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Fielding Floods for Flourishing Farms: A Framework for Assessing the Reuse of Small Flood Reservoirs as Irrigation Reservoirs

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Key Points:

- We propose a framework for assessing the potential water supply benefit of a repurposed small flood reservoir for agricultural irrigation
- Most small reservoirs would have been able to satisfy 70% or more of the irrigation demand in their area during the drought years without compromising flood protection
- The potential water supply benefit for agriculture provided by each reservoir is compared to its benefit for streamflow supplementation, indicating that some reservoirs can be useful for both

Supporting Information:

Supporting Information may be found in the online version of this article.

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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 km^2 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.

Plain Language Summary Because droughts are likely to become more common and intense as a result of climate change, new solutions for ensuring water availability—especially for farming—are necessary. Small reservoirs have been built all over the world for this purpose, but not much research exists on how they are actually operated. We model the operation of small reservoirs, which are currently flood protection reservoirs, for storing water for farms. The success of this operation is judged based on the ability of these reservoirs to provide needed water. Our models show that many of the reservoirs could supply the majority of the water that farms needed during the historic 2018–2020 drought in the southwestern German state of Baden-Württemberg, as well as for increasing water levels in the river, which means they could also be useful in future droughts as well.

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; Şen, 2021; Wisser et al., 2010). These are reservoirs typically defined as having a dam height of ≤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 & Krishnan, 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 km^3 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

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(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 catalog 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; J. Chang et al., 2019; T. J. Chang et al., 1995; Consoli et al., 2007; Ding et al., 2017; Draper & 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 & Lund, 2004; Zhao et al., 2014). The ability of such reservoirs and rulesets to enhance low flows and therefore reduce drought conditions has been demonstrated by many studies (J. Chang et al., 2019; Huang & Chou, 2005; Karamouz & Araghinejad, 2008; Padiyedath Gopalan et al., 2020; Shih & ReVelle, 1994, 1995; Singh & Mishra, 2024; You & Cai, 2008a, 2008b). 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 (L.F. U. Baden-Württemberg, 2019b, 2020, 2021; Erfurt et al., 2020; Tijdeman et al., 2022), and has been proposed and used as a benchmark event for drought studies in the region as its severity and duration were unprecedented, and may become more frequent in the future (Buras et al., 2020; Madruga de Brito et al., 2020; Rakovec et al., 2022; Shyrokaya et al., 2024). A multidisciplinary drought catalog for the region suggests that such an extended period of extreme drought conditions with such observable impacts (particularly for agriculture) has not occurred since the 1990's (Erfurt et al., 2020), for which few reliable spatial records of crop cover and irrigation exist. During the 2018–2020 years, 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; Ministerium für Umwelt, 2022b). The threat of further water stress has prompted many local governments in Germany, such as Baden-Württemberg, to begin strategic planning for water scarcity (A. N. Baden-Württemberg, 2021; Bundesamt, 2021; Ministerium für Umwelt, 2022b; Stölzle et al., 2018), 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 (L. F. U. 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,

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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 & Ehret, 2025b), 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 worst-case benchmark scenario to investigate the potential water supply benefit in an extreme event. 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 re-contextualize the results by comparing them to the results for streamflow benefit found in Ho and Ehret (2025b).

2. Methods

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 sizable 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 (Ministerium für 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 & Ehret, 2025b). The curious reader may refer to this work for detailed discussion on the reservoir selection process. This subset of reservoirs covers a variety of different catchments (some heavily forested, some heavily farmed, and some closer to urban areas) to assess a wide range of possible responses to this benchmark drought event, as the intensity of drought conditions was not uniform throughout the state. AID fulfillment was calculated for each of the 30 selected reservoirs listed in Table 1 and shown in Figure 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 additional uses for these reservoirs are primarily as ecological protection (fish and bird habitats) and recreation sites and currently have the same operating rules as flood-only reservoirs.

The modeled operation of the reservoirs is done for a single reservoir; that is, we are only considering the potential of individual reservoirs and not a system (because the vast majority of reservoirs in the region are not actively operated, downstream storage and release decisions are not affected). 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

Table 1
The 30 Reservoirs From Ho and Ehret (2025b), Along With Their Operating Parameters (Operating Capacity, Flooding Limit Q_{crit} and Retention Limit Q_r), Investigated in This Study

Category	Inundation type	Name	ID number	Operating capacity (m^3)	Q_{crit} (m^{3}s^{-1})	Q_r (m^{3}s^{-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

Note. ID numbers have been added for clarity.

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.

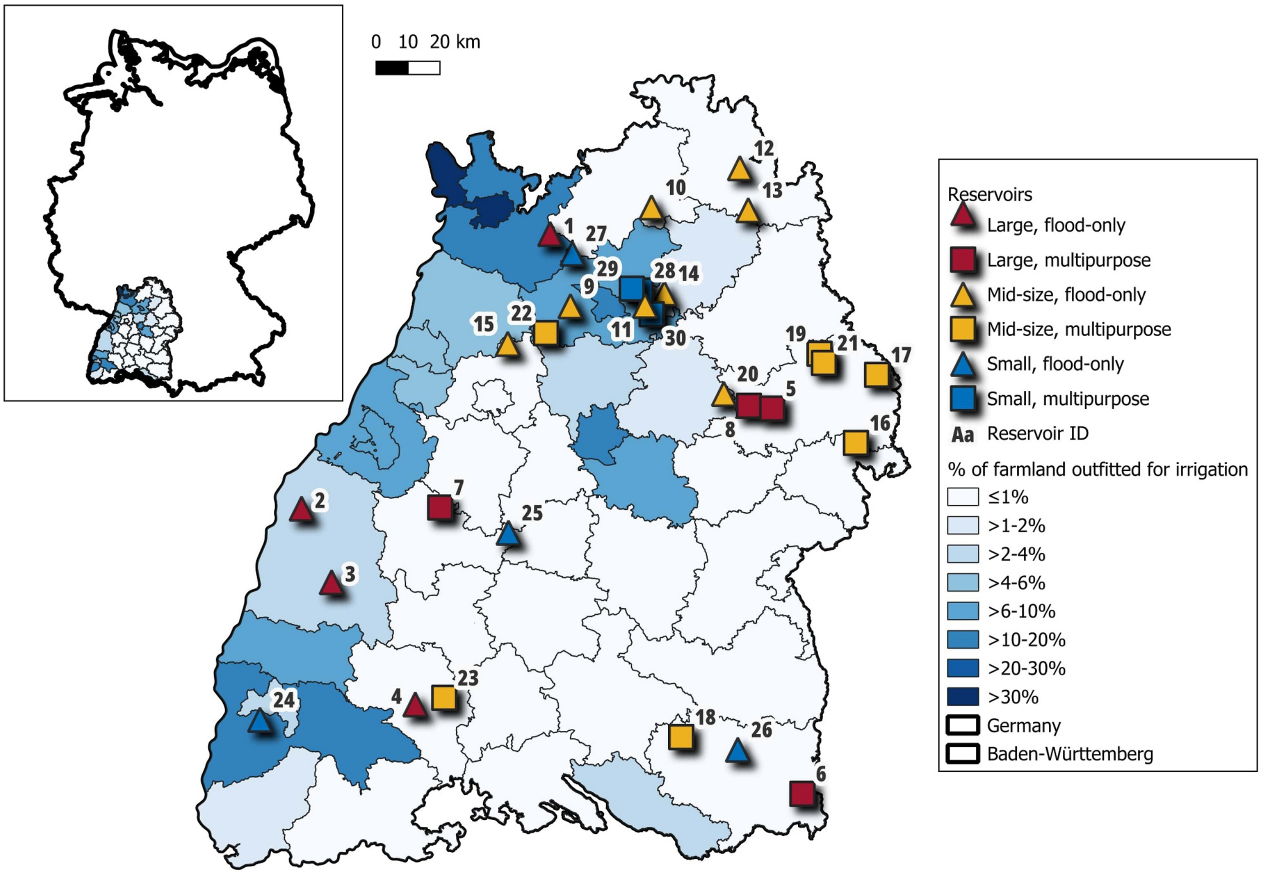

Figure 1. Proportion of farmland equipped for irrigation in Baden-Württemberg, aggregated by NUTS3 region (Bernhardt & Neuenfeldt, 2024), and the locations of the 30 reservoirs investigated in this study, labeled according to their ID number in Table 1.

2.2. Data

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 2.

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 to 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 × 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

Table 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

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 data set (Van Tricht et al., 2023) and the European EuroCrop data set (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. 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, Paredes, Hunsaker, López-Urrea, & Mohammadi Shad, 2021; Pereira, Paredes, López-Urrea, et al., 2021; 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, Paredes, Hunsaker, López-Urrea, & Mohammadi Shad, 2021; Pereira, Paredes, López-Urrea, et al., 2021; 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).

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 × 1 km resolution (DWD, 2022, 2023, 2024a, 2024b, 2024c, 2024d) and extracted at the location of the reservoir as the weather data for the 5 km^2 region.

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

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{1}$$

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:

Table 3

The Crop Types From Blickensdörfer et al. (2022) Used in This Study and Their FAO-56 Parameters (Collected From Allen et al. (1998), Pereira, Paredes, Hunsaker, López-Urrea, and Mohammadi Shad (2021), Pereira, Paredes, López-Urrea, et al. (2021), Rallo et al. (2021), and Drastig et al. (2021)) Used to Calculate Irrigation Demand

		L ini	L dev	L mid	L late	K_{cb} ini	K_{cb} mid	K_{cb} end	Zr max	h max	p
Crop	Planting date	(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-April	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-September	0	220	40	30	0.15	0.95	1.10	1.50	1.50	0.60
Fruits and Vegetables											
Orchard	15-March	20	70	90	30	0.75	1.15	0.80	2.00	4.00	0.50
Potato	15-April	30	35	50	30	0.15	1.10	0.35	0.60	0.60	0.40
Vegetables (asparagus)	15-February	50	30	100	50	0.15	0.90	0.20	1.80	0.80	0.45
Grains											
Maize	15-April	30	40	50	50	0.15	1.15	0.85	1.50	3.50	0.50
Spring barley	15-April	40	30	40	20	0.15	1.00	0.20	1.20	0.90	0.55
Spring oat	15-April	40	30	40	20	0.15	1.00	0.20	1.50	1.10	0.55
Winter barley	15-November	40	60	60	40	0.15	1.00	0.20	1.20	0.90	0.55
Winter rye	15-November	40	60	60	40	0.15	0.95	0.30	1.20	0.90	0.55
Winter wheat	15-November	40	60	60	40	0.15	1.00	0.20	1.50	1.10	0.55
Vine crops											
Grapevine	15-April	30	60	40	80	0.30	0.65	0.40	2.00	2.00	0.45
Hops	15-April	25	40	80	10	0.30	0.95	0.80	1.20	5.00	0.50

Note. 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.

$$\mathrm{RH}_{\min} = 100 \times \frac{e^0(T_{\min})}{e^0(T_{\max})} \tag{2}$$

where e^0 is the saturation vapor pressure at a given temperature T (degrees Celsius) and $\mathrm{RH}_{\min}$ is the minimum relative humidity (%). Mean relative humidity data from 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.

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 m) 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 data set 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 to 0.2; severe drought conditions from 0.05 to 0.1; extreme drought conditions from 0.025 to 0.05; and exceptional drought conditions from 0 to 0.025.

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 & Bremicker, 2006) provided by the State Agency for the Environment of Baden-Württemberg (Landesanstalt für Umwelt Baden-Württemberg, LUBW) that is in daily use for the state's flood warning system. 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 (L. F. U. Baden-Württemberg, 2024): 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 km^2 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 modeling 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 km^2 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 (L. F. U. Baden-Württemberg, 2022).

2.3. Calculating Agricultural Irrigation Demand (AID) of a Reservoir

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) and soil type (Table 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.

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):

$$ET_c = K_c ET_0 \tag{3}$$

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, Paredes, Hunsaker, López-Urrea, & Jovanovic, 2021). 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 Text S1 in Supporting Information S1), multiplied by a water stress coefficient (K_s), and the soil evaporation coefficient (K_e):

$$K_{c,act} = K_s K_{cb} + K_e \tag{4}$$

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 Text S2 in Supporting Information S1.

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:

$$I_{j+1} = \frac{D_{r,j}}{f_w} \text{ for } D_{r,j} > \text{RAW} \tag{5}$$

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

1. this planting date is an average date, meaning that there are fields planted before and after this date; and that
2. 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

$$\text{AID}_j = \sum_{\text{ARU}=1}^{n} \left(I_{\text{ARU},j} \times \text{Area}_{\text{ARU}}\right) \tag{6}$$

where $I_{\text{ARU},j}$ 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.

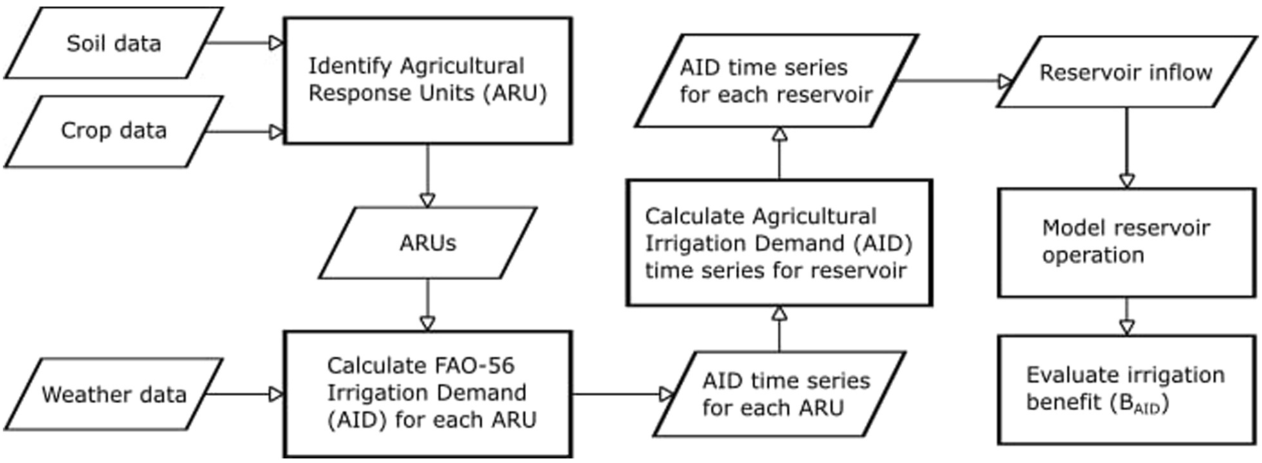

Figure 2. An overview of the components needed for the reservoir operation model.

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 2). The reservoir operation model takes as inputs the inflow to the reservoir and the AID for its region and produces time series of volume within the reservoir, outflow from the reservoir into the river, and withdrawals from the reservoir for irrigation demand. 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 non-dominant enough to justify exclusion (Appendix A).

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

1. The reservoir impounds floods per its design—that is, 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 (2025b)) 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 (2025b) 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., $Q_{in} = \mathrm{Q}_{out}$).
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 a.m. 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.

2.5. Metrics for Comparison

For each reservoir and year, statistics for each crop type in Table 3 are compiled. The planted area of a crop type ($A_{\text{crop type}}$) around a reservoir in year k is the sum of all ARU areas covered by the m unique crops in that typing:

$$\text{Area}_{\text{crop type},k} = \sum\nolimits_{1}^{m} \text{Area}_{\text{ARU,crop}} \tag{7}$$

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:

$$\text{AID}_{\text{crop type},k} = \sum\nolimits_{1}^{m} \text{AID}_{\text{ARU,crop}} \tag{8}$$

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

$$B_{\text{AID}} = 100 \times \frac{\sum \text{AID}_{\text{fulfilled}}}{\sum \text{AID}_{\text{total}}} \tag{9}$$

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 (2025b). 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

$$P_{d,t} = -\frac{1}{\sqrt{Q_{\text{out},t}}} + \frac{1}{\sqrt{Q_{70,t}}}, Q_{\text{out},t} < Q_{70,t} \tag{10}$$

where $P_{d,t}$ is the penalty for drought at time t, $Q_{\text{out},t}$ is the outflow from the reservoir (including whatever water can be supplemented from the reservoir) at time t, and $Q_{70,\text{t}}$ is the 70th 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 $Q_{70,\text{t}}$ can be found in Ho and Ehret (2025b).

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:

$$B_p = 100 \times \frac{\sum P_{d,\text{flood-only}} - \sum P_{d,\text{combined operation}}}{\sum P_{d,\text{flood-only}}} \tag{11}$$

The B_p used in this study is calculated using the streamflow supplementation operation results from Ho and Ehret (2025b) during the observation period (2017–2020); that is, 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. Results

3.1. Agricultural Irrigation Demand

There is diversity in how much $\text{Area}_{\text{crop type}}$ (grains, field crops, fruits and vegetables, and vine crops) is planted around each reservoir, resulting in variable AID (Figure 3). Although most areas are dominated by grains, some reservoirs (such as Duffernbach and Lennach) have large areas of vine crops. The amount of $\text{Area}_{\text{crop type}}$, however, does not necessarily indicate a higher $\text{AID}_{\text{crop type}}$, as different crops (and therefore crop types) are more water-intensive than others: the average $\text{AID}_{\text{crop type}}$ per $\text{Area}_{\text{crop type}}$ (i.e., the slope of the best-fit line) varies between crop types, resulting in a nonlinear relationship between Area_{all} and AID_{all} (Figure 3c). Fruits and

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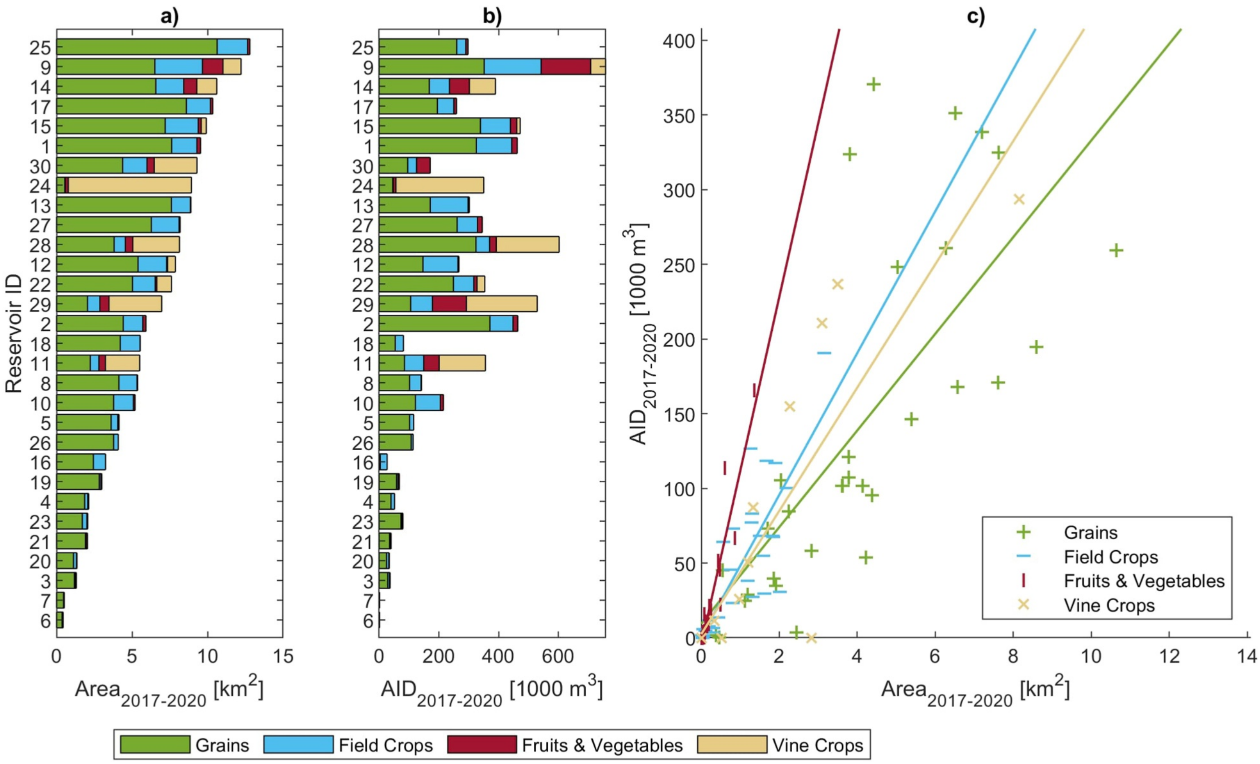

Figure 3. Statistics for each reservoir's Area (in km^2; a) and AID (in 1,000 m^3; b) for each crop type, sorted in descending order of total planted area; and the AID$_{\text{crop type}}$ plotted against the Area$_{\text{crop type}}$. The unique crops in each type are shown in Table 3.

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 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 generally coincides with periods when the percentile-based Soil Moisture Index (SMI) at the reservoirs' locations falls below the moderate drought threshold during the growing season (Figure 5). The stronger peaks of AID in 2018, 2019, and 2020 follow when the average SMI across the reservoirs' locations drops at least two categories within two months, signaling 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.

3.2. Operation for Irrigation Demand

The operation of the reservoir Doertel (Figure 6) illustrates the operating rules outlined in Section 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

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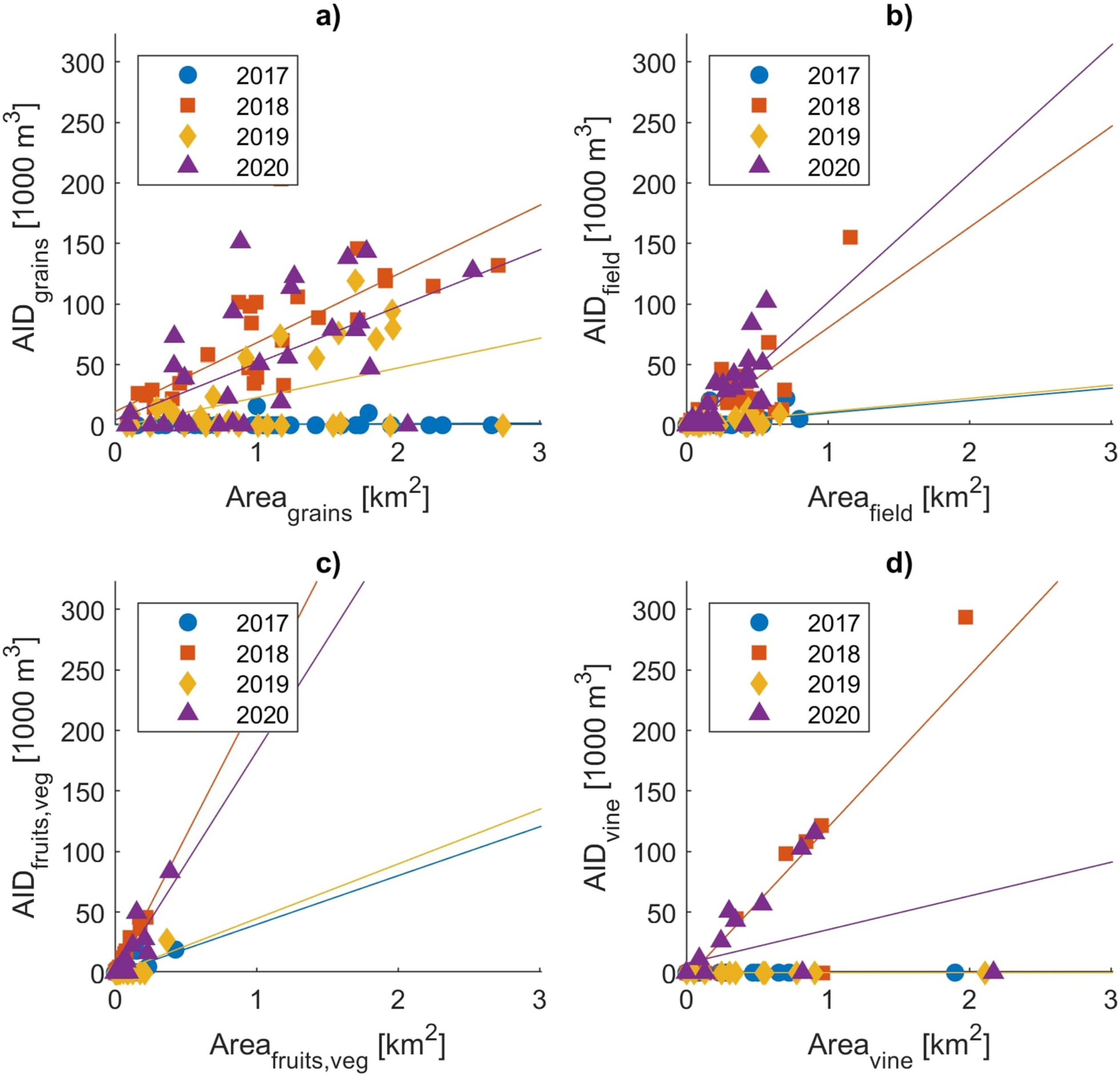

Figure 4. Comparisons of AID_{type} over $Area_{type}$ for the four different crop types, grains (a), field crops (b), fruits and vegetables (c), and vine crops (d) for each reservoir. Different years are expressed in different colors and shapes. 2018 and 2020 show significant increases in irrigation demand, regardless of planted area, in comparison to 2017 and 2019.

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 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%.

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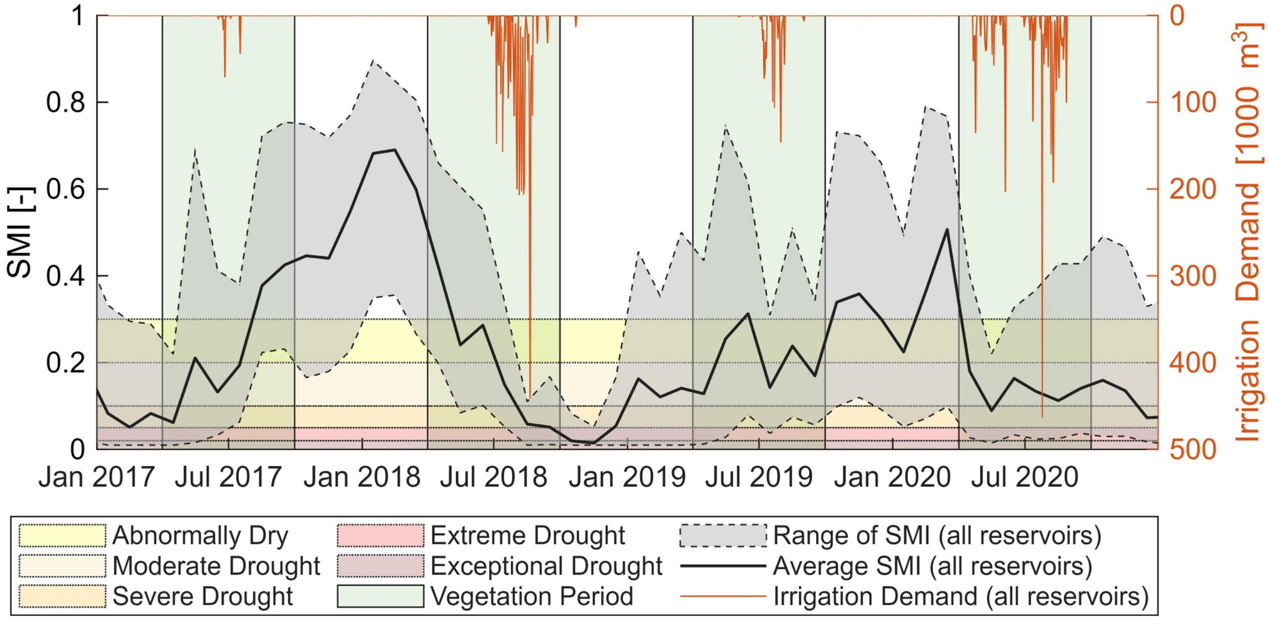

Figure 5. Progression of the percentile-based Soil Moisture Index (SMI, left) as both the range and the average across all 30 reservoirs, plotted alongside the total AID throughout the drought years. The vegetation periods of each year are marked in green.

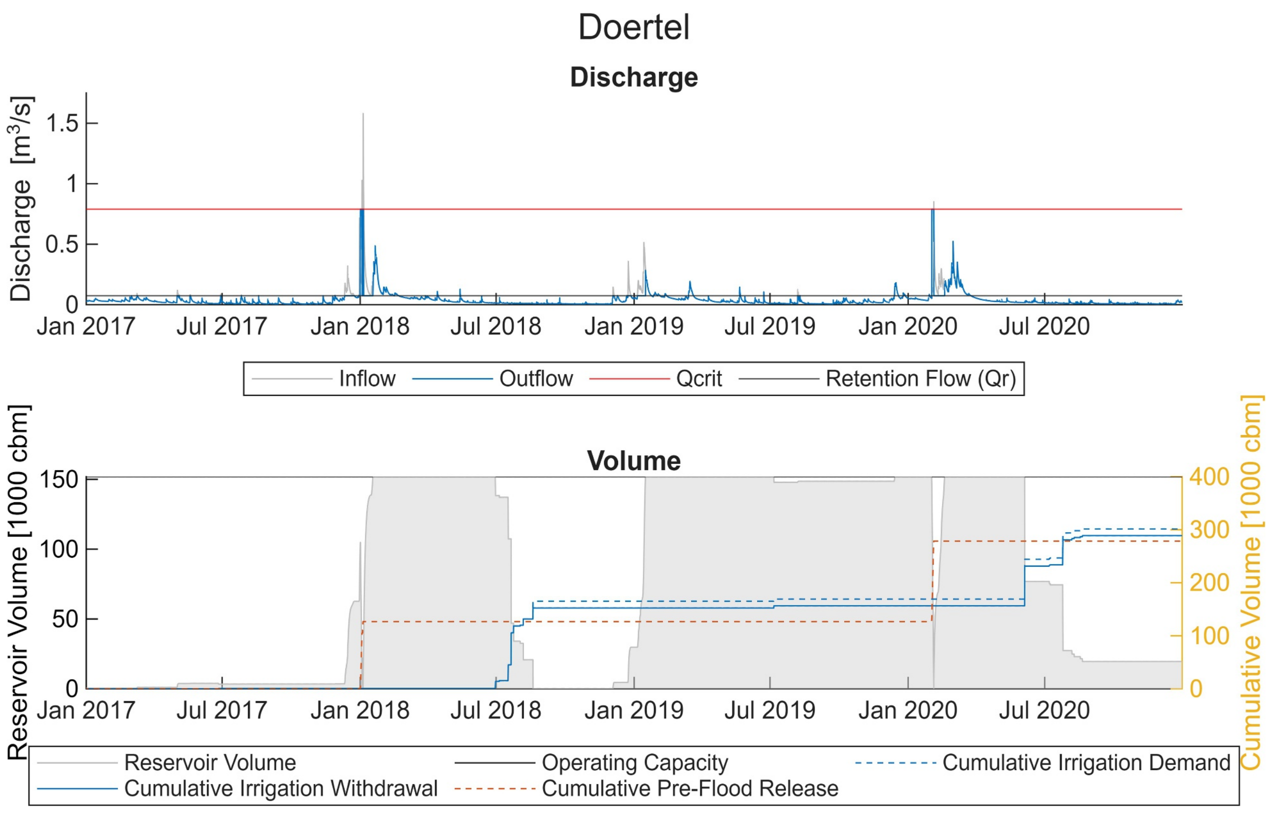

Figure 6. Plots showing the effects of reservoir operation on reservoir volume and inflow/outflow for Doertel (reservoir 13). Note that the reservoir volume time series is plotted against the left axis, and the other three time series (cumulative irrigation demand, cumulative irrigation withdrawal, and cumulative flood pre-release) are plotted against the right axis.

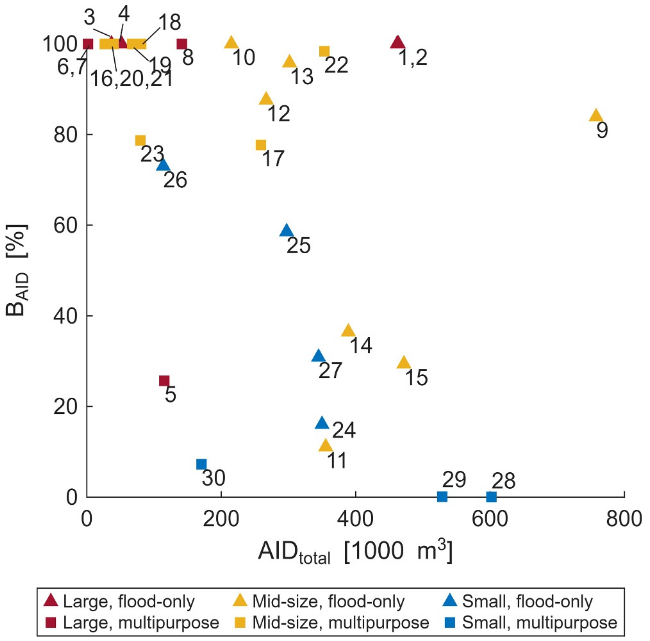

Figure 7. The total AID (in 1,000 m^3) versus the B_{AID} (as %) across all years (2017–2020) for each reservoir. Reservoirs are represented by size and by current use, and labeled by ID numbers from Table 1.

Most of the reservoirs—20 out of 30 in total—had a B_{AID} of over 70% (Figure 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 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 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.

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 (e.g., in January 2018 in Figure 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 9), where the frequent drainage has limited the reservoir's volume. Due to the dry conditions during the observation period, half of the reservoirs experienced infrequent or no flooding events, contributing to their strong performance for irrigation demand.

4. Discussion

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 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

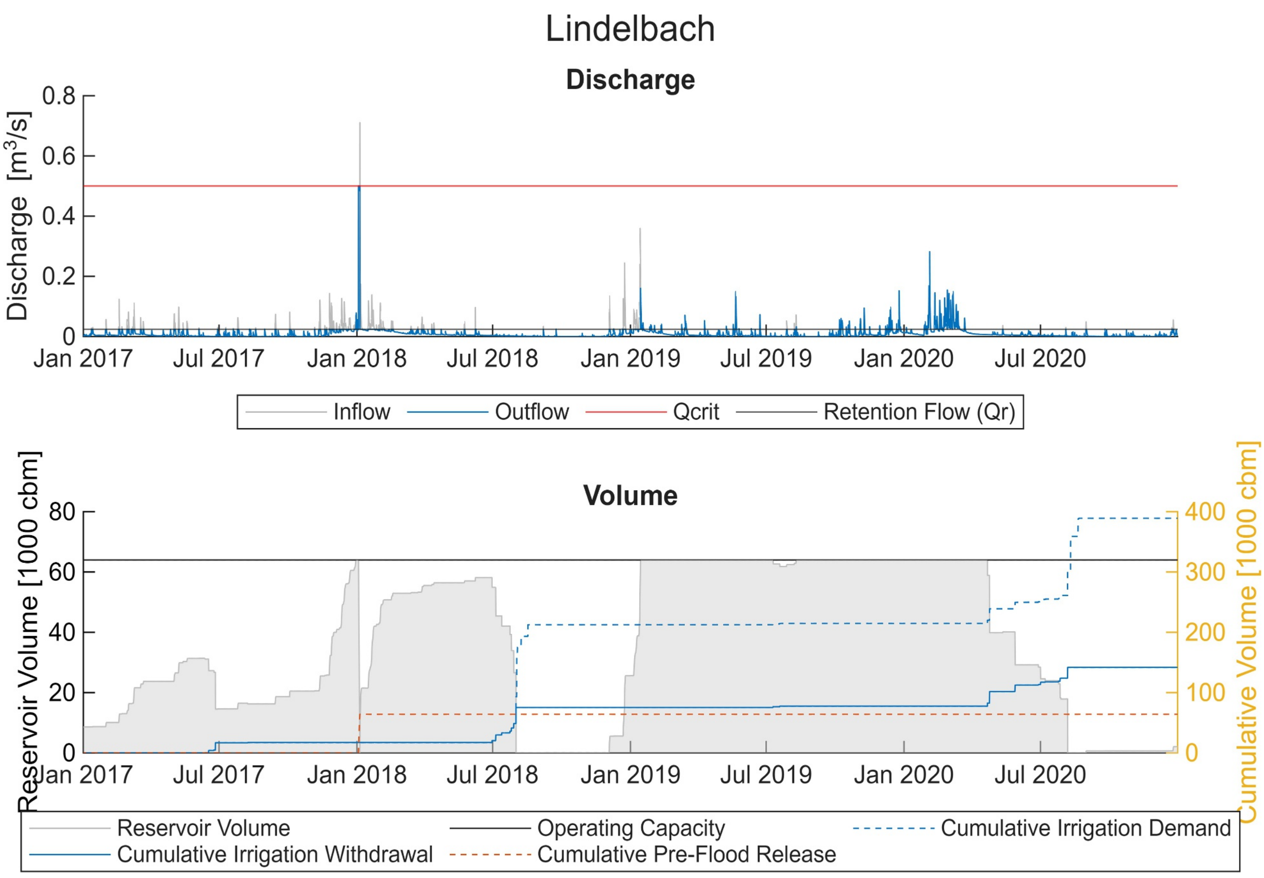

Figure 8. Plots showing the effects of reservoir operation on reservoir volume and inflow/outflow for Lindelbach (reservoir 14). Note that the reservoir volume time series is plotted against the left axis, and the other three time series (cumulative irrigation demand, cumulative irrigation withdrawal, and cumulative flood pre-release) are plotted against the right axis.

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). 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.

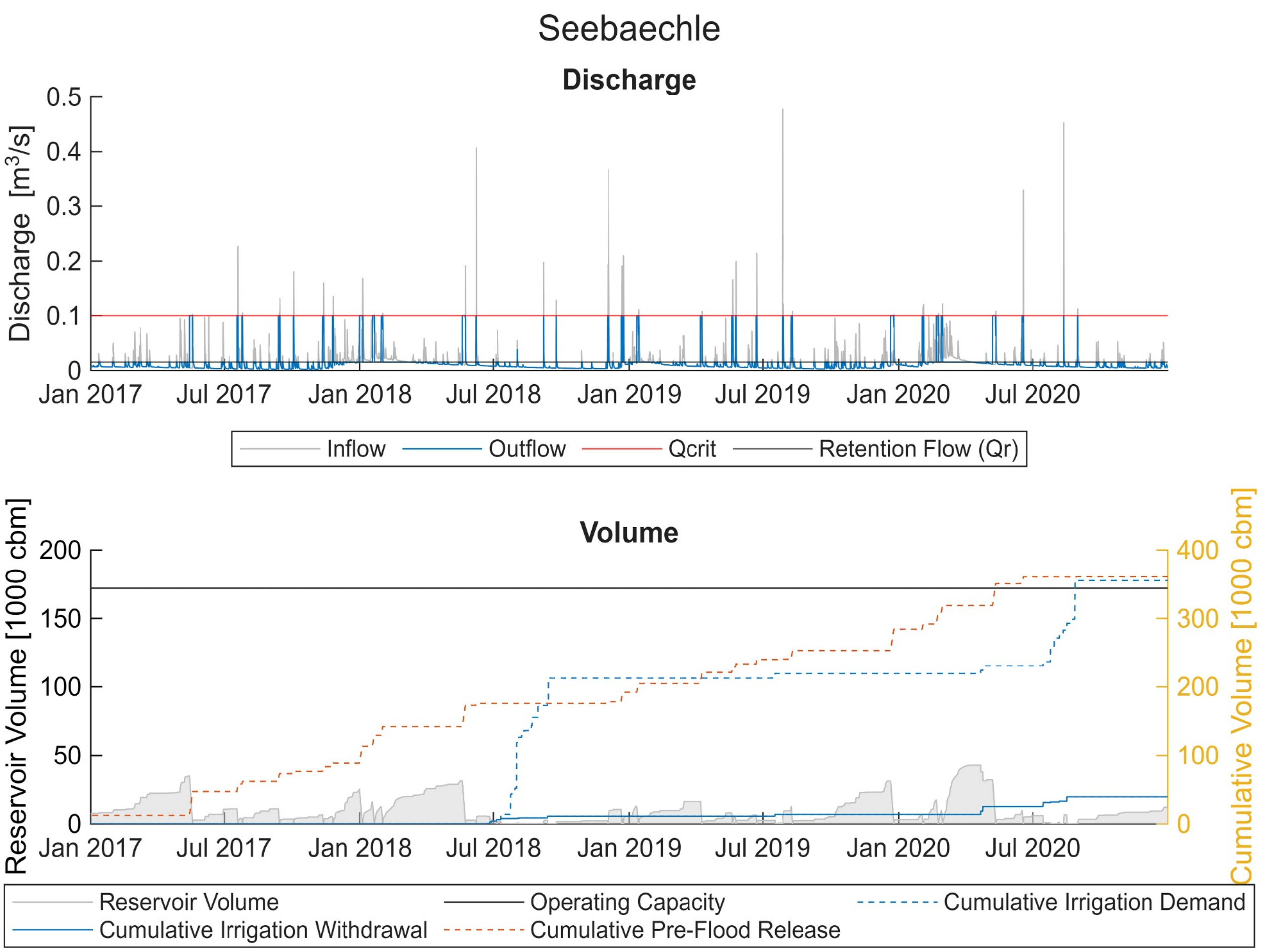

Figure 9. Plots showing the effects of reservoir operation on reservoir volume and inflow/outflow for Seebaechle (reservoir 11).

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 (L. F. U. 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 (L. F. U. Baden-Württemberg, 2019b, 2020, 2021; Ministerium für Umwelt, 2022a; Stütz, 2024). 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

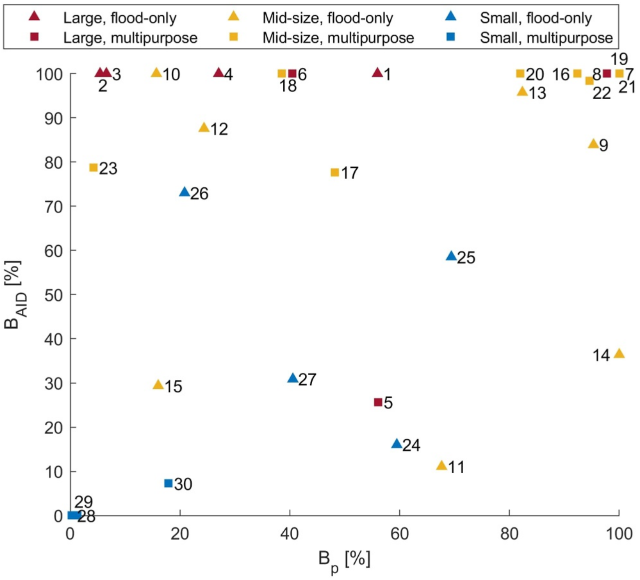

Figure 10. The agricultural benefit B_{AID} and streamflow benefit B_p—calculated per Ho and Ehret (2025b) for operation in 2017–2020 only—for each reservoir during the same period (2017–2020). Reservoirs are represented by size and by current use, and labeled by ID numbers from Table 1.

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 and 4 weeks) and intense onset (Otkin et al., 2018), these droughts currently lack a cohesive identification approach for croplands, particularly in Europe (Alencar & 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).

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 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 (2025b).

Comparisons of irrigation benefit and streamflow benefit from Ho and Ehret (2025b) 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 (2025b)—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 Appendix B).

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 before a flood to maintain flood protection, and allow direct withdrawals for irrigation purposes with a focus on their potential benefit during an extreme benchmark event. 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. There additionally remains the question of potential benefits of jointly operating several reservoirs in a system. While we have here only focused on one reservoir individually, cooperative storage and releases from multiple reservoirs in a catchment might increase the benefits of this operation and allow a more flexible operation. 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.

Appendix A: Potential Evaporation Losses From the Reservoirs

The climatic water balance as the cumulative sum of precipitation and FAO-56 reference evapotranspiration was calculated for each reservoir and is compared to the (overall) AID of all 30 reservoirs for timing of incidence. The timing of AID generally occurs before the largest P-ET_0 deficit of the year. For many reservoirs, the highest net change from the wet season to dry conditions due to the climatic water balance at the reservoir at the incidence of AID is a loss of approximately 350 mm. Because the median (operational) inundation depth of these reservoirs is approximately 4 m, this loss remains nondominant (Figure A1).

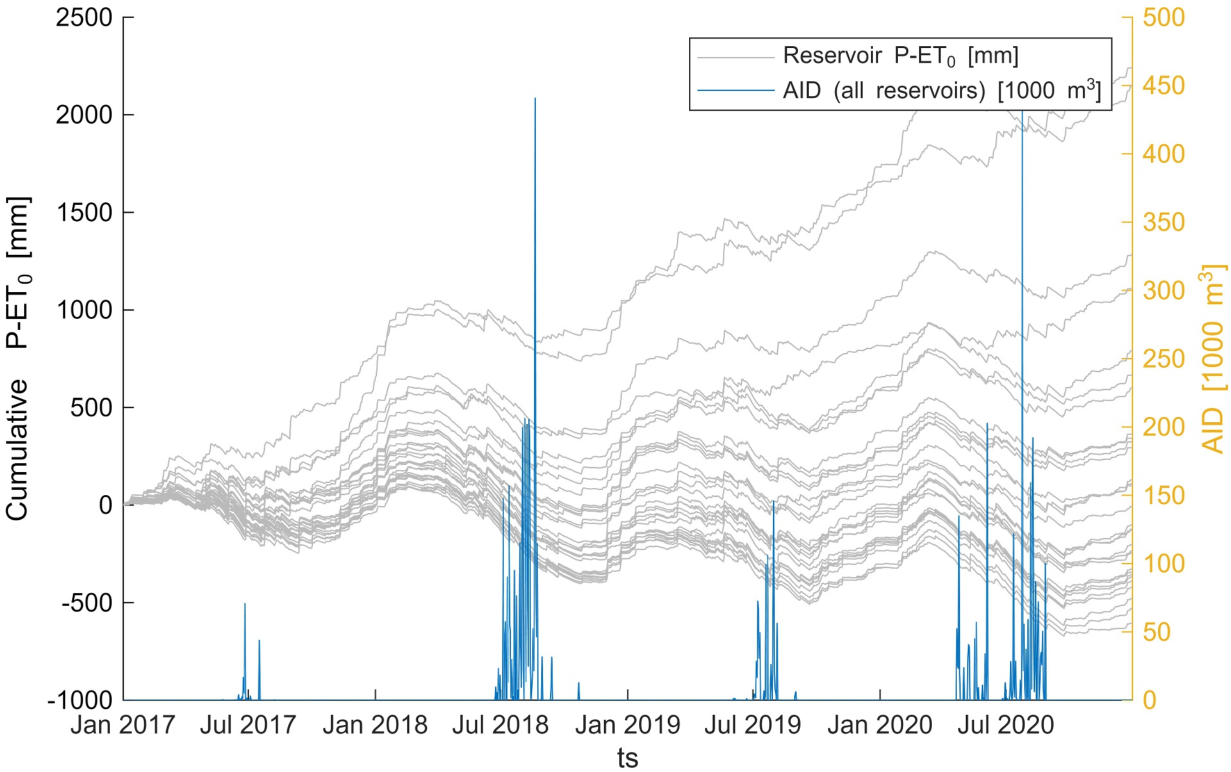

Figure A1. The cumulative climatic water balance at each reservoir and the timing of AID peaks during the observation period.

Appendix B: 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 (2025b). 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 (Figure B1).

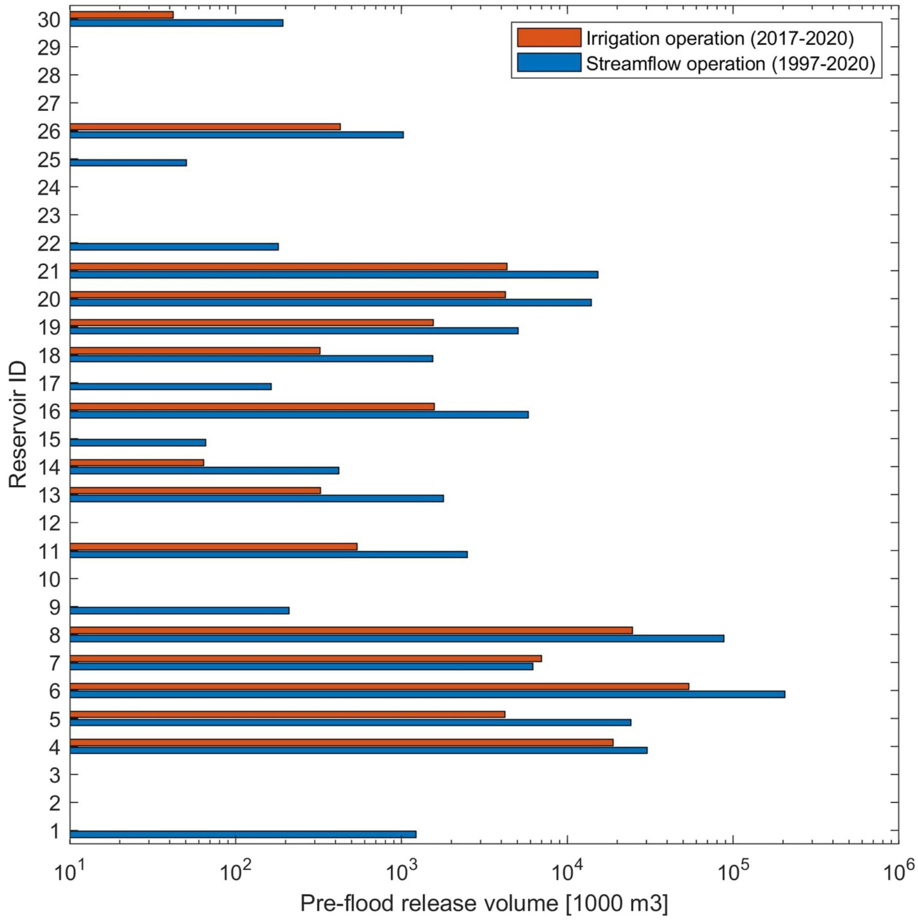

Figure B1. Pre-flood release volumes under irrigation and streamflow operation for each reservoir. Note the logarithmic scaling.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Table 1 is adapted from Ho and Ehret (2025b) with permission under CC BY 4.0. The data for Figure 1 was taken from Bernhardt and Neuenfeldt (2024) with permission under CC BY 4.0. The drought data for Figure 5 was retrieved from Boeing et al. (2025). The scripts and processed weather data from the German Weather Service (DWD, 2022, 2023, 2024a, 2024b, 2024c, 2024d), 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 Ho and Ehret (2025a) under CC BY 4.0.

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