

Assessing the cumulative impact of on-farm reservoirs on modeled surface hydrology

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Abstract

On-farm reservoirs (OFRs) are crucial water bodies for meeting global irrigation needs. Farmers use OFRs to store water from precipitation and runoff during the rainy season, which they then use to irrigate their crops during the dry season. Despite their importance to crop irrigation, OFRs can have a cumulative impact on surface hydrology by decreasing flow and peak flow. Nonetheless, there is limited knowledge on the spatial and temporal variability of the OFRs' impacts. Therefore, to gain an understanding of the cumulative impact of OFRs on surface hydrology, we propose a novel framework that integrates a top-down, data-driven, remote sensing-based algorithm with physically based models, leveraging the latest developments in the Soil Water Assessment Tool+ (SWAT+). We assessed the impact of OFRs in a watershed

located in eastern Arkansas, the third most irrigated state in the USA. Our results indicate that the presence of OFRs in the watershed is associated with a decrease in annual flow of 14-24% and a mean reduction in peak flow of 43-60%. In addition, the cumulative impact of the OFRs was not equally distributed across the watershed, varying according to the OFR spatial distribution and their storage capacity. The results of this study and the proposed framework can support water agencies with information on the cumulative impact of OFRs, aiming to support surface water resources management. This is relevant because the number of OFRs is expected to increase globally as a response to climate change under severe drought conditions.

36

1 Introduction

Inland water bodies (e.g., lakes and reservoirs) comprise a small fraction of Earth's surface; however, they are responsible for storing the vast majority of the accessible freshwater resources available on Earth. In addition, these water bodies are pivotal components of surface hydrology, playing key roles in ecosystem functioning and providing habitats for wildlife (Khazaei et al., 2022; Verpoorter et al., 2014). In particular, on-farm reservoirs (OFRs) are crucial for meeting global irrigation needs (Döll et al., 2009; Downing, 2010; Van Den Hoek et al., 2019). Farmers use OFRs to store water from precipitation and runoff during the rainy season to irrigate their crops during the dry season (Habets et al., 2018; Perin et al., 2021; Vanthof & Kelly, 2019; Yaeger et al., 2017; Yaeger et al., 2018). The number of OFRs is expected to rise worldwide in the coming decades, and estimates show that there are more than 2.1 million OFRs in the US alone (Downing, 2010; Renwick et al., 2005). OFRs are often built to manage surface water resources more efficiently and to help mitigate the impact of extreme droughts, which are projected to increase due to climate change (Habets et al., 2018; Van Der Zaag & Gupta, 2008). Although OFRs are small water bodies (< 50 ha), they can have cumulative impacts on the local and remote hydrology in the watersheds where they occur (e.g., decreasing flow and peak

53 flow) (Habets et al., 2018). Their impact may contribute to worsening the surface water stress
54 already intensified by climate change and population growth (Vörösmarty et al., 2010). Most
55 studies have focused on the cumulative impact of major large reservoirs on downstream flow
56 alteration (Chalise et al., 2021; Mukhopadhyay et al., 2021), but limited analysis has been
57 performed on the impact of OFRs on downstream flow availability.

58 To quantify the impact of OFRs on surface hydrology, it is necessary to understand [the](#)
59 [spatial and temporal variability of surface water extent in OFRs](#), as well as how the impacts are
60 related to the OFR networks, as the impacts of OFRs are not the sum of the individual OFR
61 impacts, but rather the sum and their interaction effects (Canter & Kamath, 1995; Habets et al.,
62 2018). By gathering information from several studies conducted in different countries (e.g., the
63 USA, France, Brazil), Habets et al. (2018) conducted a thorough assessment of the OFRs' impact
64 on surface hydrology and the various types of models and methods for representing OFRs
65 within the watershed. The authors concluded that the modeled OFR impacts have a wide
66 range, and that most studies reported a mean annual reduction in flow, which ranged from
67 0.2% to 36%. In addition, the variability of the impact, as identified in these previous studies,
68 was higher when assessing low flows over multiple years, with reductions ranging from 0.3 to
69 60%. In general, the estimated mean annual reduction in flow was $13.4\% \pm 8.0\%$, and the mean
70 decrease in peak flow was up to 45% (Habets et al., 2018).

71 The approaches used to quantify the cumulative impact of OFRs can be divided into
72 two classes: data-driven methods and process-based hydrological modeling. The data-driven
73 approaches include three primary methods. The first method relies on assessing measured
74 inflows and outflows of selected OFRs, aiming to quantify their hydrological functioning with
75 the assumption that the cumulative impacts are the sum of individual impacts (Culler et al.,
76 1961; Dubreuil and Girard, 1973; Kennon, 1966). A variation of the cumulative impact assessment
77 approach has been recently suggested by Hwang et al. (2021) for comparing naturalized flows
78 and controlled flows to assess the impact of large reservoir systems. The second method is
79 based on statistical analysis of the observed discharge time series of a watershed as the

80 number of OFRs increased (Galéa et al., 2005; Schreider et al., 2002). This approach is limited
81 when discriminating the specific impact of OFRs from those of land use and land cover
82 change, and when explicitly representing the OFRs in the models, given that OFRs tend to be
83 aggregated within the entire basin (i.e., OFRs surface area and/or storage are summed and
84 modeled as a unique water impoundment). The third method involves conducting a paired-
85 catchment experiment by comparing the flows from two adjacent and similar catchments:
86 one with OFRs and the other without OFRs (Thompson, 2012). This technique requires the
87 catchment properties (e.g., soils, topology, lithology, land cover) to be spatially homogeneous,
88 which is practically nonexistent at a large scale, hence, this method's applications are limited.

89 The second class of methods relates to hydrological modeling, which is the most widely
90 used approach for assessing the impacts of OFRs. A variety of models have been proposed by
91 coupling the OFRs' water balance with a quantitative approach to estimate the OFRs' water
92 volume change (Fowler et al., 2015; Habets et al., 2014; Jalowska & Yuan, 2019; Yongbo et al.,
93 2014; Ni & Parajuli, 2018; Perrin, 2012; Zhang et al., 2012). In general, the models have three main
94 components: the OFR water balance, a quantitative approach to quantify OFR inflows, and a
95 spatial representation of the OFR's network. These different model components result in
96 various limitations and assumptions—a comprehensive assessment of these three
97 components and their impact on hydrological simulations is provided in a recent review
98 (Habets et al., 2018). Therefore, when selecting a specific model to assess the impacts of the
99 OFRs, it is essential to consider the model's suitability for addressing the target issue, as well
100 as its limitations and assumptions. The selected model should also have the capability to
101 incorporate and assimilate varying land-surface conditions (e.g., soil moisture) and time-
102 varying OFR storages, which can be obtained either from local monitoring or through remote
103 sensing.

104 Most studies have used remotely-sensed products such as soil moisture (e.g., SMAP;
105 Entekhabi et al., 2010), groundwater (e.g., GRACE; (Tapley et al., 2004) and land cover
106 conditions (e.g., MODIS; (Justice et al., 1998)) for assimilating current conditions into

hydrological models. Given that OFRs tend to occur in high numbers (e.g., hundreds), multiple studies leveraged the latest developments and availability of satellite imagery to monitor the occurrence and dynamics of OFRs (Jones et al., 2017; Ogilvie et al., 2018, 2020; Perin et al., 2022; Perin et al., 2021a, 2021b; Van Den Hoek et al., 2019; Vanthof & Kelly, 2019), which could provide helpful information on local storage conditions for predicting downstream streamflow. Furthermore, these studies enabled the quantification of the number of OFRs and their spatial and temporal variability in surface water areas and storage within the watershed where they occur, providing relevant information for modeling the cumulative impact of OFRs. Despite the complementary information provided by satellite imagery, there are only a few studies that incorporated remote sensing-derived information (e.g., soil moisture derived from SMAP, groundwater based on GRACE) with hydrological modeling (Ni and Parajuli, 2018; Yongbo et al., 2014; Zhang et al., 2012), and these studies are limited to mapping the OFRs occurrence, or to snapshots of the OFRs conditions (e.g., surface area). To the best of our knowledge, no study has combined the spatial and temporal variability of the OFRs—derived from multi-year satellite imagery time series analyses—with a process-based hydrological model.

Therefore, to gain an understanding of the cumulative impact of OFRs on surface hydrology, this study proposes a new approach that systematically integrates the dynamically varying conditions of OFRs based on satellite imagery time series (Perin et al., 2022) using a top-down data-driven approach within the latest SWAT+ model. The Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012) has been widely used to model the impacts of the OFRs (Jalowska and Yuan, 2019; Kim and Parajuli, 2014; Ni et al., 2020; Ni and Parajuli, 2018; Perrin, 2012; Rabelo et al., 2021; Yongbo et al., 2014; Zhang et al., 2012), in part given by a comprehensive collection of model documentation and guidelines available online (<https://swat.tamu.edu/>). Our objectives are to (1) assess the spatial and temporal variability of the cumulative impact of OFRs at the watershed and subwatershed levels, and (2) to quantify the intra- and interannual impacts of the OFRs on flow and peak flow at the channel scale. By integrating the SWAT+ model with a remote sensing assimilation algorithm to account for the

OFRs spatial variability—which is lacking in most of studies assessing the OFRs impacts—and leveraging a digitally-mapped OFRs dataset (Yaeger et al., 2017), we are providing a new approach that can be replicated in watersheds across the world, and used to support water agencies with information to improve surface water resources management.

2 Methods

2.1 Study region

The study region is located in eastern Arkansas, USA, the third most-irrigated state in the USA (ERS-USDA, 2017). The area has a humid subtropical climate with a 30-year annual average precipitation of ~1300 mm/year (PRISM Climate Group, 2022). Precipitation is distributed mainly between March and May, with an average of ~400 mm during these months (Perin et al., 2021b). The region has experienced a steady increase in irrigated agriculture, with commonly irrigated crops including corn, rice, and soybeans (NASS-USDA, 2017). A recent study (Yaeger et al., 2017) digitally mapped 330 OFRs located in the study region (Fig. 1) using the high-resolution (1-m) National Agricultural Imagery Program archive in combination with 2015 sub-meter spatial resolution Google Earth satellite imagery. Most of the OFRs (95%) have a surface area < 50 ha, and they are concentrated in the eastern portion of the study region (Fig. 1). Currently, there is no comprehensive and up-to-date inventory of all OFRs in the basin. This limitation is partly because many of these man-made structures are located on private properties, making them difficult to document. As a result, the study only accounts for a fraction of the total OFRs present in the study region.

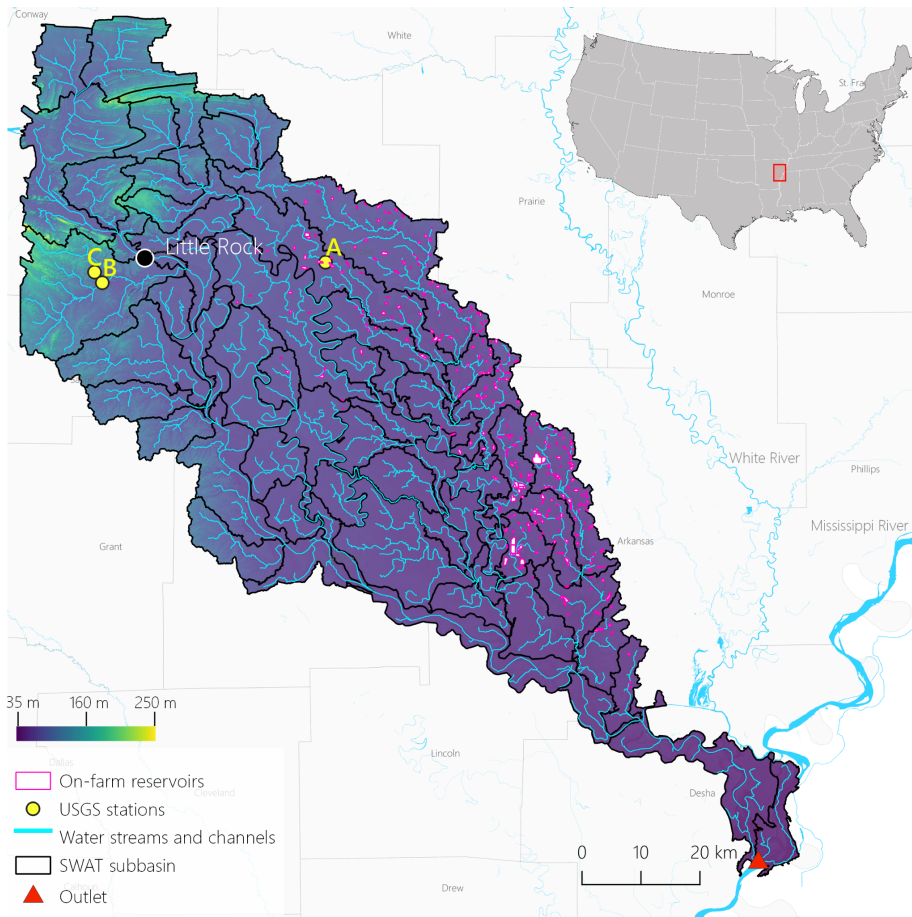


Figure 1–Study region located in eastern Arkansas, USA, the subwatersheds and surface water streams and channels delineated with SWAT+, the model outlet, the United States Geological Survey (USGS) stations (United States Geological Survey Water Data for the Nation, 2022) used for flow calibration and validation, the digitized OFRs (Yaeger et al., 2017), and the Digital Elevation Model (DEM) used in the modeling (Farr et al., 2007).

2.2 SWAT+ model setup

2.2.1 The Soil Water Assessment Tool to model the impacts of OFRs on surface hydrology

The SWAT model is a time-continuous, semi-distributed hydrological model widely used globally—more than 5,000 peer-reviewed publications have been published since its launch in the early 1980s (Publications | Soil & Water Assessment Tool (SWAT), 2022). The large number of SWAT applications globally revealed the model development needs and its limitations. To address the present and future challenges when modeling with SWAT, the model source code has undergone significant modifications, and a completely revised version of the model was proposed in SWAT+ (Bieger et al., 2017). SWAT+ utilizes the same equations as SWAT to simulate hydrological processes; however, it provides users with greater flexibility when configuring the model (e.g., defining management schedules, routing constituents, and connecting managed flow systems to the natural stream network) (Bieger et al., 2017).

The SWAT+ is undergoing constant improvements ([Chawanda et al., 2020](#); [Molina-Navarro et al., 2018](#)), and a new module ([Molina-Navarro et al., 2018](#)) has been recently developed to facilitate the optimal integration of a water body and its drainage area within simulated hydrological processes. In previous versions of the model, when delineating the watershed area draining into a water body, users were required to place an outlet at a specific point in the water stream's network, and areas between the rivers' subwatersheds flowing into the water body were therefore excluded. If these areas are disregarded, critical hydrological processes (e.g., evaporation, overland and/or groundwater flow) flowing into the water body are not accounted for (Molina-Navarro et al., 2018). This former approach can lead to inaccuracies when delineating the watershed areas, mainly when the results are used as input to an OFR model component. The newest versions of SWAT+ consider the OFRs' outline (i.e., shape and surface area) when delineating the watersheds; hence, accounting for the entire drainage area flowing into the waterbody (Molina-Navarro et al., 2018). In addition, the latest versions allow for adding more than one OFR per subwatershed by associating the OFR with

channels—components of the watersheds, as well as finer divisions and extensions of water stream reaches, enabling modeling analyses at the channel scale. When simulating the impact of the OFRs at the channel scale, there is a higher level of detail of where and when the OFRs are contributing to changes in surface hydrology, unlike the previous versions of the model, which allowed adding only a single OFR per subwatershed placed at the subwatershed outlet as a point (Arnold et al., 2012), and therefore, the analyses were conducted at the subwatershed scale.

We modeled the impact of OFRs on surface hydrology using the QSWAT+ (v.2.1.9) SWAT+ model interface together with SWAT+ Editor (v.2.1.0) to set up the model, to input the required datasets (e.g., DEM, land use and land cover layer, interpolated meteorological climate information), and to run the different modeling scenarios.

The modeled watershed (710,700 ha, Fig. 1) comprised 68 subwatersheds and a total of 642 Hydrological Response Units (HRUs)—HRUs are unique portions of the subwatersheds characterized by distinct land use and management, as well as unique soil attributes. We set up daily simulations for 30 years (1990–2020), including five years of model warm-up to establish the initial soil water conditions and hydrological processes. The watershed was delineated using the Shuttle Radar Topography Mission DEM (30 m) (Farr et al., 2007). Additionally, we set the channel length threshold to 6 km² and the stream length threshold to 60 km². We placed an outlet in the southern part of the study region—where the lowest part of the watershed is located (Fig. 1). We created the HRUs using the dominant option—this option selects the largest HRU within the subwatershed as the general HRU—within QSWAT+ interface, and used the National Land Cover Database (30 m) (Homer et al., 2020), and Gridded Soil Survey Geographic Database (gSSURGO) (Soil Survey Staff, USDA-NRCS, 2021) (100 m) as inputs to the model. The gSSURGO layers were processed according to their guidelines when using them on QSWAT+ (George, 2020). For climate data, we extracted the centroid coordinates of each subwatershed. We used these centroids to download 30 years of daily precipitation, minimum and maximum temperatures, surface downward shortwave radiation,

wind velocity, and relative humidity from the Gridded Surface Meteorological Datasets (Abatzoglou, 2013), which are available in Google Earth Engine (Gorelick et al., 2017). The time series of each subwatershed centroid was added to the SWAT+ Editor as independent weather stations.

2.2.2 Model calibration and validation procedures

We used monthly measured flow from three USGS stations (Fig. 1 and Table 1) to calibrate and validate the model flow simulations. The USGS flow time series length varied between 14 and 25 years, and we used 60% of the time series for calibration and 40% for validation for each USGS station (Table 1). We assessed the performance of the model by calculating the Coefficient of determination (r^2), Percent bias (PBIAS, %, Equation 1) (Yapo et al., 1996), and the Nash–Sutcliffe model efficiency coefficient (NSE, Equation 2) (Nash and Sutcliffe, 1970). PBIAS is the relative mean difference between the simulated and measured flow values, reflecting the model's ability to simulate monthly flows accurately. The optimal PBIAS is zero, and low-magnitude values indicate better model performance. Positive PBIAS indicates overestimation bias, whereas negative values denote underestimation bias. The NSE indicates how well the model simulates flows, ranging from a negative value to one, with a value of one indicating a perfect fit between the simulated and measured flow values. In general, the model simulations of monthly flow are considered satisfactory when r^2 ranges from 0.60 to 0.75, PBIAS ranges from $\pm 10\%$ to $\pm 15\%$, and NSE ranges from 0.50 to 0.70 (Moriassi et al., 2015).

Table 1—USGS stations, drainage areas, and the periods used for flow calibration and validation.

USGS station	Station id	Drainage Area (ha)	Period (years)	
			Calibration	Validation
07264000	(A)	53,600	1995–2010	2010–2020
07263555	(B)	25,400	2007–2014	2014–2020
07263580	(C)	5,300	1997–2011	2011–2020

$$\text{PBIAS} = \frac{\sum_{i=1}^n (Y_i - X_i)}{\sum_{i=1}^n X_i}$$

(1)

$$\text{NSE} = 1 - \frac{\sum_{i=1}^n (X_i - Y_i)^2}{\sum_{i=1}^n (X_i - \bar{X})^2} \quad (2)$$

Where X_i is the measured flow and Y_i is the simulated flow.

We conducted a sensitivity analysis using the SWAT+ ToolBox (v.0.7.6) (SWAT+ Toolbox, 2022) to reveal the most sensitive parameters when simulating flow—a total of 10 parameters (Table S 1) were tested based on previous studies that used SWAT/SWAT+ to model the impact of water impoundments on surface hydrology (Jalowska & Yuan, 2019; Yongbo et al., 2014; Ni et al., 2020; Ni & Parajuli, 2018; Perrin, 2012; Rabelo et al., 2021; Zhang et al., 2012). Following the sensitivity analysis, we selected the five most sensitive parameters (Table 2) and proceeded with a manual calibration using the SWAT+ Toolbox. We aimed to improve the model's monthly flow predictions by testing the parameters one at a time and adjusting their values between -20% and 20% in 5% increments, based on their respective ranges. The final calibrated parameters and their fitted values are shown in Table 2.

Table 2—Monthly flow calibration parameters.

Parameter	Description	Range	Value
CN2	SCS runoff curve number	35–95	0.20*
SOL_AWC	Available water capacity (mm/mm)	0.01–1	-0.20*
ESCO	Soil evaporation compensation coefficient	0.01–1	0.50
PERCO	Percolation coefficient (fraction)	0–1	0.60
CANMX	Maximum canopy storage (mm)	0–100	75

*Denotes relative percentage change.

2.3 OFRs representation in SWAT+

Multiple OFRs can be added to the same subwatershed by associating them with channels (Dile et al., 2022). The OFRs must have at least one outlet channel, and they may have none or multiple inlet channels. Therefore, most OFR-related processes within the model involve

determining what channels form inflowing and outflowing channels for each OFR. Ideally, each OFR would interact with a channel, and therefore, have a channel entering, leaving, or within the OFR. Nonetheless, it is common to have OFRs that do not intersect with any channel (Dile et al., 2022)—this is the case for 93% of the OFRs in our study region. The OFRs in our study region are not dams along the streams but instead engineered water impoundments that are indirectly connected to the main streams via pipes and pumps (Yaeger et al., 2017). A possible solution would be modifying the OFRs' shapes by dragging them to the closest channel (Dile et al., 2022). However, this would require extensive modifications of the OFRs' shapes. Additionally, when an OFR is added to a channel, it is split into two channels, and the model must account for these two newly created channels during the water routing calculations. For this reason, adding multiple OFRs to the same channel or adding multiple OFRs closely located to the same channel can be a cumbersome process that leads to numerous routing errors.

To overcome these challenges, we aggregated the OFRs' surface area and added aggregated OFRs to the model. This adaptation involved two steps. First, for each of the 330 OFRs, we searched for the closest channel by calculating the distance between the OFR's centroid and the multiple channels within each subwatershed. Then, we aggregated all the OFRs associated with each channel by summing their surface areas and adding a polygon representing the aggregated area to the OFR. This approach resulted in 69 aggregated OFRs that were added to 67 different channels located in 16 subwatersheds. The surface area of the aggregated OFRs varied between 3.05 ha and 165.67 ha, and the number of OFRs in each aggregated OFR varied between 2 and 12. To avoid confusion, for the rest of the manuscript, we refer to OFRs as the aggregated OFRs, and not the individual OFRs shown in Fig. 1.

2.4 OFR's water balance

We did not have access to water abstraction data from the OFRs; therefore, all abstractions were modeled using Equation 3, which accounts for water flowing out of the OFR,

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as well as losses due to evaporation and seepage. The volume of water in an OFR, which changes due to changes in inflows, outflows, or abstractions, is associated with changes in the surface area of the OFR. A reduction in surface area (Equation 4) typically leads to a corresponding decrease in water volume. If inflows are insufficient to fill the OFR, water will not be routed to the downstream channel.

For each of the aggregated OFR, the initial water volume (V_{stored} , see Equation 3) was calculated using the SWAT+ default rule, which is a simple multiplication of the OFR surface area by a factor of 10, similar to other studies based on SWAT+ (Ni and Parajuli, 2018; Zhang et al., 2012). For a scenario where the OFR has a surface area of 1 hectare (10,000 m²), the corresponding volume would be 100,000 m³—this is a limitation of our study, as the assumption was necessary due to the absence of available bathymetry data. In addition, since we did not have access to the OFRs' release rates, we used the model's default release rule, which sets the OFRs to release water when the spillway volume is reached—80% of the OFRs' capacity (Bieger et al., 2017). While farmers may occasionally withdraw water directly from

OFRs, in our study region, most irrigation appropriations are taken from channels and streams. This is consistent with irrigation practices in Arkansas, where large-scale surface water projects withdraw directly from rivers and distribute water via canals and pipelines. Similarly, watershed-scale modeling that incorporates irrigation withdrawals into the river system yields better flow simulations, especially during low-flow periods (Brochet et al., 2024). Given this, and in the absence of high-resolution data on reservoir-specific withdrawals, our framework assumes that inflow to OFRs already reflects upstream irrigation abstractions. Thus, Equation 3 omits an explicit irrigation withdrawal term for OFRs, and our approach focuses on quantifying the hydrological signal alterations through natural versus reservoir-influenced flow comparisons.

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$$V = V_{\text{stored}} + V_{\text{flowin}} - V_{\text{flowout}} + V_{\text{pcp}} - V_{\text{evap}} - V_{\text{seep}} \quad (3)$$

Where V is the volume of water in the OFR at the end of the day (m^3), V_{stored} is the volume of water stored at the beginning of the day (m^3), V_{flowin} is the volume of water entering the OFR during the day (m^3), V_{flowout} is the volume of water flowing out of the OFR (m^3), V_{pcp} is the volume of precipitation falling on the water body (m^3), V_{evap} is the volume of water removed from the OFR due to evaporation, and V_{seep} is the volume of water lost by seepage (m^3).

The OFR surface area is used to calculate the amount of precipitation falling on the water body and the amount of water lost through evaporation and seepage. Given the initial, OFR surface area obtained from one of the three modeling scenarios, the OFR surface area was modeled daily. The surface area varied according to the volume of water stored in the reservoir. Equation 4 is used to estimate the surface area:

$$\text{Surface area (ha)} = \beta_{\text{sa}} * V \quad \text{expsa} \quad (4)$$

$$\text{expsa} = \frac{\log_{10}(V_{\text{em}}) - \log_{10}(V_{\text{pr}})}{\log_{10}(\text{Surface area}_{\text{em}}) - \log_{10}(\text{Surface Area}_{\text{pr}})} \quad (5)$$

$$\beta_{\text{sa}} = \left(\frac{V_{\text{em}}}{\text{Surface area}_{\text{em}}} \right) \text{expsa} \quad (6)$$

Where β_{sa} is a surface area coefficient, V_{em} is the volume of water (m^3) at the emergency spillway, V_{pr} is the volume of water (m^3) at the principal spillway, $\text{Surface area}_{\text{em}}$ is the surface area (ha) at the emergency spillway, and $\text{Surface area}_{\text{pr}}$ is the surface area at the principal spillway. Spillways release the water once it reaches a specific level. Most OFRs have uncontrolled spillways, implying that there are no gates to control the outflow. The outflow through the spillway depends on the level above the spillway crest. An emergency spillway,

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whose crest is typically at a higher elevation than the principal spillway, is an additional spillway designed to release excess water during heavy flooding. The surface area of the OFR represents the water spread area corresponding to a given level in the reservoir, which typically increases as the reservoir level rises.

The volume of precipitation falling into the OFR is calculated using Equation 7:

$$V_{pcp} = 10 * R_{day} * \text{Surface Area (ha)} \quad (7)$$

Where R_{day} is the amount of precipitation falling into the OFR on a given day (mm).

Evaporation losses are calculated using Equation 8:

$$V_{evap} = 10 * \eta * E_0 * \text{Surface Area (ha)} \quad (8)$$

Where η is an evaporation coefficient (0.6), and E_0 is the potential evapotranspiration for a given day (mm).

Seepage losses are calculated using Equation 9:

$$V_{seep} = 240 * K_{sat} * \text{Surface Area (ha)} \quad (9)$$

where K_{sat} is the effective saturated hydraulic conductivity of the reservoir bottom (mm/hr).

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2.4 Scenario Analysis

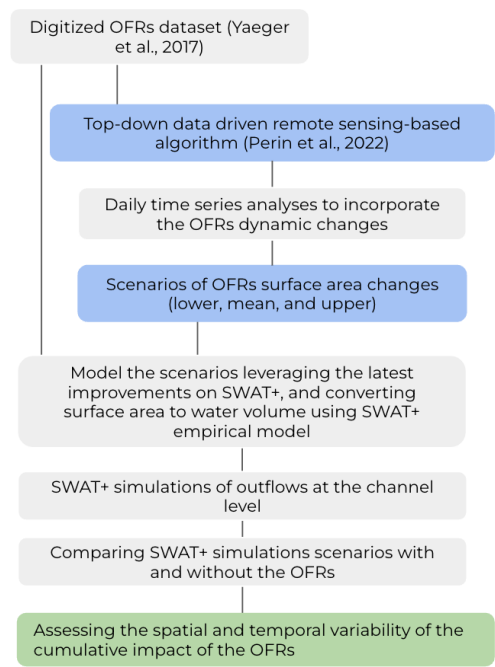
Given our representation of the OFRs in SWAT+, we assessed the impact of the OFRs on surface hydrology at the channel scale. To do so, we established a model baseline scenario without the presence of OFRs in the watershed. Additionally, we divided the channels into four classes (i.e., low and high flow classes) based on their mean baseline flow. The different class intervals were calculated using the mean flow quartiles, accounting for all channels, which resulted in the

following baseline flow classes: (1) 0.001–0.25 m³/s, (2) 0.25–0.50 m³/s, (3) 0.50–2.11 m³/s, and (4) 2.11–17.50 m³/s.

To account for the OFRs' variation in surface area (i.e., change in storage capacity), we propose a novel approach that leverages a top-down data-driven model based on satellite imagery (Fig. 2). We used this model to create three modeling scenarios using daily OFRs surface area time series—these scenarios were based on the methodology proposed by Perin et al. (2022). The authors employed a multi-sensor satellite imagery approach combined with the Kalman filter (Kalman, 1960) to calculate the daily OFRs' surface area change between 2017 and 2020. The proposed algorithm accounts for the uncertainties in both the sensor's observations and the resulting surface areas. By improving the OFR's surface area observations cadence, the algorithm enables a deeper understanding of the OFR's surface area intra- and inter-annual changes, which are key pieces of information that can be used to better assess and manage the water stored by the OFR (Perin et al., 2022). The daily surface area time series—derived by combining PlanetScope, RapidEye, and Sentinel-2 satellite imagery (Perin et al., 2022)—of each OFR was used to simulate three scenarios (i.e., lower, mean, and upper) representing the OFRs' capacity in terms of surface area. The mean scenario represents the regular condition of the OFRs, and it is the mean of the daily surface area time series derived from the Kalman filter. The lower and upper scenarios represent the lowest and highest capacities of the OFRs, based on the 95% confidence interval limits of the surface area, calculated using the daily time series. Please refer to Perin et al. (2022) for more details on how the 95% confidence interval was calculated.

The SWAT+ model does not allow for direct incorporation of a daily surface area time series because it calculates surface area dynamically (Equation 4) based on changes in water volume through the reservoir water balance equation (Equation 3). It is structured to accept a single surface area value per scenario, which then varies internally. Incorporating time-varying surface area data, such as from the Kalman filter, would require modifications to the model that are currently not supported. Therefore, a single surface area value was assigned to each

374 scenario and OFR, with lower, mean, and upper values used as starting points for the model's
375 water balance simulations. This initial surface area reflects the OFR's maximum surface area at
376 full capacity for each scenario. For example, in the lower scenario, an initial surface area of 1.2
377 ha represents the maximum area for this OFR. As model iterations proceed, the surface area is
378 recalculated based on Equation 4. The initial OFR surface area was kept constant during the
379 simulation period (Ni et al., 2020; Ni and Parajuli, 2018; Perrin, 2012). In other words, the OFR
380 surface area varied according to Equation 4, however, the maximum surface area did not
381 exceed the initial value. To assess the impact of the OFRs on surface hydrology, we compared
382 the baseline flow with the flow simulated by each surface area scenario—i.e., comparing the
383 flow changes with and without OFRs, a common approach used by previous studies (Habets
384 et al., 2018).



385

Figure 2—A new approach to integrate a top-down data-driven remote sensing-based algorithm, that assesses the OFR's dynamic conditions (Perin et al., 2022), with the latest SWAT+ model developments.

We estimated the impact of the OFRs on surface hydrology by calculating the percent change (Equation 10) of monthly flow between the baseline and the three surface area scenarios, including all OFRs. The annual impact on flow was calculated by averaging the mean percent change over the months. We also calculated the distribution of the percent change for each baseline flow class. The distribution was assessed using two-dimensional kernel density estimation (KDE) plots. Unlike discrete bins (e.g., histograms), KDE plots display a continuous density estimate of the observations using a Gaussian kernel. Additionally, we assessed the percentage changes in peak flow. For this analysis, peak flow is defined as equal to or higher than the 99th flow percentile calculated using the entire flow time series (Equation 10). It is important to keep in mind that the impact of the OFRs on this study is solely based on modeling scenarios and does not account for OFR management practices, which represents a key limitation of this simulation study.

$$\text{Percent change (\%)} = \left(\frac{Y_i - X_i}{X_i} \right) * 100 \quad (10)$$

Where X_i is the baseline flow, and Y_i is the simulated flow of each surface area scenario.

3 Results

3.1 Model calibration and validation

The model calibration and validation were done using the three USGS stations presented in Fig. 1 and Table 1, and accounting for all OFRs in the study region. When comparing the monthly simulated flow with the measured flow for the calibration period, there was a good agreement ($0.71 \leq r^2 \leq 0.93$), and a satisfactory model efficiency ($0.68 \leq \text{NSE} \leq 0.90$) for all three stations (Fig. 3). In addition, the PBIAS magnitude was < 3% for station A, and < 12% for stations B and C. Meanwhile, the validation period had r^2 ranging between 0.69 and 0.86, and the NSE

411 between 0.68 and 0.83, with PBIAS magnitude < 10% for stations A and B, and 18.12% for station
412 C. In general, for stations A and C, the model overestimated flow values (i.e., positive PBIAS)
413 mostly during flow events < 3 m³/s, and the model underestimated flow (i.e., negative PBIAS)
414 for station B during flows > 20 m³/s (Fig. 3). These findings are consistent with a previous study
415 conducted in western Mississippi near our study region (Ni and Parajuli, 2018). Even though
416 during the validation period, Station B had a PBIAS magnitude higher than 15%, the r² and NSE
417 values from both the calibration and validation periods indicate satisfactory modeling
418 performance when simulating monthly flow (Moriasi et al., 2015). Given that none of the OFRs
419 were directly connected with the streams where the stations were located (Fig. 1), and there
420 were no OFRs near stations B and C, the calibration and validation metrics with and without
421 the OFRs were very similar, with differences smaller than 1%.

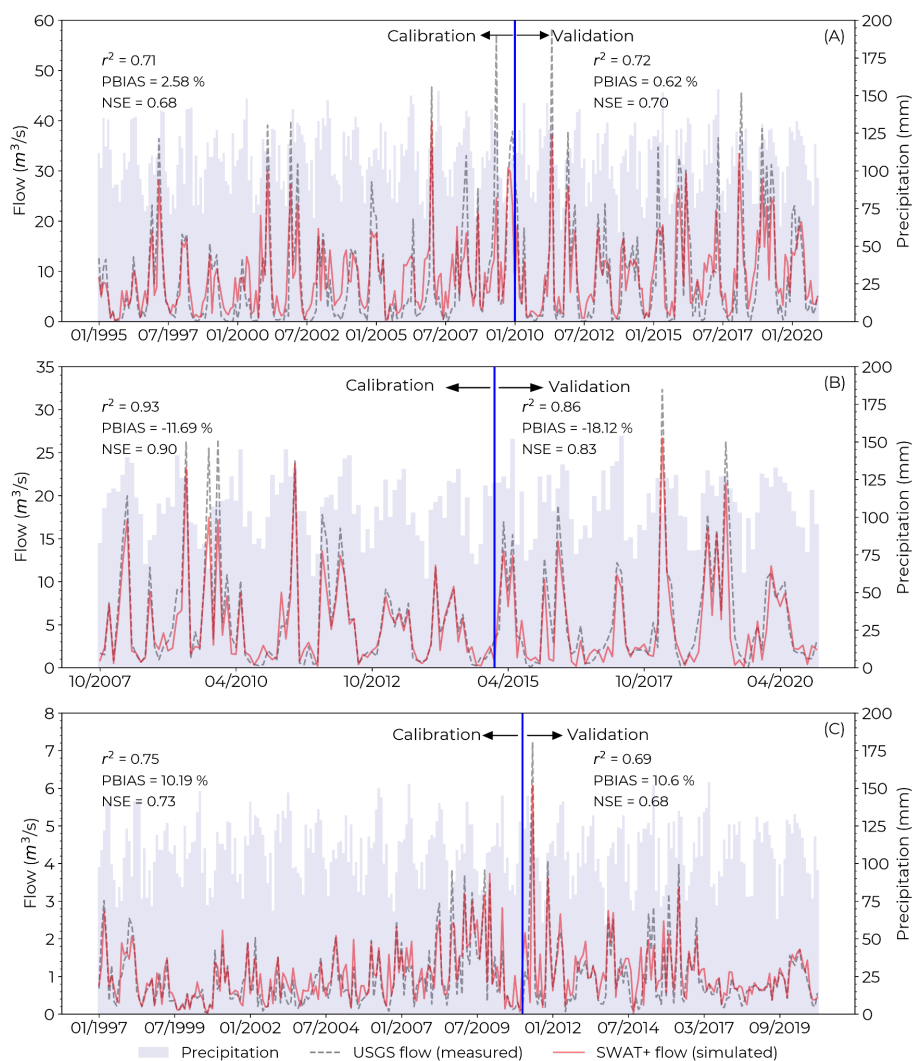


Figure 3—Flow calibration and validation time series for the three USGS stations A (07264000), B (07263555), and C (07263580). See Fig. 1 and Table 1 for more information about the USGS stations. The precipitation time series represents the monthly accumulated precipitation at the watershed scale (i.e., for the entire study region).

3.2 Percent change in flow

We assessed the impact of the OFRs on flow by comparing the baseline flow (i.e., without the OFRs) with the three surface area scenarios generated from the Kalman filter approach—lower, mean, and upper (see section 2.4, and Fig. 2). The total surface area (i.e., summing all OFRs surface area) was 2,176 ha for the lower, 2,766 ha for the mean, and 3,370 ha for the upper, and the three scenarios had a similar OFRs surface area distribution (Fig. 4). In addition, most of the OFRs had surface areas < 50 ha—78%, 71%, and 62% of the OFRs for the lower, mean, and upper scenarios.

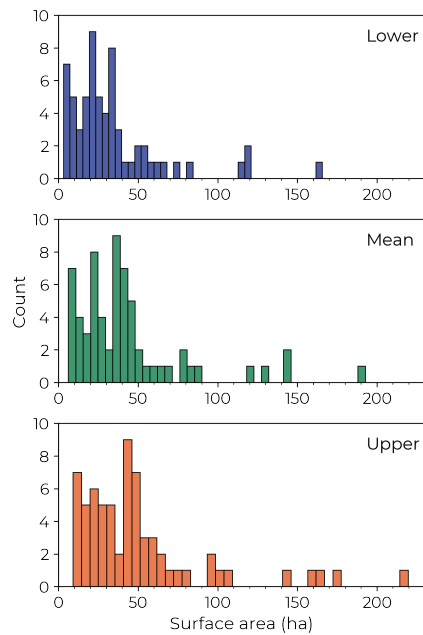


Figure 4—OFR's surface area distribution for the three surface area scenarios, lower, mean, and upper.

Figure 5 categorizes the channels into four distinct groups, with each category illustrating the percentage change in flow throughout the year, displayed along the x-axis by month. The three bar colors represent different scenarios, while bar heights illustrate variations

across channels and years. For example, the bars for January include all January data spanning from 1990 to 2020, enabling a thorough comparison of seasonal and year-to-year flow changes.

The impact of the OFRs on monthly flow varied throughout the year. The largest impacts occurred between January and May for all flow classes (Fig. 5). During these months, including all surface area scenarios, the mean decrease in flow (i.e., negative mean percent change) was $-34.4 \pm 6\%$ for class 1, $-37.6 \pm 5\%$ for class 2, $-30.0 \pm 6\%$ for class 3, and $-34.1 \pm 6\%$ for class 4. For all classes, the most significant reduction in flow occurred during March ($\sim -40\%$). Meanwhile, the impact of the OFRs was more minor during the second half of the year, in which the mean percent change in flow was $-12.0 \pm 3\%$ for class 1, $-12.5 \pm 5\%$ for class 2, $-1.4 \pm 4\%$ for class 3, and $-2.6 \pm 10\%$ for class 4 (Fig. 5).

When assessing the mean percent change per month for all surface area scenarios, the lower flow classes (i.e., (1) $0.001\text{--}0.25\text{ m}^3/\text{s}$ and (2) $0.25\text{--}0.50\text{ m}^3/\text{s}$) exhibited a negative mean percent change for all months. Nonetheless, we observed a mean positive percent change (i.e., increase in flow) for August ($5.0 \pm 1\%$) and October ($5.2 \pm 0.2\%$) for class 3, and during June ($8.2 \pm 0.3\%$), August ($7.3 \pm 0.4\%$), and October ($8.7 \pm 0.4\%$) for class 4 (Fig. 5). Furthermore, the different surface area scenarios had similar impacts on flow for all months of the year with differences smaller than 5% for all scenarios. Between January and May, for all flow classes, the mean percent change was $-32.0 \pm 6\%$ for the lower, $-34.6 \pm 7\%$ for the mean, and $-35.8 \pm 5\%$ for the upper. Between June and December, the impact on flow was $-5.4 \pm 6\%$ for the lower, $-7.3 \pm 8\%$ for the mean, and $-8.9 \pm 5\%$ for the upper.

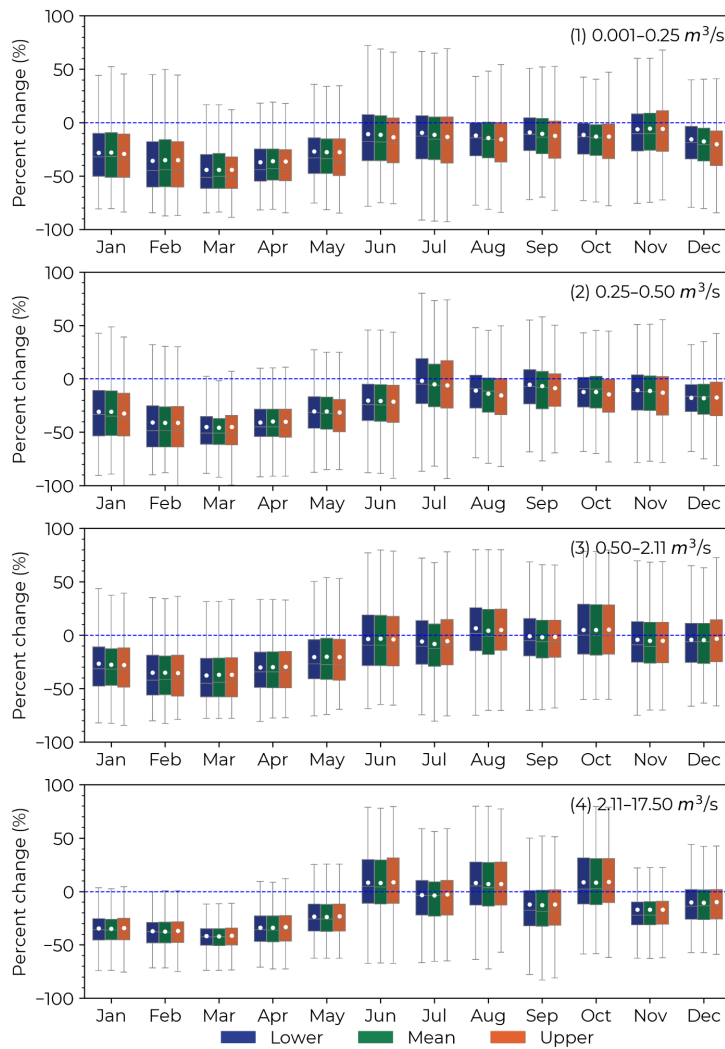


Figure 5—Monthly percent change in flow between the baseline scenario (vertical dotted blue line) and the three surface area scenarios (lower, mean, and upper), and for the four flow classes (1) 0.001–0.25 m³/s, (2) 0.25–0.50 m³/s, (3) 0.50–2.11 m³/s, and (4) 2.11–17.50 m³/s. This analysis included data from all simulated years (1990–2020).

468 Generally, the OFRs contributed to a decrease in monthly flow. However, the OFRs'
469 impact on flow exhibited significant intra- and inter-annual variability, varying according to
470 different OFRs and channels—this is highlighted by the boxplot size variability in Fig. 5, where
471 the variability was lower during the first part of the year and greater between July and August.
472 [Additionally, the monthly percent change in flow in the KDE plots \(Fig. 6\) indicates that for all](#)
473 [three scenarios and flow classes, most changes in flow fall within the range of -40% to 0%.](#) In
474 addition, all KDE plots have a triangular shape with its base on the smaller flows, denoting
475 where most of the changes occur. Even though most of the percent change in flow is negative,
476 there are circumstances in which the OFRs could positively impact flow—the increase in flow
477 is represented by faded colors in each surface area scenario (Fig. 6). The positive mean percent
478 change could be as high as 80%—see Fig. 6 for the larger flow classes, (3) 0.50–2.11 m³/s and (4)
479 2.11–17.50 m³/s. The positive impact on flow for these classes was observed during June, August,
480 and October, when a mean positive change was noted (Fig. 5, classes 3 and 4).

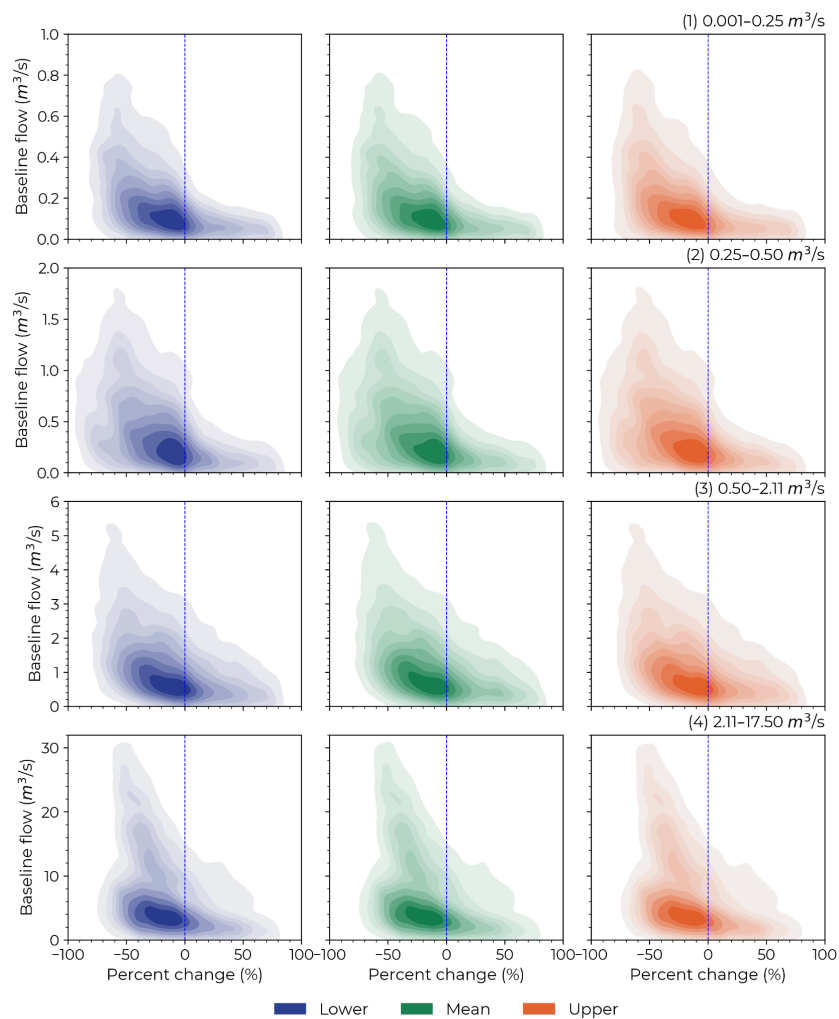
481 The annual mean percent change, for all surface area scenarios, was $-22.5 \pm 3\%$ for class
482 1, $-24.2 \pm 4\%$ for class 2, $-14.6 \pm 3\%$ for class 3, and $-16.6 \pm 3\%$ for class 4. In addition, the surface
483 area scenarios' annual changes were $-18.0 \pm 5\%$ for the lower, $-19.6 \pm 5\%$ for the mean, and -20.8
484 $\pm 6\%$ for the upper, including all flow classes. The differences between the surface area
485 scenarios shown in Fig. 5 and Fig. 6 are related to the variability of the OFR's surface area.

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491 **Figure 6**–Kernel density estimation plots smoothed using a Gaussian kernel for the monthly
 492 percent change in flow between the baseline scenario (vertical dotted blue line) and the three
 493 surface area scenarios (lower, mean, and upper) for the four flow classes (1) 0.001–0.25 m³/s, (2)
 494 0.25–0.50 m³/s, (3) 0.50–2.11 m³/s, and (4) 2.11–17.50 m³/s. Note the different range of values on
 495 the y-axis for all four flow classes.

3.3 Impact on peak flow

For each channel, we calculated the impact of the OFRs on peak flow (Fig. 7). The effect on peak flow was $-60.7 \pm 13\%$ for class 1, $-56.2 \pm 11\%$ for class 2, $-46.7 \pm 19\%$ for class 3, and $-43.9 \pm 12\%$ for class 4. When assessing the impact on peak flow based on different surface area scenarios, the mean percent change was $-49.4 \pm 18\%$ for the lower, $-50.4 \pm 17\%$ for the mean, and $-52.7 \pm 18\%$ for the upper. All peak flows occurred between January and May, which is the period of the year when the study region receives most of its precipitation (Perin et al., 2021). Except for a few outliers, there was no increase in peak flow, despite the OFRs contributing to a positive mean percent change in flow in certain months of the year (Fig. 5, classes 3 and 4).

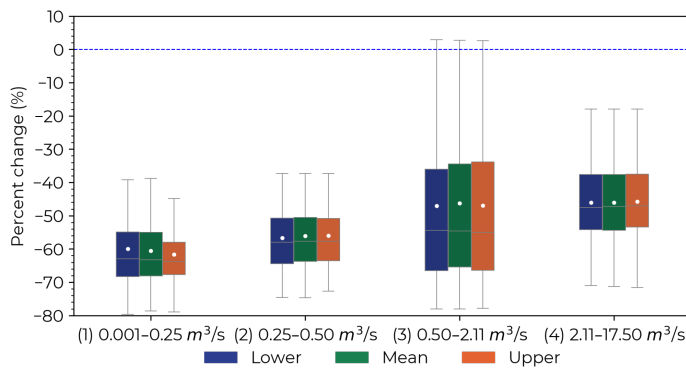
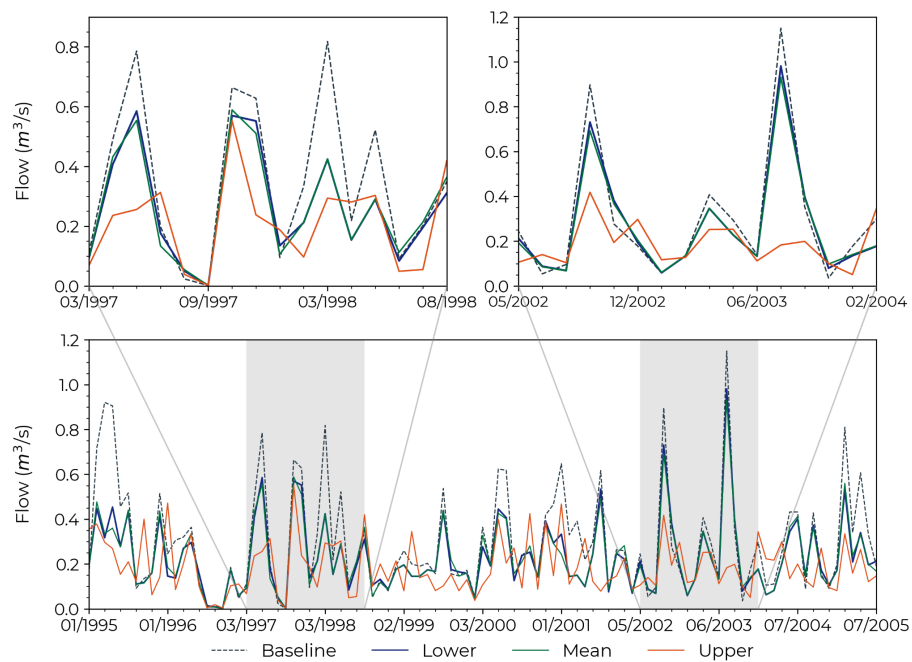


Figure 7—Percent change in peak flow between the baseline scenario (vertical dotted blue line) and the three surface area scenarios (lower, mean, and upper) for the four flow classes (1) 0.001–0.25 m^3/s , (2) 0.25–0.50 m^3/s , (3) 0.50–2.11 m^3/s , and (4) 2.11–17.50 m^3/s .

3.4 Simulated flow time series

We randomly selected a channel within the flow class 3 to demonstrate the baseline and the three surface area scenarios' flow time series between 1995 and 2005 (Fig. 8). For this channel, the annual mean percent changes in flow when comparing the baseline scenario with the lower, mean, and upper surface area scenarios were $0.99 \pm 11.8\%$, $-1.9 \pm 13\%$, and $-2.0 \pm 19\%$ —the high standard deviation for the three scenarios is explained by the interannual variability. The

515 upper surface area scenario resulted in lower flows (i.e., higher impact) compared to the lower
 516 and mean scenarios for the majority of flow events—67.8% and 57.6% for the lower and mean
 517 scenarios, respectively. Nonetheless, there are circumstances when the upper scenario yielded
 518 higher flows—32.2% and 42.4% of the events for the lower and mean scenarios, respectively
 519 (e.g., see the two insets for the periods 03/1997–08/1998 and 05/2002–02/2004). These findings
 520 indicate that the impacts that the OFRs have on flow are not entirely governed by the presence
 521 and surface area of the OFRs (i.e., the different surface area scenarios), but instead by a
 522 combination of the OFRs with varying components of modeling (e.g., terrain, land use, climate
 523 information), and different hydrological processes (e.g., run-off, precipitation, evaporation). In
 524 addition, the impact on peak flow for this channel was $-45.7 \pm 19.7\%$ for all surface area
 525 scenarios, as highlighted on two occasions (08/2002 and 08/2003) in the second inset.



526

527 **Figure 8**—A subset of the time series of simulated flow for baseline and the three surface area
528 scenarios (lower, mean, and upper) between 1995 and 2005 for a selected channel within the
529 flow class 3.

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3.5 Spatial variability of the OFR's impact on annual flow

Deleted: Overall impact of OFRs

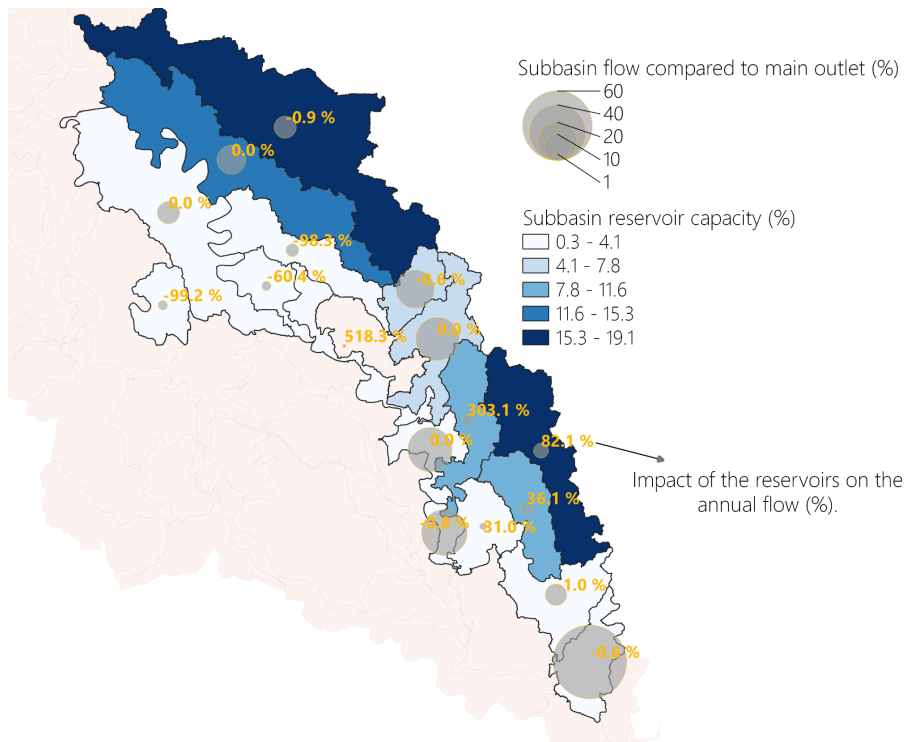


Figure 9—The cumulative impact of OFRs on annual flow for the mean scenario at the subwatersheds where the OFRs occurred. The size of the circles represents the contribution (%) of the subwatershed flow compared to the main outlet (i.e., model outlet). The subwatersheds are color-coded according to their reservoir capacity (%), which was calculated by summing the OFRs surface area in each subwatershed and dividing the sum by the total OFRs surface area (i.e., including all OFRs from all subwatersheds), with a darker color indicating a higher reservoir capacity. The percentages highlighted in yellow represent the impact of the OFRs on annual flow.

550 To assess the overall impact of the OFRs at the subwatershed level, we calculated the
551 contribution of each subwatershed flow to the main model outlet, and the subwatersheds'
552 reservoir capacity (i.e., summing the OFRs surface area at each subwatershed and dividing it
553 to the total OFRs surface area, including all OFRs from all subwatersheds) (Fig. 9). In general,
554 the highest impacts on annual flow (e.g., > 100%), with positive or negative magnitude,
555 occurred at the subwatersheds that contributed the least (< 10%) to the main model outlet—
556 these subwatersheds are represented in lighter shades of blue, and the annual impact is
557 highlighted in yellow on Fig. 9. In other words, the highest impacts on flow occurred on the
558 channels with smaller flow magnitudes (e.g., channels that presented mean flow ranging
559 between 0.001–0.25 and 0.25–0.50 m³/s, these channels were classified as class 1 and 2 in this
560 study). In addition, the subwatersheds with the highest reservoir capacities (between 15.3 and
561 19.1 %, represented in darker shades of blue) (Fig. 9) had a small (< 10%) contribution to the
562 model outlet. These subwatersheds did not present the highest impact on annual flow (e.g.,
563 the effect on annual flow for the top two subwatersheds in terms of reservoir capacity were -
564 0.9 and 82.1%).

565

566 4 Discussion

567 As OFRs will contribute to improving food production resilience by providing surface water for
568 irrigation during dry periods and severe drought events, which are expected to occur more
569 frequently due to climate change, OFRs can have cumulative impacts on the surface
570 hydrology of the watershed where they are located. ~~Studies have employed either data-driven~~
571 ~~or physically based hydrological model approaches to estimate the effects of OFRs on~~
572 ~~watersheds. However, combining these approaches provides a better understanding of the~~
573 ~~spatial and temporal variability of OFR impacts, as it incorporates the dynamic changes of~~
574 ~~OFRs into the hydrological model.~~ To quantify whether the impact of the OFRS on mean and
575 peak flow varies intra- and inter-annually, and which subwatersheds are more affected, we
576 combined a data-driven remote sensing-based model with the latest improvements in SWAT+
577 to assess the OFR impacts.

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Deleted: Studies have either used data driven or physically based hydrological model approaches to estimate OFR impacts on the watersheds, despite the fact that combining the two approaches leads to better understanding on what is the spatial and temporal variability of the OFR impacts, given that the dynamic changes of the OFRs are incorporated into the hydrological model...

578 4.1 Cumulative impact of OFRs

579 When simulating water impoundments in SWAT/SWAT+, it is common practice to
580 validate and calibrate the model using flow measurements (Evenson et al., 2018; Habets et al.,
581 2018; Jalowska & Yuan, 2019; Ni & Parajuli, 2018). In addition, other studies have validated and
582 calibrated the model using alternative variables. For example, Perrin et al. (2012) employed
583 monthly measurements of piezometric variations to assess aquifer recharge processes, and
584 Jalowska & Yuan (2019) used sediment loadings (concentration and budget) from field
585 monitoring reports to evaluate sediment simulations. Ideally, we would calibrate and validate
586 the model by accounting for the parameters governing the OFRs' water budget (e.g., inflows
587 and outflows) (e.g., Kim and Parajuli, 2014). Nonetheless, these measurements were not
588 available for the OFRs in our study region. Furthermore, a thorough calibration and validation
589 of the model would require extra flow data, covering other parts of the study region, as the
590 three USGS stations—the only data available—used in this study are located in the upper part

601 of the modeled watershed. Similar to Evenson et al. (2018), who proposed a module to better
602 represent spatially distributed wetlands and validated their model using both direct (i.e., flow
603 measurement) and indirect (i.e., wetlands surface area) approaches, our validation and
604 calibration were conducted using flow measurements. The OFR's surface area scenarios were
605 based on an algorithm that was validated with an independent higher spatial resolution
606 dataset (Perin et al., 2022).

607 There is a consensus within the scientific community that the OFRs will have a
608 cumulative impact on surface hydrology, resulting in decreased flow and peak flow. For
609 example, previous studies have found that OFRs reduce annual and monthly runoffs in
610 southeastern China (Yan et al. 2023) and Australia's Murray-Darling Basin (Robertson et al.
611 2023). The effect will vary from watershed to watershed due to the number of OFRs and the
612 OFRs' different purposes (e.g., different irrigation schedules) (Ayalew et al., 2017; Fowler et al.,
613 2015; Habets et al., 2018; Nathan & Lowe, 2012; Pinhati et al., 2020; Rabelo et al., 2021). As pointed
614 out by Habets et al. (2018), the mean annual decrease in flow from all studies was $-13.4\% \pm 8\%$.
615 Our results align with this value, which varied between $-24.2 \pm 4\%$ and $-14.6 \pm 3\%$ for all flow
616 classes. In addition, OFRs can reduce peak flow on average by 45% (Habets et al., 2018; Nathan
617 and Lowe, 2012; Thompson, 2012), and up to 70% (Ayalew et al., 2017) for certain flow events.
618 Likewise, our results are consistent with these findings, which show a mean impact on peak
619 flow ranging from $-60.7 \pm 12\%$ to $-43.9 \pm 12\%$. Furthermore, unlike previous research, our results
620 indicate that the OFRs may have a positive ($<9\%$) impact on flow (Fig. 5, classes 3 and 4). This
621 can be attributed to the level of detail in our analyses. When evaluating flow changes at the
622 channel scale, it is important to note that flow at this level is several orders of magnitude
623 smaller than at the main basin outlet. Consequently, this scale often exhibits more significant
624 percentage changes, both increases and decreases. This likely explains how OFRs can enhance
625 channel flow, primarily due to the additional water contributed by OFRs, influenced by periods
626 of increased precipitation in certain channels during specific months and years. While we
627 calculated the monthly impact on flow at the channel scale by aggregating the OFRs to the

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630 closest channel, previous studies have mainly reported the annual impact on flows (Habets et
631 al., 2018). They performed their analysis at the subwatershed scale by aggregating the OFRs to
632 a single point at the outlet of each subwatershed in SWAT (Evenson et al., 2018; Kim & Parajuli,
633 2014; Perrin, 2012; Zhang et al., 2012), or they used different modeling approaches (see Habet et
634 al., 2018).

635 By leveraging the latest improvements in SWAT+ to simulate water impoundments
636 (Molina-Navarro et al., 2018) and combining them with a novel algorithm based on time series
637 of satellite data to monitor OFRs (Perin et al., 2022), we modeled the impact of OFRs on flow at
638 the channel scale. In addition, the surface area scenarios enabled us to account for events
639 when the OFRs were at the lowest, regular, and fullest capacities according to their surface
640 area (see Fig. 2). This is an improvement over previous studies (e.g., Ni et al., 2020; Ni and
641 Parajuli, 2018; Perrin, 2012) that used a single surface area (i.e., one snapshot in time) to
642 represent the OFRs in SWAT. The small differences (<5%) between the surface area scenarios
643 in terms of mean percent change in monthly flow indicate that the OFRs' surface area variation
644 had a minimal impact on flow. For instance, during January and May, the mean monthly
645 percent change ranged between $-35.8 \pm 6\%$ and $-32.0 \pm 7\%$, and during June and December, it
646 varied between $-8.8 \pm 5\%$ and $-5.4 \pm 6\%$ for the three surface area scenarios. The same was
647 observed for peak flow, with a mean monthly impact ranging between $-52.7 \pm 17\%$ and $-49.4 \pm$
648 18% . This small variability on flow impact was observed even though the total OFR surface area
649 increased by 590 ha and 1194 ha when comparing the lower scenario with the mean and upper
650 scenarios (Fig. 5). However, the OFRs represented a small portion (< 1%) of the total area of the
651 modeled watershed (Fig. 1). These findings are related to the fact that flow simulations are
652 governed by several hydrological processes (e.g., run-off, precipitation, evapotranspiration)
653 besides the presence of OFRs on the channel (Bieger et al., 2017; Dile et al., 2022; Arnold et al.,
654 2012). In addition, when assessing the percent change in flow at the channel scale, the
655 differences in surface area between the scenarios were of a lower magnitude compared to the
656 total OFR's surface area. For instance, an OFR with a surface area smaller than 10 ha, and with

surface area variations between 10 and 20% for the three scenarios, may not lead to [significant](#) differences (e.g., > 10%) between the three scenarios.

4.2 OFRs' impacts on flow and peak flow

Our findings highlight that the impacts of the OFRs on flow and peak flow have a significant intra- and inter-annual variability (Figs. 5, 6, and 7). The impacts vary according to different OFRs and channels (Fig. 5). The most significant impacts on flow occurred during the first part of the year, between January and May, a period when peak flows typically occur. In addition, this time of the year also coincides with the period when the region receives most of its precipitation (Perin et al., 2021b), and the OFRs are at their fullest capacity (i.e., OFRs storing their maximum amount of water) (Perin et al., 2022). During the second part of the year, we observed a milder mean percent change in flow for all flow classes and all scenarios, and a greater variability in percent change, notably for July and August (Fig. 5). Moreover, most of the irrigation activities happen between June and September (Perin et al., 2021b, Yaeger et al., 2017). It is when the OFRs are at their lowest capacities (i.e., storing less water) (Perin et al., 2022), which could explain their moderate impact and higher variability during these months, even though we are not accounting for the OFRs' inflows and outflows, and not simulating irrigation events.

Additionally, the variability of the OFRs' impacts is related to the OFRs' physical properties (e.g., surface area and location in the watershed). For example, the OFR surface area will have an impact on flow and peak flow, as shown by the different surface area scenarios, and depending on where the OFR is located in the watershed, given that it may be connected to lower or higher flow channels, which contributes to their impact variability during the year (Figs. 4 and 5). Besides the OFRs' physical properties, the built-in complexity of SWAT—when simulating the presence of the OFRs and the various hydrological processes (e.g., run-off, precipitation, evapotranspiration) governing the water cycle—contributes to the differences in

the OFRs' impacts. This complexity is illustrated in Fig. 8, which shows that the upper scenario can have a higher or lower impact on flow compared to the lower and mean scenarios.

When assessing the annual impact of the OFRs accounting for each subwatershed flow compared to the main model outlet flow, and each subwatershed reservoir capacity (Fig. 9), we found that even though the presence of the OFRs can have a significant impact on flow (Figs. 5, 6, and 7), the highest impacts tend to occur on the subwatersheds that contribute the least (< 10%) to the main model outlet. In general, the highest impacts occurred on the channels with smaller flow magnitudes, and the subwatersheds with the highest reservoir capacities did not have the highest impact on flow. The changes in the OFRs' impacts along the year, and between different years, are directly related to the OFRs' water balance (Equation 3). The variations are primarily driven by the volume of water stored by the OFRs, which is modeled at a daily scale, and it varies according to total daily precipitation, evaporation, and seepage losses.

4.3 Research implications and applications to other study regions

Overall, we presented a new approach to quantitatively analyze the impact of a network of OFRs on mean and peak flow, and we described the various potential reasons behind the variability of the effects of OFRs. Our results indicate that OFRs have an uneven impact on mean and peak flow across the watershed. This variability is primarily influenced by differences in the size, water storage capacity, and the spatial distribution (i.e., their presence) of OFRs. Hence, assessing the OFR's location as well as their numbers across the watershed is important when aiming to manage the construction of new OFRs. In particular, the geospatial variability of the OFRs impacts could be taken into account by water agencies when planning and developing a network of OFRs, given it is possible to identify the areas that are under high pressure (e.g., regions with multiple OFRs that are having a significant impact on flow), and to identify areas that could benefit from the construction of new OFRs, targeting improvements on water resources management and irrigation activities.

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709 Furthermore, even though the OFR's impacts may vary significantly in different
710 watersheds (Habets et al., 2018), our approach could be transferable to other places across the
711 world, as it integrates a top-down data-driven remote sensing-based algorithm, which is based
712 on freely available and private Earth Observations datasets, with the latest SWAT+ hydrological
713 modeling developments. In addition, the widespread use of SWAT+ and its open-source nature
714 are yet another factor contributing to the transferability of the novel approach presented in
715 this study. This is relevant as the number of OFRs is expected to increase globally (Althoff et al.,
716 2020; Habets et al., 2014; Habets et al., 2018; Krol et al., 2011; Rodrigues et al., 2012), with limited
717 knowledge of how the OFRs may impact surface hydrology in different watersheds, and under
718 diverse environmental conditions. Finally, in tandem with the OFRs' key role in irrigated food
719 production, in part to adapt to climate change (Habets et al., 2018) and to alleviate the pressure
720 on surface and groundwater resources (Vanthof & Kelly, 2019; Yaeger et al., 2017; Yaeger et al.,
721 2018), their impacts on surface hydrology need to be considered to avoid exacerbating the
722 surface water stress already intensified by climate change and population growth (Vörösmarty
723 et al., 2010).

724 5 Future improvements

725 Future improvements should focus on how to better represent OFR's water management (i.e.,
726 OFR's inflows and outflows) in SWAT+. Given that each OFR has an independent water balance,
727 accounting for the OFR's water volume change would be a more realistic representation of the
728 OFR when compared to the three surface area scenarios tested in this study. Estimating the
729 OFR's volume change can be done by combining the OFR surface area time series with area-
730 elevation equations—these equations describe the OFR's bathymetry, and allow volume
731 estimation by inputting the OFR's surface area (Liebe et al., 2005; Meigh, 1995; Sawunyama et
732 al., 2006). After carefully assessing different methods to derive these equations (Arvor et al.,
733 2018; Avisse et al., 2017; Li et al., 2021; Meigh, 1995; Sawunyama et al., 2006; Vanthof & Kelly, 2019;
734 Yao et al., 2018; Zhang et al., 2016), we concluded that measured ground data of the OFRs'

735 depth—which is not available—is required to estimate the equations with an acceptable
736 uncertainty. Estimating the area-elevation equations entails several challenges, including: 1)
737 even though there are several DEMs available for the study region (Arkansas GIS Office, 2022)—
738 DEMs can be used to estimate the OFRs bottom elevation—the DEMs were collected when
739 most of the OFRs were full (i.e., bathymetry was not exposed), which limits their use in this
740 case; and 2) although the OFRs are located within the same geomorphological region, they
741 have different depth, shape and physical characteristics (Perin et al., 2022; Yaeger et al., 2017).
742 Therefore, even if a generalized area-elevation equation were calculated for our study region—
743 this is a common approach employed by other studies (Mady et al., 2020; Vanthof and Kelly,
744 2019)—that would still lead to high uncertainties in water volume changes. Ideally, each OFR
745 would have its own equation, which was not possible when this study was done. [Future work](#)
746 [should integrate data on actual evapotranspiration, ET \(Kiptala et al., 2014\) to quantify as the](#)
747 [balance between water availability and ET determines in large part the irrigation system](#)
748 [efficiency and crop productivity in the watersheds where OFRs occur.](#)

749 Efforts should also be made to improve SWAT+ capabilities to receive measured OFRs'
750 inflows and outflows. The latest version of the model has improved the hydrological
751 representation of small water impoundments in SWAT+ (Molina-Navarro et al., 2018).
752 Nonetheless, at the time of our study, the newest version of the model does not allow users to
753 input measured or calculated OFRs' inflows and outflows. Instead, the model developers
754 recommend simulating the OFR's water balance using decision tables (Arnold et al., 2018; Dile
755 et al., 2022). However, there are very limited guidelines on how to create these decision tables.
756 In addition, the tables would simulate the OFR's water balance instead of using the measured
757 or calculated volume change, which could introduce more uncertainties to the modeling
758 scenarios.

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760 6 Conclusions

761 We proposed a novel approach that combines a top-down data-driven remote sensing-based
762 algorithm with the latest developments in SWAT+ to simulate the cumulative impacts of OFRs.
763 This enabled us to assess the spatial and temporal variability of the OFR's impacts, as well as
764 the intra- and interannual changes in impact on mean and peak flow at the watershed and
765 subwatershed levels. Incorporating Earth Observation-derived information with a hydrological
766 model allowed us to capture the dynamic changes of the OFRs and to simulate their impacts
767 under different OFR capacity scenarios.

768 Our study showed that the OFRs may have an impact on flow and peak flow, which
769 exhibit significant inter- and intra-annual variability. The effect of the OFRs is not equally
770 distributed across the watershed, varying according to the OFRs' spatial distribution and their
771 surface area (i.e., water storage capacity). As the number of OFRs is expected to increase
772 globally, partially to adapt to climate change and alleviate pressure on groundwater resources,
773 their relevance to irrigated food production will also increase. It is imperative to develop new
774 frameworks to further understand the impacts of OFRs on surface hydrology. In this regard,
775 we provided a combination of different methods that can be applied in other watersheds,
776 supporting water agencies with information to enhance surface water resource management.

777 7 Author contribution

778 VP, MGT planned the study, analyzed data and modeling, and wrote and reviewed the
779 manuscript. SF and AS carried out software analyses, wrote, and reviewed the manuscript.
780 MLR and MAY data curation, wrote and reviewed.

781 8 Competing interests

782 The contact author has declared that none of the authors has any competing interests.

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785 Space Science and Technology fellowship.

786 10 Data Availability

787 The Soil Water Assessment Tool (SWAT) hydrological model, along with all necessary tools for
788 calibration, validation, and data analysis, can be accessed through SWAT's online portal:
789 <https://swat.tamu.edu/>.
790

791 The National Land Cover Database (30 m) (Homer et al., 2020) and the Gridded Soil Survey
792 Geographic Database (gSSURGO) (Soil Survey Staff, USDA-NRCS, 2021) (100 m) are accessible
793 through the USGS's portal: [https://www.usgs.gov/centers/eros/science/national-land-cover-](https://www.usgs.gov/centers/eros/science/national-land-cover-database)
794 [database](https://www.usgs.gov/centers/eros/science/national-land-cover-database), and here [https://www.nrcs.usda.gov/resources/data-and-reports/gridded-soil-](https://www.nrcs.usda.gov/resources/data-and-reports/gridded-soil-survey-geographic-gssurgo-database)
795 [survey-geographic-gssurgo-database](https://www.nrcs.usda.gov/resources/data-and-reports/gridded-soil-survey-geographic-gssurgo-database), respectively.
796

797 The climate data extracted from the Gridded Surface Meteorological Datasets (Abatzoglou,
798 2013) is available in Google Earth Engine (Gorelick et al., 2017), here
799 https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_GRIDMET.
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801 The Kalman filter derived surface area time series is available through Perin et al., (2022).

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