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Is drought protection possible without compromising flood protection? Estimating the maximum dual-use benefit of small flood reservoirs in Southern Germany

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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 optimal reservoir operating (storage and release) rules for water supply downstream in a dual flood-drought protection scheme for 30 selected modeled flood reservoirs in Baden-Württemberg. Daily target releases for drought protection are proposed based on modeled inflows from the calibrated hydrological model LARSIM. Modified operation rules are optimized in a scenario of perfect knowledge of the future by using meteorological observations as artificial weather forecasts in LARSIM. The results of different operating rules 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. Optimized reservoirs were able to release up to 80 times their volume or improve up to 95% of existing drought conditions (penalty and volume deficit) over a 24-year period, though never simultaneously—there seems to be a trade-off between relative water availability to the reservoir and ability to alleviate drought conditions. Certain reservoirs were near-optimal, others could be improved further, and still others were not very effective at reducing drought conditions. We find that relative water availability at the reservoir (expressed as the number of times the reservoir can be filled by the difference between the mean inflow and mean low flow) 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.

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 (Padiyedath Gopalan et al., 2020;

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

Shih and Revelle, 1994, 1995; Huang and Chou, 2005; Karamouz and Araghinejad, 2008; You and Cai, 2008a, b; Chang et al., 2019). Research on optimal reservoir operation rules for drought have often focused on the concept of hedging rules: simply put, we "hedge our bets" that creating a small water deficit now will be more advantageous than the consequences of a heavy deficit—which we avoid using the water stored during the small deficit periods—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). 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 (Chang et al., 1995; Balley, 1997). 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 (Wisser et al., 2010; Jurík et al., 2018; Casadei et al., 2019; Liebe et al., 2007). 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 (Jurík et al., 2018; Casadei et al., 2019). 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 and Krishnan, 2011). While they have a plethora of benefits, such as flood retention, ecosystem protection, and recreation (Jurik et al., 2015; Ogilvie et al., 2019; Liebe et al., 2007), the most common usage is to capture rainwater for supplementing agriculture. 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).

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; Jurík et al., 2018; Casadei et al., 2019); and

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

mismanagement due to poor organizational capacity at the local management level (Venot et al., 2011; Acheampong et al., 2018).

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). As climate change threatens water availability, even water-rich regions may need to diversify their sources of water—conversion of flood retention basins into drought reservoirs may be part of the solution. However, little research on optimal operating rules for small flood retention basins exist.

In this study, we seek to demonstrate the potential of converting small (in the global context) flood retention basins into combined flood-drought reservoirs without impacting their flood protection functions. We apply and optimize two-point drought hedging operations to a variety of small-to-medium sized 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 benefit in drought conditions will be those that have high inflow relative to the reservoir capacity. Here, we focus on the potential benefits of changes to reservoir operation in terms of relative water availability in relation to a streamflow drought threshold—without consideration for ecological impacts or water quality—and assume that the outflow from the reservoirs can be precisely controlled at all time steps. In doing so, we identify patterns in drought reduction effectiveness across reservoir characteristics to assist decision-makers in selecting the reservoirs most suited for such usage.

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 Data and Methods

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.

Historically, flooding has been the major hydrological problem in the region. Over 800 reservoirs have been built in Baden-Württemberg for various purposes, the most common being flood protection (over 650). 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 (Baden-Württemberg, 2021). 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.

2.2 Reservoir Selection

More than 800 reservoirs in Baden-Württemberg exist today, with total capacities ranging from 200 m^3 to 43 million m^3. In the global context, these would be small or medium-sized reservoirs; however, 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 1). Henceforth we adopt the DIN 19700 size definitions as descriptors for reservoir sizes.

A representative subset 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. Flood protection-only reservoirs tend to have higher flooding thresholds than multipurpose ones. Thus, we focus only on large, medium, or small reservoirs with flood protection functions (either with additional functions or without). We also distinguish here between reservoirs with permanent and operational inundation, as this may be relevant for technical modifications; however, because we assume for this study that all technical modifications have been made, this characteristic is not used but 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. Each category containing 15 or more reservoirs was initially assigned three slots for

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

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. 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 1.

Table 1. Reservoir categories with abbreviations and number of reservoirs selected for study.

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	-

Reservoirs with different degrees of relative water availability from each of the categories were selected to best represent the variable conditions present in the region. We define relative water availability here as the storage factor (SF), or the number of times per year that a reservoir's capacity (C) can be filled via the water that we are able to store. The water available for storage is the difference between the yearly (calculated over the 24 years of simulation) mean inflow volume (Q_{in}) and the mean low flow volume (Q_{70}; for definition and calculation see 2.4.1) (1):

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

$$SF = \frac{V(Q_{in,mean}) - V(Q_{70,mean})}{C} \quad (1)$$

The SF 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 SF, then, indicates more water availability relative to the reservoir's capacity. In alignment with our hypothesis, a reservoir with a higher SF should be able to reduce drought conditions more effectively—thus, we aimed to select reservoirs with varying values of SF from each category.

The resulting 30 reservoirs investigated in this study can be seen in Table 2 and their locations are shown in Figure 1.

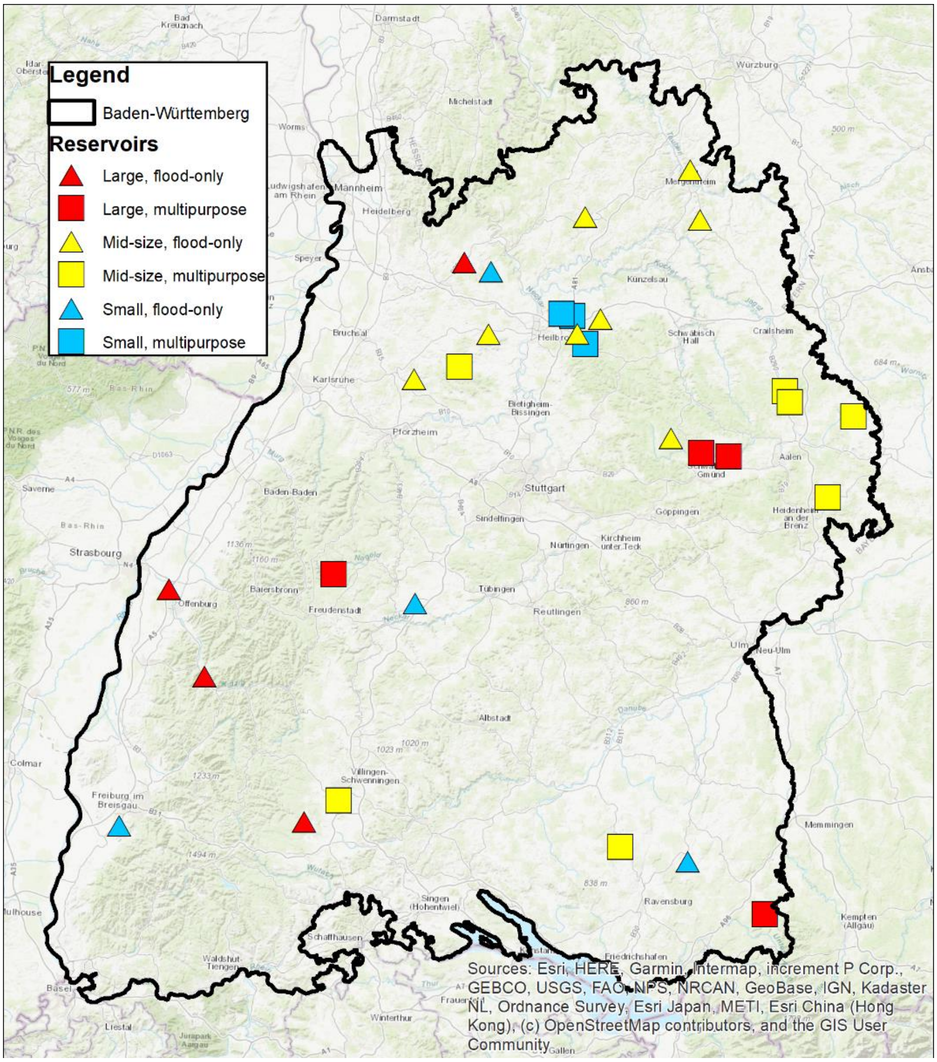


Figure 1. Locations of selected reservoirs for study in the German state of Baden-Württemberg.

Table 2. Selected reservoirs for study.

Size	Uses	Inundation Type	Name	SF [-]	LARSIM Catchment Area [km^3]

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

Large	Flood-only	Operational	Bernau	17.98	112
			Wolterdingen	24.83	185
			Mittleres Kinzigtal	149.70	797
			Gottswald	199.89	1063
	Multipurpose	Permanent	Nagoldtalsperre	5.31	39
			Federbach	5.44	10
			Rehnenmuehle	10.23	46
			Fetzachmoos	15.91	68
Mid-size	Flood-only	Operational	Seebaechle	1.23	2
			Unterbalbach	14.05	29
			Schwaigern	24.20	46
			Seckach	63.84	56
		Permanent	Doertel	2.54	2
			Lindelbach	3.00	1
			Weissacher Tal	22.75	6
	Multipurpose	Operational	Heinzental	3.96	4
			Wustgraben	5.99	6
			Hofwiesen	88.86	26
		Permanent	Michelbach	3.67	5
			Kressbach	7.31	8
			Fischbach	10.80	16
			Huettenbuehl	15.97	13
			Salinensee	69.46	7
Small	Flood-only	Operational	Wollenberg	7.11	2
			Mittelurbach	22.33	7
			Duffernbach	41.33	5
			Goettelfinger Tal	47.92	14
	Multipurpose	Permanent	Hoelzern	9.26	1
			Lennach	23.85	3
			Nonnenbach	134.69	4

2.3 Hydrological Model - LARSIM

Semi-natural inflows to each of the 30 reservoirs were calculated using a pre-calibrated version of the Large Area 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

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

water temperature). The model uses a grid structure (1 km^2 resolution) to describe meso-scale hydrological processes such as interception, evaporation using the Penman-Monteith method, snow-related processes (accumulation, compaction, and melt), flood routing, and soil water storage to evaluate discharge and water temperature. We refer to the flow as semi-natural because it also incorporates anthropogenic influences such as operations of selected reservoirs and dams (Lubw, 2024b)—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 provided model includes data from over 265 discharge gauges and 390 precipitation gauges, as well as hundreds of available meteorological stations, and is currently used in flood forecasting operations by the state agency. Its output contains 24 years of hourly data from 1997-2021 (however, two reservoirs—Gottswald and Mittleres Kinzigtal—have only 23 years of available data).

2.4 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 2.4.1);
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 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 2.4.3). Because these inputs are often relatively

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

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.

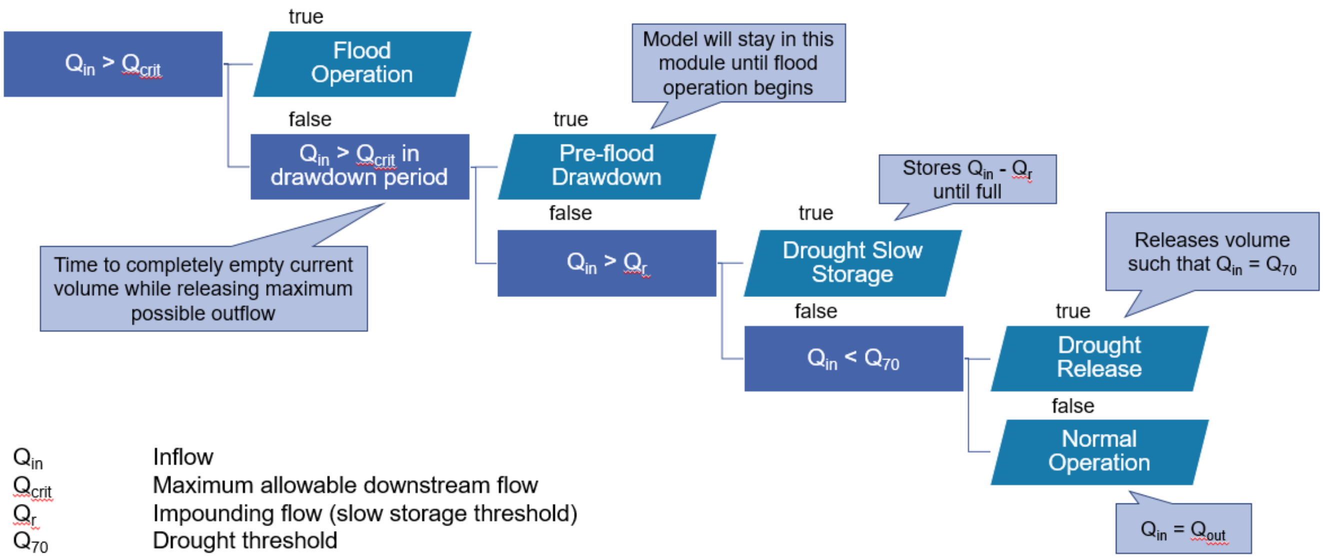


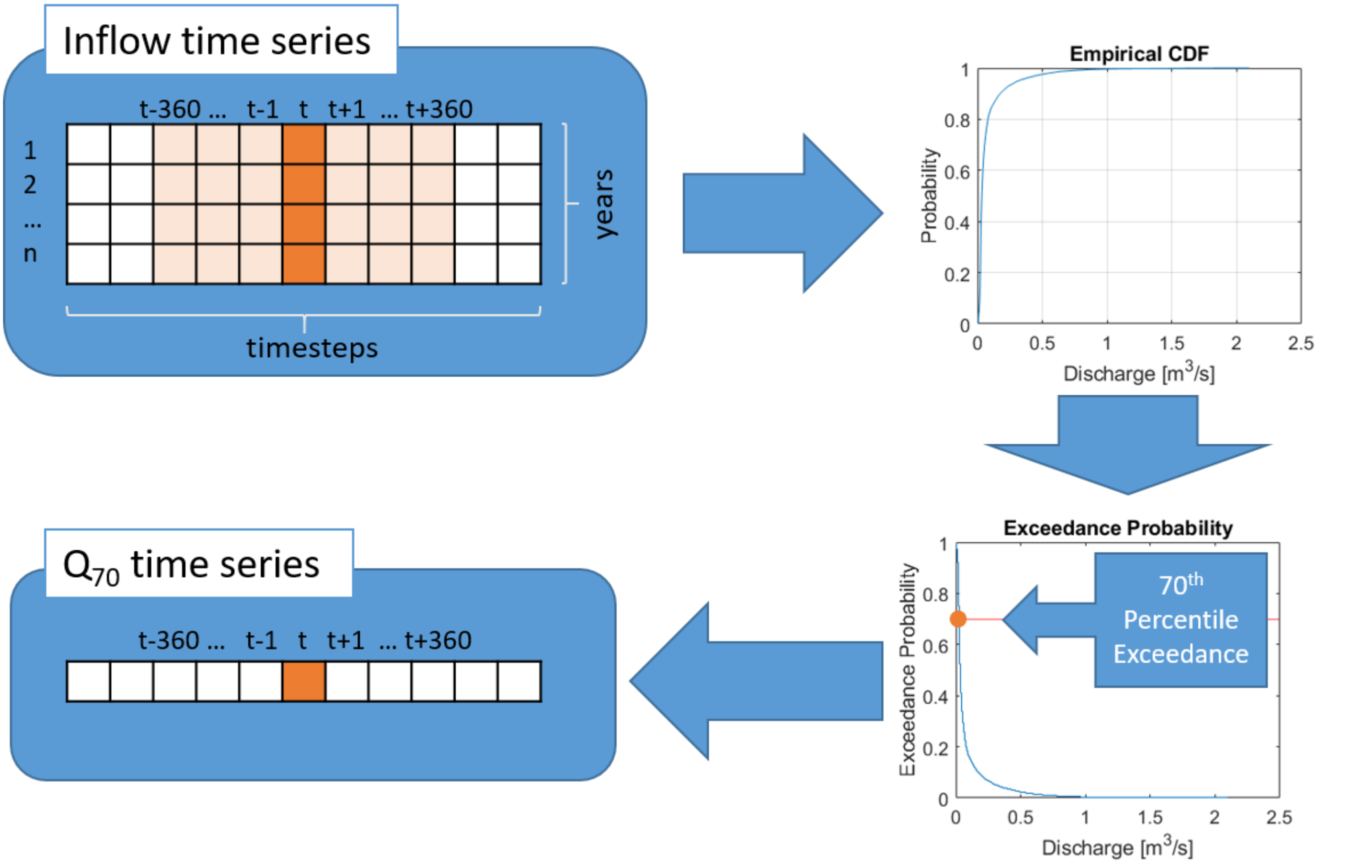
Figure 2. Decision tree for combined operation model.

2.4.1 Drought Release Targets

Previous studies on hedging rules for drought have demonstrated that such rules are most effective when allowed to vary throughout the year (Chang et al., 1995; Balley, 1997). Because drought thresholds can be extremely variable and location-specific, especially for reservoir flows, a flexible, simply-calculated method that could be quickly applied to 30 reservoirs was needed. 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 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—typical reference values in the literature range from the 70-95th percentile (Hisdal et al., 2004; Cammalleri et al., 2016; Van Loon et al., 2010). This calculation is summarized in Figure 3.

The exceedance percentile flow is a seasonally-variable low flow index based on historical values. In addition to its uses for drought monitoring, such as the 75th percentile as a warning level in Baden-Württemberg's low flow monitoring system (Lubw, 2024a), it has also been used in studies seeking to define ecological flows, though usually at the 85th percentile (Knight et al., 2011; Knight et al., 2013; Vigiak et al., 2018; Yarnell et al., 2020). The 85th percentile may also serve as a regulated lower limit for agricultural water abstraction, as noted in Salmoral et al. (2019).

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024



215 **Figure 3. Example calculation of the Q_{70} time series.**

In this study, we seek to evaluate the ability of reservoirs to alleviate droughts both mild and severe—thus, we use the 70th percentile exceedance flow (Q_{70}) as the threshold here, as it is the most lenient definition among typical values. The arithmetic mean of this Q_{70} time series is also used as an estimate of the average low flow to calculate the SF (1). This low threshold will allow us to evaluate the new rules' ability to alleviate both mild and severe droughts. If the inflow at any time step is less than Q_{70} (i.e. the discharge drops below the threshold), the combined model uses stored volume in the reservoir (if any) to supplement the outflow such that Q_{70} is reached. This strategy also allows release of water in the winter, which may be ultimately unnecessary. The hourly resolution of this demand time series may, however, be difficult to use in practice: reservoirs typically change their releases on weekly or monthly scales—in the future, known thresholds may be substituted for the percentile exceedance curve. We retain this high temporal resolution, however, for two reasons: first, to match the hourly resolution of flood forecasts and operations; and secondly, to demonstrate the theoretical maximum benefit obtainable from this method, assuming that fine control of the output at each time step is possible.

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

2.4.2 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 (2):

$$\int_{t_i+1}^{t_i+t_{down}} [Q_{crit} - Q_{in}(t)]\, dt \geq V(t_i) \quad \textbf{(2)}$$

After calculating t_{down}, the model checks if a flood begins ($Q_{in} > Q_{crit}$) within the next t_{down} timesteps. If there is a flood, the model enters the pre-flood drawdown module and remains in this module until the flood event begins. By ensuring that the flood reservoir is empty, we guarantee that the flood protection is not compromised.

2.4.3 Expressing Degrees of Reservoir Failure

Degrees of reservoir failure (i.e. of 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 used 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 of flooding downstream of the river where penalty increases significantly once the outflow $Q_{out,t}$ exceeds the flooding discharge (Q_{crit}) (3):

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

$$P_{f,t} = \begin{cases} 0, & Q_{out,t} \leq Q_{crit} \\ -5\left(Q_{out,t} - Q_{crit}\right), & Q_{out,t} > Q_{crit} \end{cases} \quad \textbf{(3)}$$

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 0.001 m^3/s are assumed to be the same as for Q_{out} of 0.001 m^3/s to avoid potential division by infinity. This results in the following penalty expressions (4):

$$P_{d,t} = \begin{cases} 0, & Q_{out,t} \geq Q_{70,t} \\ -\dfrac{1}{\sqrt{Q_{out,t}}} + \dfrac{1}{\sqrt{Q_{70,t}}}, & Q_{out,t} < Q_{70,t} \\ -\dfrac{1}{\sqrt{0.001}} + \dfrac{1}{\sqrt{Q_{70,t}}}, & Q_{out,t} \leq 0.001 \end{cases} \quad \textbf{(4)}$$

For discussion of results between reservoirs, 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 $P_{d,f}$: (5)

$$B_p = 100 \times \frac{\sum P_{d,c} - \sum P_{d,f}}{\sum P_{d,f}} \quad \textbf{(5)}$$

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 $V_{d,f}$:

$$B_v = 100 \times \frac{\sum V_{d,c} - \sum V_{d,f}}{\sum V_{d,f}} \quad \textbf{(6)}$$

The volume benefit B_v differs slightly from the penalty benefit B_p in that penalty allows heavier weighting of volume delivery at critical times: the same volume of water may reduce penalty by different amounts.

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

$$V_{d,nor} = \frac{V_d}{C} \quad \textbf{(7)}$$

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

2.4.4 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 (8);

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

- 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) (9);
- The reservoir volume cannot exceed the operating capacity and cannot be less than 0 (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}) (11); and
- The retention flow Qr must be between the highest value in the release target time series and the flooding limit (12)

$$V_t = V_{t-1} + (Q_{in,t} - Q_{out,t}) \times t \tag{8}$$

$$C = V_{full} - V_{permanent\ inundation} \tag{9}$$

$$0 \le V_t \le C \tag{10}$$

$$Q_{out,t} = \begin{cases} Q_{out,t} \le Q_{crit}, & V < C \\ Q_{out,t} > Q_{crit}, & V = C \ \ge 0 \end{cases} \tag{11}$$

$$\max(Q_{70}) < Q_r < Q_{crit} \tag{12}$$

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.

3 Results & Discussion

3.1 Optimization Results

The optimum Q_r value for each reservoir, as well as the capacity, Q_{crit}, and the range of Q_{70}, can be seen in Table 3. While the allowable ranges for Q_r vary greatly—even among similar reservoir categories—the optimal value under perfect knowledge approaches the minimum value. Although this result is not particularly surprising, given the strong assumption of perfect knowledge, it does demonstrate that a significantly lower Q_r is possible without compromising flood protection. The results for the combined operation models presented henceforth are with these values of Q_r.

Table 3. Flooding thresholds (Q_{crit}), maximum and minimum drought thresholds (Q_{70}), optimal retention flow (Q_r), and operating capacities for each of the 30 reservoirs. Note that reservoirs with permanent inundation will have smaller operating capacities.

Qcrit	Max(Q70)	Min(Q70)	Optimal Qr	Operating Capacity

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

Name	Category	[m3/s]	[m3/s]	[m3/s]	[m3/s]	[m3]
Bernau	LF	22.000	1.017	0.317	1.437	1,020,000
Wolterdingen	LF	75.000	4.653	1.355	6.060	4,720,000
Gottswald	LF	830.000	21.039	5.032	37.219	2,700,000
Mittleres Kinzigtal	LF	860.000	16.937	3.796	33.798	3,000,000
Federbach	LM	0.400	0.093	0.006	0.099	652,652
Nagoldtalsperre	LM	15.000	0.869	0.228	1.152	3,500,000
Rehnenmuehle	LM	7.000	0.533	0.054	0.662	1,741,000
Fetzachmoos	LM	15.000	1.402	0.565	1.674	2,930,000
Doertel	MF	0.790	0.019	0.003	0.035	151,880
Lindelbach	MF	0.500	0.007	0.001	0.017	64,000
Weissacher Tal	MF	2.410	0.046	0.014	0.093	33,112
Schwaigern	MF	3.320	0.157	0.021	0.221	210,000
Seckach	MF	50.300	0.697	0.242	1.689	168,400
Seebaechle	MF	0.100	0.009	0.004	0.011	172,000
Unterbalbach	MF	6.330	0.153	0.066	0.276	185,000
Fischbach	MM	3.700	0.098	0.030	0.170	310,000
Huettenbuehl	MM	4.000	0.183	0.030	0.260	335,210
Kressbach	MM	0.700	0.051	0.017	0.064	276,181
Michelbach	MM	1.000	0.030	0.009	0.049	181,625
Salinensee	MM	3.600	0.082	0.018	0.152	32,000
Heinzental	MM	1.090	0.027	0.008	0.048	233,780
Hofwiesen	MM	10.680	0.165	0.017	0.376	81,728
Wustgraben	MM	0.500	0.051	0.020	0.060	188,000
Duffernbach	SF	1.550	0.028	0.003	0.058	31,143

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

Goettelfinger Tal	SF	4.100	0.193	0.023	0.272	83,400
Mittelurbach	SF	0.500	0.090	0.057	0.098	60,000
Wollenberg	SF	3.370	0.015	0.006	0.082	30,200
Hoelzern	SM	1.500	0.004	0.002	0.034	7,703
Lennach	SM	2.100	0.011	0.004	0.053	9,600
Nonnenbach	SM	0.170	0.028	0.011	0.031	3,759

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 storage factor for all reservoirs in Figure 4, yielding interesting results. Overall, large multipurpose reservoirs were the most effective in penalty reduction while small multipurpose were the least effective. Mid-size reservoirs with both usage types have broad ranges of penalty reduction, but have similar medians. It seems that multipurpose reservoirs in general increase in effectiveness with size. Contrary to our hypothesis, reservoirs with high SF were unable to decrease penalty significantly.

The reservoirs can be roughly grouped into one of four groups based on Figure 4: low-availability (< 100 SF), high improvement (> 65%); low-availability, middling improvement (30-65%); low-availability, low improvement (< 30%); and high-availability (> 100 SF), low improvement. We explore the combined model outputs of four selected reservoirs (shown in Table 4) from each of the groupings to understand the interactions of SF, benefit, and release volume as they relate to the optimized combined model operation.

Table 4. Selected reservoirs for exploration.

Reservoir Name	Category	SF [-]	Normalized Release Volume [-]	Benefit [%]
Gottswald	LF	199.89	47.45	10.80
Heinzental	MM	3.96	2.86	89.91
Federbach	LM	5.44	2.72	58.84
Wollenberg	SF	7.11	1.19	6.25

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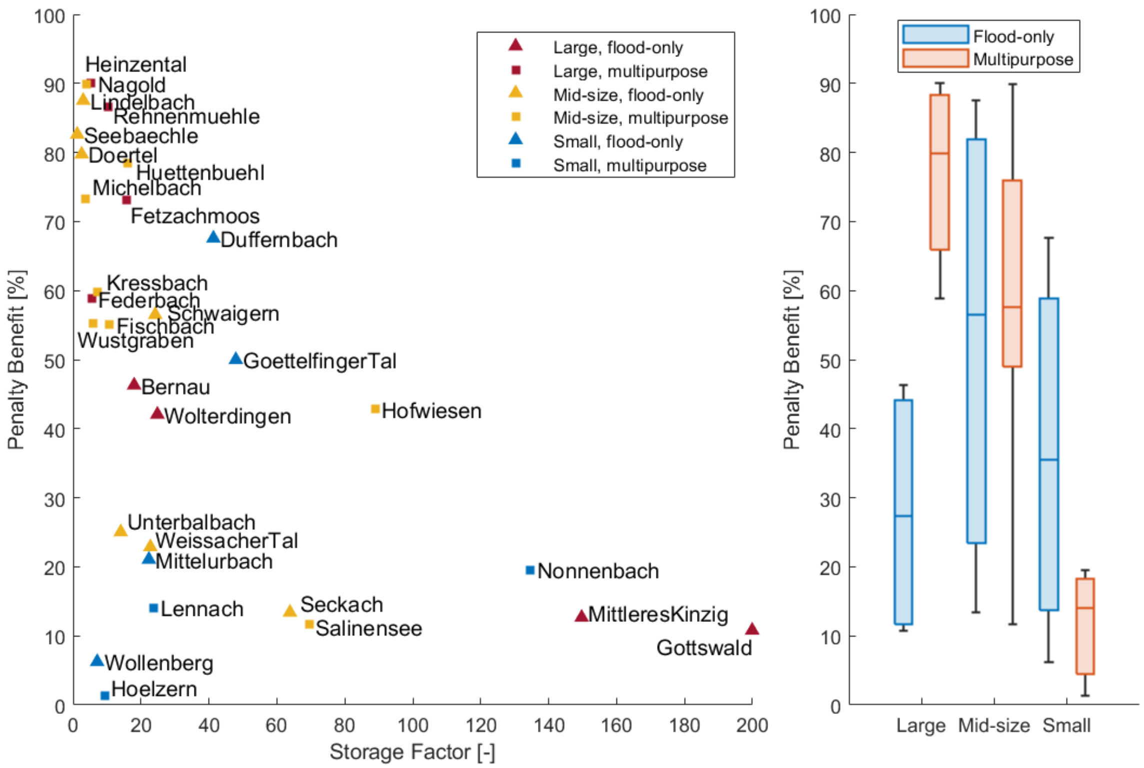

Figure 4. Penalty Benefit relative to storage factor (left) and summarized by reservoir size and use categories (right).

3.1.1 High Availability, Low Improvement - 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 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 6) are quite substantial, with deficits of up 5 m^3/s. 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.

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

This presents a problem with our hypothesis of SF as an indicator for penalty reduction. A large SF 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 5 suggests that it is the former—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 such cases, it may be more realistic to choose a different or stricter drought definition. However, the reservoir volume would likely remain too small for the deficit volumes.

3.1.2 Low Availability, High Improvement - Heinzental

Heinzental (Figure 7) is a mid-size multipurpose reservoir with a low SF but significant drought improvements. Flood events occur several times throughout the time series; however, it is able to completely protect against flood droughts while still being able to compensate for the majority of drought events. 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 at the beginning of the time series (owing to the fact that the model starts with an empty reservoir), 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. 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.

3.1.3 Low Availability, Medium Improvement – Federbach

Federbach (Figure 8) is a large multipurpose reservoir with a rather low SF in comparison to other large reservoirs. 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 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. However, its potential for drought alleviation is limited by the frequency of floods.

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

3.1.4 Low Availability, Low Improvement - Wollenberg

Wollenberg (Figure 9) is a small flood-only reservoir. In addition to having a low SF 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. One explanation could be model uncertainties: LARSIM is not typically used for small catchment sizes like that of a small reservoir, meaning that the model results could be unreliable. In this case, long-term gauge data would be needed to validate the results. Alternatively, 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 threshold. However, this could result in significant changes to the river regime. Depending on the intended purpose of the water, this could be either highly beneficial or catastrophic. 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.

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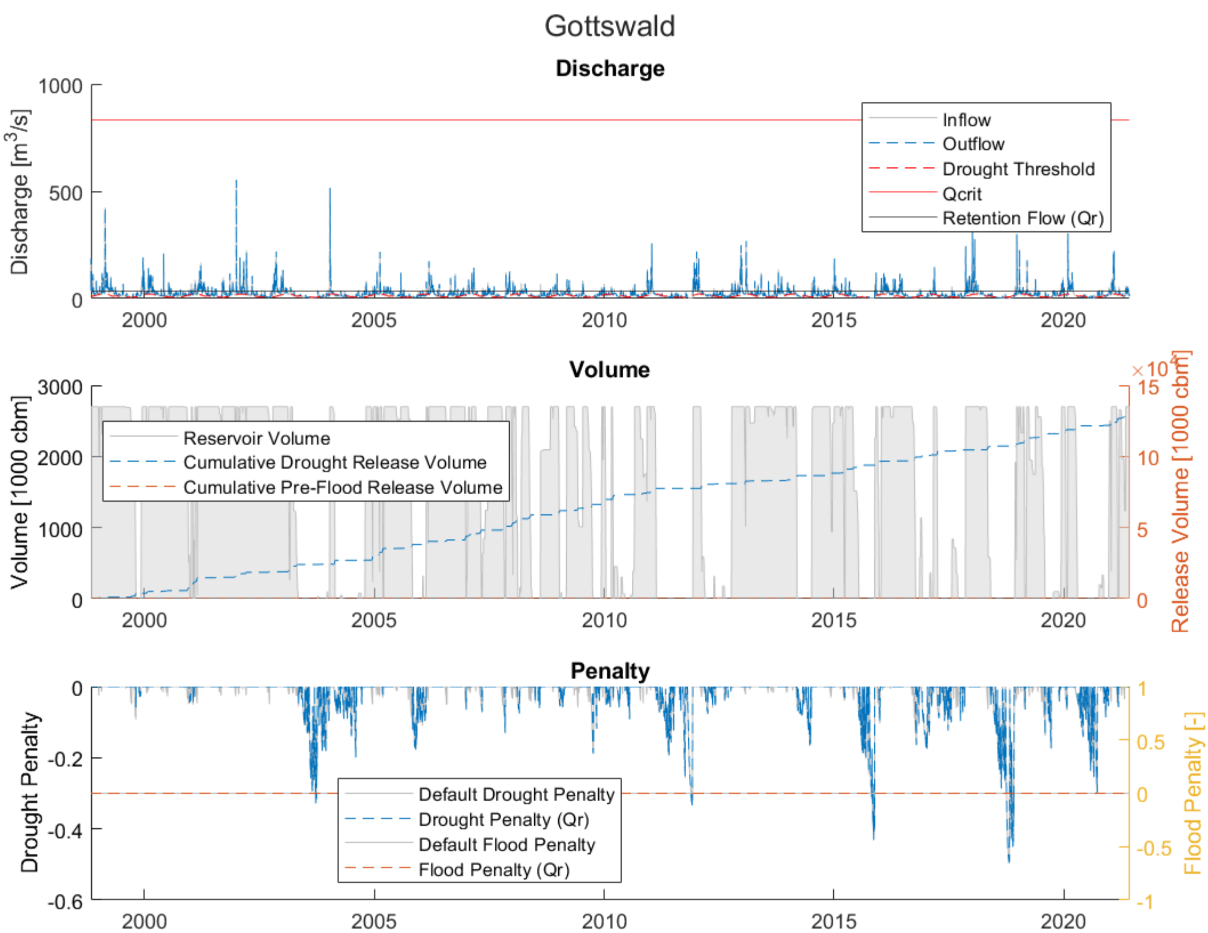

380 **Figure 5. Discharge, volume, and penalty time series for Gottswald reservoir (example of a low availability, low improvement reservoir).**

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Preprint. Discussion started: 23 July 2024

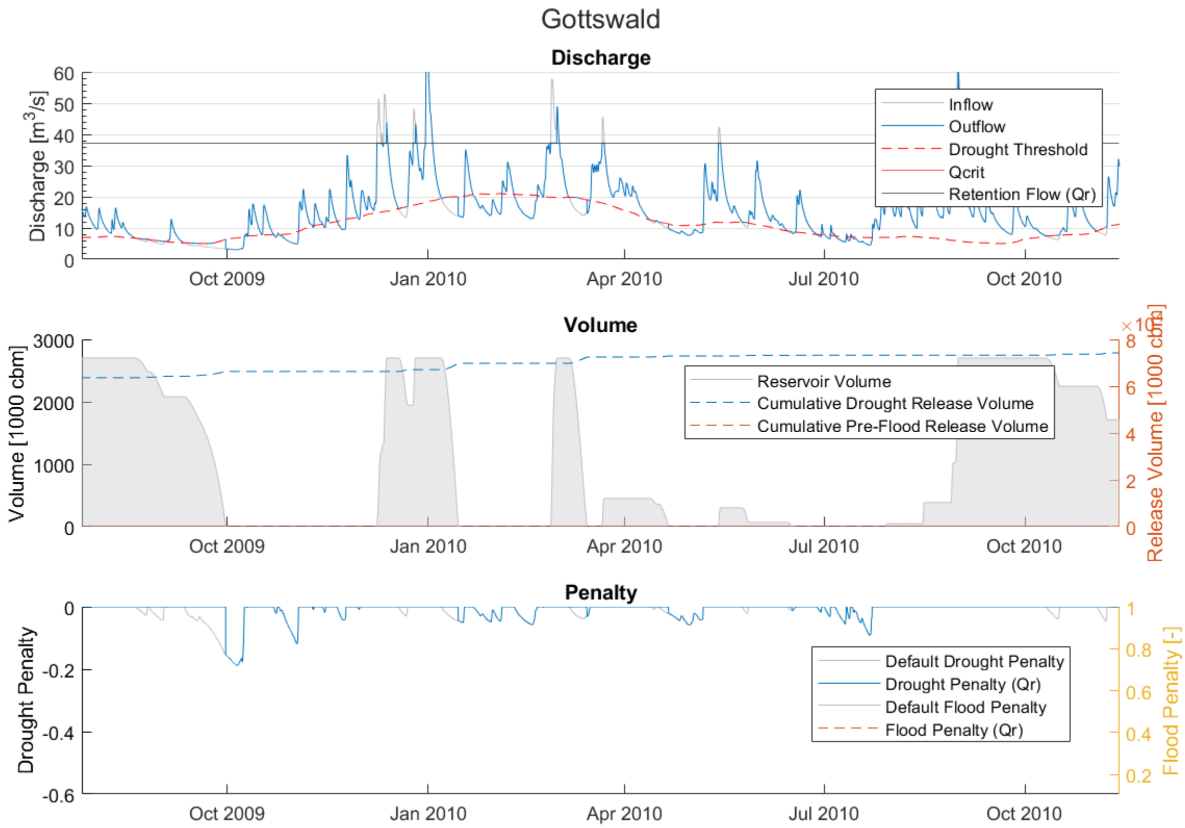

Figure 6. A closer look at a problematic period for Gottswald reservoir.

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Preprint. Discussion started: 23 July 2024

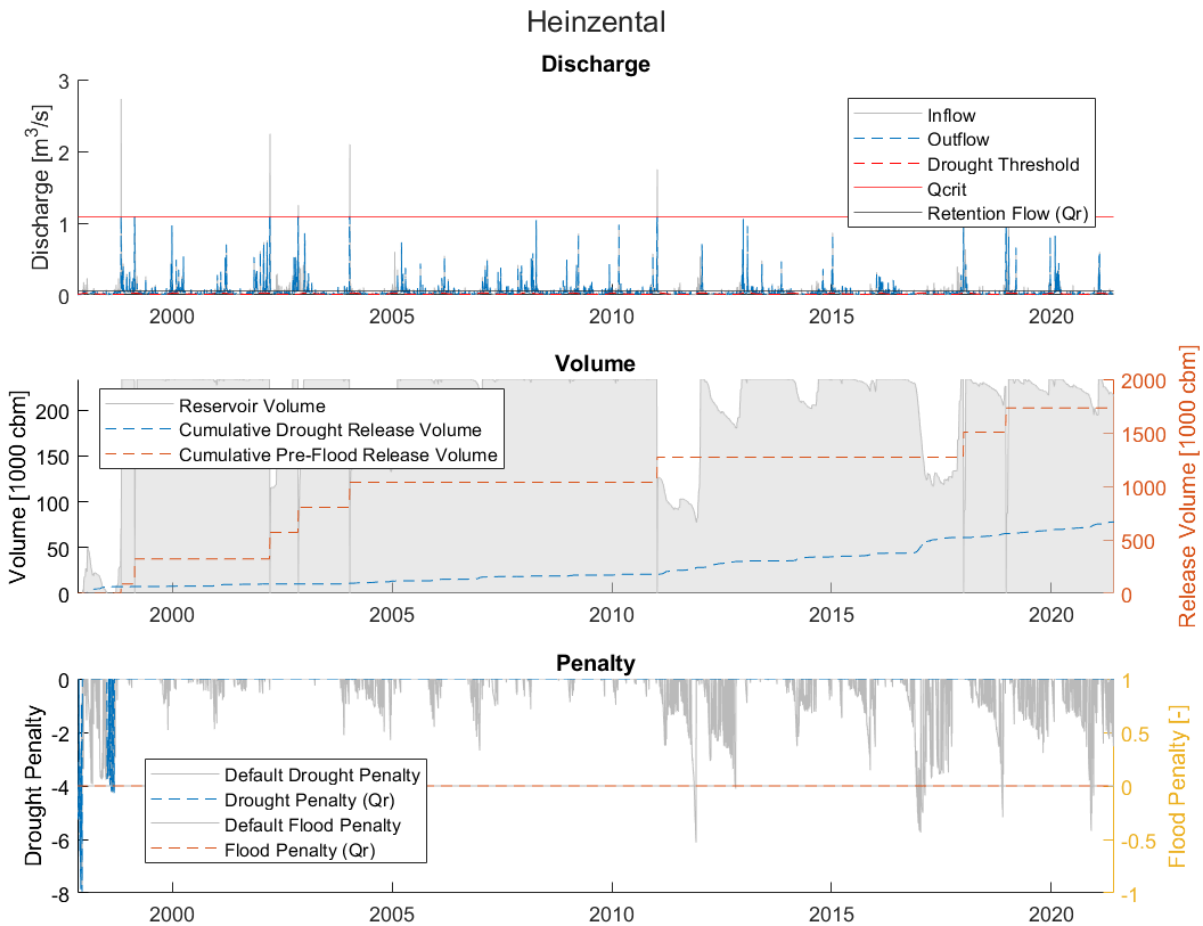

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Figure 7. Discharge, volume, and penalty series for Heinzental reservoir (example of a low availability, high improvement reservoir).

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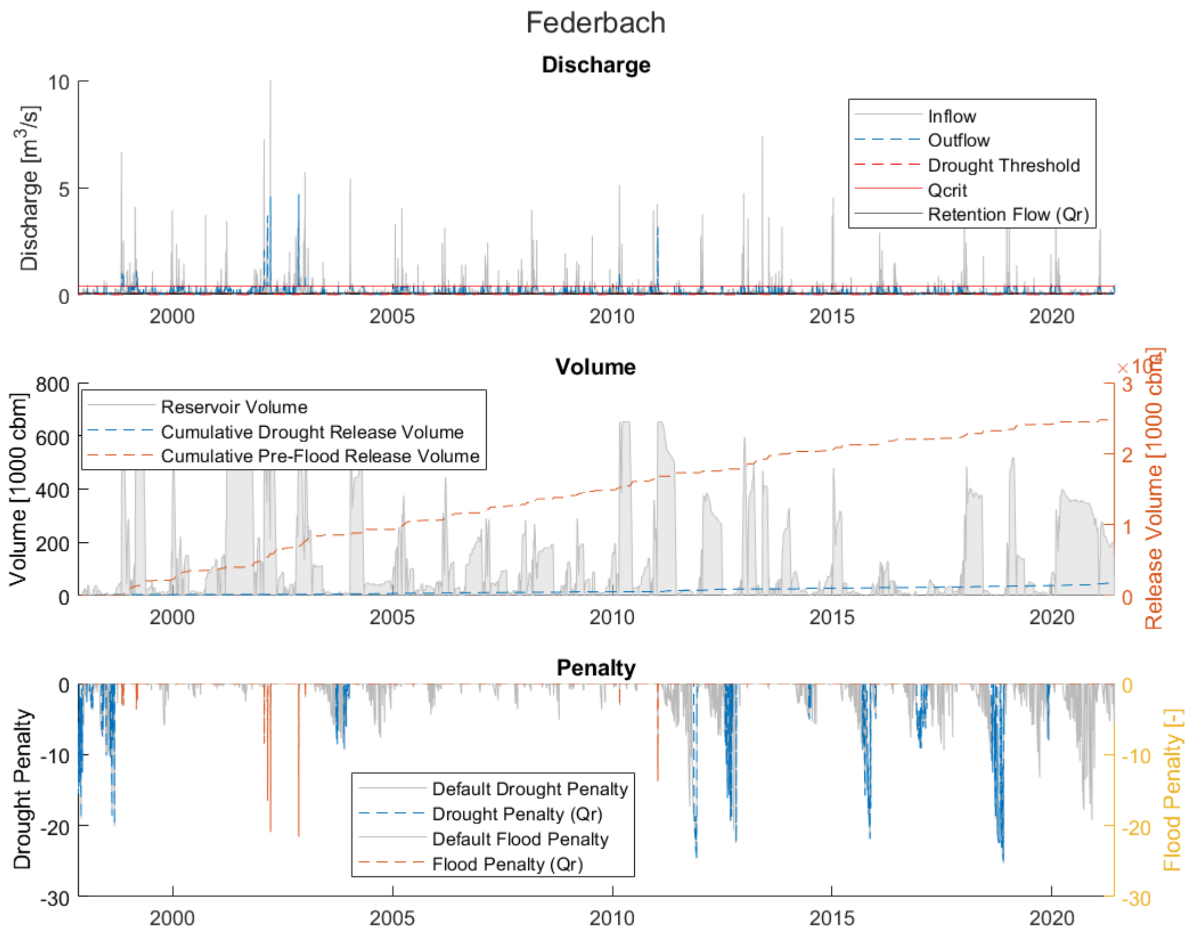

390 **Figure 8. Discharge, volume, and penalty time series for Federbach reservoir (example of a low availability, medium-improvement reservoir).**

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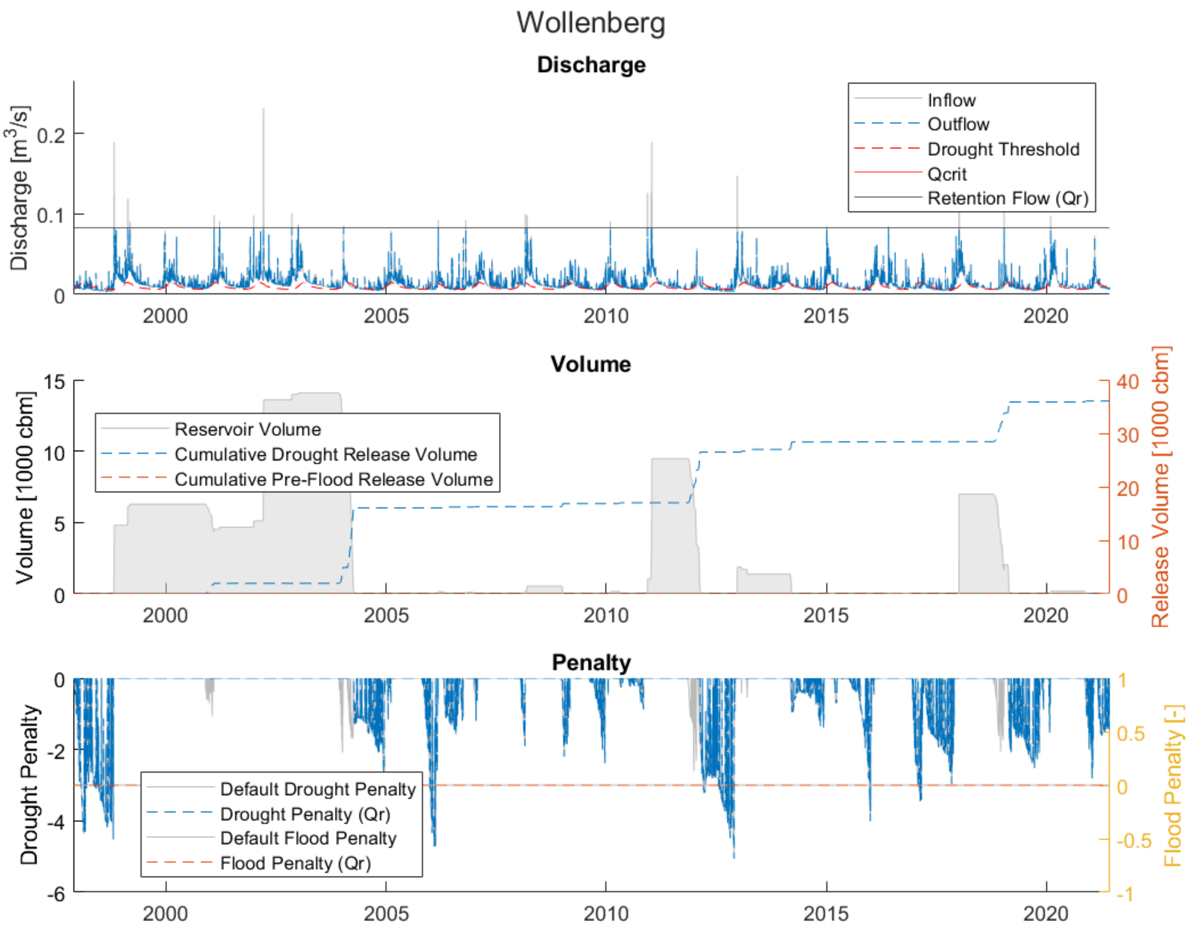


395 **Figure 9. Discharge, volume, and penalty time series for Wollenberg reservoir (example of a low availability, low improvement reservoir). The flooding limit (Q_{crit} = 3.37 m^3/s) is omitted in the discharge portion of this figure for clarity, as the flows never exceed 0.3 m^3/s during the 24 years of modelled data.**

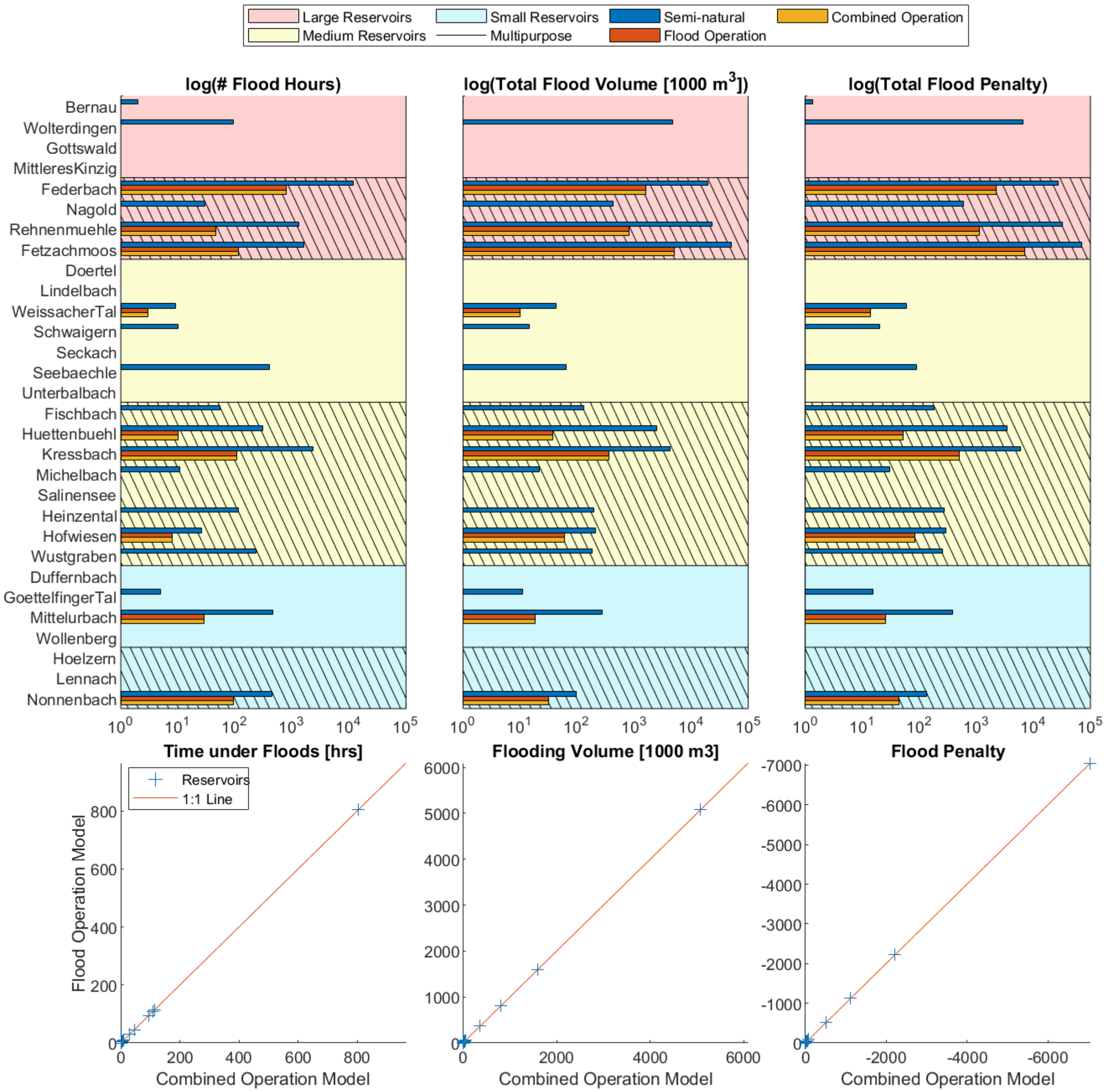
3.2 Reservoir Results

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 10). 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

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

the combined operation model. Thus, we demonstrate that it is possible to reuse these reservoirs for drought protection without
405 impacting their flood protection functions.



410 **Figure 10. 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), deviation towards the combined operation model from the 1:1 line indicates improved performance in the combined operation model. Note the differing axes and scales.**

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

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 11). 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.

The penalty and volume benefits are shown in Figure 12Figure 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 13). 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 2,000 m^3 to 128 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 irrigation water demand (IWD) of 112 mm/year as found for crops in Germany by Drastig et al. (2016) (and also

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

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 km² of agriculture per year.

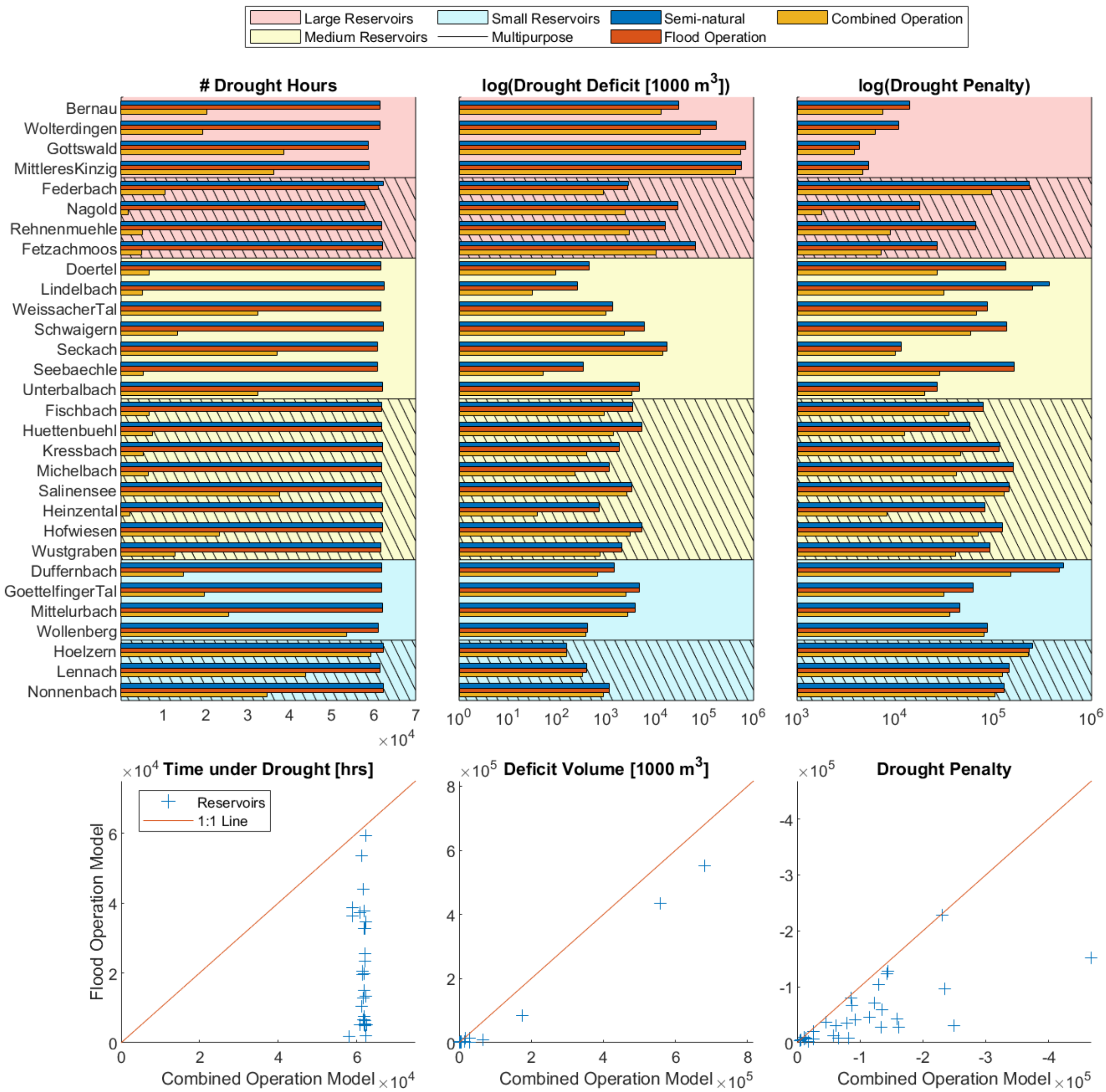


Figure 11. Drought statistics (# drought timesteps, drought deficit volume, and drought penalty) for each of the 30 reservoirs at the inflow (semi-natural) and downstream under both models (flood operation and the optimized combined operation models). In the

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Preprint. Discussion started: 23 July 2024

scatter plots (bottom), deviation towards the combined operation model from the 1:1 line indicates improved performance in the combined operation model. Note the differing axes and scales.

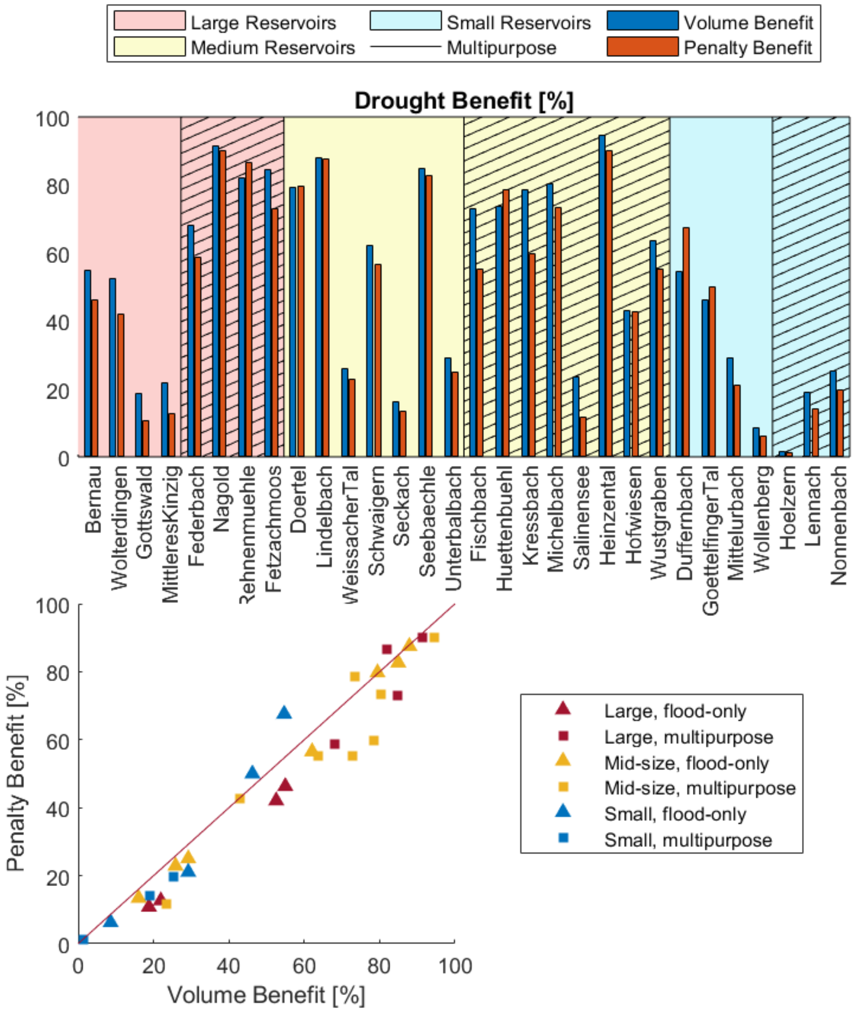

Figure 12. Comparisons of volume and penalty benefit for all reservoirs.

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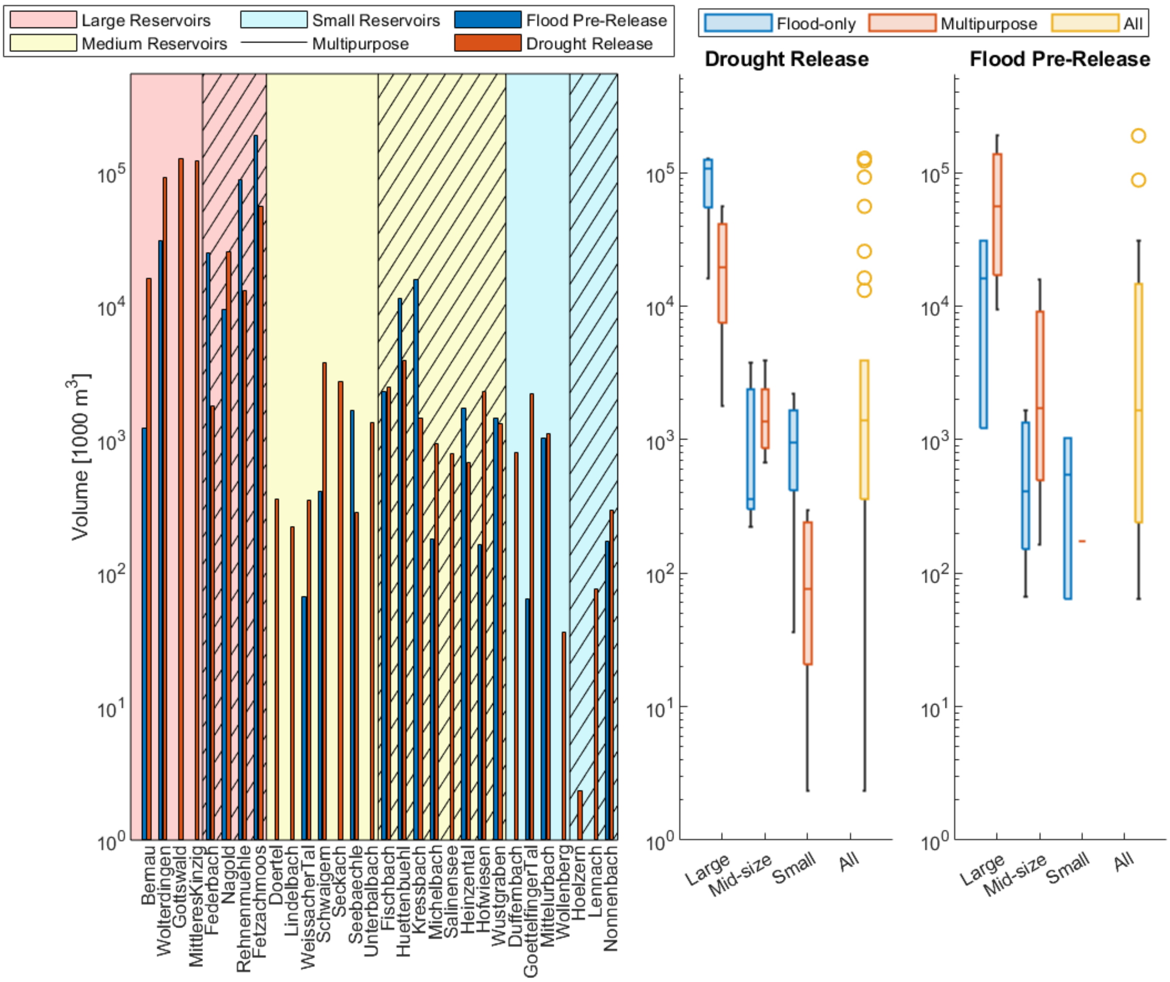
Preprint. Discussion started: 23 July 2024



455 **Figure 13. 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.**

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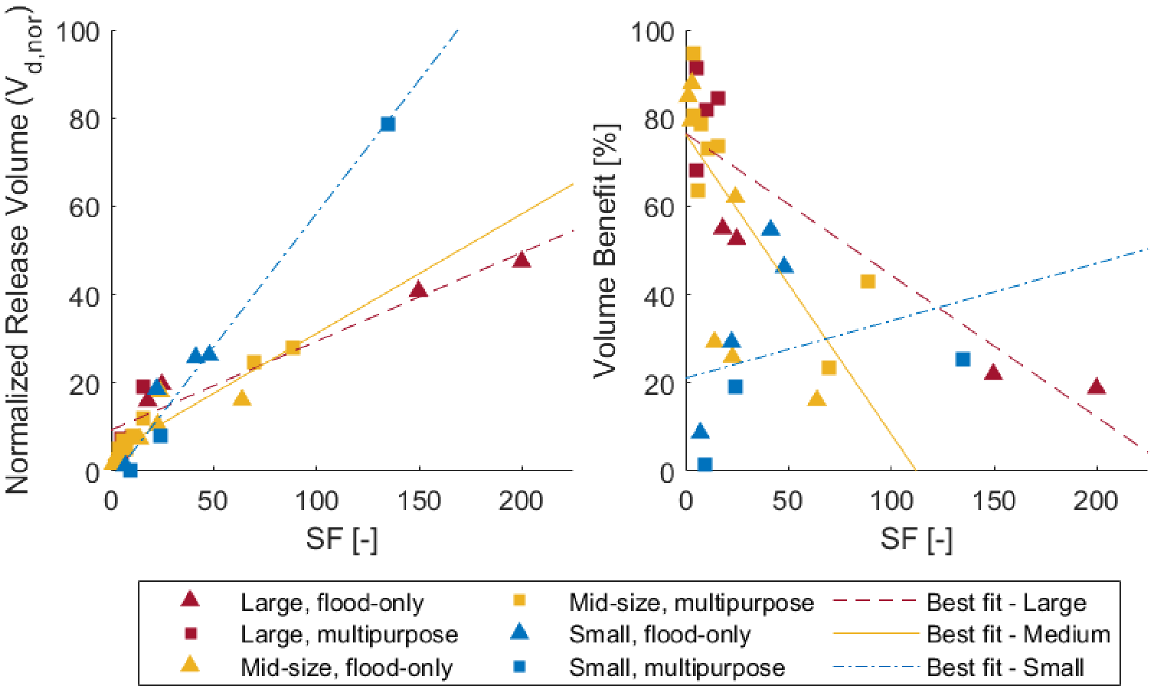
Preprint. Discussion started: 23 July 2024

3.2.3 SF and Reservoir Performance



460 **Figure 14. The relation between SF (relative water availability) and normalized release volume ($V_{d,nor}$; left) and volume benefit (B_v; right).**

As we discussed in 3.1, our hypothesis was refuted: reservoirs with a very high SF were overall unable to improve penalty benefit significantly (Figure 4, left). This unfortunately remains the same for volume benefit (Figure 14, right). While SF has a relationship with release volume, more water availability does not correlate well with higher penalty benefit or deficit volume benefit. We propose that this could be due to the limited capacities in these reservoirs: as demonstrated with Gottswald (3.1.1), the reservoir is simply too small to take advantage of the water available or to compensate for large deficits.

In the large and medium size categories, benefit generally increases with decreasing SF. For example, the low improvement, high release group consists exclusively of reservoirs with high SF. Even reservoirs with higher SF 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 SF and benefit is a strong imbalance between incoming water and the capacity. This seems unlikely to improve, even if rules are significantly changed.

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

For small reservoirs, the relationship is the opposite: benefit generally increases with increasing SF. This exception could be due to a couple of reasons. One explanation could be model uncertainties: LARSIM is not typically used for small catchment sizes like that of a small reservoir, meaning that the model results could be unreliable. In this case, long-term gauge data would be needed to validate the results. Alternatively, 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. This problem could be resolved by continuing to lower the Q_r.

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. Under these rules and for a representative subset of 30 reservoirs, we found that reservoirs can release up to 80 times their capacity and reduce drought penalties and water deficits by almost 95% over a 24-year simulation period, though not simultaneously. The median volume of water made available by this strategy is approximately 1.4 million m^3.

Contrary to our hypothesis, the relative water availability—defined in this study as the storage 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—an exception are the smallest reservoirs investigated in this study, for whom increased relative water availability tends to improve overall benefit. However, the overall lack of generalizable rule indicates that water availability may not be a good predictor for drought performance.

Despite 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 high performance when operating under uncertain operational forecasts? Many reservoirs already lose significant volumes of water when maintaining flood protection in a perfect knowledge scenario; their flood performance and remaining drought benefit in real-time operation should be investigated before pursuing in-situ implementation. The benefit of this water is only conceptually defined and has no connection to the environment or human society—how much more effective could farming operations be with this water?

https://doi.org/10.5194/egusphere-2024-2167
Preprint. Discussion started: 23 July 2024

Does the water come at times when farmers need it? Moreover, these results are predicated on the assumption 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.

5 Code and Data Availability

The map in Figure 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 https://doi.org/10.5281/zenodo.12724797.

6 Author Contribution

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.

7 Competing Intersts

The authors declare that they have no conflict of interest.

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