing and accounting of water uses, strengthening the resilience of existing water resources, improving awareness and protection incentives, and emergency planning. The potential reuse of flood reservoirs in this state for drought protection could contribute to improved resilience of water resources—provided, of course, that their flood retention capabilities are not impacted.

In this study, we seek to demonstrate the potential water supply benefit of converting pre-existing small (in the global context) flood retention basins into combined flood-drought reservoirs without impacting their flood protection functions. The purpose behind this is twofold: first, to demonstrate that combined flood and drought operation in these small reservoirs is possible in a variety of reservoir sizes; and secondly, to establish a best-case-scenario benchmark for potential combined operation performance. We simulate this operation by modifying the flood operation rules to include drought hedging operations via a retention flow above which the reservoir stores water and a drought threshold target below which we supply water. To maintain flood protection levels, we aim to have a completely empty reservoir before any flood event. The potential water supply benefit of a reservoir is assessed based on the ability of the reservoir to mitigate streamflow drought directly downstream, expressed as a penalty function that more heavily punishes streamflow drought in dry seasons. This is based on the assumption that if the streamflow falls below a seasonal low flow, there is some user (whether anthropological or environmental) that is impacted. We then optimize the retention flow for maximum penalty reduction for a variety of DIN 19700 small, medium, and large flood retention reservoirs in southwest Germany under ideal conditions—that is, with perfect knowledge of the future. We hypothesize that the reservoirs providing the most relative benefit in drought conditions will be those that have high water availability relative to the reservoir capacity. While the limited capacity reduces the reservoir's overall potential benefit, more water available for storage means that a reservoir could potentially store and release its capacity multiple times in a year, increasing the likelihood that it will be able to provide water at critical times.

We begin with a description of the study area and the process of selecting reservoirs for study. Then, we introduce the hydrological model used in this study, as well as the structure of the models representing the current and modified reservoir operations. The modified reservoir also contains two points for hedging: the drought threshold, at which water is released; and the retention flow, for which water is stored and through which the reservoir model is optimized. We then discuss the optimization results (with illustrative examples) and the reservoirs' performance in flood and drought conditions.

2.2 DATA AND METHODS

2.2.1 *Study Area*

The German state of Baden-Württemberg is in the southwest of Germany and shares borders with France and Switzerland, delineated to the west and south via the Rhine River and Lake Constance. The majority of the state belongs to subcatchments of the Rhine (those of the High Rhine, the Upper Rhine, the Neckar, and the Main tributaries), with the rest belonging to those of the Danube and Tauber catchments.

Two climate regimes dominate, according to the Köppen-Geiger classification (Beck et al., 2023). A temperate oceanic climate (Cfb) covers the majority of the state, including most of the Black Forest and the major cities, such as Karlsruhe, Stuttgart, and Freiburg im Breisgau. A humid and warm continental climate (Dfb) covers the Swabian Alb and the eastern parts of the Black Forest. Average annual precipitation from 1991-2022 ranges from 600-1200 mm in the majority of the state, though precipitation in the Black

Forest is significantly higher (1400-2100 mm). Typical reference evapotranspiration in the same time period ranges from 450 mm per year in the Black Forest and Swabian Alb to 700 mm per year in the Rhine Valley and urban areas.

2.2.2 *Reservoir Selection*

A subset of potential reservoirs for investigation is first obtained by defining and selecting relevant reservoir categories. Despite the rather large number of very small reservoirs, we exclude these for two reasons: the uncertainties produced when modelling the flows in their small catchments, and the very low expected benefits of their very small capacities. Because we explicitly study the operating rule changes of flood reservoirs, we also exclude reservoirs that do not have flood retention listed as a purpose. We similarly exclude reservoirs with explicit energy production functions, as these typically have strict operating rules that are already optimized, leaving us with two purpose types: flood protection only, or multipurpose with flood protection, where flood protection-only reservoirs tend to have higher flooding thresholds than multipurpose ones. We also distinguish here between reservoirs with permanent and operational inundation: in addition to its potential implications for technical modifications, reservoirs with operational inundation are more likely to have additional complications related to the current land use (e.g. loss of arable land, impacts to reservoir ecosystems). However, because these concerns are not relevant for optimizing water supply, this characteristic is not used in this study but is included for completeness.

The number of representative reservoirs from each category was selected based on a combination of stakeholder interest and representation within the larger subset, with the goal of investigating 30 reservoirs (Table 2.1). Because the reservoirs in this dual-use scheme are intended to operate independently, there are no constraints relating to spatial connections between reservoirs. Each category containing 15 or more reservoirs was initially assigned three slots (i.e. a reservoir from this category will be chosen) for the reservoir selection. Categories with 40 or more reservoirs were given extra slots depending on the purpose: flood-only reservoirs, which are typically operated in the same manner, were given one extra slot, while multipurpose reservoirs were given two slots due to the variety of uses potentially impacting their operation. After discussion with relevant stakeholders, an additional slot was given to both large categories to allow further investigation of their assumed higher potential. Categories are referred to in this study as a two-letter abbreviation combining their size (where L is large, M is medium, and S is small) and their usage (where F is a flood-only reservoir and M is a multipurpose reservoir). The main categories for this study, their abbreviations, and their distributions (in both the overall reservoir set and the selected subset) can be found in Table 2.1.

Reservoirs with different degrees of relative water availability from each of the categories were selected to investigate the various hydrological regimes within the region. We define relative water availability here as the availability factor (AF), or the average number of times per year that a reservoir's capacity (C, in cubic meters) can be filled via the water that we are able to store based on the entire simulation period (excluding the warm-up; i.e. 1998-2021). The water available for storage is the difference between the mean (calculated over the 24 years of simulation) yearly inflow

Table 2.1: Reservoir categories with abbreviations and number of reservoirs selected for study. Each category abbreviation is a combination of its size (large = L, medium = M, and small = S) and its usage (F = flood-only, M = multipurpose).

Size (DIN19700)	Dam Height [m]	Capacity [m^3]	Category	Existing Purpose	Inundation Type	# of Reservoirs	# of Selected Reservoirs
Large	≥ 15	$> 1{,}000{,}000$	LF	Flood protection only	Permanent	6	-
					Operational	16	4
			LM	Multipurpose	Permanent	26	4
					Operational	4	-
Medium	6-15	100,000 – 1,000,000	MF	Flood protection only	Permanent	18	3
					Operational	183	4
			MM	Multipurpose	Permanent	47	5
					Operational	17	3
Small	4-6	50,000 – 100,000	SF	Flood protection only	Permanent	9	-
					Operational	128	4
			SM	Multipurpose	Permanent	23	3
					Operational	3	-
Very Small	≤ 4	$< 50{,}000$	VF	Flood protection only	Permanent	6	-
					Operational	143	-
			VM	Multipurpose	Permanent	13	-
					Operational	16	-

(Q_{in}) volume rate and the mean low flow ($Q_{70,mean}$; for definition and calculation see 2.4.1) volume rate, in cubic meters per second (eq. 2.1):

$$AF = \frac{(Q_{in,mean} - Q_{70,mean}) \times 365\ days}{C} \tag{2.1}$$

The AF can be interpreted as a combined indicator representing the relationship between the water availability in the catchment and the reservoir's ability to store or release it. A higher AF, then, indicates more water availability relative to the reservoir's capacity. While a reservoir's capacity inherently limits its ability to regulate streamflow, more available water should allow a reservoir to refill more quickly after emptying. In essence, it would increase the likelihood that, in drought conditions, a reservoir would have water to release. This assumption is the basis for our hypothesis that a reservoir with a higher AF should be able to reduce drought conditions more effectively. To test this, we selected reservoirs with varying values of AF, estimated from local long term statistics (Baden-Württemberg, 2016), from each category. For each combination of category and inundation type, reservoirs whose estimated AFs were close to the 50^{th}, 25^{th}, and 75^{th} percentile were selected (the distributions of estimated AF for each of the categories can be seen in Appendix A.1). A few other reservoirs (Gottswald, Mittleres Kinzigtal, and Fetzachmoos) were selected based on stakeholder interest.

The resulting 30 reservoirs investigated in this study can be seen in Table 2.2 and their locations are shown in Figure 2.1. The results of the hydrological model LARSIM at these locations were used to then re-calculate the AFs.

2.2.3 *Reservoir Models*

Two reservoir operation models were programmed: one modeling the current operation (i.e. the flood-optimized condition), and one modeling the potential combined (i.e. flood and drought) operation.

The flood operation model consists of three modules: flood operation, in which discharge above the flooding limit downstream (Q_{crit}) is stored until the reservoir's operating capacity is reached; flood release, which empties the reservoir once the flood wave passes; and normal operation, in which there is no change to the reservoir's volume. Q_{crit} is the design flood for the reservoir; if there are urban areas downstream, this is typically the 100-year flood . If the reservoir is full before the flood wave passes, the additional water is returned to the river channel and is considered flood failure. This is a generalized version of the current reservoir operation rules for all selected reservoirs, regardless of existing uses. (In the interest of completeness, we note that some of these reservoirs have seasonally variable operational capacities—this variation has been ignored in this study.)

The combined operation model expands on the flood operation model in three ways:

1. The reservoir releases water for drought once the discharge has fallen below a certain drought-related threshold (in this study, we use the 70^{th} percentile exceedance flow; for calculation, see section 2.2.3.1);

2. To increase water available for drought releases, the model introduces a retention flow (Q_r) above which the reservoir impounds water (when $Q_{in} > Q_r$, the reservoir

Table 2.2: Selected reservoirs for study, along with their capacities, the flow at which they begin impounding floods (Q_{crit}), their operating capacity, their calculated availability factor AF, their catchment area in LARSIM, and the ratio of the actual catchment area to the LARSIM catchment area (used to re-scale the inflow). Note that reservoirs with permanent inundation will have smaller operating capacities than their total capacity.

Category	Inundation Type	Name	Operating Capacity [m³]	Q_{crit} [m^3s^{-1}]	AF [-]	LARSIM Catchment Area [km²]	Area Ratio [-]
LF	Operational	Bernau	1,020,000	22.00	17.91	112	1.00
		Gottswald	4,720,000	830.00	195.90	1063	1.65
		Mittleres Kinzigtal	2,700,000	860.00	150.1	791	1.13
		Wolterdingen	3,000,000	75.00	24.56	185	0.97
LM	Permanent	Federbach	652,652	0.400	5.25	10	1.08
		Fetzachmoos	3,500,000	15.00	17.23	4	1.04
		Nagoldtalsperre	1,741,000	15.00	5.29	39	0.93
		Rehnenmuehle	2,930,000	7.00	10.05	46	0.98
MF	Operational	Schwaigern	151,880	3.32	20.41	37	1.46
		Seckach	64,000	50.30	68.44	56	0.62
		Seebaechle	33,112	0.10	1.91	2	1.04
		Unterbalbach	210,000	6.33	14.38	29	1.24
	Permanent	Doertel	168,400	0.79	7.78	2	0.97
		Lindelbach	172,000	0.50	6.32	1	1.02
		Weissacher Tal	185,000	2.41	35.16	6	2.11
MM	Operational	Heinzental	310,000	1.09	7.50	6	1.22
		Hofwiesen	335,210	10.68	91.97	26	1.02
		Wustgraben	276,181	0.50	6.21	6	1.00
	Permanent	Fischbach	181,625	3.70	11.21	16	1.00
		Huettenbuehl	32,000	4.00	19.79	13	1.05
		Kressbach	233,780	0.70	7.09	8	0.98
		Michelbach	81,728	1.00	4.48	5	1.16
		Salinensee	188,000	3.60	57.45	5	1.01
SF	Operational	Duffernbach	31,143	1.55	46.70	5	1.07
		Goettelfinger Tal	83,400	4.10	38.42	12	1.56
		Mittelurbach	60,000	0.50	22.84	7	1.02
		Wollenberg	30,200	3.37	36.73	8	1.55
SM	Permanent	Hoelzern	7,703	1.50	5.74	1	1.00
		Lennach	9,600	2.10	7.37	1	0.99
		Nonnenbach	3,759	0.17	141.15	4	1.04

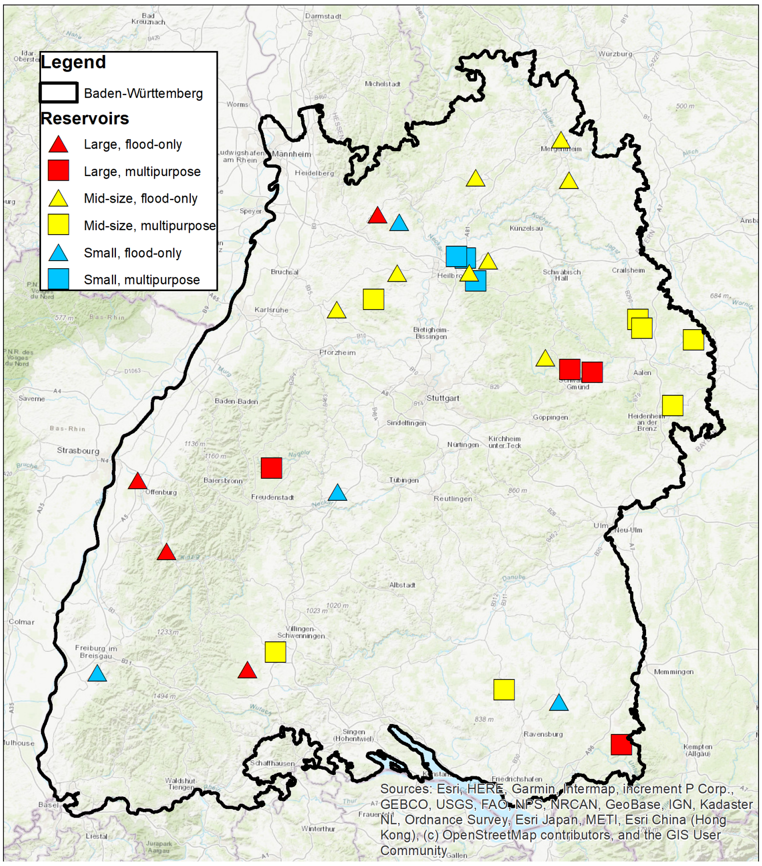

Figure 2.1: Locations of selected reservoirs for study in the German state of Baden-Württemberg.

stores $Q_{in} - Q_r$). This is the variable parameter through which we optimize the model; and

3. Instead of releasing the retained flood volume immediately after the flood wave passes, the reservoir holds onto the water until the drought threshold is met (in which case it releases the water) or another flood wave is predicted. The forecast horizon for the flood wave in this perfect-knowledge scenario is the drawdown time, or the time the reservoir needs to empty the current volume. If a flood wave does occur, the reservoir empties its contents and remains empty (i.e. ignores the Q_r filling condition) until the flood wave begins. In this way, we ensure that the flood retention capability of the reservoir is not compromised.

This model only requires an inflow time series, a flooding limit, and the reservoir capacity, and produces a drought threshold time series that is used to calculate a volume time series, an outflow time series, and a penalty time series, which seeks to evaluate the reservoir's performance (for calculation and explanation, see section 2.2.3.3). Because these inputs are often relatively accessible, this model is rather flexible and can be applied to many reservoirs, even those outside of Baden-Württemberg. A flow chart of the combined operation model can be seen in Figure 2.2.

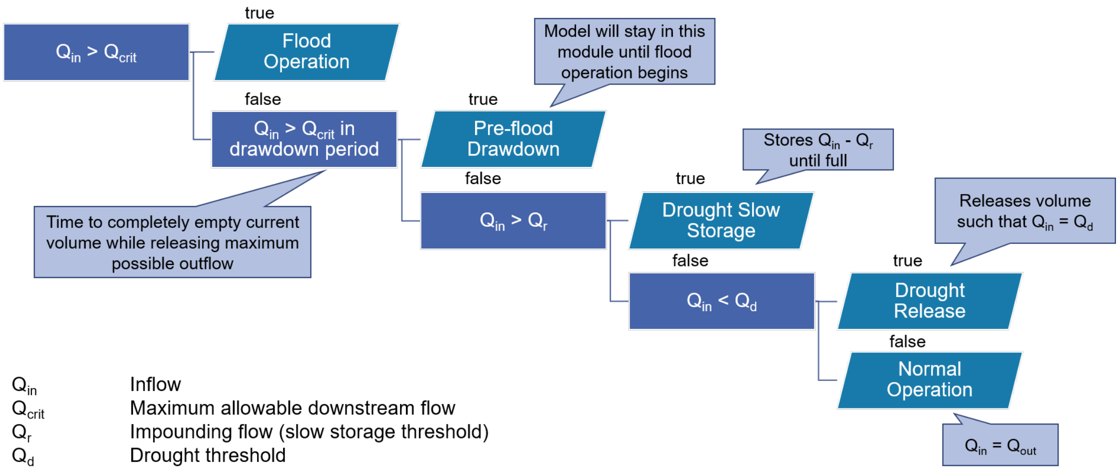

Figure 2.2: Decision tree for combined operation model.

2.2.3.1 *Drought Release Targets*

Drought remains a complex and multivariate phenomenon that affects multiple sectors, though different users may experience these effects at different times. This makes drought difficult to quantify and define. A distinction should be drawn between drought events and drought conditions: drought conditions are levels of intense dryness below a certain threshold, whereas drought events are prolonged periods of drought conditions (usually with a minimum duration of 30 days). Given that a reservoir's most immediate impact is on streamflow, we focus here on its potential ability to decrease streamflow drought conditions via streamflow drought thresholds as a preliminary step into its ability to reduce drought. A truly comprehensive drought reduction approach would not just consider hydrologic variables but also consider management techniques (which is beyond the scope of this paper) for soil moisture, agricultural, and ecological drought within a given catchment to manage the prolonged dryness. However, hydrological droughts still have implications for impacts on other sectors, such as reduced drinking water or irrigation water availability (Van Loon, 2015), and many healthy ecosystems depend on certain flows at certain times (Yarnell et al., 2020). Streamflow drought, often expressed as a threshold level, is a common hydrological drought indicator.

Because such thresholds can be extremely variable and location-specific, especially for reservoir flows, a method that could be applied to different 30 reservoirs was needed. This method should also allow for seasonal variability, as previous studies on reservoir hedging rules for preventing drought have demonstrated that such rules are most effective when allowed to vary throughout the year (Balley, 1997; Chang et al., 1995). The drought release targets in this study should therefore be a streamflow drought threshold that allows for seasonal variability that could be applied anywhere.

The drought threshold used in this study is the percentile exceedance flow per Cammalleri et al. (2016), with a minor adjustment for the hourly time step of the model output. For each time step t within a year, we collect a 721 x n matrix of discharge values: 721 represents all the hourly time steps in a 30-day moving window (with an additional value to center the window on t), which is applied to all the years in the dataset (n). The cumulative distribution function curves for discharge, and then the percentile

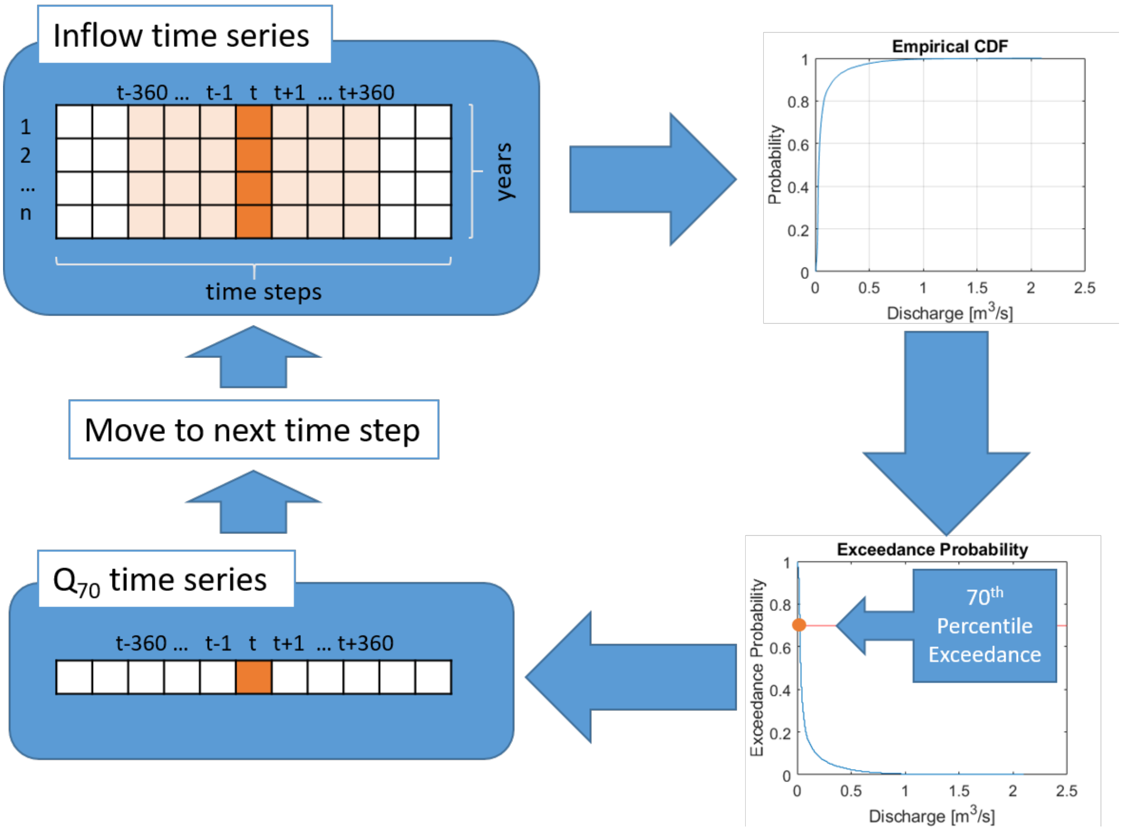

Figure 2.3: Example calculation of the Q70 time series.

exceedance curves, are derived based on the values in this matrix. The threshold value at each timestep is the discharge corresponding to the chosen percentile exceedance. This means that at the 70^{th} percentile, this threshold discharge is exceeded 70% of the time. Typical reference values in the literature range from the $70\text{-}95^{th}$ percentile (Cammalleri et al., 2016; Hisdal et al., 2004; Van Loon et al., 2010) and are generally adjusted for river dynamics (flashier rivers, for example, would typically select a higher percentile)—though in the interest of consistent inter-reservoir comparisons, we will choose a singular percentile threshold for all reservoirs. Then the steps are repeated until there is a value for each hourly time step in a year. The result is a seasonally-variable drought threshold for that time step that is dependent only on a streamflow time series, making it easily applicable to different locations. This calculation is summarized in Figure 2.3.

The choice of percentile has a notable effect on the detection of streamflow droughts: a higher percentile exceedance generally means more intense drought conditions and fewer drought events (Cammalleri et al., 2016; Tallaksen et al., 2009). We use the 70^{th} percentile exceedance flow (Q_{70}) as the threshold here, as it is the most lenient definition among typical values and allows insight on the reservoirs' ability to mitigate not only severe drought conditions but also mild ones. If the inflow at any time step is less than Q_{70} (i.e. the discharge drops below the threshold), we assume that there is some user of the water—whether human or otherwise—that is being impacted by water scarcity in the river. To mitigate these consequences, the combined model uses stored volume in the reservoir (if any) to supplement the outflow such that Q_{70} is reached. This low threshold will allow us to evaluate the new rules' ability to alleviate both mild and severe droughts. The arithmetic mean of this Q_{70} time series is also used as an estimate of the average low flow to calculate the AF in Eq. 2.1.

The exceedance percentile flow is commonly used to represent streamflow drought conditions when defining drought events (Cammalleri et al., 2016; Hisdal et al., 2004; Tallaksen et al., 2009; Van Loon and Van Lanen, 2012; Van Loon et al., 2010) and is currently used (at the 75^{th} percentile) as a warning indicator for low flow in Baden-Württemberg (Baden-Württemberg, 2024b). The percentile exceedance has also been used in studies seeking to define ecological flows, though usually at the 85^{th} percentile (Knight et al., 2011, 2013; Vigiak et al., 2018; Yarnell et al., 2020). The 85^{th} percentile may also serve as a regulated lower limit for agricultural water abstraction, as noted in Salmoral et al. (2019).

The hourly resolution of this study's demand time series may be difficult to use in practice: reservoirs typically change their releases on weekly or monthly scales. We retain this high temporal resolution, however, to match the hourly resolution of flood forecasts and operations. In the future, known thresholds or demand curves (derived e.g. from local irrigation demands) may be substituted for the percentile exceedance curve.

2.2.3.2 *Pre-Flood Drawdown Time*

The combined operation model was programmed with the assumption of perfect knowledge of inflow and in particular of flood onsets. In practice, this means the forecasting horizon (t_{down}) should be calculated for every non-flood time step. The forecasting horizon is the time t_{down} such that the potential release from the reservoir is greater than or equal to the volume at the end of the current time step (eq. 2.2):

$$\int_{t_+1}^{t_i+t_{down}} [Q_{crit} - Q_{in}(t)]dt \geq V(t_i) \qquad (2.2)$$

After calculating t_{down}, the model checks if a flood begins ($Q_{in} > Q_{crit}$) within the next t_{down} timesteps. This is, in effect, a perfect-knowledge flood forecast. If there is a flood, the model enters the pre-flood drawdown module in which the reservoir is emptied by releasing the water at Q_{crit}. Once emptied, the reservoir remains empty until the flood event begins. By ensuring that the flood reservoir is empty before onset, we guarantee that the flood protection function is not compromised.

2.2.3.3 *Expressing Degrees of Reservoir Failure*

Degrees of reservoir failure (i.e. excess discharge above Q_{crit} and deficit discharge below Q_{70}) in both flood and drought at each time step are expressed in this model as penalties. Flood (P_f) and drought penalties (P_d) calculated using the flood operation model are considered the baseline penalties for each reservoir and are handled as separate time series. The penalties serve three functions in this study:

1. To evaluate the preservation of flood protection during the optimization phase. The flood penalty in the flood operation model ($P_{f,f}$) is used as the baseline

standard—if the flood penalty of a combined model run ($P_{f,c}$) shows a higher penalty than the $P_{f,f}$ at any time step, the solution is rejected.

2. To assign hypothetical "damages" to reservoir failure in both drought and flood. Flooding volume should always be strongly penalized; however, assigning a flat value to all flood volumes is not ideal because it will be unable to capture increases in flood volumes. In drought failures, greater water deficits should be more heavily penalized than smaller ones.

3. To evaluate the effect of the changes to operating rules by comparing the reduction in "damages" from the optimized models.

As with the drought threshold definitions, these penalty functions can be replaced with a different method of expressing degrees of failure as a function of discharge or height, if a river rating curve exists (e.g. monetary flood damage per unit excess discharge).

Because the flood penalty at time t ($P_{f,t}$) is only used to ensure flooding does not increase, a simple calculation is desired. Moreover, no penalty should be given if the reservoir outflow is less than or equal to the downstream flooding discharge. Here, it is a linear transformation (arbitrarily given a slope of 5) of flooding downstream of the river where penalty increases significantly once the outflow $Q_{out,t}$ exceeds the flooding discharge (Q_{crit}) (eq. 2.3):

$$P_{f,t} = \begin{cases} 0 & \text{if } Q_{out,t} \leq Q_{crit} \\ -5(Q_{out,t} - Q_{crit}) & \text{if } Q_{out,t} > Q_{crit} \end{cases} \tag{2.3}$$

The drought penalty functions at time t ($P_{d,t}$) are selected based on the assumption that small deviations of Q_{out} from the drought threshold Q_{70} will be less impactful (and therefore less penalized), while also strongly penalizing outflows closer to zero. For this, we chose a square root function, which penalizes small deviations lightly but increases exponentially as the discharge approaches zero. Penalties for Q_{out} below 0.00001 $m^3 s^{-1}$ are assumed to be the same as for Q_{out} of 0.00001 m^3 s^{-1} to avoid potential division by infinity. This results in the following penalty expressions (eq. 2.4):

$$P_{d,t} = \begin{cases} 0 & \text{if } Q_{out,t} \geq Q_{70,t} \\ \frac{-1}{\sqrt{Q_{out,t}} + \frac{1}{\sqrt{Q_{70,t})}}} & \text{if } Q_{out,t} < Q_{70,t} \\ \frac{-1}{\sqrt{0.00001}} + \frac{1}{\sqrt{Q_{70,t}}} & \text{if } Q_{out,t} \leq 0.00001 \end{cases} \tag{2.4}$$

Because penalty at *t* is a function of the seasonally variable Q_{70} at that time step, penalty also has an element of seasonality. The penalty per missing unit volume of water changes with Q_{70}: it will be higher in seasons where Q_{70} (and therefore streamflow in general) is low, and lower in seasons where Q_{70} is high. For example, the penalty of missing 1 m^3 s^{-1} if Q_{70} is 2 m^3 s^{-1} is -0.293; if Q_{70} is 10 m^3 s^{-1}, the penalty is -0.0171. In this way, the model correctly penalizes shortages in the dry season more heavily than during the wet season.

For discussion of results between reservoirs, we evaluate the reduction of penalty and drought deficit volume between the combined operation model and the flood operation model. These comparisons are done without results from the first year of operation to allow for a warm-up period.

We express the penalty benefit for drought (B_p) as the percent reduction in total drought penalty from the flood operation model ($P_{d,f}$) in comparison to that of the combined operation model ($P_{d,c}$), normalized by the $P_{d,f}$ (eq. 2.5):

$$B_p = 100 \times \frac{\sum P_{d,f} - \sum P_{d,c}}{\sum P_{d,f}} \tag{2.5}$$

Because penalty has an element of seasonality, the benefit per unit volume of water is also seasonal: the benefit associated with providing 1 m^3 s^{-1} will be higher when Q_{70} is low than when Q_{70} is high.

We similarly describe the volume benefit for drought (B_v) as the percent reduction from the total drought deficit volume of the flood operation model ($V_{d,f}$) in comparison to that of the combined operation model ($V_{d,c}$), normalized by the $V_{d,f}$ (eq. 2.6):

$$B_V = 100 \times \frac{\sum V_{d,f} - \sum V_{d,c}}{\sum V_{d,f}} \tag{2.6}$$

The volume benefit B_v differs slightly from the penalty benefit B_p in that penalty allows heavier weighting of water delivery at critical times: the same volume of water may reduce penalty by different amounts, depending on the season. In contrast, the volume benefit assumes that every unit of water is equally valuable, regardless of when it is delivered.

The total volume released by the reservoir for drought protection purposes (V_d) is normalized by the reservoir capacity (C) (eq. 2.7):

$$V_{d,nor} = \frac{V_d}{C} \tag{2.7}$$

Thus, $V_{d,nor}$ indicates the number of times the reservoir's complete capacity is given for drought protection over the model simulation.

2.2.3.4 *Optimization of Retention Flow for Drought Mitigation*

The reservoir model was programmed with the following constraints:

- The reservoir volume at the end of time t (V_t) is equal to the volume at t-1 plus the difference between the inflow ($Q_{in,t}$) and outflow ($Q_{out,t}$) at time t (eq. 2.8);
- The operating capacity C is the operational volume of the reservoir; in other words, the difference between the full reservoir volume and the permanent inundation volume (which, for operationally-inundated reservoirs, is zero) (eq. 2.9);
- The reservoir volume cannot exceed the operating capacity and cannot be less than 0 (eq. 2.10);

- The reservoir outflow at time t ($Q_{out,t}$) is dependent on the current volume and the inflow. Moreover, $Q_{out,t}$ can only exceed Q_{crit} in a flood failure scenario (i.e. normal releases cannot exceed Q_{crit}) (eq. 2.11); and
- The retention flow Qr must be between the highest value in the release target time series and the flooding limit (eq. 2.12)

$$V_t = V_{t-1} + (Q_{in,t} - Q_{out,t}) \times \ t \tag{2.8}$$

$$C = V_{full} - V_{permanent\ inundation} \tag{2.9}$$

$$0 \leq \ V_t \leq \ C \tag{2.10}$$

$$Q_{out,t} = \begin{cases} Q_{out,t} \leq Q_{crit} & \text{if } V < C \\ Q_{out,t} > Q_{crit} & \text{if } V - C > 0 \end{cases} \tag{2.11}$$

$$\max (Q_{70}) < Q_r < Q_{crit} \tag{2.12}$$

The constraint on the retention flow Q_r comes from the logic of the reservoir operation. If the inflow to the reservoir exceeds Q_{crit}, the reservoir will already be retaining water; thus, Q_r must be less than Q_{crit} in order to allow storage of non-flood water. A lower $Q_{r,}$ then, is more likely to increase total water storage for drought but will have no effect on flood protection. If the inflow to the reservoir is below Q_{70}, the reservoir will release stored volume to increase the outflow to the threshold. Each reservoir under the combined operation model was simply optimized by testing 50 equidistant values of Q_r between the maximum of Q_{70} and Q_{crit} to cover the range of possible values. The resulting P_f and P_d were used to evaluate the run: any Q_r that resulted in an increase of P_f was excluded from simulation, and the Q_r that resulted in the lowest drought penalty (i.e. highest benefit) was considered the optimal Q_r for the reservoir.

2.3 RESULTS & DISCUSSION

2.3.1 *Optimization Results*

The reservoirs' Q_{crit}, maximum and minimum Q_{70}, and the optimal Q_r are available in Appendix A.2.

To evaluate the reservoirs' effectiveness in reducing drought conditions, we plot the penalty benefit (which is a function of both drought time and deficit) against the availability factor for all reservoirs in Figure 2.4, yielding interesting results. It seems that reservoirs with high flood pre-release volumes and lower AF (such as Rehnenmuehle,

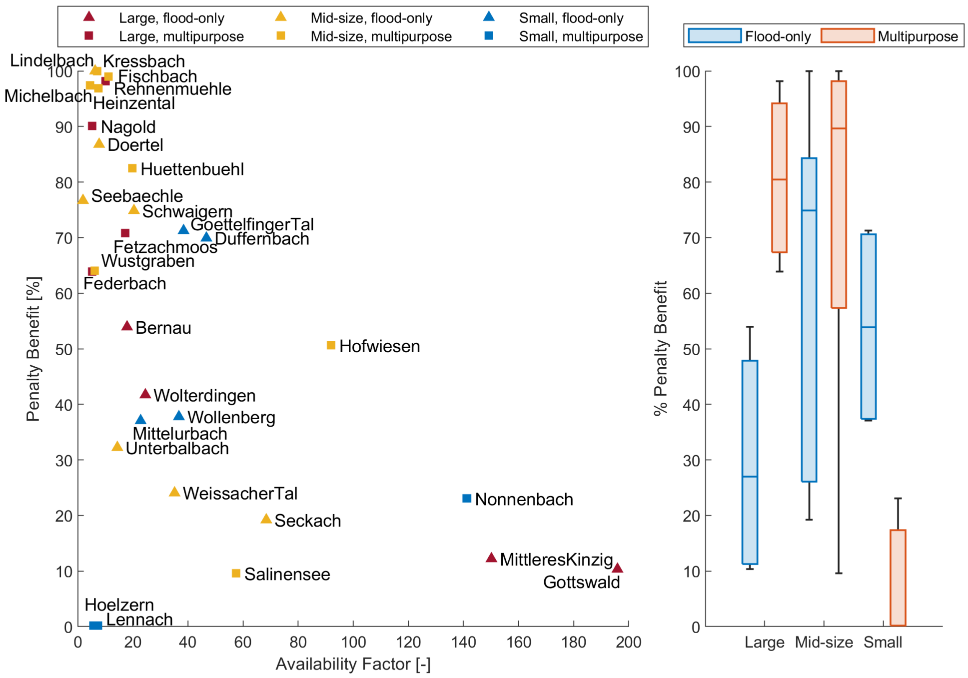

Figure 2.4: Penalty Benefit relative to availability factor (left) and summarized by reservoir size and use categories (right).

Fetzachmoos, Heinzental, and Federbach) still were able to reduce penalty significantly: this is interesting, as it implies that reservoirs with less water available can still refill quickly enough after a flood event to supply water during drought deficits.

Indeed, contrary to our hypothesis, reservoirs with high AF were unable to decrease penalty significantly. It seems that overall, there is an inverse relationship between benefit and availability in the large and mid-size categories, with small reservoirs being standout exceptions. Overall, LM, MF, and MM reservoirs were the most effective at reducing drought: all LM reservoirs had penalty benefits of over 70%, while more than half of MM and MF reservoirs had benefits of over 50%. Our sample of SF reservoirs as a category outperformed LF reservoirs, indicating that even small reservoirs can have noticeable benefits for local streamflow drought reduction.

SM reservoirs, however, are almost completely ineffective. In the cases of Hoelzern and Lennach, it is because the reservoirs had a Q_{crit} that was so high in comparison to the modeled inflow—in the 24 years of simulation, they were generally on the scale of 0.005 m^3 s^{-1} and did not experience a single flood wave large enough to impound water. Even the lowest Q_r value tested barely allowed for any storage of water in the combined scenario. Thus, there was almost no water available to release. Even when there was water available, as in the case of Nonnenbach, there was simply not enough volume in the reservoir to compensate for the drought deficits. Because of this, we consider these reservoirs generally unsuitable for a combined use strategy under these conditions.

The reservoirs can be roughly grouped into one of five groups based on Figure 2.4: the two SM reservoirs with almost no benefit; low-availability (< 100 AF), high benefit (> 60%) reservoirs; reservoirs with middling benefit (50-60%); reservoirs with

Table 2.3: Selected reservoirs for exploration.

Reservoir Name	Category	AF [-]	Normalized Release Volume [-]	Benefit [%]
Gottswald	LF	195.90	46.90	10.35
Heinzental	MM	7.50	5.85	96.87
Hofwiesen	MM	91.97	28.68	50.64
Federbach	LM	5.25	2.65	63.91
Wollenberg	SF	36.73	21.58	37.78

low availability and low benefit ($< 45\%$); and high-availability (> 100 AF) reservoirs with low benefit. In the next sections, we explore the combined model outputs of selected reservoirs (shown in Table 2.3) from the non-SM groupings to understand the interactions of AF, benefit, and release volume.

2.3.1.1 *High Availability, Low Benefit - Gottswald*

Gottswald is a large flood-only reservoir with very high relative water availability—the highest of all the selected reservoirs—but is only able to reduce roughly 11% of the total penalty. Investigation into the discharge, volume, and penalty time series (Figure 2.5) shows that while high discharge events are common, strong drought penalties are also common and long-lasting. Because no flood waves greater than Q_{crit} occur within the simulation years, there is no pre-flood release from the reservoir and all water released is for the purpose of drought protection. The reservoir—as a result of the introduction of Q_r—is able to store and release significant amounts of water, as one would expect of a location with high relative water availability. However, even when filled to its capacity, the reservoir is unable to release enough water to overcome anything beyond the mildest drought peaks, often reaching zero before the drought conditions intensify. Even deficits with relatively small penalties such as those in October 2009 and January 2010 (see Figure 2.6) are quite substantial, with deficits of up 5 m^3 s^{-1}. The reservoir at full capacity (2.7 million m^3) can only sustain this deficit for just over six days. Thus, while the reservoir's current capacity is capable of supplementing water for short periods of time, the deficit volume is simply too big in comparison.

This presents a problem with our hypothesis of AF as an indicator for penalty reduction. A large AF per our definition would indicate either a very small volume relative to the typical catchment flows or a very strongly variable catchment flow. The discharge time series in Figure 2.5 suggests that it is the latter—indeed, the discharge time series shows extremely strong peaks that are over 100 times the Q_r which fill the reservoir quite quickly, while drought deficits drain the water almost as quickly. The reservoir volume is simply too small to take advantage of the available water. At the same time, the large deficits are (at least in part) a result of the Q_{70} as the drought definition: in a highly variable flow regime, this lenient definition may select flows that are unrealistically high for dry conditions. In these cases, it may be more realistic to choose a higher percentile exceedance for a more optimized operation. However, we retain the use of Q_{70} so that the operation of different reservoirs in this study are analyzed at the same relative thresholds.

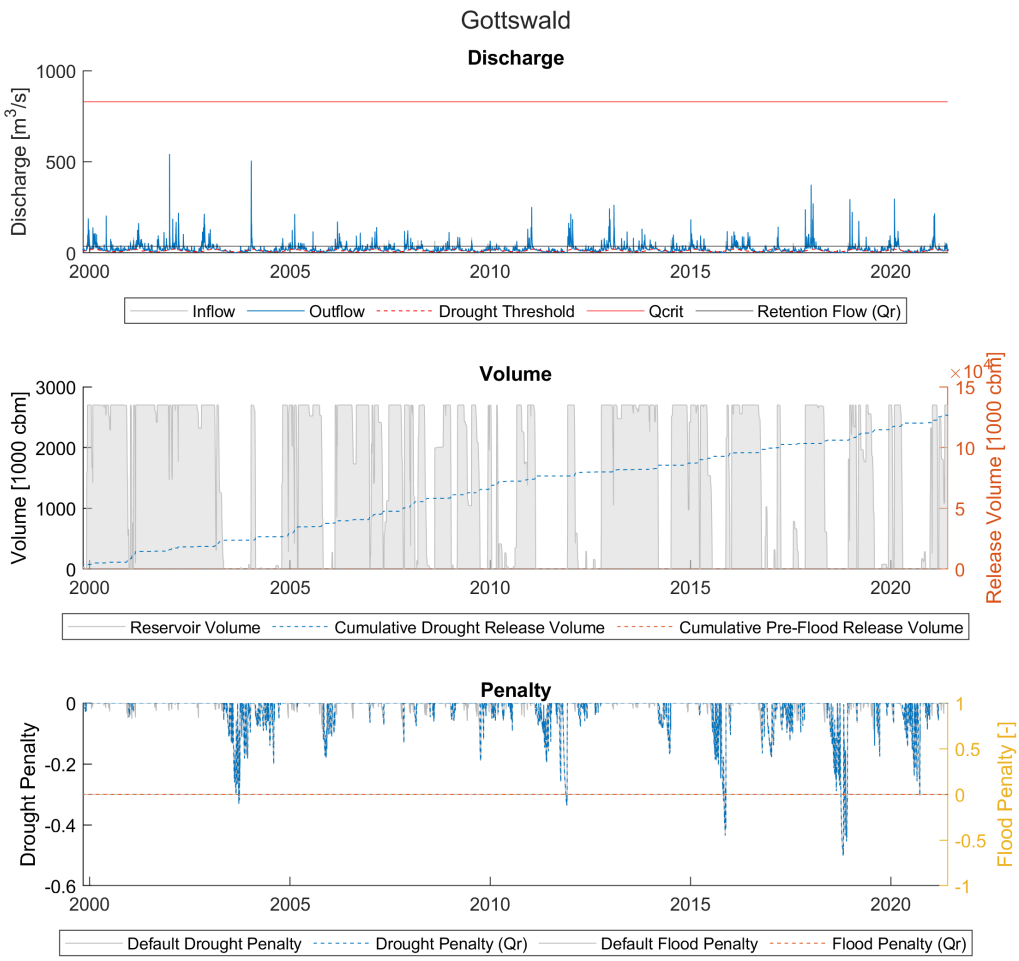

Figure 2.5: Discharge, volume, and penalty time series for Gottswald reservoir (example of a high availability, low benefit reservoir).

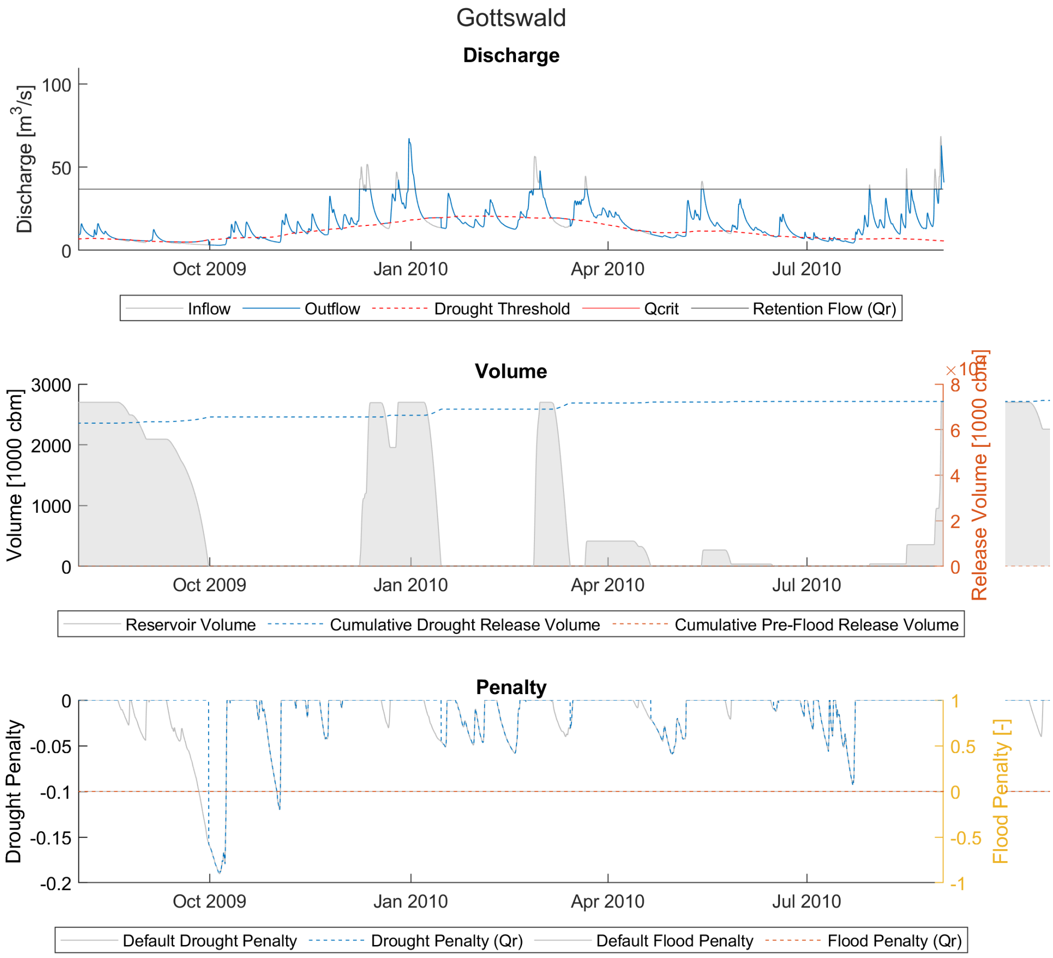

Figure 2.6: A closer look at a problematic period for Gottswald reservoir.

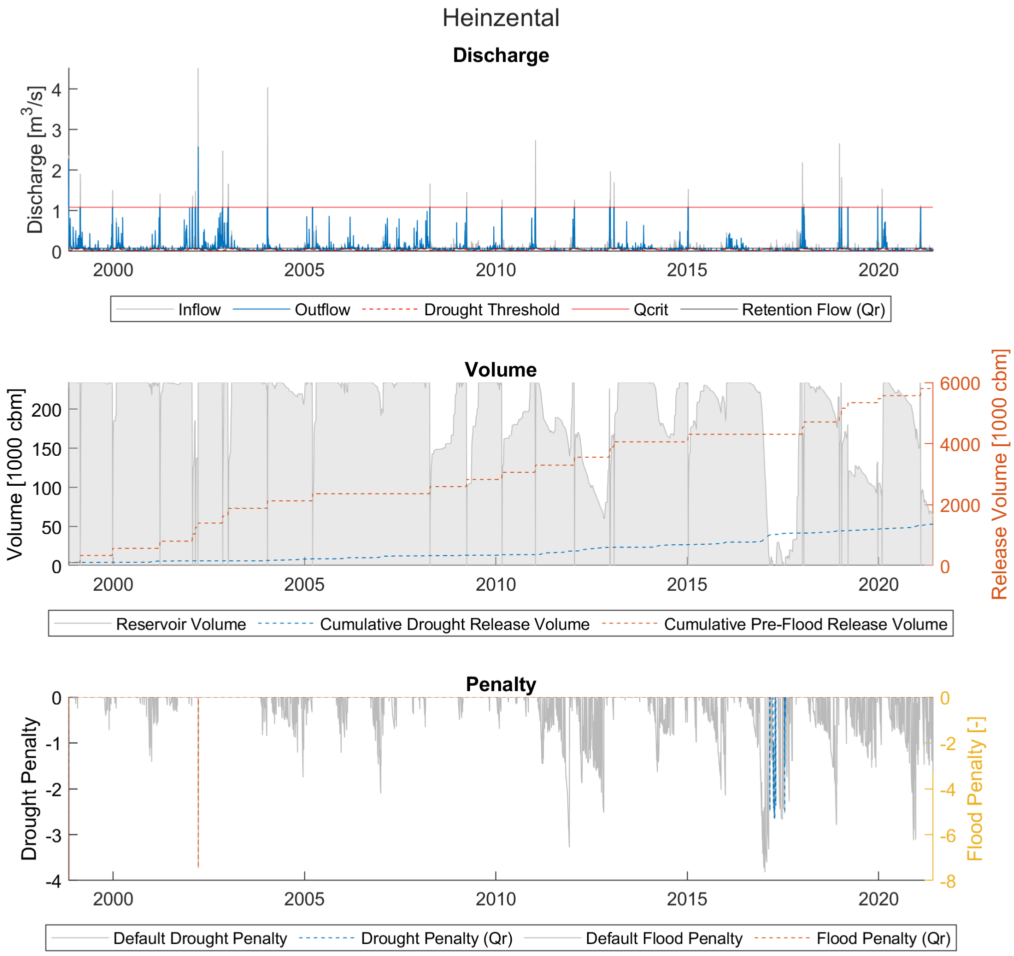

Figure 2.7: Discharge, volume, and penalty time series for Heinzental reservoir (example of a low availability, high benefit reservoir).

2.3.1.2 *Low Availability, High Benefit - Heinzental*

Heinzental (Figure 2.7) is a mid-size multipurpose reservoir with a low AF but significant drought improvements. Flood events occur several times throughout the time series; however, it is able to completely protect against flood events while still being able to compensate for the vast majority of drought conditions. In contrast to Gottswald, Heinzental requires significantly less water to overcome the drought conditions at the inlet, often completely overcoming the penalty conditions entirely before even half the volume is used. The only times the reservoir fails to overcome drought are following a sharp intensification of drought conditions immediately after a flood event in 2011, and in 2017 after compensating for another intensification of drought conditions. This seems to be due to the very stringent drought threshold: the maximum value in the threshold time series is 0.05 $m^3\ s^{-1}$. Even if upstream the river were dry (i.e. no inflow to the reservoir), the reservoir's capacity could supply that discharge for 54 days. It is likely that any further changes to the reservoir's rules could improve the efficiency of such reservoirs, as it is already quite high.

2.3.1.3 *Low Availability, High Benefit – Federbach*

Federbach (Figure 2.8) is a large multipurpose reservoir with a rather low AF in comparison to other large reservoirs. As it is on the lower end of the high-benefit reservoirs, it demonstrates some limitations that impact a reservoir's benefit. It frequently impounds flood volumes—this means that much of the stored volume is released not for drought protection but to ensure an empty reservoir for flood protection. Unfortunately, the reservoir fails in a couple of flood events; however, because the reservoir in the flood-only operation also could not completely retain these events, these do not represent an increase in flood risk. Additionally, the reservoir often struggles to reach full capacity (roughly 652,000 m^3) due to the frequent flood pre-releases, as the flood waves are often not enough to fill the reservoir completely. Despite this, the reservoir does manage to eliminate many of the smaller drought penalty events. Assuming the reservoir needed to supplement the maximum Q_{70} of 0.0932 m^3 s^{-1} to a dry riverbed, Federbach's capacity could last for almost 81 days. In this sense, it is the opposite of Gottswald—a reservoir with a capacity that is more than capable of delivering the needed water, making its benefit quite high. However, its potential for drought alleviation is limited by the frequency of floods.

2.3.1.4 *Middling Benefit – Hofwiesen*

Hofwiesen (Figure 2.9) is a mid-size multipurpose reservoir with the highest AF of all selected mid-size reservoirs. The reservoir is able to compensate for a lot of drought penalties with its capacity and, in line with our hypothesis, its high water availability allows it to refill quickly, allowing it to give more water in drought conditions. However, the reservoir fails with strong and prolonged drought signals, such as those extending from 2011 through 2012 and from 2018 through 2020, despite being able to refill a couple of times. Bernau, which is the other reservoir with middling benefit, shows similar behavior. Overall, this reservoir grouping is capable of dealing with smaller, shorter drought conditions in the river.

2.3.1.5 *Low Availability, Low Benefit - Wollenberg*

Wollenberg (Figure 2.10) is a small flood-only reservoir. In addition to having a low AF among small reservoirs, it also has the lowest improvement of all reservoirs. As with many reservoirs in this grouping, it is rather clear that the low benefit comes from a lack of water: the reservoir is only able to fill a few times, in part because the reservoir never experiences any floods. Indeed, the flooding limit is more than 10 times the highest discharge. This is an indication that the reservoir could be overbuilt: in other words, Q_{crit} is too large in comparison to the average flow. In our simplified optimization process where we test 50 evenly spaced values between Q_{crit} and the drought threshold, this results in a Q_r that never allows the reservoir to completely fill. Even when Q_r is reached, the reservoir only reaches 1/3 of its usable capacity (30,200 m^3). With the reservoir levels so low most of the time, the reservoir can hardly compensate for any drought events. It seems likely that further decreasing Q_r would significantly increase the volume of stored water and possibly the benefit.

Such a solution poses another general question—how far should the Q_r be lowered? It seems that, given perfect knowledge, it should be possible to lower Q_r to the drought

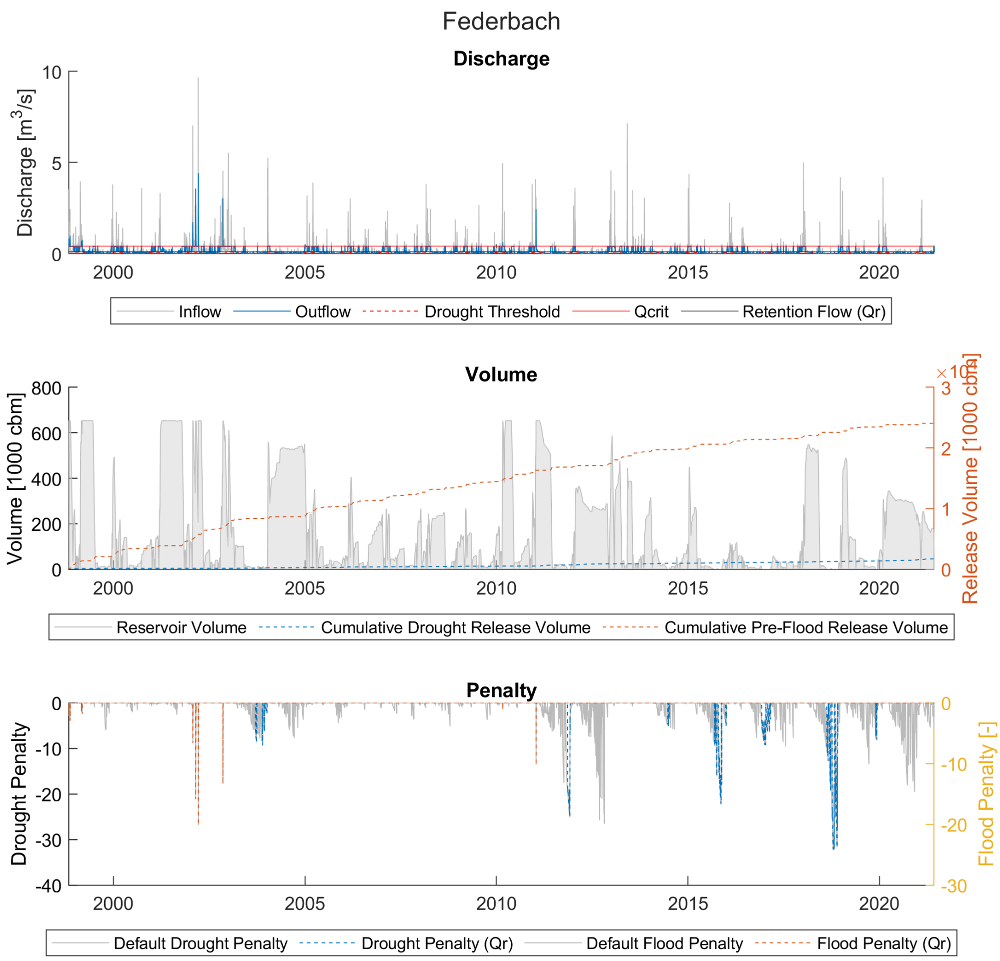

Figure 2.8: Discharge, volume, and penalty time series for Federbach reservoir (example of a low availability, high benefit reservoir).

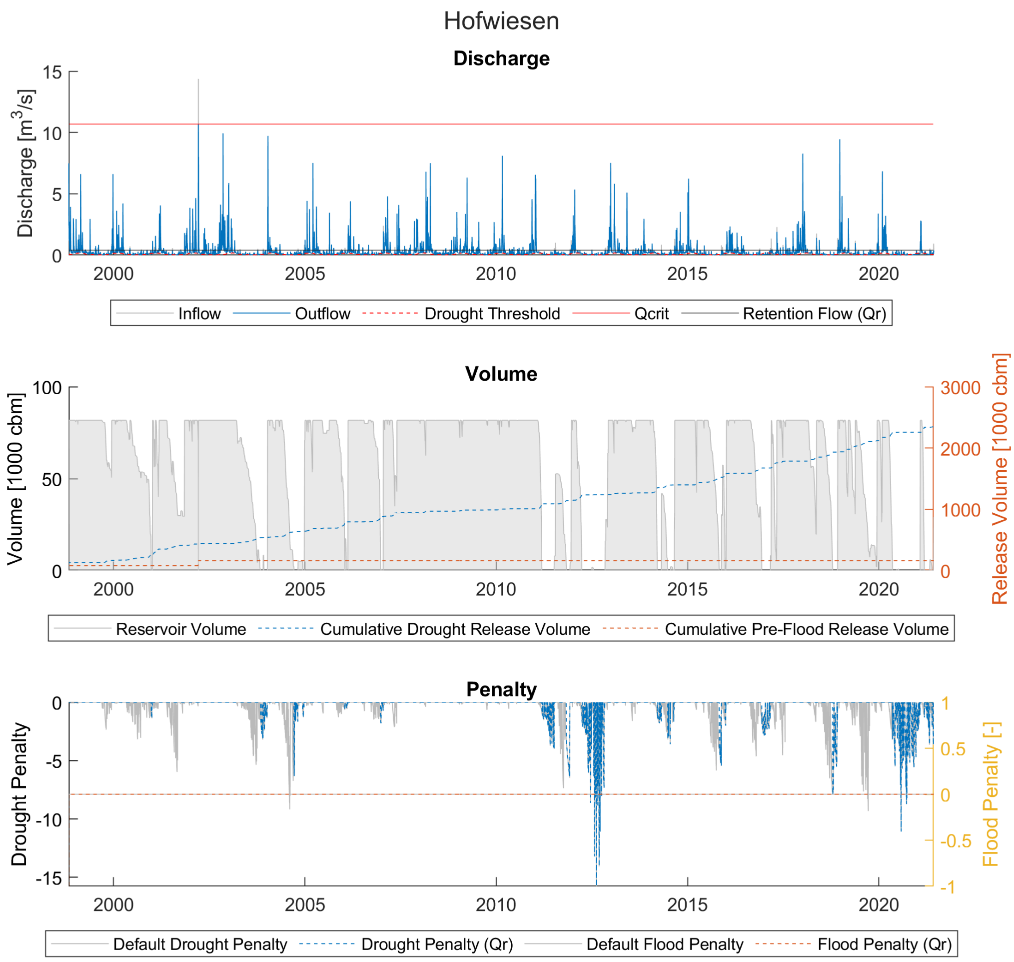

Figure 2.9: Discharge, volume, and penalty time series for Hofwiesen reservoir (example of a middling-benefit reservoir).

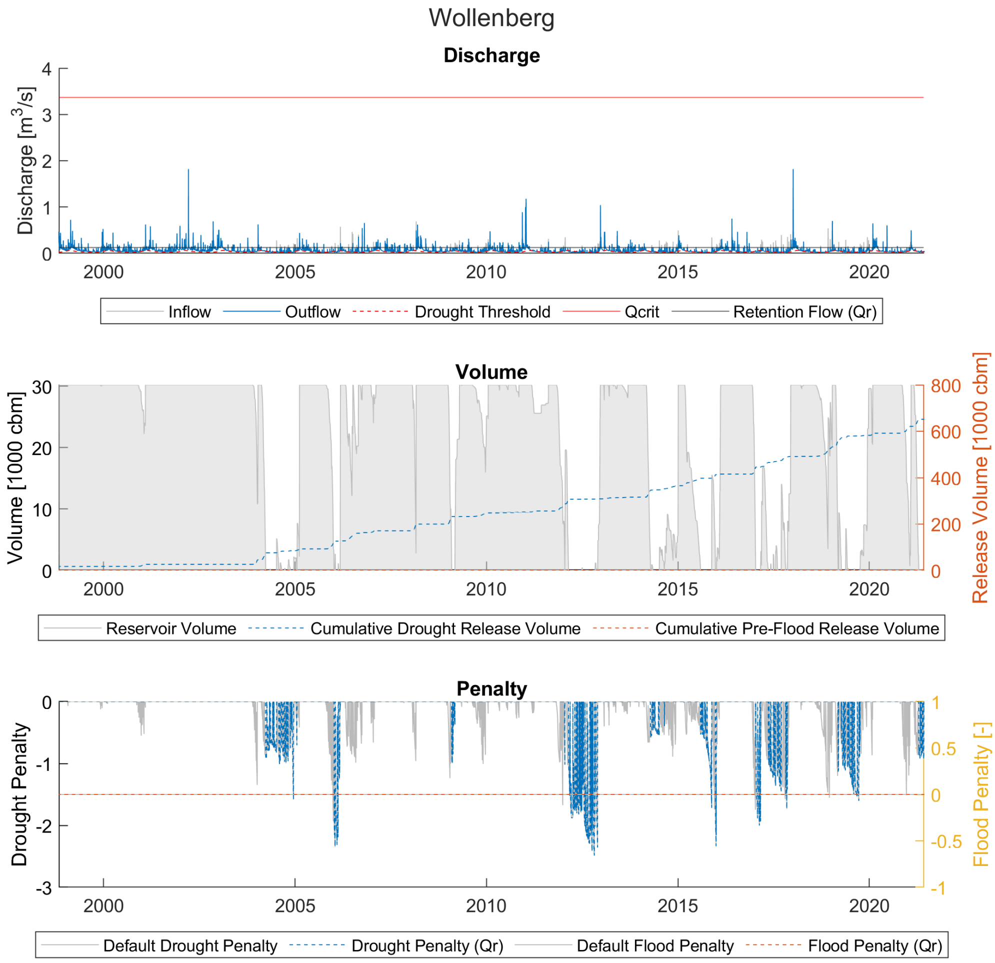

Figure 2.10: Discharge, volume, and penalty time series for Wollenberg reservoir (example of a low availability, low benefit reservoir). The flooding limit (Q_{crit} = 3.37 m^3 s^{-1}) is omitted in the discharge portion of this figure for clarity, as the flows never exceed 0.3 m^3 s^{-1} during the 24 years of modelled data.

threshold. However, this could result in significant and potentially catastrophic changes to the river regime. For example, aquatic species that require moderate flooding from time to time could be severely affected by the attenuated discharges from a much lower Q_r. At the same time, a highly regulated river regime could be beneficial for agricultural planning or industry. Because our study focuses on the general benefits of reservoirs for water supply without making assumptions about the uses downstream, these questions are ultimately outside the scope of this paper but should be considered for future studies.

2.3.2 *Reservoir Results*

2.3.2.1 *Flood Protection*

We reaffirm the maintenance of flood protection by tracking the total amount of time in floods, the total volume of all flood waves, and the flood penalty for the inflow, the flood-only model, and the optimized combined operation model (Figure 2.11). 10 reservoirs were able to retain all flood events—both volume and time—in the simulation period during the flood operation model. 11 reservoirs did not experience any flood events in the same period. These reservoirs maintained the same level of flood protection in the combined operation model—that is, they experienced no floods under combined operation. While nine reservoirs did experience flood failures in the flood operation model, the degrees of failure did not increase after optimizing the combined operation model. Thus, we demonstrate that it is possible to reuse these reservoirs for drought protection without impacting their flood protection functions.

2.3.2.2 *Drought Protection*

We plot similar metrics to evaluate the overall reduction of drought conditions in terms of hours, deficit volume, and penalty between different model runs (Figure 2.12). While we include the semi-natural condition for completeness, the focus in this discussion remains between the approximation of the current situation—the flood operation model—and the optimized combined operation model. Between the flood and combined operation models, there are significant reductions in time under drought for almost all reservoirs, while the reductions in deficit volume and penalty are not nearly as marked. This is again due to the model releasing water from the reservoir as soon as the threshold is reached—because the deficit volumes at the beginning of a drought spell are smaller, the reservoir can supply water for longer. Changing the timing of releases to increase overall benefit would reduce the improvement in time. While this can be desirable, the purpose of the drought releases should also be considered: it may, for example, be more beneficial to alleviate drought conditions for longer if they happen to occur during critical times for agriculture or protected ecosystems. Interestingly, several reservoirs (Federbach, Lindelbach, and Duffernbach) in the flood operation model result in an improvement in drought metrics compared to the inflow—in these cases, there were flood events that were immediately followed by drought conditions, so the immediate release of flood water happened to compensate for some drought deficits.

Drought penalty and drought deficit volume have a relationship that is significantly less straightforward than their flooding counterparts. For example, while the large flood-only reservoirs have the largest total deficits, they also have the smallest penalties. This is because of the way that penalty adds "urgency" to the deficit volume: given equal deficit volumes, if the discharge is closer to zero, the (magnitude of the) penalty increases significantly. This adaptation is critical to ensuring that releases to flows that are low in both frequency (i.e. under the Q_{70}) and low in magnitude (i.e. low discharge) are properly valued. On the other hand, this means that if flows are high, the penalty for drought flows will not be high in magnitude. Thus, the penalty benefit is a clearer metric for analysis of the reservoir's performance.

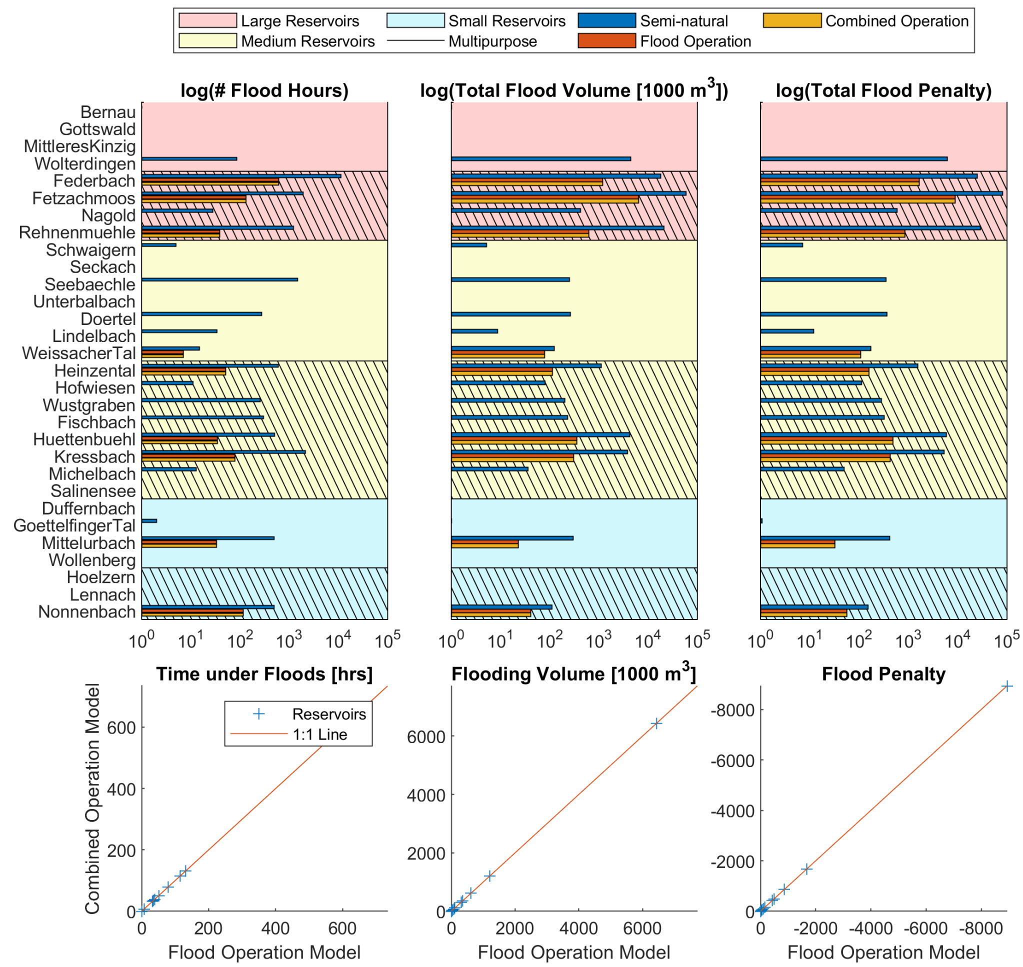

Figure 2.11: Flood statistics (# of timesteps with floods, total flood volume, and flood penalty) for each of the 30 reservoirs at the inflow (semi-natural) and downstream under both models (flood operation and the optimized combined operation models). In the scatter plots (bottom), the x-values for each point denote the score in the flood operation model and the y-values denote the score in the combined operation model. A lower value in the combined operation model (i.e. deviation towards 0 from the 1:1 line) indicates improved performance. Note the differing axes and scales.

The penalty and volume benefits are shown in Figure 2.13. The relationship between volume and penalty benefit here can be illustrative. Because of the "urgency" weighting, whether or not the penalty benefit is higher than the volume benefit may give an indication to how effective these release rules are. A higher volume benefit, for example, would imply that water was mostly given at less-critical times. This is the case for most of the reservoirs. The handful of reservoirs with relatively equal volume and penalty benefits may be able to satisfy critical deficits if the conditions are right, whereas the few with higher penalty benefit can be considered quite effective in their release timings.

However, the reductions in deficit—in other words, the water the reservoir is able to supply—remain rather significant for most reservoirs (Figure 2.14). Flood pre-releases are also shown to contextualize how much water saved for drought is "lost" when maintaining flood protection. Multipurpose reservoirs have the highest pre-release volumes—this is likely due to their lower Q_{crit}, which is more frequently reached. Total drought release volumes range from 387 m^3 to 127 million m^3. The median drought release volume is roughly 1.4 million m^3 over the simulation period, or approximately 58,000 m^3 per year. Assuming an average irrigation water demand (IWD) of 112 mm/year as found for crops in Germany by Drastig et al. (2016) (and also assuming this water could be given at the right time), this median could fulfil the irrigation demand for half a square kilometre of farmland for 24 years. If all the reservoirs' drought releases were used purely for supplying this IWD, the water gained using the combined operation model could sustain almost 180 km^2 of agriculture per year. This has powerful implications for satisfying agricultural demands in a warming world: these reservoirs could be used to provide needed irrigation.

2.3.2.3 *SF and Reservoir Performance*

As we discussed in Section 2.3.1, reservoirs with a very high AF were overall unable to improve penalty benefit significantly (Figure 2.4, left). This unfortunately remains the same for volume benefit (Figure 2.15, right), but seems to have a strong correlation with normalized release volume. In all reservoir categories, release volume increases with increasing availability. While AF has a relationship with release volume, having more water available and more water released does not correlate well with higher penalty benefit or deficit volume benefit.

In the large and medium size categories, benefit generally increases with decreasing AF. For example, the low improvement, high release group consists exclusively of reservoirs with high AF. Even reservoirs with higher AF tend to have lower penalty reduction within their groups. A potential explanation is the chosen release rules: the model releases water as soon as inflows drop below the drought threshold. Because the deficits are small at first, the amount of penalty reduced per unit can be quite small. Changing the model so that the timing of reservoir releases such that water is given at the drought peaks could improve the penalty benefit further, though at the cost of complicating the model and the release rules. This would not, however, improve the volume benefit. An alternative explanation for the disconnect between AF and benefit is a strong imbalance between incoming water and the capacity. This seems unlikely to improve, even if rules are significantly changed. For small reservoirs, the relationship between AF and benefit is skewed by the general unsuitability of SM reservoirs. The low penalty benefit of these reservoirs is echoed in the low volume benefit. Overall,

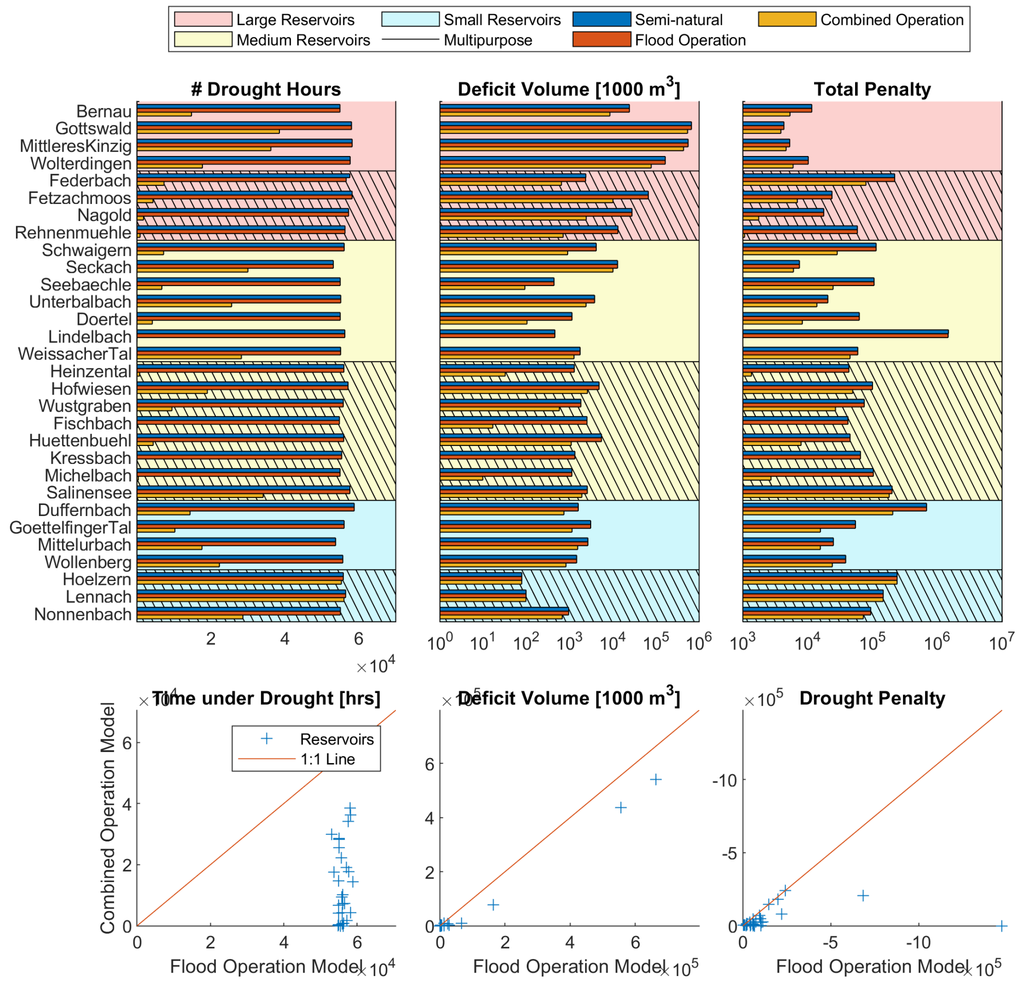

Figure 2.12: Drought statistics (# drought timesteps, drought deficit volume, and drought penalty) for each of the 30 reservoirs at the inflow (semi-natural) and downstream under both models (flood operation and the optimized combined operation models). In the scatter plots (bottom), the x-values for each point denote the score in the flood operation model and the y-values denote the score in the combined operation model. A lower value in the combined operation model (i.e. deviation towards 0 from the 1:1 line) indicates improved performance. Note the differing axes and scales.

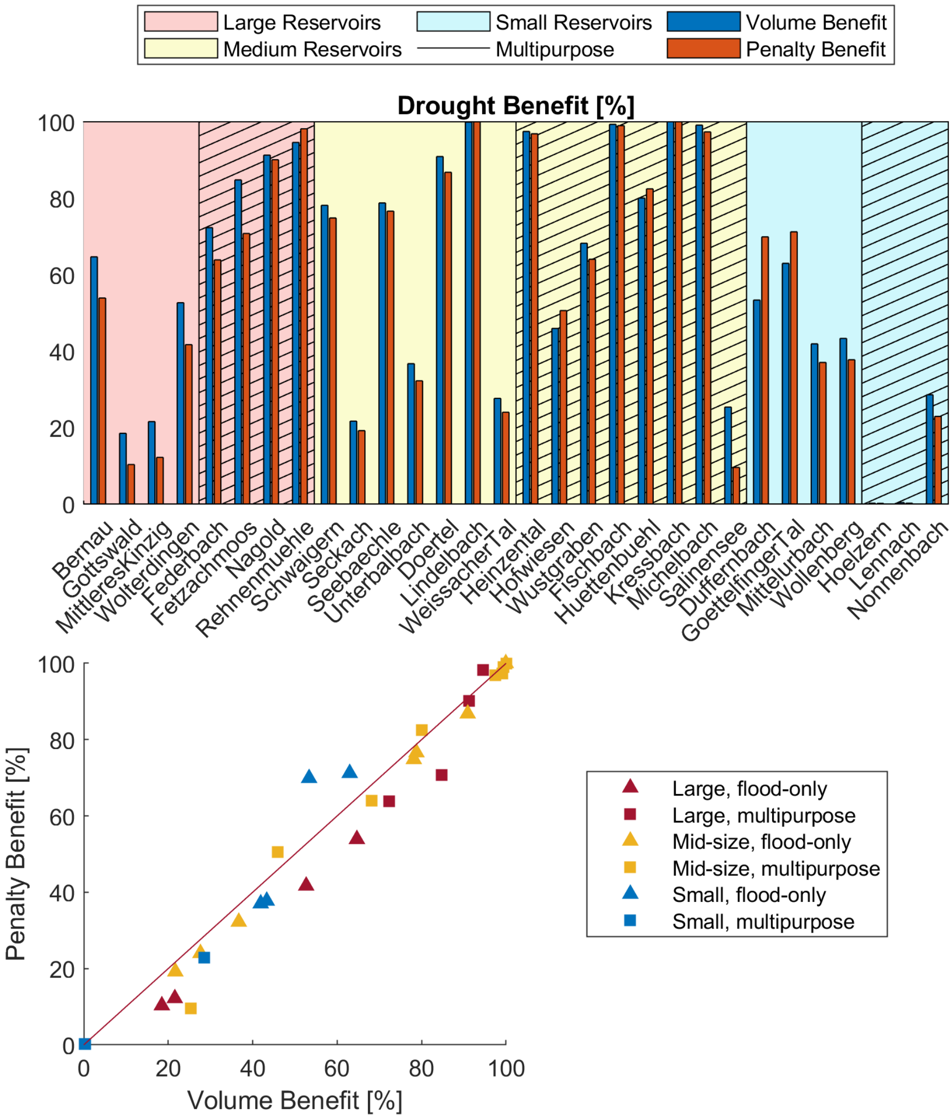

Figure 2.13: Comparisons of volume and penalty benefit for all reservoirs.

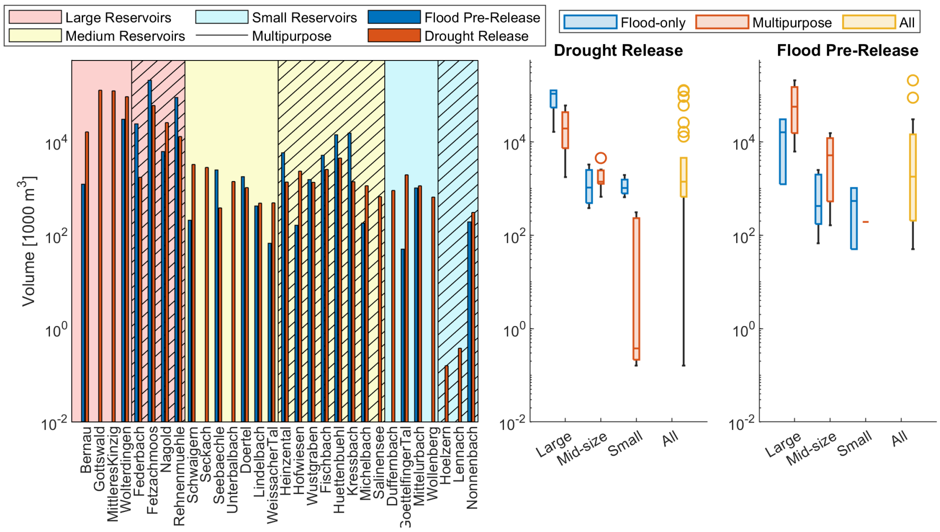

Figure 2.14: Comparisons of total releases for drought protection and pre-releases for flood protection in the optimized combined operation model over the simulation period. Reservoirs with no flood pre-release volumes were omitted from the respective plots.

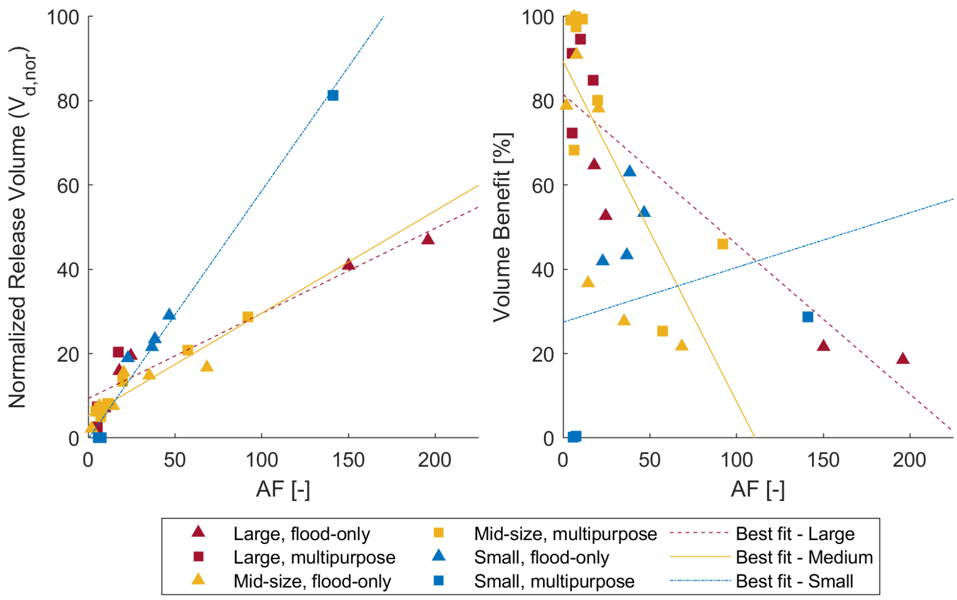

Figure 2.15: The relation between AF (relative water availability) and normalized release volume ($V_{d,nor}$; left) and volume benefit (B_v; right).

small reservoirs show a generally increasing volume benefit with increasing AF. This holds even if we do not consider the reservoirs with almost no benefit.

2.4 CONCLUSION

Under conditions of perfect knowledge, small (relative to typical reservoir studies) flood reservoirs can be repurposed for drought protection without impeding their flood protection functions. We expand the reservoir function by applying a retention flow above which we store water and supplying a drought threshold below which we release water, and maintain the flood functions by ensuring the reservoir is empty before a flood event. This method is a generalized framework through which flood reservoirs—even those outside of our study area—can be evaluated for drought protection. We tested these new rules for a representative subset of 30 reservoirs to determine if water availability would be a suitable indicator for a reservoir's availability to mitigate streamflow drought conditions (defined in this study as the hourly 70^{th} percentile exceedance). This hypothesis is built on the assumption that more available water for storage would mean that the reservoir would be more likely to have water available during drought conditions, and thus reduce drought more effectively. We found a range of results: there are reservoirs that can release up to 80 times their capacity with limited benefit for streamflow drought prevention, others that can reduce streamflow drought conditions and water deficits by almost 95% over a 24-year simulation period, and still those that have potential but are limited by either the capacity or by constraints for flood protection. The median volume of water made available by this strategy across all reservoirs is approximately 1.4 million m^3, and the amount of streamflow drought reduction (benefit) ranges from nearly no effect to complete elimination of drought conditions.

Contrary to our hypothesis, the relative water availability (defined in this study as the availability factor, or the number of times per year that the reservoir can be filled using the difference between the mean and mean low flow) did not have a strong relationship to a reservoir's ability to curtail drought conditions. While it does have a strong relationship with the amount of water released for drought protection, the operation strategy of releasing water as soon as the drought threshold was reached meant that water was being delivered at less-than-optimal times. High relative water availability seems to indicate drought conditions with considerable volume deficits for which the current reservoir volume cannot compensate, even if the retention flow were to be reduced further. Low relative water availability generally indicates milder drought conditions that can often be compensated by the reservoir's volume, resulting in high improvement. For mid-size and large reservoirs, the relationship between availability and benefit seems to be the inverse of what we expected—an exception are the small multipurpose reservoirs investigated in this study, which seem to function poorly under these operation rules. However, the overall lack of generalizable rule indicates that water availability may not be a good predictor for drought reduction performance across all reservoir sizes.

Alongside the positive implications this work has for the role of repurposed flood reservoirs for increased water resources resilience, this work poses additional questions. For example, would the reservoirs still maintain their performance when operating under uncertain forecasts? This work, in considering a perfect-forecast scenario, provides a useful best-case scenario of benefit which can serve as a benchmark for evaluating the impact of forecasting on reservoir operations. Reservoirs with frequent floods already see limitations on their drought reduction performance in these best-case scenarios. The potential benefits (and, perhaps, consequences) of operation with flood forecasts, which will inevitably have false alarms or misses, should also be investigated.

There remains additional questions regarding the true benefit and potential consequences of the provided water. We assumed that any additional water volume—irrespective of nutrient quality or temperature—is beneficial. This is not necessarily the case, as fragile aquatic ecosystems could be damaged by an influx of poor quality water. Further work is needed to determine tangible benefits or even consequences of the water potentially supplied by these methods, as well as potential consequences from the land use change within the reservoir. Moreover, the benefit of the water in this study is based on streamflow statistics, with the assumption that any water provided during a streamflow shortage would be inherently beneficial, and that water provided in dry-season shortages would be even more beneficial. While useful for demonstrating the potential of such a strategy under many different conditions of reservoir size and water availability (as was done in this study), this benefit unfortunately remains quite abstract and divorced from explicit consequences to the environment or human society. A clear next step in the development of a combined flood-drought strategy for small flood reservoirs is the investigation of the ability of combined operation to satisfy a particular demand, such as agriculture, in drought conditions.

Part III

FIELDING FLOODS FOR FLOURISHING FARMS

This chapter is a reprint of the following study that was submitted to the scientific journal Earth's Future:

Ho, Sarah Quynh-Giang, Jacob Jeff Bernhardt, Kerstin Stahl, and Uwe Ehret (2025). "Fielding floods for flourishing farms: a framework for assessing the reuse of small flood reservoirs as irrigation reservoirs." In: doi: 10.22541/essoar.175260001.13781003/v1.

3 FIELDING FLOODS FOR FLOURISHING FARMS

ABSTRACT

Due to the increased intensity and frequency of droughts under a warming world, agricultural irrigation demand (AID) is likely to increase in many regions of the world—not just in semi-arid and arid regions, but also in temperate regions. Small reservoirs have often been touted as a decentralized solution to increase water supply resilience, but little research on their potential operating rules exists. In this study, we propose a framework to assess the potential water supply benefit of reusing flood reservoirs as small reservoirs for agricultural irrigation via modeled operation based on hedging rules, using the German state of Baden-Württemberg as an example. Because of their exceptional dryness, the 2018-2020 drought years in Baden-Württemberg can be used as a benchmark for the potential benefit provided by a reservoir to agriculture in its region. Our framework estimated the AID in a 5 km² region around reservoirs, whose operations were modeled to store smaller flood waves and allow withdrawals for irrigation, while simultaneously maintaining their protection against their design flood. Our results suggest that, operated under best-case scenarios, 20 of the 30 tested reservoirs could have contributed more than 70% of their local AID during the drought years, indicating that the proposed operating rules may be quite suitable for this purpose. Comparisons with previous work indicate some high-performing reservoirs could also be suitable for streamflow supplementation. This framework for assessing repurposed flood reservoirs could help determine their role in increasing water resiliency in the face of increasing drought frequency in a warming world.

3.1 INTRODUCTION

Small reservoirs have often been named as a potential decentralized solution to water scarcity in regions across the globe, such as Italy, Slovakia, Ghana, Burkina Faso, Zimbabwe, and Brazil (Casadei et al., 2019; Jurík et al., 2018; Liebe et al., 2007; Mady et al., 2020; Owusu et al., 2022; Wisser et al., 2010; Şen, 2021). These are reservoirs typically defined as having a dam height of $\leq$15 m, a surface area of $<$ 0.1 km², and / or a storage volume of up to 1-2 million m³ (Casadei et al., 2019; Jurík et al., 2018). Because they are smaller, they are cheaper to construct and maintain, and can be implemented in otherwise remote locations (Qadir et al., 2007). They can also be much more easily adapted to local conditions and can be managed locally (Venot et al., 2011). In a global-scale analysis of their potential impact, small reservoirs in certain regions were estimated to potentially increase green water flow—in other words, agricultural water—by up to 1,100 km³ per year, with an estimated ~35% increase in cereal production (Wisser et al., 2010). Research has suggested that recommissioning small reservoirs could maintain or even increase crop yields in an uncertain future (Heinzel et al., 2022), which is likely a driving reason behind the high increase in the number of remotely-sensed reservoirs in water-stressed Europe (Aminzadeh et al., 2024). As climate change impacts destabilize traditional water availability patterns, decentralized small-scale solutions such as small reservoirs may play a leading role in mitigating drought effects in more temperate regions of the globe.

One of the main challenges in incorporating small reservoirs into regional analyses of water availability is the lack of data available to catalogue them. Even large global databases of reservoirs, such as HydroLAKES (Messager et al., 2016) and the Global Reservoir and Dam database (GRanD) (Lehner et al., 2011), do not include them. While reservoir operation and optimization for drought and irrigation has been researched throughout the years (Cañón et al., 2009; Chang et al., 2019; Chang et al., 1995; Ding et al., 2017; Draper and Lund, 2004), these studies mainly focus on the impacts of large reservoirs and rely on machine learning methods to derive operating rules. However, research indicates that simpler rulesets based on hedging rules, under which artificial shortages of water are created to store water for future use, may be sufficient (Ding et al., 2017; Draper and Lund, 2004). The ability of such reservoirs and rulesets has been demonstrated by many studies (Chang et al., 2019; Huang and Chou, 2005; Karamouz and Araghinejad, 2008; Padiyedath Gopalan et al., 2020; Shih and ReVelle, 1994, 1995; Singh and Mishra, 2024b; You and Cai, 2008a,b). While there are studies that have sought to identify small reservoirs and their potential impacts on the water balance using higher resolution remote sensing data to drive physically based models (Aminzadeh et al., 2024; Casadei et al., 2019; Mady et al., 2020), the lack of knowledge about a region's small reservoirs and their capacities seems to be a limiting factor in investigating the operating rules for small reservoirs.

In Central Europe, droughts have become more recurrent and intense over the past decades (Boeing et al., 2022; Cai et al., 2015). In particular, the recent 2018-2020 and 2022 droughts have highlighted the vulnerability of European agriculture to water shortages (Boergens et al., 2020; Brás et al., 2021). The increasing frequency and severity of droughts due to climate change exacerbate these challenges (Spinoni et al., 2017), posing substantial threats to food security as droughts become a major driver of yield reduction in global agriculture (Lesk et al., 2016; Naumann et al., 2021). The combined effects of heatwaves and droughts during these years led to substantial economic losses as farms experienced losses in productivity. For instance, the 2018 drought resulted in significant yield reductions for major crops such as wheat, barley, and maize across Europe (Beillouin et al., 2020), corroborating previous research indicating it as a high hazard zone (Geng et al., 2016). Research has suggested that, in the absence of adaptation measures, strong decreases in crop productivity can be expected in central and southern Europe as a result of anthropogenic climate change (Naumann et al., 2021; Thober et al., 2018).

The 2018-2020 and 2022 droughts were among some of the most devastating in Germany's recent history (Baden-Württemberg, 2019b, 2020, 2021; Erfurt et al., 2020; Tijdeman et al., 2022), and has been proposed as a benchmark event for drought studies in the region, as droughts of this severity may become more frequent in the future (Rakovec et al., 2022). Anomalies in precipitation, along with higher temperatures, created soil moisture deficits that challenged various sectors across the typically humid and temperate country, including agriculture (Shyrokaya et al., 2024), likely contributing to the increase in demand for irrigation. By 2022, the area of irrigated cropland in the southwestern state of Baden-Württemberg had increased by 61% from 2009 levels. The demand for irrigation will likely continue to increase with persistent drought conditions (Bernhardt et al., 2022; Fliß et al., 2021; Hirschfeld, 2015; McNamara et al., 2024). Anthropogenic influences, such as heavy groundwater withdrawals and structural changes in the landscape, exacerbated issues of water insecurity (KLIWA, 2021; Umwelt, 2022a). The threat of further water stress has prompted many local governments in Germany, such as Baden-Württemberg, to begin strategic planning for water scarcity (Bundesamt, 2021; Stölzle et al., 2018; Umwelt, 2022b), including ways to store water for drought.

Baden-Württemberg, located in the temperate regions of southern Germany, is accustomed to floods as the main hydrological hazard in the region, and provides a rich database of reservoirs in various sizes (Baden-Württemberg, 2019a). There are over 800 flood reservoirs built in this region, with just over 600 meeting the size and dam criteria of small reservoirs. The increasing occurrence of agricultural drought in temperate regions, however, emphasizes the need for enhanced water supply resilience. While the potential benefit of repurposing flood reservoirs as small reservoirs to harvest flood water for streamflow drought conditions in Baden-Württemberg has been demonstrated (Ho and Ehret, 2025), the potential water supply benefit from their reuse as agricultural small reservoirs remains unclear.

In this study, we develop a framework to assess the irrigation demand and the potential water supply benefit of reusing flood reservoirs as small reservoirs for agricultural drought protection via modeled operation rules, using the 2018-2020 drought years in Baden-Württemberg as a benchmark to investigate the potential water supply benefit. This study therefore deals with the following research questions:

1. Can small flood reservoirs be repurposed via operation rules based on hedging rules to simultaneously provide water for irrigation while maintaining flood protection?
2. Could repurposed flood reservoirs in Baden-Württemberg have supplied the necessary irrigation demand in their local areas during the 2018-2020 drought without compromising flood protection?
3. Do reservoirs that potentially provide water supply benefit to agriculture also have the ability to benefit streamflow supplementation?

This paper begins with an overview of the study area and data used for the investigation. We outline the reservoir models and calculation of the irrigation demand time series for each reservoir, which form an operating framework that is applicable to other regions as well. We then briefly explore the agricultural irrigation demand (AID) results for the 2017-2020 period in Baden-Württemberg, highlighting the increase in demand for the 2018-2020 drought years, before investigating the results of reservoir operation for AID. Finally, we recontextualize the results by comparing them to the results for streamflow benefit found in Ho and Ehret (2025).

3.2 METHODS

3.2.1 *Study Area*

The German state of Baden-Württemberg is in the southwest of Germany and shares borders with France and Switzerland. The majority of the state belongs to subcatchments of the Rhine, with the rest belonging to those of the Danube and Tauber catchments. Predominant crops in the region include grains (wheat, maize, barley, oats), rapeseed, and perennial cultures such as orchards, strawberries, and asparagus. There are also sizeable vineyards in some areas of the state. Much of the agricultural land in the state is rainfed—only 2.6% of agricultural area is fitted for irrigation (Bernhardt et al., 2025). If demand not only for summer irrigation but also for frost protection (Umwelt, 2022a) continues to increase (Hirschfeld, 2015; Stütz, 2024), expansions to irrigation infrastructure would likely be necessary. Currently, groundwater is a major source of irrigation (Bernhardt et al., 2025), but a decreasing trend of groundwater recharge in the region and competing drinking water abstractions (Fliß et al., 2021) may result in a need for surface water sources for irrigation in the future.

This study builds on previous work on the potential of flood reservoirs for drought protection (Ho and Ehret, 2025). The curious reader may refer to this work for detailed discussion on the reservoir selection process. AID fulfillment was calculated for each of the 30 selected reservoirs listed in Table 3.1 and shown in Figure 3.1. While these reservoirs are small and at most mid-size on the global scale, they are named in this study by size according to the German standard DIN19700 (LUBW, 2007), in which large reservoirs have a capacity of over 1 million cubic meters, medium reservoirs a capacity of 100,000-1 million cubic meters, and small a capacity of 50,000-100,000 cubic meters. The reservoir categories are a two-letter combination of first a size class (L is large, M is mid-size, and S is small) and current usage class (flood-only, F, or multipurpose, M).

The modeled operation of the reservoirs is done for a single reservoir; i.e., we are only considering the potential of individual reservoirs and not a system. Q_{crit}, pulled from the operation data, is the maximum allowable flow downstream of a river. We assume that any flow below this will not impact the safety of downstream reservoirs. For the streamflow supplementation case, any release from an upstream reservoir will be beneficial for streamflow supplementation of the downstream reservoir: ignoring this effect means erring on the safe side. The reservoirs are currently either operationally inundated (i.e. only store water during a flood) or permanently inundated (i.e. have a permanent inundation level needed for additional purposes). Reservoirs with existing multipurpose functions were assumed to have their additional purposes filled so long as they maintained their permanent inundation volume. This is guaranteed in this study, as the operation of the reservoirs is modeled using the operating capacity (defined as the difference between the capacity and the permanent inundation volume) only, and no additional withdrawals or releases outside of this operating capacity is allowed. Investigation into the operating rules of multipurpose reservoirs with operational inundation yielded no volume requirements to fulfill those purposes; these purposes are thus assumed to be fulfilled via normal operation. Reservoirs with hydropower usage were excluded from this study, as their strict outflow requirements are incompatible with the intended operation strategies in this study.

Table 3.1: The 30 reservoirs from Ho and Ehret (2025), along with their operating parameters (operating capacity, flooding limit Q_{crit}, and retention limit Q_r), investigated in this study. ID numbers have been added for clarity.

Category	**Inundation Type**	**Name**	**ID**	**Operating Capacity [m³]**	**Q_{crit} [m^3s^{-1}]**	**Q_r [m^3s^{-1}]**
LF	Operational	Bernau	1	1,020,000	22.00	1.43
		Gottswald	2	4,720,000	830.00	36.81
		Mittleres Kinzigtal	3	2,700,000	860.00	33.85
		Wolterdingen	4	3,000,000	75.00	6.01
LM	Permanent	Federbach	5	652,652	0.400	0.10
		Fetzachmoos	6	3,500,000	15.00	1.79
		Nagoldtalsperre	7	1,741,000	15.00	1.15
		Rehnenmuehle	8	2,930,000	7.00	0.65
MF	Operational	Schwaigern	9	151,880	3.32	0.20
		Seckach	10	64,000	50.30	1.74
		Seebaechle	11	33,112	0.10	0.02
		Unterbalbach	12	210,000	6.33	0.28
	Permanent	Doertel	13	168,400	0.79	0.07
		Lindelbach	14	172,000	0.50	0.02
		Weissacher Tal	15	185,000	2.41	0.12
MM	Operational	Heinzental	16	310,000	1.09	0.08
		Hofwiesen	17	335,210	10.68	0.38
		Wustgraben	18	276,181	0.50	0.06
	Permanent	Fischbach	19	181,625	3.70	0.17
		Huettenbuehl	20	32,000	4.00	0.30
		Kressbach	21	233,780	0.70	0.06
		Michelbach	22	81,728	1.00	0.06
		Salinensee	23	188,000	3.60	0.14
SF	Operational	Duffernbach	24	31,143	1.55	0.06
		Goettelfinger Tal	25	83,400	4.10	0.23
		Mittelurbach	26	60,000	0.50	0.10
		Wollenberg	27	30,200	3.37	0.13
SM	Permanent	Hoelzern	28	7,703	1.50	0.03
		Lennach	29	9,600	2.10	0.05
		Nonnenbach	30	3,759	0.17	0.03

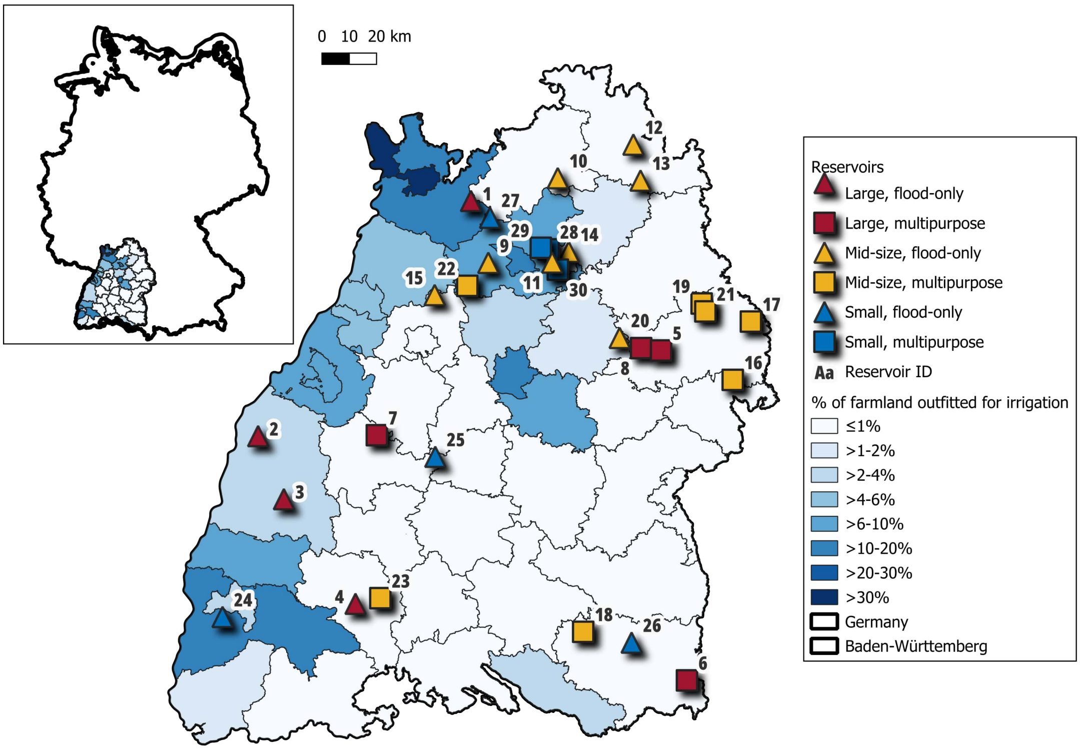

Figure 3.1: Proportion of farmland equipped for irrigation in Baden-Württemberg, aggregated by NUTS3 region (Bernhardt & Neuenfeldt, 2024), and the locations of the 30 reservoirs investigated in this study, labeled according to their ID number in Table 3.1

Table 3.2: The soil textures and the accompanying soil parameters used for the calculation of irrigation demand.

Soil Category (KA5)	Field Capacity [%]	Permanent Wilting Point [%]	Most similar USDA soil texture	stage 1 REW
ss	11.0	4.0	Sand	4.5
ls	24.3	6.8	Sandy loam	8
us	30.5	8.5	Silt loam	9.5
sl	31.0	13.0	Silt loam	9.5
ll	33.8	18.3	Silt loam	9.5
tl	35.3	21.7	Silt clay loam	9.5
su	36.5	11.0	Silt	9.5
lu	36.3	12.0	Silt	9.5
tu	36.5	17.5	Silty clay	10
ut	38.0	24.0	Silty clay	10
lt	41.3	28.5	Silty clay	10

3.2.2 *Data*

3.2.2.1 *Soil Data*

The topsoil classification determines the field capacity (FC) and wilting point (WP), which are critical for the irrigation calculations. The topsoil textures for each reservoir's region were taken from Düwel et al. (2007). This map, drawn on a 1:1,000,000 scale, uses the German soil classification system detailed in the 5th edition of the German soil mapping guide (Ad-Hoc-Arbeitsgruppe, 2005) to allow for consistency with local reported results, though maps of any textural class system (such as the USDA soil conservation service soil triangle) can be used so long as the FC and WP for each soil type are available. The FC and the WP are defined here as the volume percentage of water held by suction pressures of pF $\geq$ 1.8 (~60 hPa) and pF $\geq$ 4.2 (~1.5 mPa), respectively. These parameters for the general topsoil categories given in Düwel et al. (2007) are the arithmetic mean of all of its subgroups' parameters (assuming the middle dry bulk density category). An additional parameter—the readily evaporable water (REW) for the FAO-56 method—is tabulated in Allen et al. (1998) based on the category's most similar USDA soil texture. The final parameters used for the irrigation demand calculation can be found in Table 3.2.

3.2.2.2 *Crop Data*

This study accounts for crop specificity and changes in cropping pattern by calculating the irrigation demand for various crops every year using the crop maps over Germany from 2017-2020 from Blickensdörfer et al. (2022). These maps used a random forest classifier to process various remote sensing products and indicate 25 agricultural land cover classes in Germany on a 10 m x 10 m resolution. Each year, a given pixel on the map could be either a summer crop or a winter crop, in which case the planting date would begin in the previous year. The irrigation demand calculations for each year, therefore, begin in September of the previous year—for example, the 2017 calculations begin in September 2016. However, because the reservoir operation model uses 2016 as a warm-up year, only the irrigation in the calendar years 2017-2020 remain relevant for the study. Similar products, such as the global WorldCereal raster dataset (Van Tricht et al., 2023) and the European EuroCrop dataset (Schneider et al., 2023), can be used when evaluating for different regions.

For this study, we focus on irrigation demand of the 18 productive agricultural crops shown, along with their FAO-56 crop parameters, in Table 3.3. These parameters (with the exception of those obtained from Drastig et al. (2021) for winter rapeseed) are taken from Allen et al. (1998) and the updated parameters produced in recent years (Pereira et al., 2021a,c; Rallo et al., 2021). Because there is no general "vegetable" set of FAO-56 parameters, we selected those of asparagus. This is because of its dominance in the growing region—it is the most common vegetable, making up 26% of all farmland dedicated to vegetables in 2017, according to regional statistics (Hartmann, 2017). We do not consider the irrigation demands of fallow fields, forests, grasslands, or pastures.

For the purposes of discussing the results of AID across reservoirs, we group the crops into overarching crop types based on the groupings in the Pereira crop parameter papers (Pereira et al., 2021a,c; Rallo et al., 2021). These are grains (maize, barley, oat, rye, and wheat), field crops (all legumes, sugar beets, and oil crops like rapeseed and sunflower), fruits and vegetables (asparagus, orchards, and potatoes), and vine crops (grapes and hops).

3.2.2.3 *Weather Data*

The necessary data for the calculation of irrigation demand are relative humidity, daily maximum and minimum temperature, precipitation, wind speed, and FAO-56 grass reference evapotranspiration. This data was downloaded from the German Weather Service (DWD) as raster data on a 1 km x 1 km resolution (DWD, 2022, 2023, 2024a,b,c,d) and extracted at the location of the reservoir as the weather data for the 5 km² region.

Hourly wind speed at 10 meters height from DWD was aggregated to a daily time step, then converted to the wind at 2 meters height using the following adjustment from eq. 47 of Allen et al. (1998) (eq. 3.1):

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{3.1}$$

Where u_z is the wind speed at height (in meters) z above ground.

Daily minimum relative humidity for irrigation demand calculations was estimated using eq. 64 from Allen et al. (1998) for estimating relative humidity (eq. 3.2):

$$RH_{min} = 100 \times \frac{e^0(T_{min})}{e^0(T_{max})} \tag{3.2}$$

where e^o is the saturation vapor pressure at a given temperature T (degrees Celsius) and RH_{min} is the minimum relative humidity (%). Mean relative humidity data from

Table 3.3: The crop types from Blickensdörfer et al. (2022)used in this study and their FAO-56 parameters (collected from Allen et al. (1998), Drastig et al. (2021), Pereira et al. (2021a,c), and Rallo et al. (2021)) used to calculate irrigation demand. Parameters for asparagus were used in place of the general vegetable classification. Several non-productive classifications, such as grasslands, fallow land, and small woody features, were not included.

Crop	**Planting Date**	**L ini**	**L dev**	**L mid**	**L late**	**Kcb ini**	**Kcb mid**	**Kcb end**	**Zr max**	**h max**	**p**
		[days]				**[-]**			**[m]**	**[m]**	**[-]**
Field Crops											
Broad bean	15-May	15	25	35	15	0.15	1.05	0.30	0.70	0.80	0.45
Lupine	15-May	15	25	35	15	0.15	1.05	0.30	0.70	0.80	0.45
Peas	15-May	15	25	35	15	0.15	1.10	1.05	1.00	0.60	0.45
Soy	15-May	20	35	60	25	0.15	1.10	0.25	1.40	0.80	0.50
Sugar beet	15-Apr	50	40	50	40	0.15	1.00	0.65	1.20	0.50	0.55
Sunflower	1-May	25	35	45	25	0.15	1.15	0.25	2.00	2.00	0.45
Winter rapeseed	15-Sep	0	220	40	30	0.15	0.95	1.10	1.50	1.50	0.60
Fruits & Vegetables											
Orchard	15-Mar	20	70	90	30	0.75	1.15	0.80	2.00	4.00	0.50
Potato	15-Apr	30	35	50	30	0.15	1.10	0.35	0.60	0.60	0.40
Vegetables (asparagus)	15-Feb	50	30	100	50	0.15	0.90	0.20	1.80	0.80	0.45
Grains											
Maize	15-Apr	30	40	50	50	0.15	1.15	0.85	1.50	3.50	0.50
Spring barley	15-Apr	40	30	40	20	0.15	1.00	0.20	1.20	0.90	0.55
Spring oat	15-Apr	40	30	40	20	0.15	1.00	0.20	1.50	1.10	0.55
Winter barley	15-Nov	40	60	60	40	0.15	1.00	0.20	1.20	0.90	0.55
Winter rye	15-Nov	40	60	60	40	0.15	0.95	0.30	1.20	0.90	0.55
Winter wheat	15-Nov	40	60	60	40	0.15	1.00	0.20	1.50	1.10	0.55
Vine Crops											
Grapevine	15-Apr	30	60	40	80	0.30	0.65	0.40	2.00	2.00	0.45
Hops	15-Apr	25	40	80	10	0.30	0.95	0.80	1.20	5.00	0.50

DWD was used to correct these estimates—if the estimated minimum was higher than the mean data for the day, the value was replaced with the observed data.

3.2.2.4 *Drought Data*

Agricultural drought data in the form of the percentile-based Soil Moisture Index (SMI) for the total soil column (0-2 meters) is used in this study to contextualize the degree of drought intensity during the observation period (Boeing et al., 2022) and is not strictly necessary for the framework. This dataset was retrieved from the UFZ Drought Monitor (Boeing et al., 2025), which has a 1.2 km spatial resolution, though only the data in pixels containing the reservoirs are used. The SMI has monthly values indicating the percentile rank (from 0 to 1, where 0 is the driest and 1 is the wettest) of the month's soil moisture in comparison to historical values in the same month (using the years 1974-2023 as a statistical basis). The SMI signals abnormally conditions from values of 0.2-0.3; moderate drought conditions from 0.1-0.2; severe drought conditions from 0.05-0.1; extreme drought conditions from 0.025-0.05; and exceptional drought conditions from 0-0.025.

3.2.2.5 *Reservoir Inflows*

In lieu of gauge data, which were not available for these reservoirs, semi-natural inflows to each reservoir were calculated using a pre-calibrated version of the Large Area Runoff Simulation (LARSIM) model (LARSIM-Entwicklergemeinschaft, 2023; Ludwig and Bremicker, 2006), provided by the State Agency for the Environment of Baden-Württemberg (Landesanstalt für Umwelt Baden-Württemberg, LUBW). LARSIM is a process-based water balance model that can be either semi- or fully distributed, and takes as inputs geographic data (elevation, land use, and soil parameters) and hydrometeorological data (precipitation, air temperature, humidity, windspeed, radiation, and water temperature) to provide streamflow simulations and operational streamflow forecasts in the region. We refer to the resulting discharges as semi-natural because the model also incorporates anthropogenic influences such as operations of water treatment plants and selected reservoirs and dams (Baden-Württemberg, 2024a): if a selected reservoir is upstream of another selected reservoir, we include the current calibrated operations of the upstream reservoir for the inflow to the downstream.

The model uses a grid structure with a 1 km² resolution to describe meso-scale hydrological processes. While typically used for large catchments (and calibrated to higher-order river discharges), it is also capable of modelling smaller headwater catchments by selecting the proper model output location. For the purposes of this study, these model output locations were selected to have LARSIM-delineated catchments that are as similar as possible to the reservoir's catchment (e.g. connecting tributaries, catchment area). However, due to the 1 km² grid and different channel routing procedures, the LARSIM catchment area may differ slightly from the true catchment area. We adjust for this by multiplying the resulting discharge by the ratio of true catchment area to LARSIM catchment area (the exception here being reservoir Fetzachmoos, whose main structure as a diversion dam is not in the river network and whose delineated catchment area does not model the water that should be impounded). The average calibrated NSE value for the gauge stations downstream of the reservoirs (where available) is 0.76, indicating a reliable model performance.

3.2.3 *Calculating Agricultural Irrigation Demand (AID) of a Reservoir*

3.2.3.1 *Regions for calculation – Agricultural Response Units (ARUs)*

The region around the reservoir for which AID should be calculated is dependent on the assumption of how the water should reach the farmer. Many plots of high-value crops such as orchards and grapevines are not only far from the river but also uphill, meaning this would also require installation of additional infrastructure to pump the water against gravity or to move it across areas with no stream channels. A potential solution could be to deliver the water via trucks as a stopgap measure until the infrastructure for more intentional delivery methods are built. This would mean that the region potentially supplied by the reservoir is not just immediately downstream, but anywhere within a reasonable distance. For this study, we assume that such a solution is possible and needed (both financially and physically) and limit the reasonable distance to a 5 km^2 rectangular (for compatibility with gridded raster data) buffer area centered around each reservoir.

Calculation of the reservoir region's agricultural irrigation demand was simplified using an adaptation of the hydrological response unit where, in hydrological models, areas are grouped by hydrological similarty. This is done to reduce the computational effort. Instead of uniquely calculating the demand for each pixel of land within the reservoir's region, we searched for areas of agricultural similarity as an agricultural response unit (ARU) under the rationale that areas with the same crop cover, soil type, and weather conditions would require the same amount of irrigation at the same time. Each ARU is a unique combination of crop cover (Table 3.3) and soil type (Table 3.2)—the 18 unique crops and 11 unique soil categories result in a total of 198 possible ARUs. All areas within the reservoir's 5 km^2 region consisting of winter wheat on sandy soil, for example, would be considered one ARU.

3.2.3.2 *The FAO-56 Dual Crop Method for Irrigation Demand*

The irrigation demand for each ARU is calculated using the Food and Agriculture Organization's (FAO) guidelines for computing crop water requirements in the FAO Irrigation and Drainage Paper no. 56 (Allen et al., 1998, 2005). The method primarily deals with the calculation of a crop's evapotranspiration (ET_c) using a crop-specific coefficient (K_c) modifier to grass reference evapotranspiration (ET_0) (eq. 3.3):

$$ET_c = K_c ET_0 \tag{3.3}$$

However, it is also able to compute crop water requirements—in other words, irrigation demand. This method—and its various adaptations, such as the German Geisenheimer method (Zinkernagel et al., 2022) and the CropWat (Smith, 1992) and AquaCrop (Steduto et al., 2009) models, among others (Pereira et al., 2020)—has since been used to calculate $ET_{c,act}$ and AID on the basis of the ET_0 in many studies worldwide

(Pereira et al., 2021b). While we briefly outline the method here, detailed explanations can be found in Allen et al. (1998, 2005).

In this study, we use the dual crop coefficient method, where the actual K_c ($K_{c,act}$)is the sum of the climate-corrected basal crop coefficient (K_{cb}; for details on the climate correction, see appendix B.3), multiplied by a water stress coefficient (K_s), and the soil evaporation coefficient (K_e) (eq. 3.4):

$$K_{c,act} = K_s K_{cb} + K_e \tag{3.4}$$

This $K_{c,act}$ is distinguished from a general K_c in that the K_s allows for consideration of non-standard conditions, such as water stress. Under standard conditions (i.e. sufficient water, normal levels of salinity), $K_s = 1$ and the equation simplifies to the standard dual-crop equation. The crop-specific K_{cb} values are tabulated and vary with crop growth cycles, while K_s and K_e are calculated via a daily soil moisture balance. The soil moisture balance is calculated using a two-sided approach where water is consumed from both the soil surface and the root zone. For more details, including the assumptions made for calculating runoff depth, see appendix B.4.

In this study, we calculate a crop's irrigation demand as the amount of water (in mm per day) needed to avoid water stress and restore the soil moisture storage to field capacity. This is assumed to be done—though certainly not the case in reality—via sprinkler irrigation and with 100% efficiency, applied the morning after the readily available water (RAW) is depleted. These assumptions serve to illustrate the bare minimum volume of water needed for irrigation. The needed irrigation depth is calculated as follows (eq. 3.5):

$$I_{j+t} = \frac{D_{r,j}}{f_w} \text{ for } D_{r,j} > RAW \tag{3.5}$$

where $D_{r,j}$ is the cumulative depletion depth (mm) in the root zone and f_w is the fraction of wetted area.

Because this calculation is done for each ARU, it also assumes that all cropped areas in the ARU are planted on the same day, and that this planting date is consistent from year to year. While in practice this is certainly not the case, we do so on the assumptions that

- this planting date is an average date, meaning that there are fields planted before and after this date; and that
- even if the irrigation demand is offset by a week due to differences in planting date, the reservoir would not be able to refill entirely during this time as to significantly supplement the delayed irrigation demand.

The irrigation demand (AID) of the region on day *j* can be summarized as (eq. 3.6)

$$AID_j = \sum_{ARU=1}^{n} (I_{ARU,j} \times Area_{ARU}) \tag{3.6}$$

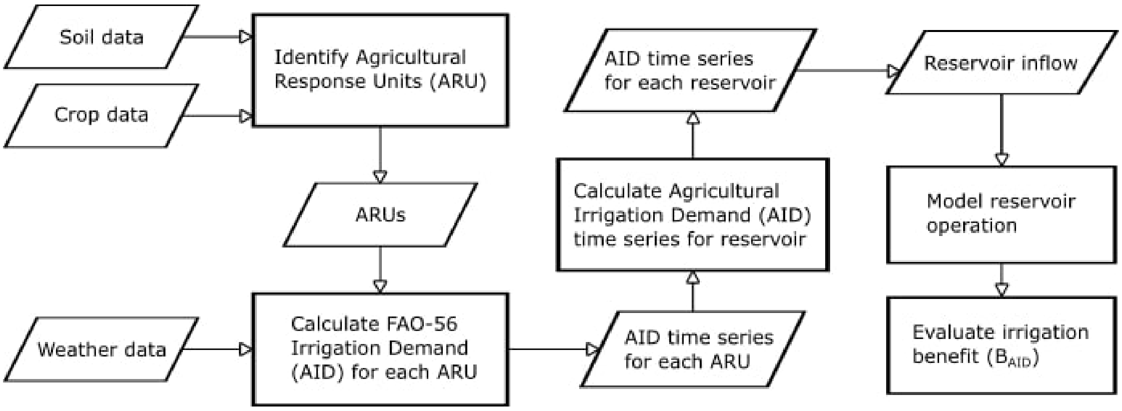

Figure 3.2: An overview of the assessment framework.

where $I_{ARU,j}$ is the irrigation depth on day j of a given ARU and $Area_{ARU}$ is the area covered by this ARU, and this product is accumulated across the n unique ARUs that exist in a reservoir's area. This AID is the withdrawal schedule for operating the reservoir.

3.2.4 *Reservoir Operation Model*

The potential benefit of a reservoir is assessed based on the ability of its modeled operation rules to satisfy AID without impairing flood protection (Figure 3.2). The reservoir operation model takes as inputs the inflow to the reservoir and the AID for its region—calculated using the FAO-56 dual crop method (Allen et al., 1998)—and produces time series of volume within the reservoir, outflow from the reservoir, and releases or withdrawals from the reservoir. These are done under assumptions of perfect knowledge of future reservoir inflow and without losses to the reservoir from sedimentation buildup, evaporation, and infiltration in order to obtain the most optimistic water supply benefit. While evaporative losses in particular could be quite significant in more arid regions, we found that evaporation losses at the reservoirs were either wholly offset by gains from precipitation or non-dominant enough to justify exclusion (appendix B.1).

The modeled operation of the reservoirs is slightly adjusted from the combined operation model in Ho and Ehret (2025) and is based on hedging rules. In summary, the model operates following these rules:

1. The reservoir impounds floods per its design—i.e., it stores water above a critical discharge (Q_{crit}). However, instead of releasing the retained floodwater immediately after the flood wave passes (as it currently does), the reservoir saves the water until the need to supply agricultural water demand (replacing the Q_{70} drought threshold in Ho and Ehret (2025)) arises– in which case it releases water to completely meet this demand, if possible– or another flood wave (above Q_{crit}) is predicted. If a flood wave is predicted, the reservoir empties completely before the onset of the flood in order to maintain the complete flood protection volume, thus preserving the maximum flood protection function. Flood protection operation is the primary use of these reservoirs and is strictly followed.

2. To increase water available for irrigation, the model stores water when the inflow is greater than the retention flow (Q_r), which in this study are the optimal values found in Ho and Ehret (2025) for each reservoir. These values allowed for storage of smaller flood waves without compromising flood protection, and at the same time minimizing the alteration of the natural flow regime in the river by harvesting water only in cases of elevated flow. Should the reservoir's capacity be full, however, these higher flows will be passed through (i.e., $Q_{in} = Q_{out}$).

3. We allow withdrawals from the reservoir based on calculated irrigation demand. These withdrawals have no particular withdrawal rate limit—rather, we assume that this withdrawal is done instantaneously at 6 AM on the day that irrigation is scheduled. This is due to our assumptions on how the water would be withdrawn.

Although this reservoir operates under a perfect-knowledge conditions for flood warning, we do not take future inflow conditions into account—in other words, there is no explicit optimization of current versus future irrigation water needs, nor adjusted releases for small flood waves. The reservoir operation model begins in 2016, a year before the observation period (2017-2020), to allow for a warm-up time.

3.2.5 *Metrics for comparison*

For each reservoir and year, statistics for each crop type in Table 3.3 are compiled. The planted area of a crop type ($A_{crop\ type}$) around a reservoir in year k is the sum of all ARU areas covered by the m unique crops in that typing (eq. 3.7):

$$Area_{croptype,k} = \sum_{1}^{m} Area_{ARU,crop} \tag{3.7}$$

Similarly, the AID of a crop type in year k is the sum of the AID in each of the ARUs covered by the m crops in that typing (eq. 3.8):

$$AID_{croptype,k} = \sum_{1}^{m} AID_{ARU,crop} \tag{3.8}$$

The water supply benefit to irrigation demand B_{ID} from the reservoir, is summarized as the percentage of the AID that the reservoir can fulfill (eq. 3.9):

$$B_{AID} = 100 \times \frac{\sum AID_{fulfilled}}{\sum AID_{total}} \tag{3.9}$$

The streamflow penalty P_d and the streamflow benefit B_p are metrics developed for evaluating a reservoir's performance for streamflow supplementation in Ho and Ehret (2025). The penalty is applied when the reservoir cannot supply the needed water to maintain a minimum flow (an hourly-varying 70th percentile exceedance flow, Q_{70}) in the river, taking the general form (eq. 3.10)

$$P_{d,t} = -\frac{1}{\sqrt{Q_{out,t}}} + \frac{1}{\sqrt{Q_{70,t}}}, \text{where } Q_{out,t} < Q_{70,t} \tag{3.10}$$

where $P_{d,t}$ is the penalty for drought at time t, $Qout_{,t}$ is the outflow from the reservoir (including whatever water can be supplemented from the reservoir) at time t, and $Q_{70,t}$ is the 70^{th} percentile exceedance flow at time t. Penalties in low flow season will generally be higher than in high flow season, taking into account that deficits are more impactful when water is already scarce. Further details on calculating the $Q_{70,t}$ can be found in Ho and Ehret (2025).

The streamflow benefit B_p refers to the reservoir's ability to provide water and reduce streamflow penalty. This is based on the difference between the penalty in the flood-only (i.e. current) operation and the penalty in a combined (flood and streamflow supplementation) operation scheme (eq. 3.11):

$$B_p = 100 \times \frac{\sum P_{d,\text{flood only}} - P_{d,\text{combined operation}}}{P_{d,\text{flood only}}} \tag{3.11}$$

The Bp used in this study is calculated using the streamflow supplementation operation results from Ho and Ehret (2025) during the observation period (2017-2020); i.e., this is the benefit for only streamflow operation. The B_{AID} is calculated based on the operation for only irrigation benefit and flood protection; similarly, the B_p is calculated based on the operation for only streamflow supplementation and flood protection. A combined streamflow and irrigation benefit is not considered in this study.

3.3 RESULTS

3.3.1 *Agricultural irrigation demand*

There is diversity in how much $Area_{\text{crop type}}$ (grains, field crops, fruits and vegetables, and vine crops) is planted around each reservoir, resulting in variable AID (Figure 3.1). Although most areas are dominated by grains, some reservoirs (such as Duffernbach and Lennach) have large areas of vine crops. The amount of $Area_{\text{crop type}}$, however, does not necessarily indicate a higher $AID_{\text{crop type}}$, as different crops (and therefore crop types) are more water-intensive than others: the average $AID_{\text{crop type}}$ per $Area_{\text{crop type}}$ (i.e. the slope of the best-fit line) varies between crop types, resulting in a nonlinear relationship between $Area_{\text{all}}$ and AID_{all} (Figure 3.3, c). Fruits and vegetables were found to be the most water intensive with an average of 116 mm per year, followed by field crops (47 mm per year), then vine crops (41 mm per year). Grains had the lowest demand per unit area, requiring an average of 32 mm per year. Thus, while total planted area can hint at potential irrigation demand, the crop specificity of agricultural fields should be observed when calculating irrigation demands.

The average $AID_{\text{crop type}}$ per $Area_{\text{crop type}}$ fluctuates between different years (Figure 3.4). 2018 and 2020 showed the highest AID overall for all crop types. There was no AID for all vine crops and very little for grain crops in 2017, whereas both field crops and fruits and vegetables had some AID. AID in 2019 were comparable to 2017 levels for field crops, fruits and vegetables, and vine crops, but were higher than 2017 levels for grains (while simultaneously still being less than 2018 and 2020 demand).

The onset of AID coincides quite well with periods when the percentile-based Soil Moisture Index (SMI) falls below the moderate drought threshold during the growing

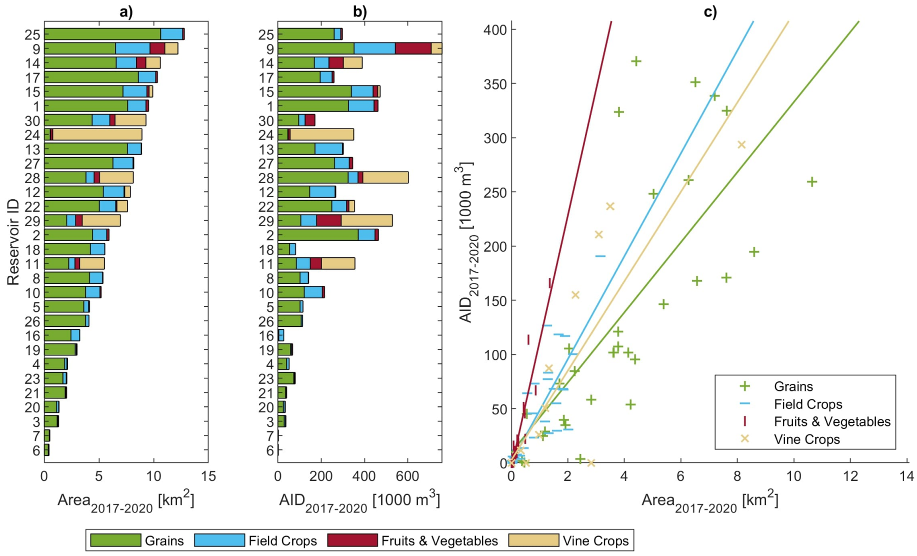

Figure 3.3: Statistics for each reservoir's Area (in km²; a) and AID (in 1000 m³; b) for each crop type, sorted in descending order of total planted area; and the $AID_{crop\ type}$ plotted against the $Area_{crop\ type}$. The unique crops in each type are shown in Table 3.3

season (Figure 3.5). The stronger peaks of AID in 2018, 2019, and 2020 follow when the average SMI drops at least two categories within two months, signalling a rapid decline in soil moisture accompanied by a lack of precipitation. Irrigation demand outside of the growing season is limited due to the lower number of crops in winter (reducing the area potentially needing irrigation) and higher precipitation. Indeed, there is only one AID peak outside the growing season, occurring at the end of 2018, when drought conditions were at their worst overall. The index is a comparative measure to past conditions in the same month and not a direct measure of soil moisture; it is thus possible that exceptional drought conditions for a location that normally has near-saturated soil moisture would only result in a little AID.

3.3.2 *Operation for irrigation demand*

The operation of the reservoir Doertel (Figure 3.6) illustrates the operating rules outlined in section 3.2.4. At first, the reservoir stores all inflow above Q_r until the first flooding event, before which all the volume is released from the reservoir (indicated by the sharp decrease in volume and the sharp increase in pre-flood release in January 2018). Then, during the flood event, all inflow above Q_{crit} is stored in the reservoir, refilling it to near capacity. Once capacity is reached, the reservoir releases all inflow to maintain the current volume. The first withdrawals for AID are scheduled in July 2018, and the reservoir is almost able to entirely fulfill this demand—by the end of the growing season, a small difference between AID_{total} (the cumulative irrigation demand) and the $AID_{fulfilled}$ (the cumulative irrigation withdrawal) can be observed. The reservoir remains empty due to an absence of flows above Q_r until around January 2019, when the reservoir is able to retain more water. The 2019 growing season only requires a small amount of withdrawal from the reservoir, which is easily refilled, and thus the reservoir

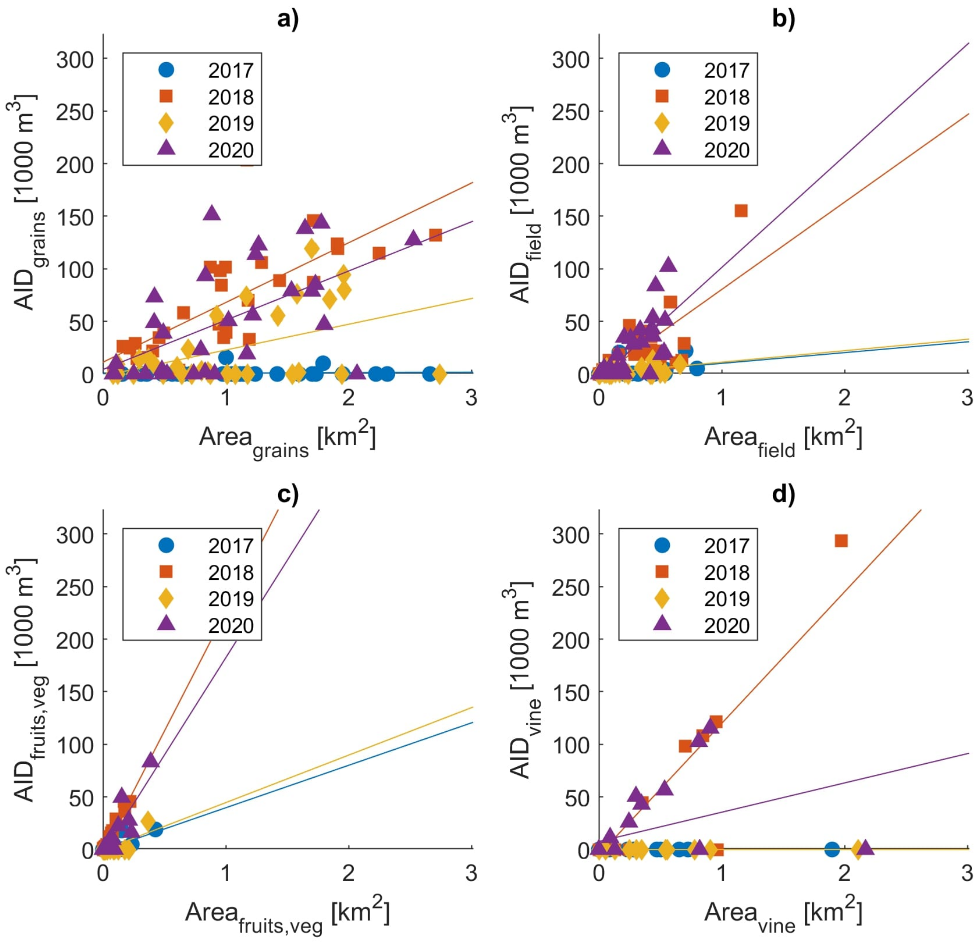

Figure 3.4: Comparisons of AID_{type} over $Area_{type}$ for the four different crop types, grains (a), field crops (b), fruits and vegetables (c), and vine crops (d) for each reservoir. Different years are expressed in different colors and shapes. 2018 and 2020 show significant increases in irrigation demand, regardless of planted area, in comparison to 2017 and 2019.

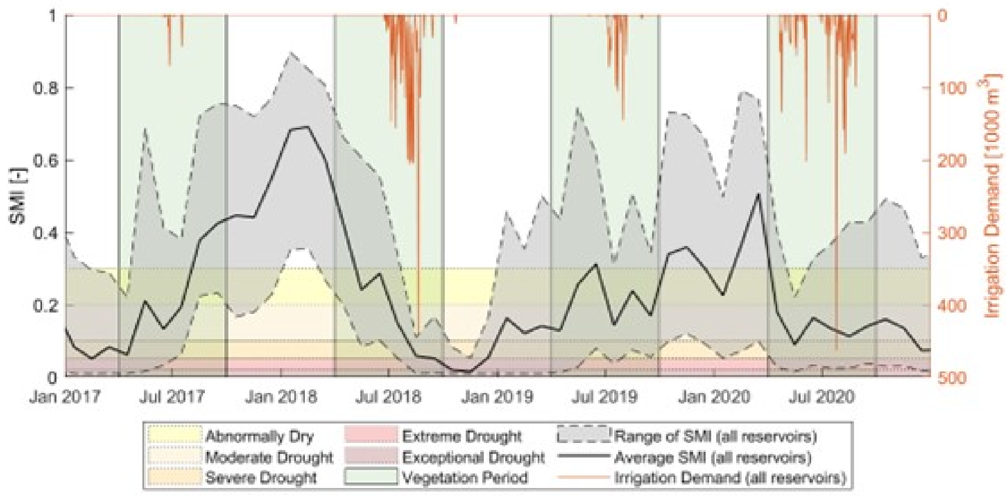

Figure 3.5: Progression of the percentile-based Soil Moisture Index (SMI, left) as both the range and the average across all 30 reservoirs, plotted alongside the total AID throughout the drought years. The vegetation periods of each year are marked in green.

remains full until the next flood wave occurs. The remaining winter season high flows are enough to refill the reservoir once more despite another pre-release event in January 2020, allowing it to fulfill the remaining AID during the 2020 growing season. The B_{AID} for this reservoir was 95.8%.

Most of the reservoirs—20 out of 30 in total—had a B_{AID} of over 70% (Figure 3.7), even if the total demand was on the higher end of the spectrum. These reservoirs were almost all large or mid-size reservoirs, with one small reservoir also performing quite well. Generally, the fulfilled demand decreases as the total demand increases.

Among the reservoirs that fulfill less than 70% of demand, there are three major limitations to reservoir performance. The first is, in the case of Lennach and Hoelzern, that there simply was not enough inflow to store water in the reservoir—in other words, flow rarely exceeded Q_r. The empty reservoirs were thus unable to fulfill any irrigation demand. We examine the other major limitations using Lindelbach (reservoir 14) and Seebaechle (reservoir 11) as examples.

The second limitation is the operating capacity. In the Lindelbach reservoir (Figure 3.8), there are withdrawal events in summer 2018 and 2020 where the demand vastly outstrips the reservoir's operating capacity, which is 64,000 m^3. In 2018, many of the summer crops required irrigation within the same two weeks, draining the reservoir's entire operating capacity in a short span. Moreover, the low flows experienced during the second half of 2018 meant that the reservoir could not recharge enough water to provide meaningful amounts to the surrounding areas for a second time in the growing season. The reservoir was only able to refresh its storage in the wet season at the end of 2018. This was echoed in the summer of 2020: while the demand was distributed more throughout the growing season and the reservoir was able to supply most of it, low summer flows meant that it could not refill enough to meet the remaining growing season demand and ultimately limited its effectiveness.

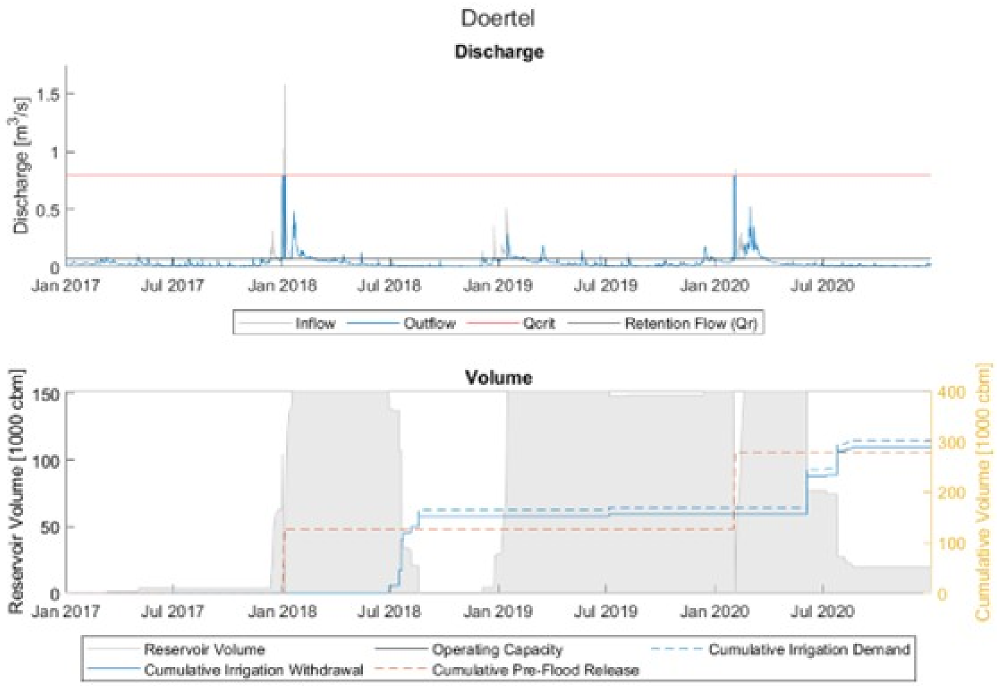

Figure 3.6: Plots showing the effects of reservoir operation on reservoir volume and inflow/outflow for Doertel (reservoir 13). Note that the reservoir volume time series is plotted against the left axis, and the other three time series (cumulative irrigation demand, cumulative irrigation withdrawal, and cumulative flood pre-release) are plotted against the right axis.

The third limitation is due to the need for flood operation during the vegetation period. Because the flood protection of the reservoir should not be impaired, the reservoir must be pre-emptied before a flood (for example, in January 2018 in Figure 3.8). While some of the water may be regained during the flood, the reservoir is not always guaranteed to (and, from the point of view of flood protection, should rarely) fill completely. This limits the amount of water available in the reservoir. The more frequently that this occurs during the vegetation period, the more likely it is that some irrigation demand will occur after the reservoir has been emptied, and thus cannot be met. This is quite visible in the operation of Seebaechle (Figure 3.9), where the frequent drainage has limited the reservoir's volume. Due to the dry conditions during the observation period, most of the reservoirs experienced very few flooding events, contributing to their strong performance for irrigation demand.

3.4 DISCUSSION

3.4.1 *Q1: The proposed framework for repurposing and evaluating flood reservoirs*

This framework consists of two main components: the calculation of AID and the reservoir operation. The simplification of high-resolution spatial data for crop cover and soil type into ARUs reduces computational effort, as—rather than calculating AID for every pixel individually—the FAO-56 calculation method for AID is only executed a

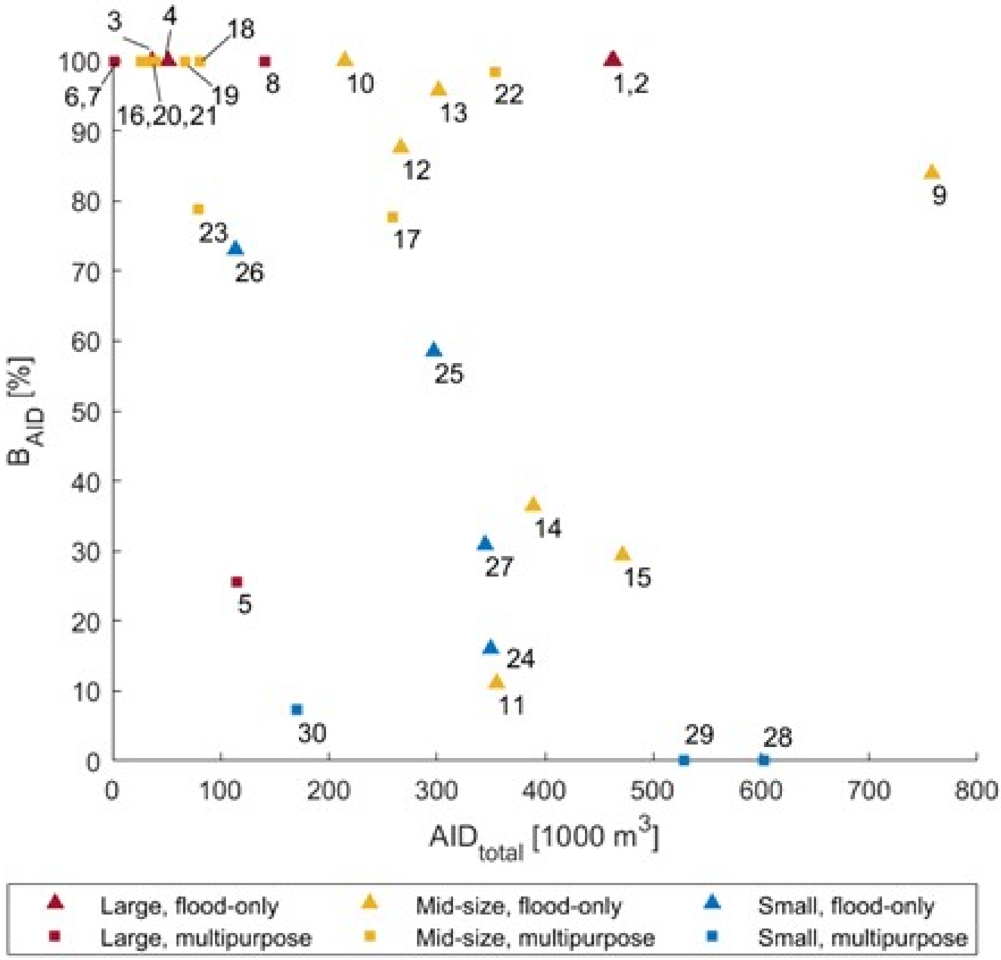

Figure 3.7: The total AID (in 1000 m^3) vs. the B_{AID} (as %) across all years (2017-2020) for each reservoir. Reservoirs are represented by size and by current use, and labeled by ID numbers from Table 3.1

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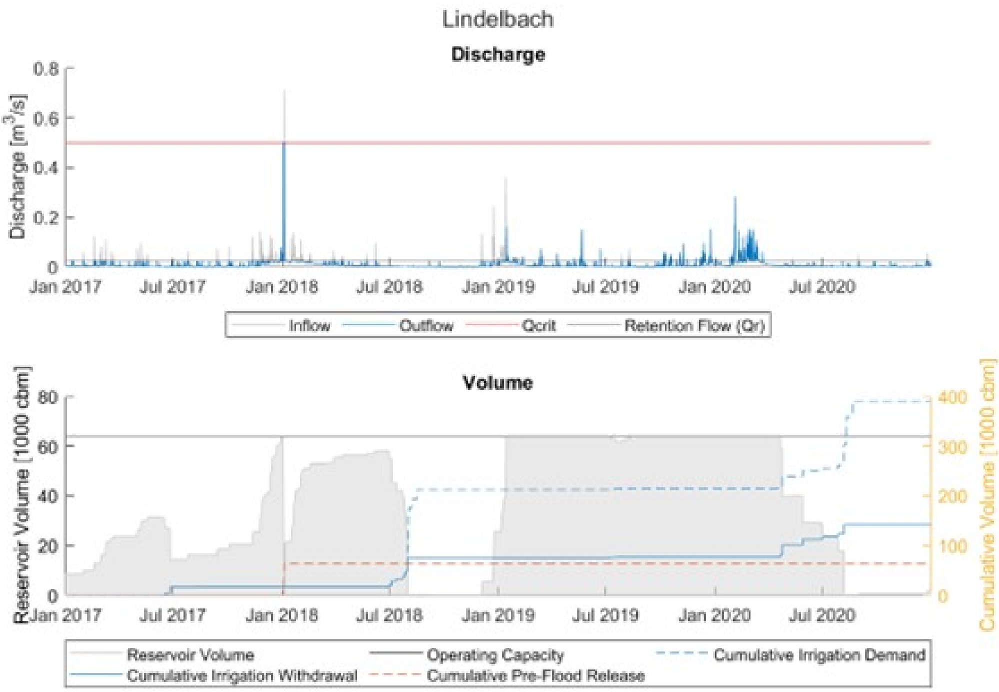

Figure 3.8: Plots showing the effects of reservoir operation on reservoir volume and inflow/outflow for Lindelbach (reservoir 14). Note that the reservoir volume time series is plotted against the left axis, and the other three time series (cumulative irrigation demand, cumulative irrigation withdrawal, and cumulative flood pre-release) are plotted against the right axis.

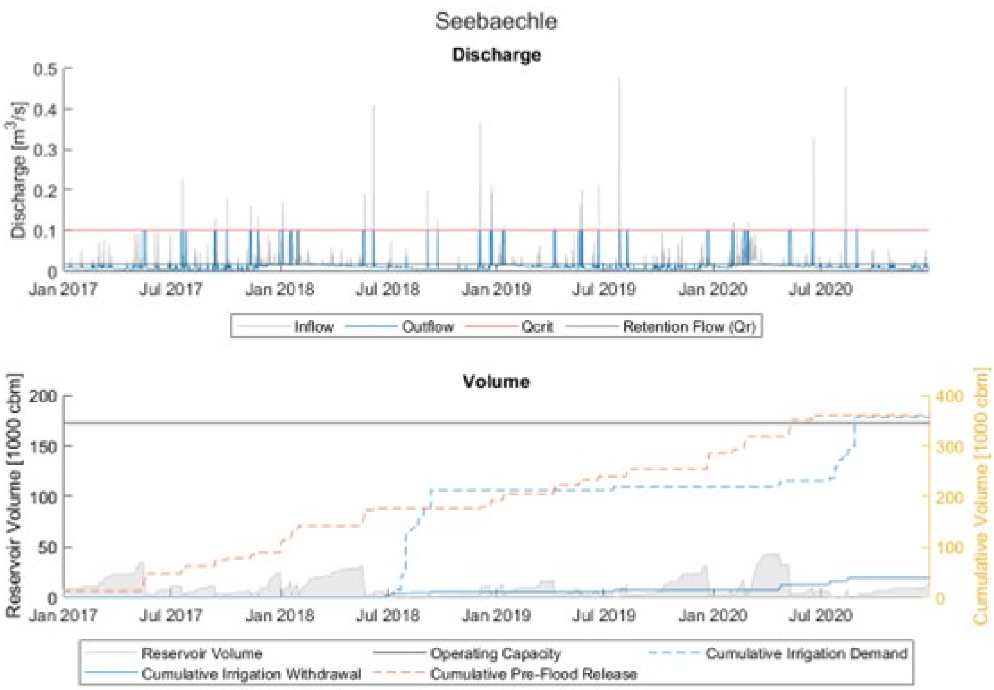

Figure 3.9: Plots showing the effects of reservoir operation on reservoir volume and inflow/outflow for Seebaechle (reservoir 11). Note that the reservoir volume time series is plotted against the left axis, and the other three time series (cumulative irrigation demand, cumulative irrigation withdrawal, and cumulative flood pre-release) are plotted against the right axis.

limited of times per reservoir. However, the AID is also simplified: all areas in the ARU are assumed to be planted on the same day, experience the same weather, have perfectly efficient irrigation methods, and grow at the same rate, resulting in the same AID. The actual AID should be much higher due to less-than-perfect efficiency, and should be scattered over several days or even weeks due to different planting days. If the AID from fallow fields, grasslands, forests, and shrubs were also desired, the AID of the region should increase as well. Despite this uncertainty, the flexibility of the inputs—a crop map, the tabulated FAO-56 crop parameters, a soil map, and some weather data—make this AID calculation method usable in regions around the globe, provided the inputs are available. This framework is therefore recommended as a starting point for the investigation of repurposing flood reservoirs, and not as a final decision tool.

The reservoir operation model in this framework demonstrates that simultaneous operation of small flood reservoirs for agricultural irrigation and flood protection is possible and potentially useful, despite the simplicity of the operating rules. Indeed, two-point hedging rules were found by Draper and Lund (2004) to be near-optimal for many water supply use cases, as it was here. These rules are also informed by Ding et al. (2017)'s findings that, with sufficiently low uncertainty (afforded here by the perfect knowledge), the multiobjective problem of optimizing reservoirs for both flood control or water conservation can simplify to either objective. As these reservoirs are currently not used for irrigation, the proposed operation of these reservoirs could expand water supply options in the region even when prioritizing flood protection by releasing all stored water—of the 20 reservoirs with 70% or more B_{AID}, 11 of them experienced flood events (see appendix B.2). The requirement to have an empty reservoir at the beginning of the flood allows the reservoir to have its maximum flood protection capability. At its core, this part of the framework only requires a few inputs: a time series of AID (which could either be calculated per the above method or provided from another source such as historical irrigation schedules), the inflow time series to the reservoir (which we have modeled here as a replacement for gauge data), and the current operation rules of the reservoir (the operating capacity and the flood protection limit). This enables the modeled operation of, in theory, any reservoir.

However, the operation presented in this framework remains an optimistic scenario. The simplification of the multiobjective problem is currently possible due to the perfect-knowledge assumption in this method. Future studies will investigate the effects of uncertain forecasts on the overall feasibility of this method; however, the perfect-knowledge scenario provides a useful and low-data benchmark option for screening potential reservoirs. Losses due to evaporation, sedimentation, and infiltration were not considered in this study, though they could be substantial in the right conditions (Aminzadeh et al., 2024; Owusu et al., 2022; Sichingabula, 1997). While still suitable as a starting point for investigation, further study could refine the framework to include these losses.

3.4.2 *Q2: Performance of reservoirs during the 2018-2020 drought*

In our simulations, most reservoirs were able to supply at least 70% of the irrigation demand in a 5 km^2 area surrounding the reservoir, with many able to supply the entirety of the irrigation demand. Similar water supply benefits to agriculture have been noted in literature about small reservoirs in arid and semi-arid regions (Acheampong et al., 2018; Wisser et al., 2010). High-performing reservoirs in this study were generally those with larger operating capacities.

The 2018-2020 European drought presented challenges for agriculture in Baden-Württemberg, resulting in the need for irrigation in a temperate region where rainfall alone had previously been mostly sufficient. Our estimations of AID increased significantly during the 2018-2020 years in comparison to 2017, which was a warm but otherwise normal year climatically. That the AID per area in 2017 and 2019 is quite similar in most crop types is likewise consistent with reports, as 2019—despite still being too warm and suffering from the 2018 drought year—had a near-average year of precipitation (Baden-Württemberg, 2020). In all cases, the yearly per-unit-area AID is significantly higher in 2018 and 2020 than in 2017 and 2019, which is consistent with what has been reported (Baden-Württemberg, 2019b, 2020, 2021; Stütz, 2024; Umwelt, 2022a). Analysis of total water storage anomalies from April 2002 through November 2019 also indicated that 2018 and 2019 were the two driest summers on GRACE record (Boergens et al., 2020). Indeed, 2018 ranks among the top 10 most severe drought years between 1801 and 2019 for a variety of drought indicators (Erfurt et al., 2020). The resulting groundwater abstractions, which are a primary source of both drinking water and irrigation in the region (Bernhardt et al., 2025; Fliß et al., 2021), may become a point of conflict in the future if future water demand outpaces the groundwater recharge rate, which has indeed been decreasing over the last few decades (Fliß et al., 2021). However, surface water reservoirs are a currently underutilized resource for irrigation (Bernhardt et al., 2025), and demand for irrigation in the region grows in dry years (McNamara et al., 2024). The strong performance of most reservoirs during the exceptional 2018-2020 drought years serves as a useful indicator for the potential of repurposed reservoirs for enhanced resilience– because they are successful in a landmark and well-known event, they are likely to be successful in a future where drought events are more intense and more frequent.

Moreover, these results have interesting implications for flash droughts. Typically understood to be drought events with a rapid (generally between 2-4 weeks) and intense onset (Otkin et al., 2018), these droughts currently lack a cohesive identification approach for croplands, particularly in Europe (Alencar and Paton, 2022). Recent studies have suggested that having adequate water supply during a flash drought onset can result in improved outcomes for vegetation, as the conditions associated with flash drought (higher temperatures, more radiation) could increase productivity during the onset (Ho et al., 2023).

3.4.3 *Q3: Comparison with metrics for streamflow benefit*

We found that 7 of the 30 reservoirs had at least 70% B_{AID} for both streamflow and agricultural demand (Figure 3.10). These are primarily mid-size reservoirs, the majority of which are multipurpose reservoirs, with one large multipurpose reservoir. The remaining reservoirs that performed well for agriculture generally were quite unsuccessful for streamflow supplementation. Only one reservoir showed outstanding results for streamflow benefit despite poor agricultural demand fulfillment. A handful of reservoirs resulted in low benefit in both streamflow and agriculture uses. As discussed in the previous section, these reservoirs were those low operating capacities, frequent flooding events, and insufficient water for storage. These limitations are consistent with those found in Ho and Ehret (2025).

Comparisons of irrigation benefit and streamflow benefit from Ho and Ehret (2025) reveal that many more reservoirs were beneficial in the irrigation case than in the streamflow case. The dynamics of when and how much water is needed in these two use cases can illustrate why these differences between irrigation and streamflow benefits occur. In all of these reservoirs, the peaks in AID occur overwhelmingly in the summer rather than in small steps consistently throughout the year. This has positive implications for a seasonal operation that allows for ecological connectivity in the fall and winter. Reservoirs with larger operating capacities are also therefore more likely to be successful, as a single large peak is more likely to be satisfied by a larger than a smaller reservoir. In contrast, while the largest spikes in streamflow improvement also occur in the summer, streamflow supplementation occurs year-round and with smaller releases. This allows smaller operating capacities to also have an impact on streamflow benefit. The absence of flooding events in half of the reservoirs—six more than in Ho and Ehret (2025)—during the observation period also meant that fewer reservoirs lost water due to flood protection, though this is likely driven by the significantly shorter time series (see appendixB.2).

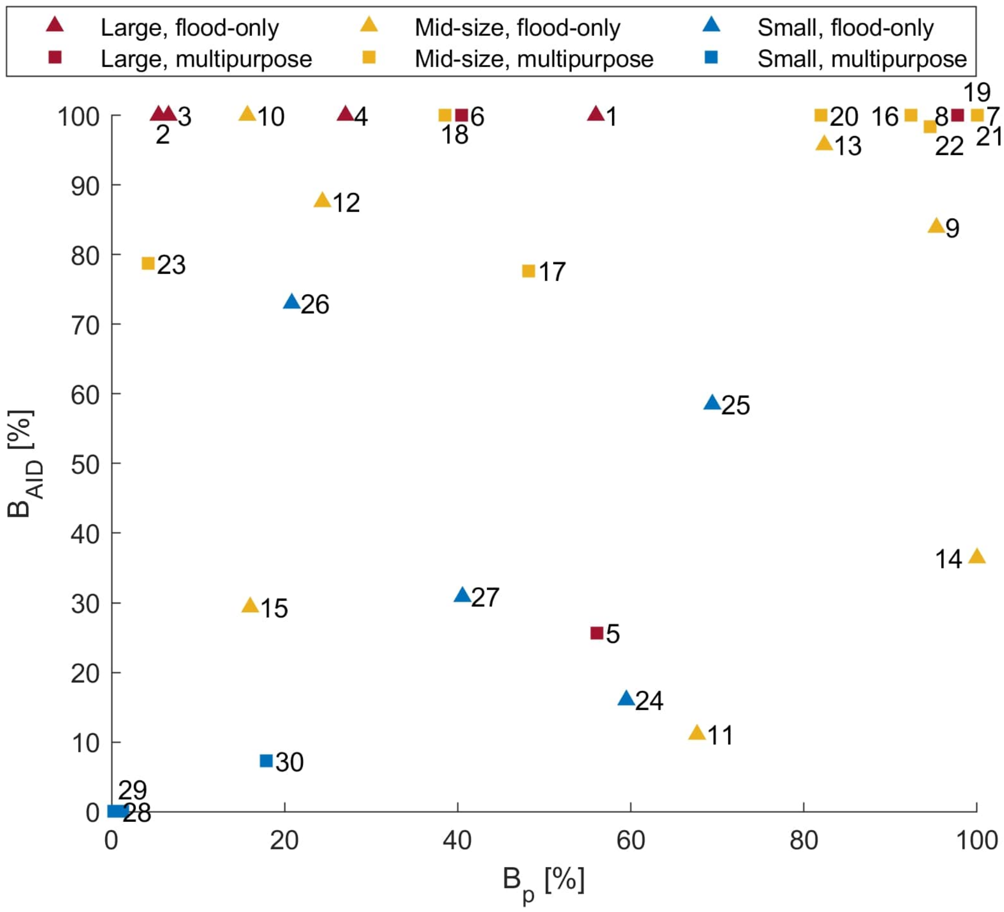

Figure 3.10: The agricultural benefit B_{AID} and streamflow benefit B_p—calculated per Ho and Ehret (2025) for operation in 2017-2020 only— for each reservoir during the same period (2017-2020). Reservoirs are represented by size and by current use, and labeled by ID numbers from Table 3.1

3.5 CONCLUSIONS

In this study, we built upon previous research to develop a modeling framework for assessing the benefit of repurposing small flood reservoirs for agricultural irrigation. By modeling specific operating rules, we were able to simulate the reservoirs' ability to store more water, empty the reservoir before a flood to maintain flood protection, and allow direct withdrawals from the reservoir for irrigation purposes. With respect to our initial questions, we find:

1. The proposed operating rules based on hedging rules can allow small flood reservoirs to at least partially fulfill irrigation demand without compromising flood protection;

2. Repurposing flood reservoirs in Baden-Württemberg in the period 2017-2020 could have provided significant water supply benefit to agriculture during the 2018-2020 drought; and

3. Though some can provide significant benefit to agriculture and streamflow supplementation, most tested reservoirs are suited to either one purpose or the other.

Comparisons of agricultural and streamflow benefit naturally lend themselves to the question of which is more beneficial and, therefore, should be used. This is, unfortunately, not a question this framework can answer, as it depends on the unique demands at each reservoir and a more concrete cost-benefit analysis. For example, if the streamflow supplementation is of sufficient water quality to protect fragile ecosystems of endangered species or to supplement flow to a level that is navigable by ships, this may be the better application. Absent these conditions, agricultural irrigation may be the better use, though potential ecological conflicts could be avoided by diverting the stored water into another dedicated basin, preserving ecological connectivity.

Furthermore, the long-term reliability of this potential water supply should still be investigated: would this source be reliable over decades? Would the value of water provided exceed the costs (both ecological and constructional) of implementing such a change? The definitions of benefit in this framework lack the nuanced analysis necessary to directly conduct such a cost-benefit analysis, but can provide the foundations for starting them: the irrigation time series provided from this framework could be used as an input for a crop model to determine the yield increase—and from there, the economic benefit—enabled by the reservoir. This framework for assessing the potential water supply benefit of repurposed flood reservoirs could allow water managers to investigate new possibilities for diversifying water resources in a changing climate.

Part IV

FORECASTED FLOODS FOR FARMS AND (LOW) FLOWS

This chapter is a reprint of the following study that was submitted to the scientific journal Hydrological and Earth System Sciences (HESS):

Ho, Sarah Quynh-Giang, Robert Lang, and Uwe Ehret (2025). "Forecast-based operation of re-purposed small reservoirs for floods, farms, and (low) flows."

4

FORECASTED FLOODS FOR FARMS AND FLOWS

ABSTRACT

The increased frequency and intensity of hydrological extremes, including drought, due to anthropogenic climate change will drive the need for enhanced water supply resilience, even in water-rich countries. Previous studies have shown that small reservoirs have considerable potential for expanding water supply for various purposes, including when repurposed from flood-only reservoirs for both flood and drought protection. However, whether these repurposed reservoirs retain the same flood protection ability when operating under forecasts is still unclear, as reservoir operation under forecasts has primarily been researched in the context of large reservoirs. In this study, we investigated potential operating rules under forecasts for 30 small-to-midsize flood reservoirs to a) determine if the uncertainty introduced by forecasts degrades the performance of repurposed reservoirs so significantly as to render the concept unusable, b) identify patterns in the relationship between forecast accuracy and optimal reservoir performance, and c) identify patterns in optimal reservoir operation rules, under the constraint that flood protection should not be compromised. Performance is determined by the modelled ability to either supplement streamflow to avoid low flows or to provide water for irrigation purposes in the area of the reservoir. 1000 combinations of three operation parameters—the warning threshold at which flood pre-release begins, the rate at which water is released from the reservoir for flood pre-release, and the inflow at which the reservoir begins storing water—were tested for maintenance of flood protection (viability) and benefit for the reservoir's additional uses. While some reservoirs indeed were no longer beneficial when optimized to operate under forecasts, many still maintained benefits above 40%, with a couple even surpassing their performance under perfect knowledge. Comparing changes in benefit from the perfect-knowledge operation to forecast accuracy indicated that high rates of hits, false alarms, and misses (HFM) could explain the largest decreases in performance, while other forecast accuracy metrics were less impactful. However, even if HFM were low but nonzero, a poorly-timed false alarm could drain a reservoir's storage before a spike in demand, causing a noticeable loss in performance. Investigation of reservoirs' potential benefits under forecasts should therefore be done via simulation rather than approximated via characterizing indices. Optimal operation rules tended to be those that most closely mimicked the perfect knowledge operation, i.e. aggressive storage thresholds and a tendency to hold onto the water storage for as long as is safe, but more conservative operating rules were also able to provide benefits as well. The models for forecast operation and optimization produced for this study can be used by water managers to assess if existing small flood reservoirs can feasibly be used to increase water supply resilience in a changing world.

4.1 INTRODUCTION

Droughts have long been recognized as significant natural hazards that impose severe impacts on multiple sectors worldwide. Shortages in water, coupled with higher temperatures, reduce crop yields and can even impact livestock mortality, ultimately resulting in massive economic losses (Caretta et al., 2022; Matiu et al., 2017). The increasing frequency and severity of droughts due to climate change exacerbate these challenges (Spinoni et al., 2017), posing substantial threats to food security as agricultural droughts become a major driver of yield reduction worldwide (Lesk et al., 2016; Naumann et al., 2021). Prolonged lower river levels as a result of hydrological drought can affect river ecology—for example, low flow indices are commonly part of an assessment of flows for ecological protection (Poff et al., 2017; Vigiak et al., 2018; Yarnell et al., 2020). Lower river levels can also limit or reduce riverine transport, which may have significant effects on the economy (Christodoulou et al., 2020; Jonkeren et al., 2007).

Small reservoirs have often been named as a potential decentralized solution to water scarcity in regions across the globe, such as Italy, Slovakia, Ghana, Burkina Faso, Zimbabwe, and Brazil (Casadei et al., 2019; Jurík et al., 2018; Liebe et al., 2007; Mady et al., 2020; Owusu et al., 2022; Wisser et al., 2010; Şen, 2021). These are reservoirs typically defined as having a dam height of $\leq$15 m, a surface area of $<$ 0.1 km^2, and / or a storage volume of up to 1-2 million m^3 (Casadei et al., 2019; Jurík et al., 2018). Because they are smaller, they are cheaper to construct and maintain, and can be implemented in otherwise remote locations (Qadir et al., 2007). They can also be much more easily adapted to local conditions and can be managed locally (Venot et al., 2011). Research has suggested that recommissioning small reservoirs could maintain or even increase crop yields in an uncertain future (Heinzel et al., 2022), which could be a reason behind the high increase in the number of remotely-sensed reservoirs in water-stressed Europe (Aminzadeh et al., 2024). As climate change impacts destabilize traditional water availability patterns, decentralized small-scale solutions such as small reservoirs may play a leading role in mitigating drought effects in more temperate regions of the globe.

Droughts are not the only natural hazards affected by reservoirs—in many temperate regions around the globe, the primary hydrological hazard has long been floods. The disastrous floods in Germany, Belgium, and the Netherlands in 2021 (Ludwig et al., 2023; Mohr et al., 2023) remain heavy on the public conscience, and many flood reservoirs have been built specifically for this purpose. Bartholomeus et al. (2023) argue, however, that over-preparing for floods may have left these countries underprepared for drought, and call for resilience measures that enable an integrated approach for managing both floods and droughts. The combination of the two objectives in reservoir operations is difficult due to their inherently competing nature, but can be effective when done correctly (Balley, 1997; Chang et al., 1995). Recent research in the state of Baden-Württemberg, Germany, has suggested that repurposing small flood reservoirs for drought under perfect-knowledge conditions can be quite impactful for satisfying local agricultural irrigation demand and for improving low-flow conditions in rivers (Ho et al., 2025; Ho and Ehret, 2025). However, their performance when operating under forecasts remains unproven.

The impact of forecasts in reservoir operation and optimization has been an active topic. Forecasted reservoir operations have often relied on the concept of hedging—in other words, that an increase in short-term risks, e.g. by continuing to keep water storage despite incoming floods, can increase long-term benefits by increasing water supply (Draper and Lund, 2004; Hui et al., 2016; Zhao et al., 2014). Many studies report that reservoir operations benefit from (or at the very least, are not negatively affected by) operation under forecasts in comparison to the case where no future information is available (Chen et al., 2016; Delaney et al., 2020; Mostaghimzadeh et al., 2022; Schwanenberg et al., 2015). The value of these forecasts are affected by two factors: forecast uncertainty and forecast horizon (the time into the future which is forecasted). Zhao et al. (2011) found that reservoir performance generally decreases with increasing uncertainty, but that the magnitude of this decrease depends on the type of forecasting product used (probabilistic, deterministic, or semi-probabilistic forecasts). Forecast uncertainty tends to increase with increasing forecast horizon; however, studies have shown that a balance between forecast uncertainty and horizon can be achieved to benefit performance (Zhao et al., 2019; Zhao et al., 2012). Turner et al. (2017) argued that, when operating for demands for water, this relationship breaks down—high forecast accuracy no longer necessitates improvement. Further research suggests that the value of the forecasts may decrease or disappear altogether, depending on the specific objectives and constraints (Doering et al., 2021). These results, however, are primarily in the context of large reservoirs. Given the potential benefits of small repurposed flood reservoirs for drought resilience under perfect knowledge, the value of forecasts in the operation of these reservoirs should be investigated.

This study aims to demonstrate the potential benefits of repurposing small flood reservoirs for drought protection when operating under forecasts in comparison to perfect-knowledge scenarios, particularly under the constraint that the reservoir flood protection function should not be compromised. Specifically, we optimize the operation rules of 30 reservoirs in southwest Germany, modified from Ho et al. (2025) for irrigation demand fulfilment and Ho and Ehret (2025) for streamflow supplementation, to make decisions based on available streamflow forecasts without increasing downstream flooding. The results aim to answer the following questions:

- Q1: Does the uncertainty introduced by using forecasts for decision-making significantly decrease the performance of repurposed small reservoirs' operation such that it is no longer beneficial?
- Q2: What is the relationship between forecast accuracy and decrease in optimal performance between the perfect-knowledge and forecasting operations?
- Q3: What operating rules are most likely to be optimal, and how do these differ from current operation rules?

We begin with an overview of the study area and reservoirs selected for study, then describe the methods used to generate the historical streamflow forecasts, inflow time series, streamflow supplementation demand and irrigation demand time series for each reservoir. We continue with an explanation of the forecast operation model for optimization, the metrics for which the reservoirs are optimized, and the metrics for comparing with perfect-knowledge optimization. Finally, results are presented in the context of the three questions above and are discussed accordingly.

4.2 DATA AND METHODS

4.2.1 *Study Area*

The German state of Baden-Württemberg is in the southwest of Germany and shares borders with France and Switzerland. The majority of the state belongs to subcatchments of the Rhine, with the rest belonging to those of the Danube catchments. Two climate regimes dominate, according to the Köppen-Geiger classification (Beck et al., 2023). A temperate oceanic climate (Cfb) covers the majority of the state, including most of the Black Forest and the major cities, such as Karlsruhe, Stuttgart, and Freiburg im Breisgau. A humid and warm continental climate (Dfb) covers the Swabian Alb and the eastern parts of the Black Forest. Average annual precipitation from 1991-2022 ranges from 600-1200 mm in the majority of the state, though precipitation in the Black Forest is significantly higher (1400-2100 mm). Typical reference evapotranspiration in the same time period ranges from 450 mm per year in the Black Forest and Swabian Alb to 700 mm per year in the Rhine Valley and urban areas.

This study builds on previous work on the potential of flood reservoirs for drought protection (Ho et al., 2025; Ho and Ehret, 2025). The curious reader may refer to these works for detailed discussion on the reservoir selection process. While the selected reservoirs (Table 4.1) are small and at most mid-size on the global scale, they are named in this study by size according to the German standard DIN19700 (Lubw, 2007), in which large reservoirs have a capacity of over 1 million cubic meters, medium reservoirs a capacity of 100,000-1 million cubic meters, and small a capacity of 50,000-100,000 cubic meters, and by current usage (flood-only or multipurpose). These reservoirs are currently primarily operated for flood protection, impounding floods once the flooding limit Q_{crit} is exceeded, and are modelled in this work as individual reservoirs without regards to their function in a system.

4.2.2 *Weather and Streamflow Forecasts*

4.2.2.1 *Historical Weather Forecasts*

To reproduce the exact forecasting situation of operational flood forecasting for the period 2010 through 2021, the original weather forecast datasets archived by the flood forecasting center of Baden-Württemberg were used for this re-simulation (Table 4.2). This meteorological dataset combines three forecasting products supplied by the German Meteorological Service (DWD), namely COSMO-DE (Baldauf et al., 2016), COSMO-D2 (Baldauf et al., 2018), and ICON-D2 (Reinert et al., 2025), which at the time were the most advanced products available for hydrological water-balance forecasting. Missing variables were substituted with observed weather data at the time of forecasting. Further differences in these products are horizontal and vertical model resolution and further optimization of meteorological sub-processes.

4.2.2.2 *Historical Streamflow Forecasts and Inflow Time Series*

The historical streamflow forecasts were generated using the process-oriented water balance Large Area Runoff Simulation Model, also known as LARSIM (Bremicker, 2000;

Table 4.1: The 30 reservoirs from Ho and Ehret (2025), along with their operating parameters (the operating capacity and the flooding limit Q_{crit}), investigated in this study. ID numbers have been added for clarity. The maximum of the Q_{70} low-flow time series (see 4.2.3) is included as an indicator of the river regime.

Category	Inundation Type	Name	ID	Operating Capacity [m^3]	Q_{crit} [m^3s^{-1}]	Max(Q_{70}) [m^3s^{-1}]
LF	Operational	Bernau	1	1,020,000	22.00	1.013
		Gottswald	2	4,720,000	830.00	20.619
		Mittleres Kinzigtal	3	2,700,000	860.00	16.988
		Wolterdingen	4	3,000,000	75.00	4.602
LM	Permanent	Federbach	5	652,652	0.400	0.090
		Fetzachmoos	6	3,500,000	15.00	1.518
		Nagoldtalsperre	7	1,741,000	15.00	0.865
		Rehnenmuehle	8	2,930,000	7.00	0.523
MF	Operational	Schwaigern	9	151,880	3.32	0.134
		Seckach	10	64,000	50.30	0.747
		Seebaechle	11	33,112	0.10	0.014
		Unterbalbach	12	210,000	6.33	0.156
	Permanent	Doertel	13	168,400	0.79	0.060
		Lindelbach	14	172,000	0.50	0.014
		Weissacher Tal	15	185,000	2.41	0.070
MM	Operational	Heinzental	16	310,000	1.09	0.059
		Hofwiesen	17	335,210	10.68	0.171
		Wustgraben	18	276,181	0.50	0.053
	Permanent	Fischbach	19	181,625	3.70	0.101
		Huettenbuehl	20	32,000	4.00	0.227
		Kressbach	21	233,780	0.70	0.050
		Michelbach	22	81,728	1.00	0.036
		Salinensee	23	188,000	3.60	0.069
SF	Operational	Duffernbach	24	31,143	1.55	0.031
		Goettelfinger Tal	25	83,400	4.10	0.154
		Mittelurbach	26	60,000	0.50	0.092
		Wollenberg	27	30,200	3.37	0.063
SM	Permanent	Hoelzern	28	7,703	1.50	0.003
		Lennach	29	9,600	2.10	0.004
		Nonnenbach	30	3,759	0.17	0.029

Table 4.2: Weather forecast products and variables used to generate the historical streamflow forecasts.

Years	Product	Forecast Variables	Spatial Resolution	Forecast Horizon	Updating Interval
2010-2017	COSMO-DE	Precipitation	2.8 km	27 hrs	3 hrs
2018-2020	COSMO-D2	Precipitation, air temperature, global radiation, wind speed, air pressure, relative humidity	2.2 km	27 hrs	3 hrs
2021	ICON-D2	Precipitation, air temperature, global radiation, wind speed, air pressure, relative humidity	2 km	Up to 48 hrs	3 hrs

Bremicker et al., 2013; Haag and Luce, 2008; Haag et al., 2022), and is currently used operationally in several countries in Europe, including the study area Baden-Württemberg. Discharge concentration and river routing are simulated in hourly resolution and on a 1 x 1 km grid, whereas evapotranspiration, snow dynamics, the soil water balance and runoff generation are modelled using hydrological response units. For this evaluation, the models were re-run in the same configuration currently used at the federal flood forecasting center of Baden-Württemberg to produce deterministic forecasts and inflow time series for each reservoir. The forecast horizon was limited to a maximum of 24 hours to limit forecast uncertainty, with a new forecast initiated every hour of the evaluation period (2010–2021) using the most recent meteorological forecast.

At the transition point from measured data to actual forecasts, the model is automatically optimized at the gauge catchment level on the basis of comparing simulated and measured discharge. If the configuration files allow optimization for the current discharge range, and if deviations between simulated and observed discharge exceed a predefined threshold (5%), multiple optimization routines are triggered. The system then automatically selects the most plausible adjustment process as described in detail by Luce et al. (2006). When discrepancies are caused by localized rainfall or snowmelt errors, a correction factor modifies the water supply over the forecast period. If mismatches instead result from storage dynamics (e.g. recession after a flood peak), the model updates the filling levels of its hydrological storages (interflow, direct runoff, groundwater). These corrections are constrained within predefined ranges of adjustment factors (Luce et al., 2006). Due to these corrections, however, the resulting modelled streamflow for each reservoir differs slightly from those used in Ho and Ehret (2025) and Ho et al. (2025).

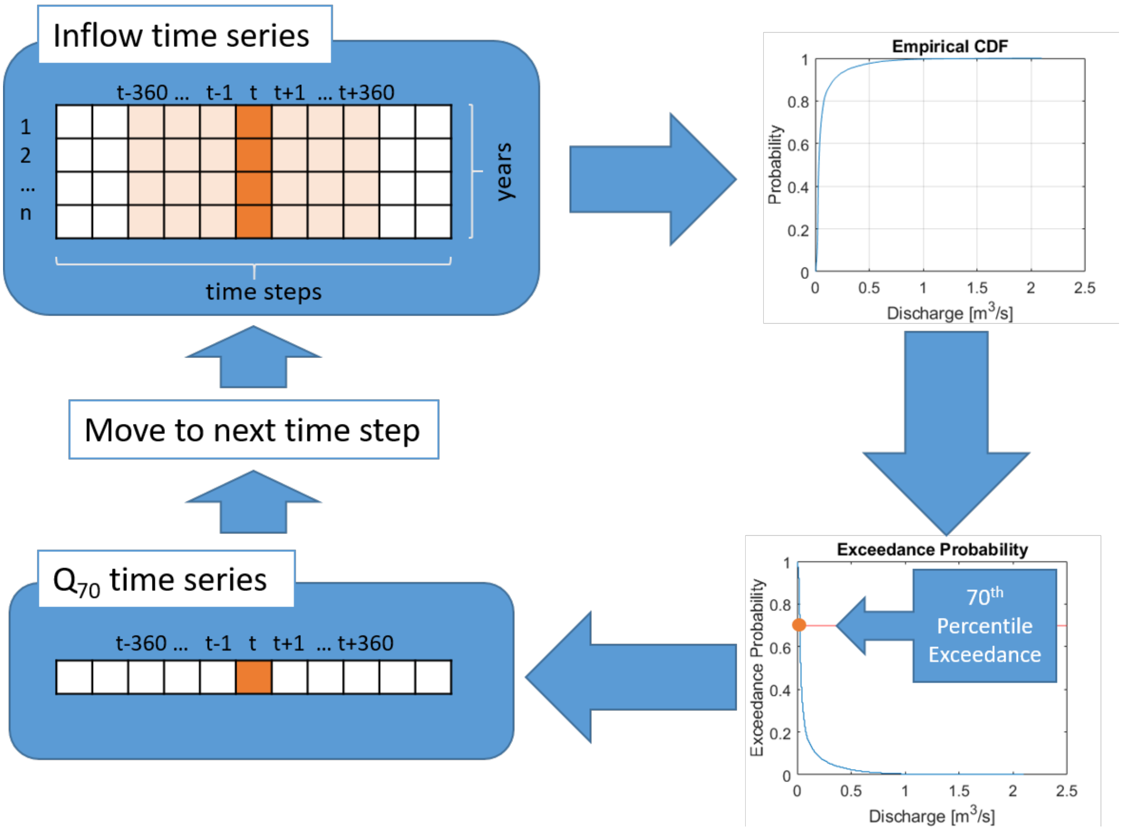

Figure 4.1: Example calculation of the Q_{70} time series, reprinted with permission from Ho and Ehret (2025).

4.2.3 *Streamflow Demand Time Series*

Streamflow demand is based on the hourly 70^{th} percentile exceedance flow (Q_{70}) of the reservoir's inflow time series. This Q_{70} is calculated following the adjusted method of Cammalleri et al. (2016) presented in Ho and Ehret (2025) (Figure 4.1). For each time step t within a year, we collect a 721 x n matrix of discharge values: 721 represents all the hourly time steps in a 30-day moving window (with an additional value to center the window on t), which is applied to all the years in the dataset (n). The cumulative distribution function curves for discharge, and then the percentile exceedance curves, are derived based on the values in this matrix. The threshold value at each timestep is the discharge corresponding to the chosen percentile exceedance.

4.2.4 *Irrigation Demand Time Series*

Time series of irrigation demand for each reservoir were taken from Ho et al. (2025). These were calculated for a 5 km² square-shaped region around each reservoir for a variety of different crops. Crop cover and soil texture maps were obtained from Schwieder et al. (2024) and Düwel et al. (2007), respectively, and used to identify agricultural response units (ARUs)—areas of the same crop and soil cover within a region. The irrigation demand (AID) of each ARU was calculated using the FAO-56 method (Allen et al., 1998) using a collection of plant growth and soil parameters from various sources (Ad-Hoc-Arbeitsgruppe, 2005; Allen et al., 1998; Pereira et al., 2021a,c; Rallo et al., 2021). For more details, please refer to Ho et al. (2025). The total AID time series of each reservoir is the sum of each ARU's AID (eq. 4.1):

$$AID = \sum_{ARU=1}^{m} AID_{ARU} \tag{4.1}$$

4.2.5 *Forecast Operation Model*

The reservoir's operation under forecasts (Figure 4.2) is modelled by running forward in time by comparing various state variables and threshold parameters (Table 4.3):

1. If the current inflow Q_{in} is above the flooding limit Q_{crit}, it impounds the floods by storing flow above the flooding limit (flood operation module) until the operating capacity C is reached; else, it makes a decision based on the most recent forecast.
2. If a forecast is unavailable, the reservoir repeats the previous operation module.
3. If the highest forecasted value is larger than the flooding limit ($\max(Q_{in,forecast}) > Q_{crit}$), the reservoir releases volume such that the outflow is Q_{crit} (flood pre-release module).
4. If the highest forecast value is greater than the warning threshold Q_{thresh} ($\max(Q_{in,forecast}) > Q_{thresh}$), the reservoir releases volume such that the outflow is $Q_{release}$ (partial pre-release module).
5. If the forecast fails both of these conditions, the model operates based on the current inflow Q_{in}—if Q_{in} is greater than the retention flow Q_r, the reservoir will store water such that the outflow is Q_r (drought fill module).
6. If there is a need for water—either Q_{in} is below the streamflow drought threshold or there is irrigation demand—the reservoir will release volume to meet the demand.

The model can be operated for either streamflow or irrigation operation (it cannot do both at the same time) and is a modified version of the models in Ho et al. (2025) and Ho and Ehret (2025). For either use, the model is optimized for highest benefit by adjusting Q_r (as in the aforementioned studies), the Q_{thresh}, and/or the $Q_{release}$ using the following variables:

1. percQ_thresh, which is the threshold percentage of the flooding limit (Q_{crit}) which we will indicate as a forecast warning level (Q_{thresh}) (eq. (4.2)):

$$Q_{thresh} = percQ_{thresh} \times Q_{crit} \tag{4.2}$$

2. percQ_release, which is the percentage of Q_{crit} that will be released to pre-empty the reservoir at the rate $Q_{release}$ (eq. 4.3):

$$Q_{release} = percQ_{release} \times Q_{crit} \tag{4.3}$$

Table 4.3: Key variables for the forecast operation model.

Abbreviation	Description
C	Operational capacity of the reservoir (full minus permanent inundation volume)
Q_{crit}	Flooding limit; critical flow above which reservoir impounds floods
$Q_{in,t}$	Inflow to the reservoir at time t
$Q_{in,forecast}$	Forecasted inflow to the reservoir
$Q_{70,t}$	70^{th} percentile exceedance flow at time t
AID_t	Agricultural irrigation demand of the reservoir's area at time t
Q_{thresh}	Warning flow at which partial pre-release module begins
$Q_{release}$	Reservoir outflow during the partial pre-release module
Q_r	Retention flow at which water is stored in the reservoir; optimization variable
$percQ_{thresh}$	Q_{thresh} expressed as a percentage of Q_{crit}; optimization variable
$percQ_{release}$	$Q_{release}$ expressed as a percentage of Q_{crit}; optimization variable

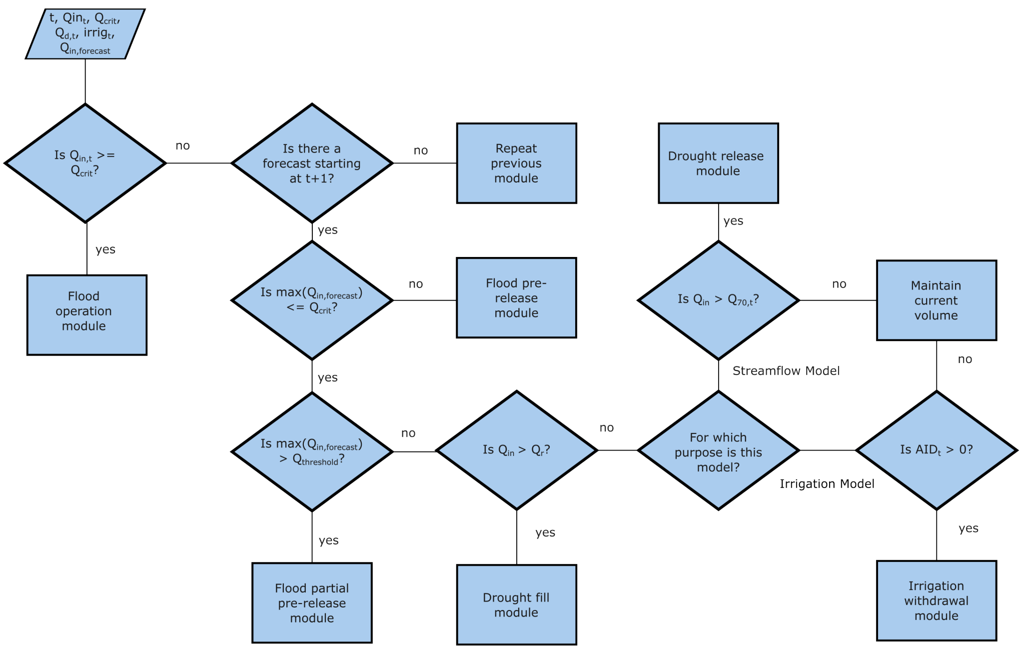

Figure 4.2: The decision tree for the forecast operation model.

4.2.6 *Metrics for Comparison & Evaluation*

4.2.6.1 *Determination of Benefit*

Benefits in this study are expressed as percent reduction of a negative outcome, which are in turn expressed via penalty functions.

FLOOD PROTECTION BENEFIT Flood protection remains the cornerstone of the reservoir's operation—in no circumstances are increases of flooding volume acceptable. Flood penalty is simply defined in Ho and Ehret (2025) as (eq. 4.4)

$$P_{f,t} = \begin{cases} 0 & \text{if } Q_{out,t} \leq Q_{crit} \\ -5(Q_{out,t} - Q_{crit}) & \text{if } Q_{out,t} > Q_{crit} \end{cases} \tag{4.4}$$

and expresses the amount of water above Q_{crit} that the reservoir cannot impound, multiplied by a scalar (here chosen arbitrarily as 5).

Because the in-situ reservoir operation rules are currently optimized for flood protection, no increase in flood protection (i.e. no flood protection benefit) is expected using the forecast operation model. However, in all optimization efforts, only parameter sets that do not increase flood penalty shall be considered.

STREAMFLOW SUPPLEMENTATION – PENALTY BENEFIT The streamflow penalty P_d and the streamflow benefit B_p are metrics developed for evaluating a reservoir's performance for streamflow supplementation in Ho and Ehret (2025).

The streamflow benefit B_p refers to the reservoir's ability to provide water and reduce streamflow penalty, represented as the percentage of penalty reduced by the operation (ranging from 0 to 100%, where higher is better). This is based on the difference between the penalty in the flood-only (i.e. current) operation and the penalty in a combined (flood and streamflow supplementation) operation scheme:

$$B_p = 100 \times \frac{\sum P_{d,flood-only} - \sum P_{d,combinedoperation}}{\sum P_{d,flood-only}} \tag{4.5}$$

AGRICULTURAL IRRIGATION DEMAND – IRRIGATION BENEFIT The benefit from the reservoir in the case of irrigation demand is summarized as the percentage of the irrigation demand that the reservoir can supply (ranging from 0 to 100%, where higher is better) (eq. 4.6):

$$B_{AID} = 100 \times \frac{\sum AID_{fulfilled}}{\sum AID_{total}} \tag{4.6}$$

The AID_{total} is the sum of the irrigation demand time series for all crops within a reservoir's area, and the $AID_{fulfilled}$ is the water withdrawn for irrigation purposes by the irrigation model.

4.2.7 *Optimization for Forecast Operation*

The forecast operation models were tested using 1,000 different parameter sets consisting of combinations of 10 values each of Q_r, percQ_thresh, and percQ_release. These parameters were constrained as follows (eqs. 4.7, 4.8, 4.9):

$$max(Q_{70}) < Q_r < Q_{crit} \tag{4.7}$$

$$max(Q_{70}) < Q_{crit} \times percQ_{thresh} < Q_{crit} \tag{4.8}$$

$$0.05 < percQ_{thresh}, percQ_{release} \leq 1 \tag{4.9}$$

For comparing values of Qr across reservoirs, we normalize the optimal Qr with the reservoir's Qcrit (eq. 4.10):

$$percQ_{crit} = \frac{Q_r}{Q_{crit}} \tag{4.10}$$

Each parameter set was tested in both the irrigation and streamflow cases to determine changes in flood penalty; i.e., if there was any increase in flood volume that was not retained by the reservoir. Viable parameter sets were those that had no increase in flood penalty, and the optimal parameter set was the viable parameter set that had the highest benefit for the use case. It is likely that a reservoir could have more than one optimal parameter set (i.e. a Pareto front).

4.2.7.1 *Forecast Accuracy*

The quality of forecasts for a given reservoir is evaluated based on their accuracy in comparison to the inflow time series, i.e. the percentage of forecasts that correctly predict floods (hits; H), incorrectly predict floods (false alarms; F), incorrectly predict no floods (misses; M), and correctly predict no floods (correct rejections; R). For this purpose, any instance of $Q_{in,forecast}$ greater than or equal to Q_{crit} will result in a flood forecast, regardless of forecast horizon. A high rate of F+R indicates that the reservoir did not have many flooding events. High percentages of H+F trigger frequent flood pre-release; in other words, there will be less water available for the intended usage. A relatively high MM would likely indicate that the reservoir's priority should remain flood protection, as an empty reservoir would reduce the risk of flood damage due to faulty forecasts.

The quality of these forecasts can be further described using additional variations of the confusion matrix. The critical success index (CSI) describes the rate of successful event identification over both forecasted and missed events, ranging from 0 (worst) to 1 (best) (eq. 4.11):

$$CSI = \frac{H}{H + M + F} \tag{4.11}$$

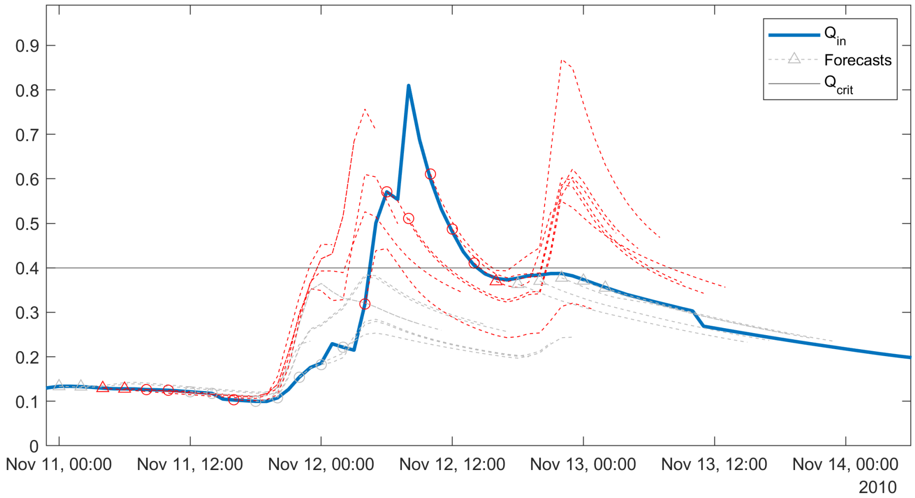

Figure 4.3: A three-day sample of forecasts generated by LARSIM for Federbach reservoir (for clarity, only every other forecast is shown). The marker, placed at the first value of each forecast, is a circle if a flood occurred during the forecast horizon and a triangle if no flood occurred. Red color indicates the forecast predicted a flood event; gray indicates no flood predicted. In this sample, there are 9 hits, 7 misses, 3 false alarms, and 7 correct rejections.

The precision of the forecast describes the rate of successful flood forecasts compared to all predicted floods, where a higher score (maximum 1, minimum 0) indicates that if a flood is forecasted, it is more often correct:

$$\text{precision} = \frac{H}{H+F} \tag{4.12}$$

The recall of the forecast describes the rate of successful flood forecasts compared to all true floods, where a higher score (maximum 1, minimum 0) indicates that more of the flood events were identified:

$$\text{recall} = \frac{H}{H+M} \tag{4.13}$$

The F1 score is the harmonic mean between precision and recall, allowing for a balanced representation of both, where a higher score (maximum 1, minimum 0) indicates better performance (eq. 4.14):

$$\text{F1} = \frac{2 \times (\text{precision} \times \text{recall})}{\text{precision} + \text{recall}} \tag{4.14}$$

Thus, the forecasts for the sample event (Figure 4.3) have a CSI of 0.474, a precision of 0.750, a recall of 0.563, and an F1 score of 0.643. This could be interpreted as having a moderate ability of forecasting an event (medium CSI), a high accuracy when predicting flood events (high precision), a moderate ability to identify an actual event (medium recall), and a moderate-to-high overall accuracy (F1 score).

4.2.7.2 *Comparison with the Perfect Knowledge Scenario*

The forecast model benefits for each reservoir is evaluated in comparison to its perfect-knowledge scenario to determine the impact of forecasts in operation. Ho and Ehret (2025) and Ho et al. (2025) provide perfect-knowledge scenarios for the streamflow and agricultural reuse models; however, due to differences in the model setup (see section 4.2.2.2), the reservoir inflow time series—and therefore the benefits—are different. Therefore, the perfect-knowledge benefits have been rerun with the new inflow time series using the methods presented in Ho and Ehret (2025) and Ho et al. (2025).

4.3 RESULTS

4.3.1 *Optimization Results*

The number and performance of resulting viable parameter sets varied greatly, with some reservoirs having no viable parameter sets and others having more than 900 (Figure 4.4). The optimal parameter set is the one with the highest benefit—for some reservoirs, there are multiple optimal sets (i.e. Pareto-optimal sets). Small reservoirs have considerably lower benefits, especially those that are currently multipurpose reservoirs, as they often struggled to store water. Mid-sized and large multipurpose reservoirs perform overall quite well; however, many non-optimal parameter sets still provide considerable benefit to both use cases. Should an optimal parameter set be deemed unfeasible for other reasons (e.g. a need to increase flood safety margins), there remain many other viable options.

The distribution of the benefits can also be informative. Some reservoirs have large gaps between clusters of equally-performing parameter sets, resulting in a very discontinuous distribution. In the irrigation usage case, this may not be too surprising, as the demand itself is quite disjointed: due to the assumptions when calculating the demand time series, water for an entire ARU is requested on the same day and is not staggered. Its fulfillment on any given day is also limited by the reservoir's volume—once the entire volume is given for the season, there are rarely additional increases in benefit. In the streamflow usage case, however, this could indicate forecasts that require frequent pre-releases or consistent water shortages limiting the overall viability of the reservoir.

The frequency patterns of successful viable parameter combinations differ considerably from those of optimal parameter combinations (Figure 4.5, 4.6). In both use cases (streamflow and irrigation), the frequency hotspots of viable parameter sets indicate highly conservative rules: low warning thresholds (percQ_thresh), high release rates (percQ_release), and high storage thresholds (percQ_crit) resulting in reduced storage serve to minimize volume stored and maximize volume released before a flood. These rules are similar to the in-situ operation rules (store only flood waves and release volume as soon as possible) and are therefore most likely to result in no increased flood penalty; however, they are less likely to produce any benefit (see appendix C) due to reduced water storage.

In contrast, frequency hotspots of pareto-optimal sets indicate highly aggressive rules: high warning thresholds and low storage thresholds serve to maximize volume stored and hold it for as long as possible. These mimic the optimal rules found in the

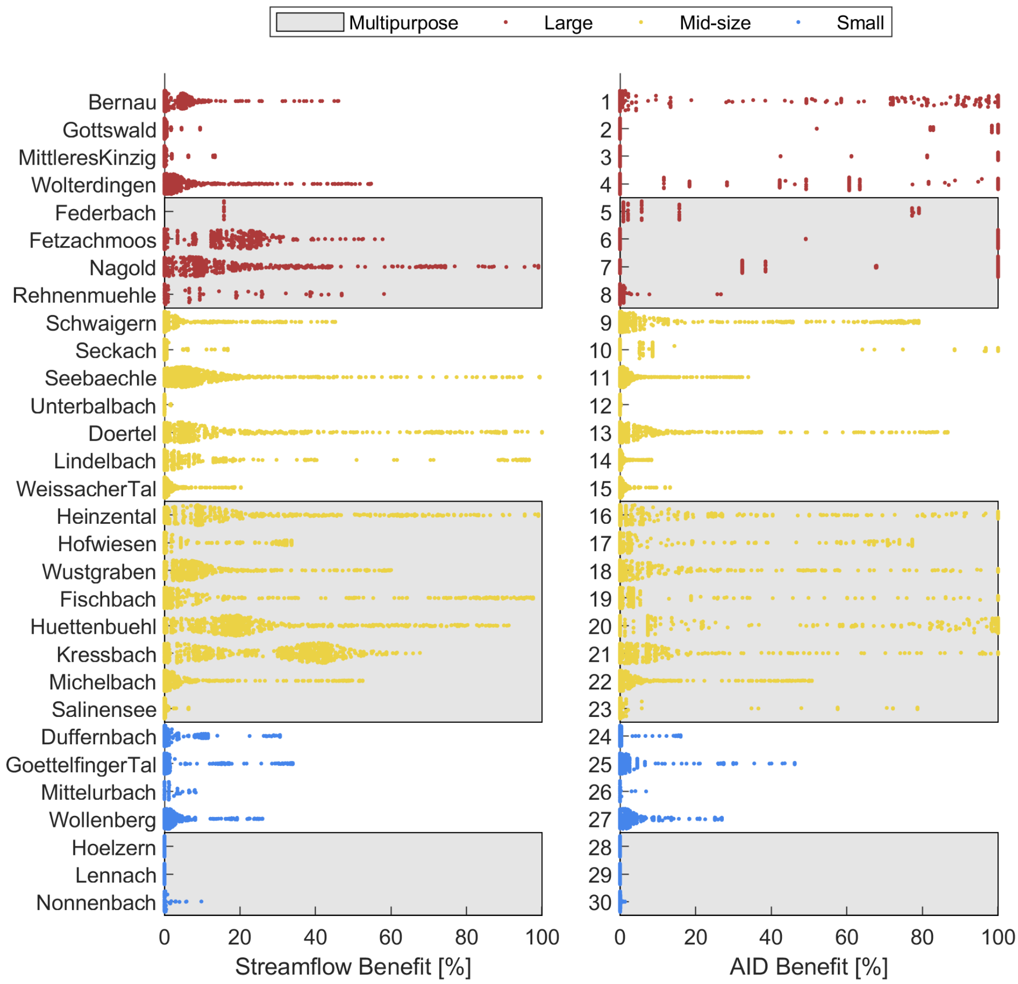

Figure 4.4: Distributions of the performance of viable parameter sets for the selected reservoirs.

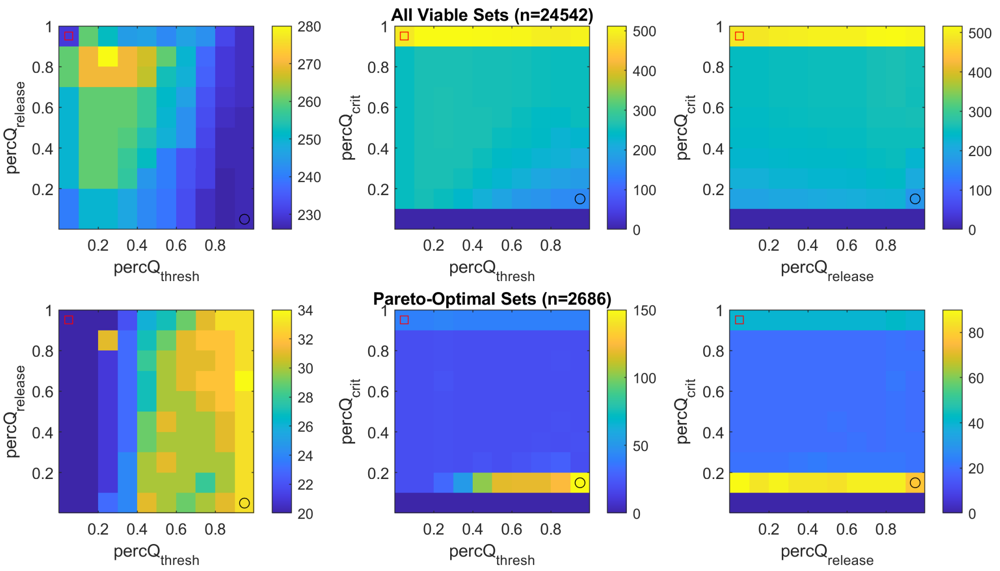

Figure 4.5: Color indicates frequency of a given parameter combination in either all viable parameter sets or pareto-optimal sets for streamflow-optimized forecast operation. The red square indicates the current (flood-optimized) operation rules, whereas the black circle indicates the perfect-knowledge operation rules.

perfect-knowledge scenarios. This is also reflected in heatmaps of average benefit for parameter combinations (see appendix C). Indeed, in both uses, the vast majority of pareto-optimal sets occur when percQ_thresh is between 0.8 and 1.0 and percQ_crit is between 0.1 and 0.2 (values under 0.1 are not permitted). An exception can be found in streamflow optimal sets at percQ_thresh between 0.2 and 0.3—this is due to large multipurpose reservoirs, such as Federbach, which tend to have a low Q_{crit} relative to its volume and thus need more time (enabled by a lower warning threshold) for a successful pre-release. This is not reflected in irrigation due most likely to the shorter time series and the seasonal nature of the demand. The relatively high occurrence frequencies at percQ_crit are due to reservoirs that experience little to no benefit. The variety of high performing release rates indicate that this parameter will be the most impactful in the optimization scheme.

4.3.2 *Comparing Forecasted to Perfect-Knowledge Conditions*

The agricultural and streamflow benefits from the optimal parameter sets were compared with those from the perfect-knowledge conditions (Figure 4.7). In most cases, and as to be expected, the perfect-knowledge operation for resulted in higher benefits than the optimized forecast operation, with a median difference of 13% (mean 17%) for streamflow supplementation and a median difference of 0% (mean 8.5%) for irrigation demand—while surprising, this is because 15 reservoirs maintained their performance when operated for irrigation. Seven reservoirs operated for streamflow and 15 operated for irrigation still maintain a benefit greater than 70% (compared to 14 for streamflow and 20 for irrigation in the perfect-knowledge scenario). In fact, in some cases the reservoir's performance actually increased under forecast operation—this occurred

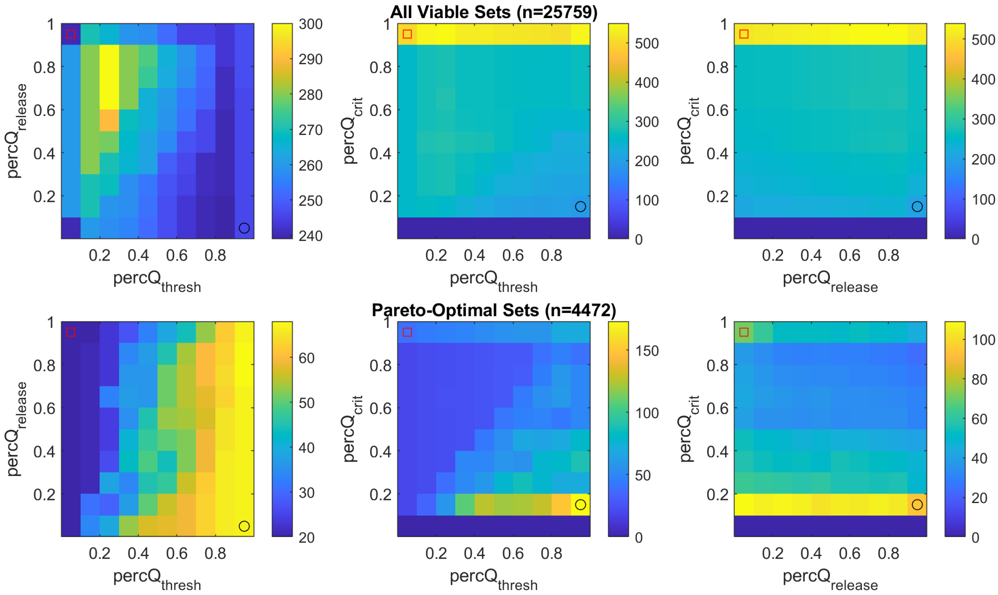

Figure 4.6: Color indicates frequency of a given parameter combination in either all viable parameter sets or pareto-optimal sets for irrigation-optimized forecast operation. The red square indicates the current (flood-optimized) operation rules, whereas the black circle indicates the perfect-knowledge operation rules.

in two reservoirs (Seebaechle and Doertel) in the streamflow operation case, and two (Federbach and Seebaechle) in the irrigation case. This is because of a slight nuance in the partial pre-release module: in the perfect-knowledge optimization, the reservoir is required to be completely empty before a flood. In contrast, the optimized forecast only requires that flooding conditions do not increase, effectively increasing the flexibility of the reservoir and allowing water to remain in the reservoir before a flood. In reservoirs with frequent flooding, this increases the water available for drought, as water storage is carried over from one flood event to the next.

4.3.3 *Influence of Forecast Accuracy*

The accuracy of the reservoir forecasts from 2010-2021 was rather varied (Table 4.4). Forecasts at nine reservoirs correctly found no flooding events. Of the remaining 20 reservoirs, seven had forecasts with F1 scores of less than 0.5 (indicating poor performance), seven had forecasts with F1 scores between 0.5 and 0.75 (indicating good performance), and six had forecasts with F1 scores of at least 0.75 (indicating high performance).

One could expect that high occurrence rates of H, F, and / or M would significantly impact benefits, as these would incur action from the reservoir. Indeed, reservoirs with a change in benefit of at least 50% (Rehnenmuehle, Unterbalbach, Federbach, and Mittelurbach) do have among the highest rates of HFM (Figure 4.8)—though in the case of Federbach's irrigation optimization, this benefit is in the positive direction. High HFM, however, is not a prerequisite for a large change in benefit—other reservoirs with large changes (20-40%) have HFM of less than 2%, indicating that low floodingflooding

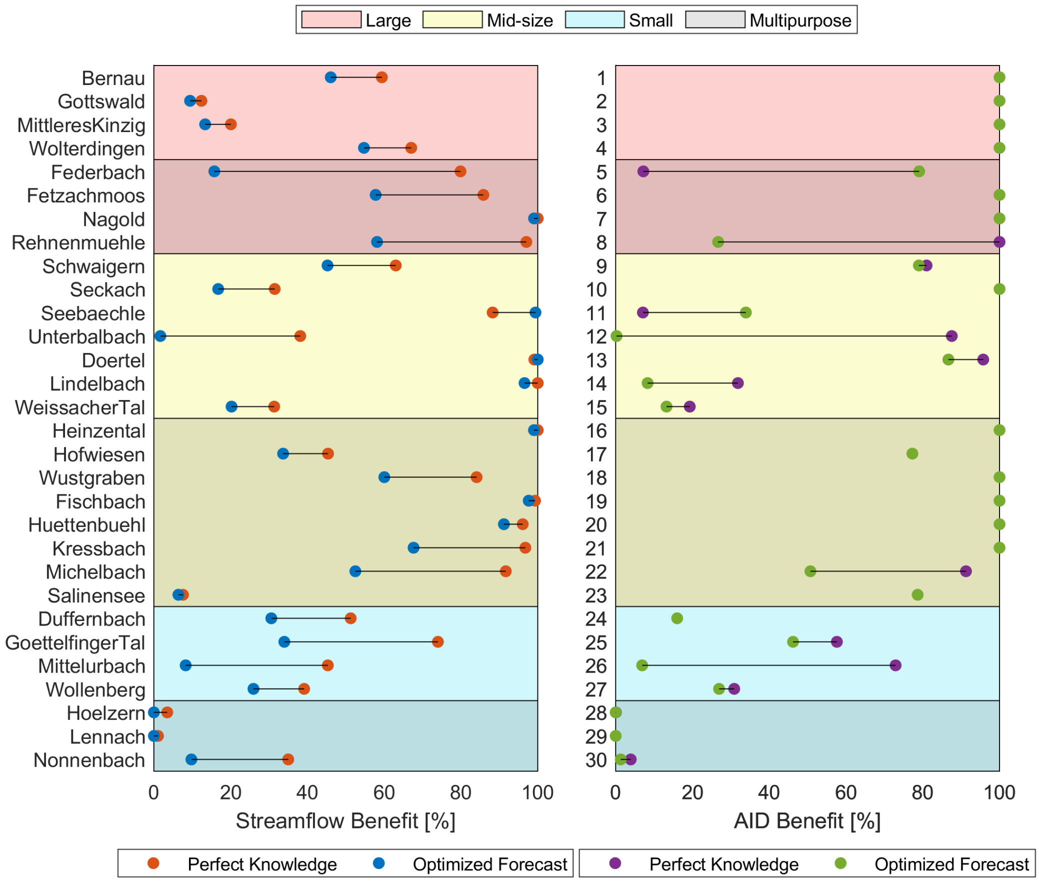

Figure 4.7: Differences in performance between the optimal performance under perfect knowledge and uncertain forecasts. If only the optimized forecast is visible, the optimized forecast and perfect knowledge performed equally well; if only the perfect knowledge is visible, there were no viable parameter sets for operation under forecasts.

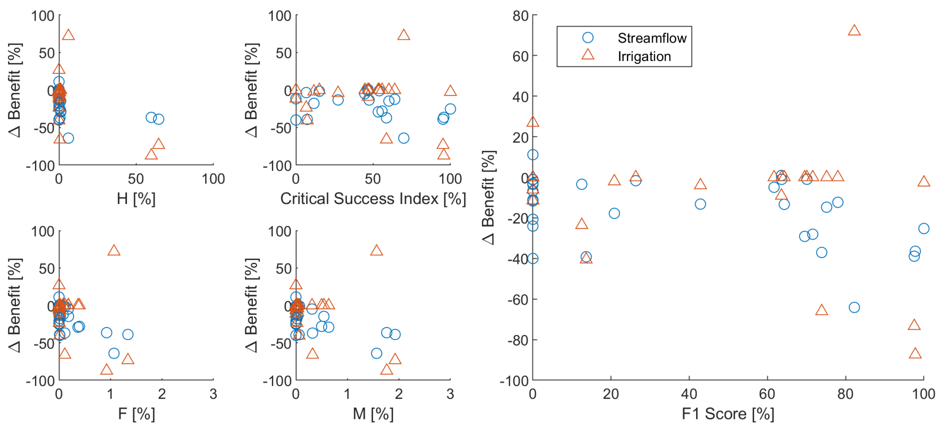

Figure 4.8: Relationships between different accuracy metrics and change in benefit for each reservoir and use case.

rates does not mean that benefits will remain unchanged. Other accuracy metrics (CSI and F1 score) seem to have less of an explanatory impact, as the four reservoirs with the greatest changes in benefit scored high in both CSI and F1.

4.4 DISCUSSION

The primary finding of the study is that, even when operating in a more realistic scenario (i.e. with uncertain forecasts), the concept of repurposing small flood reservoirs for irrigation or/and streamflow supplementation as presented in Ho and Ehret (2025) and Ho et al. (2025) can still provide significant benefits in a range of viable parameter sets. Though the performance of most reservoirs was noticeably affected by the forecasts (indeed, some reservoirs were no longer beneficial to a particular purpose), many were able to maintain benefits above 40%. These were generally reservoirs that did not experience a flood event during the observation period and had well-performing forecasts. Small reservoirs—in particular, small multipurpose reservoirs—had very little benefits whereas large and mid-size reservoirs generally performed quite well, which is consistent with previous findings (Ho et al., 2025; Ho and Ehret, 2025). Ideal parameter sets were those that imitated the operation rules under perfect knowledge: to store water at a storage threshold as low as possible, and to hold onto the water as long as is safe. Although these aggressive parameter sets were typically the highest-performing, more conservative rulesets could also viably provide some benefit as well.

While forecast quality remains the biggest uncertainty in this study, as LARSIM is not typically used to model small catchments (and forecasting in small catchments is already quite tricky), these are the best forecasts that we can currently generate for most of these reservoirs:: the model setup is the same as the current operational setup in use in the study area, and the forecast horizon is a brief 24 hours. Our results showed that typical forecast metrics—namely the critical success index (CSI) and the F1 score—alone did not explain large changes in reservoir benefits from the perfect knowledge case. Indeed, it seemed that flood occurrences were the deciding factor here. Reservoirs with high HFM in their forecasts were emptied frequently for flood protection and

Table 4.4: Forecast accuracy statistics (hits, H; misses, M; false alarms, F; correct rejections, R; critical success index, CSI = H/(H+F+M), precision, H/(H+F); recall, H/(H+M); and F1 score, $2/(\text{recall}^{-1}+\text{precision}^{-1})$) at all reservoir locations. The names of reservoirs with changes in benefit of more than 50% are bolded.

	Reservoir	H [#]	M [#]	F [#]	R [#]	CSI	Precision	Recall	F1
1	Bernau	54	42	18	105079	0.47	0.75	0.56	0.64
2	Gottswald	0	0	0	105193	-	-	-	-
3	MittleresKinzig	0	0	0	105193	-	-	-	-
4	Wolterdingen	234	40	92	115159	0.64	0.72	0.85	0.78
5	**Federbach**	6406	1648	1123	96016	0.70	0.85	0.80	0.82
6	Fetzachmoos	1183	524	416	103068	0.56	0.74	0.69	0.72
7	Nagold	48	16	25	105102	0.54	0.66	0.75	0.70
8	**Rehnenmuehle**	67828	2026	1407	33932	0.95	0.98	0.97	0.98
9	Schwaigern	5	19	19	105150	0.12	0.21	0.21	0.21
10	Seckach	1155	571	194	103273	0.60	0.86	0.67	0.75
11	Seebaechle	0	0	0	105193	-	-	-	-
12	**Unterbalbach**	62825	1854	973	39539	0.96	0.98	0.97	0.98
13	Doertel	41	34	13	105103	0.47	0.76	0.55	0.64
14	Lindelbach	2	22	6	105163	0.07	0.25	0.08	0.13
15	WeissacherTal	0	0	0	105193	-	-	-	-
16	Heinzental	140	72	88	104891	0.47	0.61	0.66	0.64
17	Hofwiesen	0	0	3	105188	0.00	0.00	-	0.00
18	Wustgraben	0	0	0	105192	-	-	-	-
19	Fischbach	30	43	125	104995	0.15	0.19	0.41	0.26
20	Huettenbuehl	416	329	188	104260	0.45	0.69	0.56	0.62
21	Kressbach	1205	669	388	102931	0.53	0.76	0.64	0.70
22	Michelbach	6	64	12	105111	0.07	0.33	0.09	0.14
23	Salinensee	0	0	0	105192	-	-	-	-
24	Duffernbach	0	0	0	105193	-	-	-	-
25	GoettelfingerTal	0	0	15	105178	0.00	0.00	-	0.00
26	**Mittelurbach**	646	339	118	104089	0.59	0.85	0.66	0.74
27	Wollenberg	15	38	2	105138	0.27	0.88	0.28	0.43
28	Hoelzern	0	0	0	105193	-	-	-	-
29	Lennach	0	0	0	105193	-	-	-	-
30	Nonnenbach	512	0	0	105193	1.00	1.00	1.00	1.00

thus have the greatest change in reservoir benefits—if this is the only (or the biggest) reservoir in this basin, this may make the reservoir critical for flood protection, and could potentially be deprioritized as a candidate for scope expansion on the basis of flood safety and reduced benefit. On the other hand, while most reservoirs with low HFM in their forecasts had little change in their benefit, others still had noticeable decreases in performance. This is primarily due to timing—a loss of water storage due to HFM before an incurrence of demand means that less demand can be fulfilled. Thus, although high HFM is generally indicative of frequent pre-release and therefore lowered benefit, low HFM does not necessarily mean high benefit, a finding that is consistent with Turner et al. (2017), who found that high forecast accuracy (i.e. low HF) had diminishing returns in reservoirs operated for water demand. Because the success of a reservoir is effectively decoupled from these quality metrics, investigations of a reservoir's potential should thus be conducted via simulations as outlined in this study and not estimated on the basis of forecast quality.

4.5 CONCLUSION

This study demonstrated that, with modified operating rules, small flood reservoirs can be converted to additionally provide streamflow or irrigation supplementation—even when operating under uncertain forecasts, and without compromising flood protection. This approach can also be applied to other regions to help water managers evaluate potential changes to their reservoirs as well. In particular, the three questions posed in the introduction can be answered as follows:

- Q1: For most reservoirs tested, the use of forecasts still resulted in tangible benefits for reservoirs optimized for streamflow or irrigation supplementation.
- Q2: Two common forecast metrics—critical success index (CSI) and F1 score—were shown to be less impactful for explaining drops in reservoir success than simple flood occurrence statistics (i.e. the ratio of hits, misses, and false alarms, HFM). Although high HFM was shown to noticeably change the benefits gained from a reservoir, low HFM is not a guarantee that benefits will remain unchanged. The timing of the floodflood events is also important.
- Q3: The operating rules that are most optimal are aggressive rules that mimic the rules found in Ho and Ehret (2025) and Ho et al. (2025)— rules that maximize water stored and that maximize how long the water is held. Current rules are, in contrast, those that minimize water storage and maximize the time the reservoir is empty.

The presented results can also be used to guide selection of future rulesets. Because the performance distributions of viable rulesets are rather discontinuous for some reservoirs, it is more advisable to optimize a reservoir individually using the developed toolbox than to attempt to pick a ruleset based on previous reservoirs. The computational resources consumed in this endeavor depends on the volume of forecasts available and the number of parameter sets tested. However, an optimal ruleset may ultimately be undesirable for other reasons—for example, if increased safety margins are desired to account for future river regime changes due to climate change, more conservative rulesets might be better. Understanding whether a ruleset is aggressive or conservative can guide the decision in the proper direction for its usage.

Ultimately, whether or not a small flood reservoir should be converted for either of these purposes is a subjective question. While this study attempts to solve for the water supply benefit part of this equation, other considerations (such as impacts to water quality and downstream ecosystems, cost, and necessary safety margins) must be taken into account when deciding on potential scope expansion of a reservoir. Indeed, research has suggested that a reservoir effect (i.e. dependability of water infrastructure drives increased demand, analogous to the levee effect in flood protection) may, in the long term, result in worsened water shortages in the future (Di Baldassarre et al., 2018). We hope, however, that the tools and results presented in this study enable water managers to initiate informed discussions about using their existing reservoirs to enhance water supply resilience.

Part V

CONCLUSIONS

5 CONCLUSIONS

5.1 SYNTHESIS

This dissertation built up a variety of models to represent the operation of repurposed flood reservoirs in perfect-knowledge conditions and under uncertain forecasts. With these, I demonstrated the potential water supply benefit of these reservoirs for two purposes: streamflow supplementation and irrigation demand.

In chapter 2, I measured the benefit to streamflow supplementation using a function to determine the value of the quantity and timing of water delivered by the modeled reservoirs in relation to low-flow conditions. The reservoirs stored water when water was plenty and released water such that the downstream conditions would meet or exceed the 70^{th} percentile exceedance flow, and emptied in time for a flood event. Thus, the answers to the questions posed in the introduction are as follows:

- Q2.1: Is the simultaneous operation of small reservoirs for both protection against streamflow drought conditions and against floods possible across a range of different reservoir sizes?
  - Yes, it is possible under the perfect-knowledge conditions tested in this chapter, though the benefits to streamflow drought conditions varied.
- Q2.2: Is there a relationship between characteristics of water availability and reservoir performance in reducing streamflow drought conditions?
  - There is no strong relationship between water availability and the ability to reduce streamflow drought conditions. This is primarily due to the timing of availability (high winter flows) not coinciding with the timing of highest need (critical low flows in the summer).

In chapter 3, I measured the benefit to irrigation demand by modelling the agricultural irrigation demand around each reservoir individually and determining how much of this demand the reservoirs could fulfill. Similar to chapter 2, the reservoirs stored water when water was plenty, but instead of releasing water, allowed withdrawals when irrigation demand occurred. This analysis focused on the years 2017-2020, which include the landmark 2018-2020 drought years that caused massive increases in agricultural irrigation demand in the region. The questions from the introduction can thus be answered:

- Q3.1: Can small flood reservoirs be repurposed via operation rules based on hedging rules to simultaneously provide water for irrigation while maintaining flood protection?
  - Yes, it is possible under the perfect-knowledge conditions tested in this chapter, though the benefits to irrigation varied.

- Q3.2: Could repurposed flood reservoirs in Baden-Württemberg have supplied the necessary irrigation demand in their local areas during the 2018-2020 drought without compromising flood protection?
  - Yes, these repurposed reservoirs could have provided significant water supply benefit to agriculture during the 2018-2020 drought years.
- Q3.3: Do reservoirs that potentially provide water supply benefit to agriculture also have the ability to benefit streamflow supplementation?
  - Though some reservoirs can provide significant benefit to both agriculture and streamflow supplementation, most reservoirs tested were suited to either one purpose or the other.

In chapter 4, I investigated the main assumption in the previous two chapters: the assumption of perfect-knowledge conditions. The models in this chapter make a decision based on the current inflow and the forecast available to them at each point in time. If a flood was occurring, flood operation took priority; else, the reservoir could either pre-release volume in anticipation of a flood in its forecast, store water when water was plenty and no flood was forecasted, release or allow withdrawal of water as needed, or simply pass water through. These allowed me to answer the questions from the introduction:

- Q4.1: Does the uncertainty introduced by using forecasts for decision-making significantly decrease the performance of repurposed small reservoirs' operation such that it is no longer beneficial?
  - For most reservoirs tested, the use of forecasts still resulted in tangible ($> 40\%$) benefits for reservoirs optimized for either use case.
- Q4.2: What is the relationship between forecast accuracy and decrease in optimal performance between the perfect-knowledge and forecasting operations?
  - Common forecast metrics were shown to be less impactful for explaining drops in reservoir success than simple flood occurrence statistics, but low flood occurrence alone was not a guarantee of high maintained performance– the timing of the flood events could drain reservoirs before critical drought conditions.
- Q4.3: What operating rules are most likely to be optimal, and how do these differ from current operation rules?
  - The most successful operating rules were rules that stored aggressively and held onto the water for as long as possible, mimicking the rules under the perfect-knowledge scenarios developed under the two previous chapters. In contrast, current rules are overly aggressive and seek to relinquish volume as soon as possible.

5.2 CONCLUSION

The core question of this dissertation is the potential water supply benefits of repurposing (global-scale) small flood reservoirs for drought protection in a temperate region. I selected 30 small-to-medium-sized (on the global scale) reservoirs in Baden-Württemberg, Germany, based on various use, size (subdivided by German standards into small, mid-size, and large based on total volume), and water availability metrics and modeled their operation under various conditions. Through the perfect-knowledge benchmark cases, I demonstrated that the benefit ceiling is quite high– several of these reservoirs could fulfill almost all of the water needed for both uses– though a few reservoirs were entirely unsuitable. The benefit ceiling remained high even when operating under forecasts, as many reservoirs maintained high performance metrics on a level similar to their perfect-knowledge situations. The performance decay between perfect-knowledge and forecasted conditions were shown to be less related to forecast accuracy metrics and more to flood incidence. In other words, the number of floods forecasted were more impactful than the accuracy or quality of the forecast. Though the incorporation of forecasts required a change to the operating rules in order to incorporate safety margins, the optimal rules under forecasting still approximated the optimal operating rules under perfect knowledge. Ultimately, many reservoirs are still able to provide modest benefits for both streamflow supplementation and agricultural demand.

I was unable to identify if there are any indicators that can easily filter out unsuitable reservoirs or identify especially suitable reservoirs. The first attempt was based on the water availability– however, the number of times (on average) that the reservoir could be refilled in a year was ultimately not descriptive in describing the benefit to streamflow, due primarily to the timing of water availability not aligning with the timing of need. The performance for streamflow benefit was similarly nondescriptive in identifying reservoirs with high benefit for agriculture, as the timing of both demands (the year-round demand of streamflow versus the summer-dominant demand of agriculture) ultimately do not align. Even high performance in perfect knowledge conditions, combined with high forecast accuracy metrics and low flood incidence, could not reliably indicate high performance under forecasts.

However, a few general statements can be made when looking at different size and use characteristics. For example, small reservoirs under forecasting generally did not perform well– while a couple did perform well in perfect-knowledge conditions, the performance decay from forecasts reduced the benefits for almost all small reservoirs in both use cases (with one exception) to under 40%. Mid-size multipurpose (with one exception) and large flood-only reservoirs, on the other hand, were all quite successful for agricultural benefit, even under forecasts. Though one could certainly argue based on the results that "small reservoirs are not particularly effective", the sample size of this study is too small to be universally conclusive. Further studies are needed to expand this sample size. Therefore, no conclusive generalization such as "larger is always better" or "multipurpose is always better" can be made.

Thus, when investigating reservoirs for potential conversion to additionally provide drought protection, each reservoir should be modeled and analyzed individually. This is possible using the models produced in the course of this dissertation. These require, at minimum, basic operating rules of the reservoir (flooding limit and operating capacity) and an inflow time series to the reservoir (which can be either modeled or historical) for the streamflow application. Additional weather data (precipitation, evapotranspiration, wind speed, air temperature, and humidity), crop coverage and FAO-56 parameters, and soil types and parameters are necessary for the irrigation use case, the vast majority of which can be obtained using remote sensing data. Inflow forecasts, which are likely the most difficult data to obtain for a small reservoir, are only necessary for the forecasting model. While the difficulty of obtaining the necessary data can vary, the operation of the models themselves are computationally inexpensive and quite general, lending them to easy adaptation in different regions around the world.

This dissertation ultimately only answers one part of the question, ”Should we convert flood reservoirs into multipurpose reservoirs?”– namely, the water supply benefit. A holistic cost-benefit analysis of this question needs to also consider the potential costs: in the introduction, I discussed various issues with reservoirs. These include issues of water quality, the ”reservoir effect” of increasing reliance on the additional water supply from reservoirs potentially increasing future damages from drought, and the ecological consequences of interruptions to the river's regime. My work, which was focused on deducing the water supply benefits of these reservoirs, does not address these issues, as these are quite nuanced topics that are extremely context dependent. Some issues may be legally mandated, and some costs will be subjective. These are nevertheless important issues that will require more studies. Moreover, the destabilizing effect of climate change may change the potential benefits of these reservoirs in the future. This can, of course, be a change that disrupts the water availability at critical times or increases flooding risk (thus decreasing the potential benefits of a repurposed reservoir) or a change that further necessitates adaptation.

One drought-related hazard projected to increase under climate change, including in Europe, is flash drought (Christian et al., 2023; Shah et al., 2023). In contrast to ”normal” droughts, which accumulates water deficits slowly over months, flash drought is characterized by a short period (typically two weeks to a month, but depending on the study, up to two months) from onset to maximum intensity of water deficit, which can be missed in the coarser scale of seasonal climate forecasts or drought monitors (Alencar and Paton, 2022; Christian et al., 2024; Lisonbee et al., 2021; Pendergrass et al., 2020). The effects of this on agriculture and vegetation can be quite stark (Lovino et al., 2024; Otkin et al., 2016). While recent research indicates that agriculture in humid regions is less affected than in arid regions, particularly under the influence of sufficient water availability (Ho et al., 2023; O and Park, 2023), the rapid onset may make organizing a centralized response to such a hazard difficult, particularly if the size of the affected area is quite large. Research has additionally indicated that flash drought can also result in rapid decreases in streamflow (Bakar et al., 2025; Singh and Mishra, 2024a). Fortunately, dams and reservoirs have been shown to have an attenuating influence on streamflow flash drought (Singh and Mishra, 2024b). The decentralized nature of the repurposed small flood reservoirs could thus prove a boon for both agricultural and streamflow flash drought response, offering an exciting direction for future research in this topic.

Ultimately, my hope for this work is that people will use the tools I have built to begin informed conversations about water supply resilience in a warming world.

Part VI

APPENDIX

APPENDIX TO CHAPTER II

A.1 AF ACROSS DIFFERENT CATEGORIES

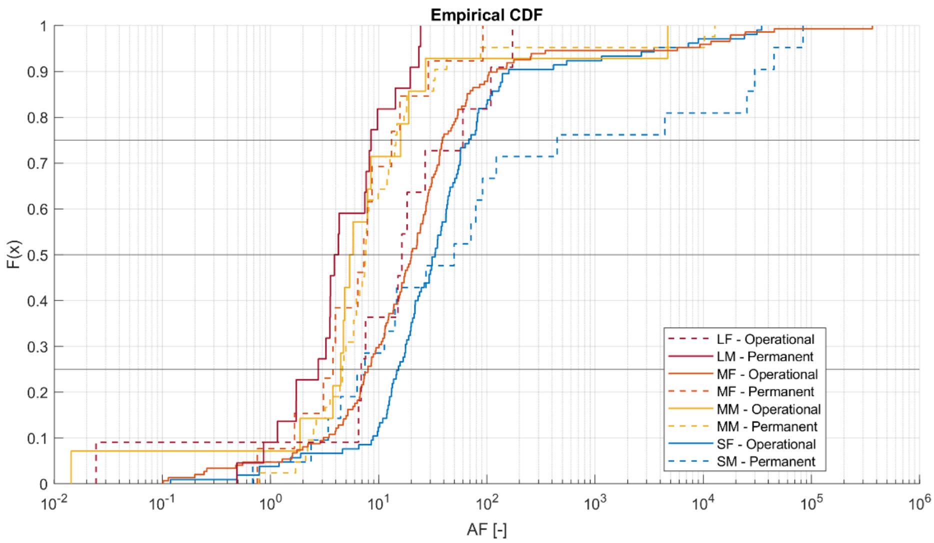

Figure A.1: Empirical CDF plots of AF for all reservoirs in the selected categories (see Table 2.1), estimated using local statistics. Reservoirs were selected based on their estimated AF, usually at the 25th, 50th, and 75th percentiles (and including the 87th and 12th percentiles if possible), to cover a broad range of water availability within a category.

A.2 OPTIMAL Q_R

		Qcrit	Max(Q70)	Min(Q70)	Optimal Qr
Name	**Category**	**[m3/s]**	**[m3/s]**	**[m3/s]**	**[m3/s]**
Bernau	LF	22.000	1.01	0.32	1.43
Gottswald	LF	75.000	20.62	4.93	36.81
Mittleres Kinzigtal	LF	830.000	16.99	3.81	33.85
Wolterdingen	LF	860.000	4.60	1.34	6.01
Federbach	LM	0.400	0.09	0.01	0.10
Fetzachmoos	LM	15.000	1.52	0.61	1.79
Nagoldtalsperre	LM	7.000	0.86	0.23	1.15
Rehnenmuehle	LM	15.000	0.52	0.05	0.65
Schwaigern	MF	0.790	0.13	0.02	0.20
Seckach	MF	0.500	0.75	0.26	1.74
Seebaechle	MF	2.410	0.01	0.01	0.02
Unterbalbach	MF	3.320	0.16	0.07	0.28
Doertel	MF	50.300	0.06	0.01	0.07
Lindelbach	MF	0.100	0.01	0.00	0.02
Weissacher Tal	MF	6.330	0.07	0.02	0.12
Heinzental	MM	3.700	0.06	0.02	0.08
Hofwiesen	MM	4.000	0.17	0.02	0.38
Wustgraben	MM	0.700	0.05	0.02	0.06
Fischbach	MM	1.000	0.10	0.03	0.17
Huettenbuehl	MM	3.600	0.23	0.04	0.30
Kressbach	MM	1.090	0.05	0.02	0.06
Michelbach	MM	10.680	0.04	0.01	0.06
Salinensee	MM	0.500	0.07	0.01	0.14
Duffernbach	SF	1.550	0.03	0.00	0.06
Goettelfinger Tal	SF	4.100	0.15	0.02	0.23
Mittelurbach	SF	0.500	0.09	0.06	0.10
Wollenberg	SF	3.370	0.06	0.02	0.13
Hoelzern	SM	1.500	0.00	0.00	0.03
Lennach	SM	2.100	0.00	0.00	0.05
Nonnenbach	SM	0.170	0.03	0.01	0.03

Table A.1: Flooding thresholds (Q_{crit}), maximum and minimum drought thresholds (Q_{70}), and optimal retention flow (Q_r) for each of the 30 reservoirs.

B

APPENDIX TO CHAPTER III

B.1 POTENTIAL EVAPORATION LOSSES FROM THE RESERVOIRS

The difference between the sum of precipitation during the observation period ($\Sigma P_{2017\text{-}2020}$) and the sum of FAO-56 reference evapotranspiration ($\Sigma ET_{0,2017\text{-}2020}$) was calculated for each reservoir (Figure B.1). Overall, potential evaporative losses to the reservoir are mostly (if not entirely) offset by gains due to precipitation. The highest rate of net loss to any reservoir is 151 mm per year—although this is non-negligible, it is also non-dominant and is thus excluded from this study.

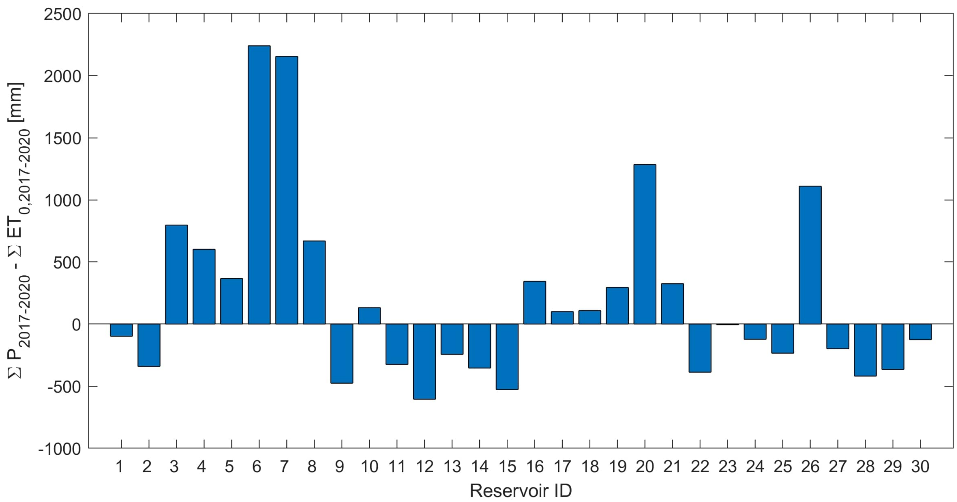

Figure B.1: The climatic water balance at each reservoir during the observation period.

B.2 COMPARISONS OF FLOOD PRE-RELEASE VOLUMES

The total volume of water lost to flood protection (pre-flood release volume) for each reservoir in this study is compared to that of Ho and Ehret (2025) (Figure B.2). Fewer reservoirs needed to pre-release for floods in this study, due primarily to the shorter observation period in this study. Reservoirs that experienced flood events (i.e. needed to pre-release flood volume) but still had a $B_{ID} > 70\%$ are 6, 7, 8, 13, 16, 17, 18, 19, 20, 21, and 26.

B.3 CLIMATIC ADJUSTMENTS FOR THE FAO-56 METHOD

The FAO-56 dual crop method requires climate adjustments to $K_{cb,mid}$ for growing seasons where the average wind speed at 2 meters is much higher or much lower than

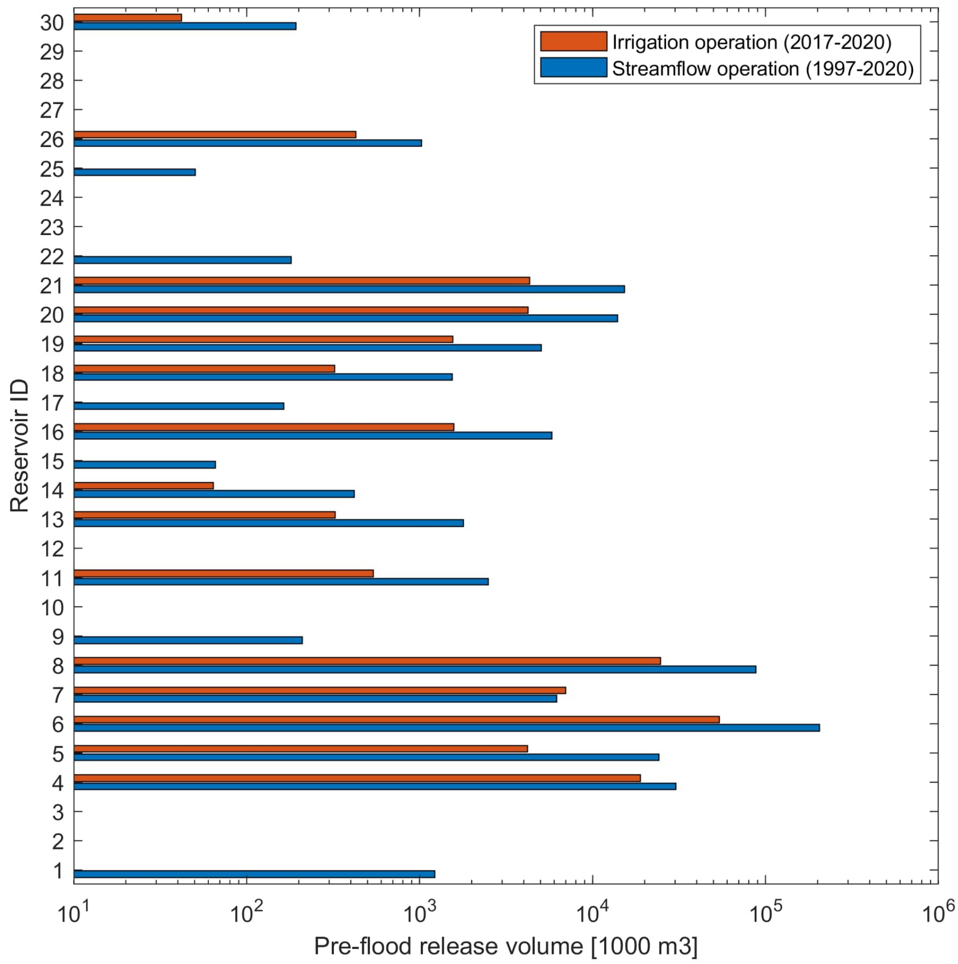

Figure B.2: Pre-flood release volumes under irrigation and streamflow operation for each reservoir. Note the logarithmic scaling.

2 meters per second and/or where the average minimum relative humidity is much higher or much lower than 45%:

$$K_{cb,mid,adj} = K_{cb,mid} + [0.04 \times (u_{2,avg} - 2) - 0.004 \times (RH_{min,avg} - 45)] \times (\frac{h_{max}}{3})^{0.3} \quad \text{(B.1)}$$

where $K_{cb,mid}$ is the mid-season basal crop coefficient (dimensionless), $u_{2,avg}$ is the mean wind speed at 2 meter height over the mid- and late-season growing stages (m/s), and $RH_{min,avg}$ is the mean of the minimum relative humidity over the mid- and late-season growing stages (%). If $RH_{min,avg} > 45\%$, an additional correction to $K_{cb,end}$ is also required:

$$K_{cb,end,adj} = K_{cb,end} + [0.04 \times (u_{2,avg} - 2) - 0.004 \times (RH_{min,avg} - 45)] \times (\frac{h_{max}}{3})^{0.3} \quad \text{(B.2)}$$

These climate adjustments were checked for and applied to every region for every year.

B.4 THE DAILY SOIL MOISTURE BALANCE OF THE FAO-56 METHOD

The daily surface soil moisture on day j, controlled by plant transpiration and soil evaporation in tandem, is governed by the following equation

$$D_{e,j} = D_{e,j-1} - \left(P_j - RO_j\right) - \frac{I_j}{f_w} + \frac{E_j}{f_{ew}} + T_{ei,j} + DP_{ei,j} \tag{B.3}$$

where
D_e is the cumulative depletion depth in the soil surface (mm),
P is the precipitation depth (mm),
RO is the runoff depth (mm),
I is the irrigation depth (mm),
f_w is the wetted fraction of the soil (dimensionless),
E is the soil evaporation depth (mm),
f_{ew} is the exposed wetted fraction of the soil (dimensionless),
T_{ei} is the plant transpiration depth (mm), and
DP_{ei} is the deep percolation depth from the evaporating layer (mm).

We use a maximum rain infiltration rate of 30 mm/day, as suggested by Smith (1992) as a default value in CROPWAT, to estimate runoff depth. We thus assume that any precipitation below 30 mm/day is used to directly replenish the surface soil moisture and bring the depletion depth to 0. For further information on solving the soil moisture balance, we refer the reader to the original papers (Allen et al., 1998; Allen et al., 2005).

The root zone depletion is dominated by plant transpiration and drives the calculation of water stress and irrigation demand. Water stress conditions ($K_s < 1$) begin when all readily available water (RAW) in the root zone—which is a function of plant rooting depth and available water content—has been depleted (i.e., depletion depth is greater than the RAW). The root zone soil moisture follows a separate soil moisture balance:

$$D_{r,j} = D_{r,j-1} - \left(P_j - RO_j\right) - I_j + CR_j + ET_{c,j} + DP_j \tag{B.4}$$

where
D_r is the cumulative depletion depth in the root zone (mm),
P is the precipitation depth (mm),
RO is the runoff depth (mm),
I is the net irrigation depth over the wetted surface (mm),
CR is the capillary rise from the water table (assumed to be zero in this study as the water table is more than 2 m below the soil surface for all reservoirs) (mm),
ET_c is the crop evapotranspiration (calculated based on the soil surface layer) (mm), and
DP_i is the deep percolation depth from the root zone (mm).

C

APPENDIX TO CHAPTER IV

C.1 HEATMAPS OF BENEFIT

Heatmaps of the average benefit, where the color indicates the average benefit of the parameter combination across all reservoirs, reveal that aggressive parameter sets are higher-performing (Figures C.1, C.2). Given that they are more frequently optimal, this should not be surprising; however, these plots indicate that a variety of parameter combinations can yield similar benefits.

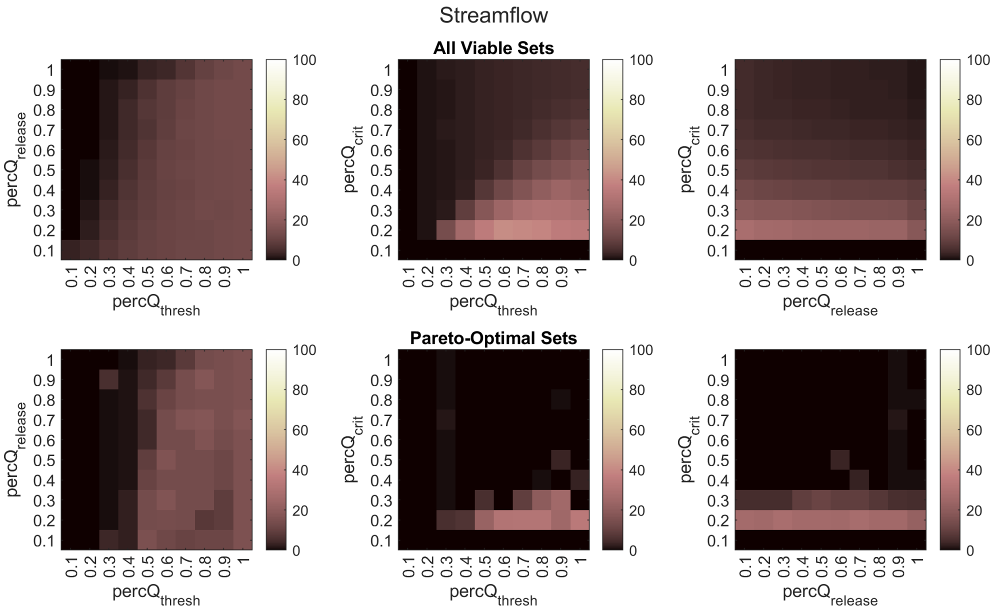

Figure C.1: Average benefit for each pair of parameters in the streamflow use case.

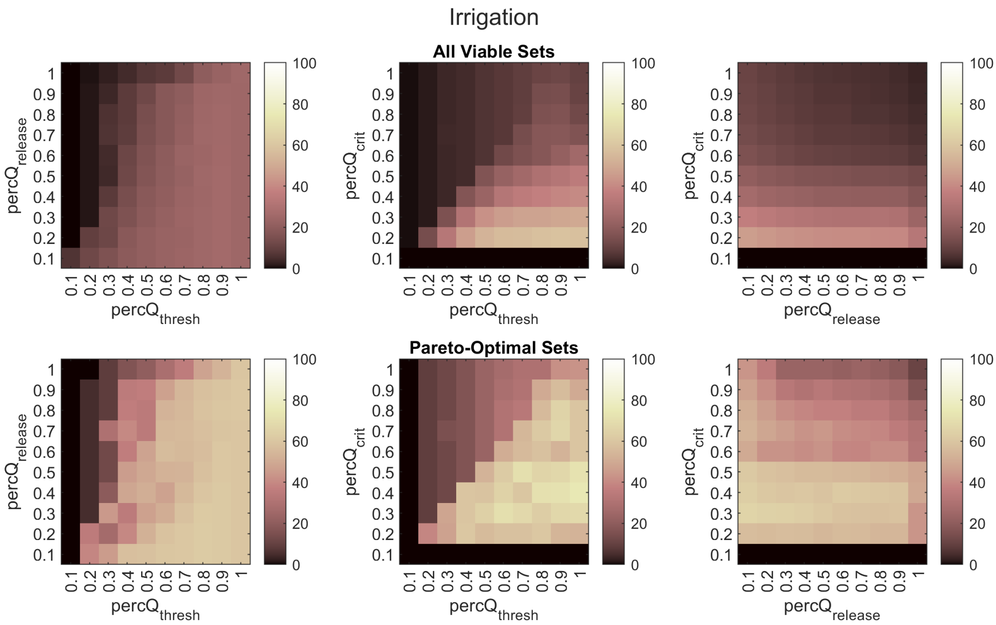

Figure C.2: Average benefit for each pair of parameters in the irrigation use case.

AUTHOR CONTRIBUTIONS AND CODE AVAILABILITY

Chapter 2:

Ho, S. Q.-G., & Ehret, U. (2025). Is drought protection possible without compromising flood protection? Estimating the potential dual-use benefit of small flood reservoirs in Southern Germany. *Hydrological and Earth System Sciences, 29*(13), 2785-2810. doi:10.5194/hess-29-2785-2025

Sarah Quynh-Giang Ho (SQH) and Uwe Ehret (UE) conceived and designed the methodology and reservoir models, which was coded, implemented, and executed by SQH. Data analysis was performed primarily by SQH, with input and guidance from UE. SQH wrote the initial draft of the paper. UE supervised the research and contributed to the improvement of the paper.

The map in Figure 2.1 was created using ArcGIS® software by Esri with map data from OpenStreetMap (openstreetmap.org/copyright). ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. All the relevant data for the reservoir models (semi-natural inflow results from LARSIM, Q_{70} target time series, reservoir parameters, and outflow time series), as well as the developed code to run / optimize the reservoir models, are available through doi:10.5281/zenodo.12724797.

Chapter 3:

Ho, S. Q.-G., Bernhardt, J. J., Stahl, K., and Ehret, U. (2025). Fielding floods for flourishing farms: a framework for assessing the reuse of small flood reservoirs as irrigation reservoirs. *Under review.* 10.22541/essoar.175260001.13781003/v1.

SQH conceived and designed the methodology with input and support from Jacob Jeff Bernhardt (JJB), Kerstin Stahl (KS), and UE. The reservoir models were coded, implemented, and analyzed by SQH with input and guidance from KS and UE. SQH wrote the initial draft of the paper with contributions from JJB. All authors contributed to the improvement of the paper.

Table 3.1 is adapted from Ho and Ehret (2025) with permission under CC BY 4.0. The data for Figure 3.2 was taken from Bernhardt and Neuenfeldt (2024) with permission under CC BY 4.0. The scripts and processed weather data from the German Weather Service (DWD, 2022, 2023, 2024a,b,c,d), crop maps from Blickensdörfer et al. (2022) (Schwieder et al., 2024), and soil map (Düwel et al., 2007) for the irrigation demand calculations, as well as the scripts and reservoir data (including inflows) for the reservoir operation model, are available at doi:10.5281/zenodo.15705912 under CC BY 4.0.

Chapter 4:

Ho, S. Q.-G., Lang, R., and Ehret, U. (2025). Forecast-based operation of re-purposed small reservoirs for floods, farms, and (low) flows. *Under review.*

SQH and UE conceived and designed the methodology and reservoir models, which was coded, implemented, and executed by SQH. SQH wrote the initial draft of the paper with assistance from Robert Lang (RL). RL produced the forecast data for the analysis and contributed to the improvement of the paper. Data analysis was performed by SQH, with input and guidance from UE. UE supervised the research and contributed to the improvement of the paper.

The data and MATLAB scripts developed to run these models—along with a detailed documentation package—can be downloaded at doi:10.5281/zenodo.17183389.

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 *Fielding Floods for Farms and (Low) Flows* 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 übernommene Inhalte als solche kenntlich gemacht.
3. Die Arbeit oder Teile davon habe ich bislang nicht an einer Hochschule des In- oder Auslands als Bestandteil einer Prüfungs- oder Qualifikationsleistung vorgelegt.
4. Die Richtigkeit der vorstehenden Erklärungen bestätige ich.
5. Die Bedeutung der eidesstattlichen Versicherung und die straf-rechtlichen 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, 2026

Sarah Quỳnh-Giang Ho

SCIENTIFIC CONTRIBUTIONS

FIRST AUTHOR; PEER-REVIEWED INTERNATIONAL PUBLICATIONS

Ho, S. Q.-G., Tian, L., Disse, M., & Tuo, Y. (2021). A new approach to quantify propagation time from meteorological to hydrological drought. *Journal of Hydrology*, *603*, 127056. https://doi.org/10.1016/j.jhydrol.2021.127056

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Bosse, R. (2022). *Nutzungserweiterung von Hochwasser-Stauanlagen für den Schutz vor Wassermangel: Untersuchung zur Wirksamkeit und notwendiger baulicher Anpassungen am Beispiel des Lein-Einzugsgebiets.* (M.Sc.). Karlsruhe Institute of Technology, Karlsruhe.

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