

Assessing the Hydrological and Social Effects of Three Gorges Reservoir Using a Modified SWAT Model

Xin Dai^{1,2}, Lunche Wang^{*1,2}, Qian Cao^{1,2}, Zigeng Niu^{1,2}, Zengliang Luo^{1,2}, Yuhua Luo^{1,2}

1. Hubei Key Laboratory of Regional Ecology and Environmental Change, School of Geography and Information Engineering, China University of Geosciences (Wuhan), Wuhan 430078, China

2. State Key Laboratory of Biogeology and Environmental Geology, School of Geography and Information Engineering, China University of Geosciences (Wuhan), Wuhan 430078, China

ABSTRACT: As a crucial human activity, dam construction can profoundly impact the surface hydrology patterns. The Three Gorges Reservoir (TGR), as one of the largest hydraulic engineering projects in the world, has gained continuous attention for its eco-hydrological effects. However, further investigation is necessary to understand the runoff and social impacts of the TGR on the Upper Yangtze River. This study first employed a modified SWAT model to simulate runoff, compared scenarios with and without the TGR, and finally evaluated water supply and demand in the Upper Yangtze River. The results showed a significant increasing trend in the surface water area of the Upper Yangtze River from 2000–2020. The modified SWAT model performs well in simulating the runoff, with Nash-Sutcliffe Efficiency and Percent Bias improved by 0.04–0.30 and 2–31.90, respectively. Scenario simulation results revealed that the TGR reduced seasonal differences in runoff. During the flood season, the runoff volume at the Yichang Station in the scenario with the TGR is lower than in the scenario without the TGR, peaking at 4 500 m³/s. Conversely, in the dry season, the runoff volume of the scenario with TGR is higher, with a maximum increase of 1 500 m³/s. The region exhibiting the greatest runoff variations is the Yangtze River's main stem in the Three Gorges Reservoir region. Besides, the TGR notably alleviated the water supply-demand imbalance in Chongqing during the winter and spring seasons, with a maximum increase of 0.16 in the supply-demand index. This study can contribute significantly to understanding the natural and social impacts of the TGR from the perspective of hydrological and scenario simulation.

KEY WORDS: Three Gorges Reservoir, the Upper Yangtze River, a modified SWAT model, water supply, water demand.

0 INTRODUCTION

Climate change and human activities are two crucial causes influencing the spatial and temporal distribution of runoff and water resources (Drenkhan et al., 2023; Loaiciga et al., 1996). Climate factors include temperature, precipitation, evapotranspiration, etc. (Qiu et al., 2023; Gotske and Victoria, 2021). Human activities influencing runoff involve changes in land use, dam construction, agricultural irrigation, and the return flow of surface water and groundwater extraction (Hao et al., 2023; Xia and Zhang, 2008). Dam construction can influence the surface water hydrological pattern and have significant socio-economic impacts (Peñas and Barquín, 2019; Lu et al., 2018). The Three Gorges Reservoir (TGR), was

first filled with water in June 2003, as one of the largest hydraulic engineering projects globally, and the ecological and hydrological effects it has introduced are a long-term research topic.

Numerous studies have investigated the hydrological impact of the TGR on the middle and lower reaches of the Yangtze River. The main focus is on changes in flow/runoff (Wang et al., 2013), sediment load, and the impact on large lakes in the middle and lower reaches (Liu et al., 2016). River discharge research primarily involves quantifying changes in flow by analyzing long-time series variations in monitoring data from hydrological stations (Guo et al., 2018). Most studies focused on the impact of the Three Gorges on the downstream lakes (Yu et al., 2019). The operation of the TGR further alters the influence of the Yangtze River flow on the interrelation with Poyang Lake and Dongting Lake, disrupting the hydrological processes and water resources in the lake basin (Zhang et al., 2022; Zhou et al., 2019). In summary, a clear understanding of the ecological and hydrological impact of the Three Gorges on the middle and lower reaches of the Yangtze River has been formed. Studies are

*Corresponding author: wang@cug.edu.cn

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mostly conducted within the TGR region on the upper reaches of the Yangtze River. Investigations into the effects of land use changes (Liang et al., 2020; Seeber et al., 2010; Zhang et al., 2009), geological hazards (Wang et al., 2019; Hu et al., 2012), regional climate (Wu et al., 2023), flood control benefits (Zhang et al., 2021), water quality (Xu et al., 2020), and soil erosion (Huang et al., 2020) are included. The large-scale inundation of land and the subsequent massive resettlement of urban and rural residents within the TGR area have led to changes in land use. The land-type transition process has submerged riverbanks and adjacent areas, making the river environment into a static or semi-static water system (Fatahi Nafchi et al., 2021). Also, the spatiotemporal patterns of soil nutrient status and vegetation in the riparian zone have changed due to the Three Gorges Project (Ye et al., 2019). Overall, further exploration is needed to reveal the ecological hydrological effects on the whole upper reaches of the Yangtze River.

The construction of the TGR also changed the social and economic patterns. Many studies have launched the social impacts of the TGR from the perspective of ecosystem services. For instance, Shuai et al. (2021) explored the interactive relationship between ecosystem services and the multidimensional poverty reduction index. Gou et al. (2021) investigated the temporal dynamics of ecosystem services within the TGR area and examined the relationship with socio-ecological factors. Utilizing quantitative data within the TGR area, Arif et al. (2022) explored the impact of tourism-based recreational activities on ecosystem functions. Although the construction of the TGR submerged several lands in the reservoir area, posing adverse effects on agriculture, its effective flood control function can mitigate flooding in highly-developed agricultural regions (Zhai et al., 2021). The balance between water supply and demand is also a current research focus. Different regions are facing trends of population growth, followed by an increase in household, industrial, and agricultural water demand. To achieve sustainability, it is crucial to investigate the variables influencing the sustainability of water supply and demand (Karamouz et al., 2017). However, there is relatively limited research currently to quantify the impact of the TGR on the water supply-demand balance in the Upper Yangtze River.

Watershed runoff assessment commonly employs three methods: observational method, hydrological time series analysis, and watershed hydrological modeling. Most studies focus on the longtime-scale changes in hydrological elements, comparing differences before and after the impoundment of the TGR (Zhou et al., 2019; Guo et al., 2018). Hydrological models are widely used because the hydrological processes can be simulated. Hydrological models are categorized into centralized hydrological models and distributed hydrological models. Among them, distributed hydrological models are most commonly applied in hydrological process simulation research, such as the SWAT model (Arnold et al., 2012; Zhao et al., 2024), VIC model (Liang et al., 1996), HSPF

model (Duda et al., 2012), SWMM model (Lowe, 2010), etc. Francesconi et al. (2016) reviewed multiple studies assessing ecosystem services using the SWAT model in various locations, including the United States, Japan, India, and other regions. Based on different study areas and objectives, numerous optimizations and improvements in methods based on the original model emerged (Maleki Tirabadi et al., 2022; Kassem et al., 2020). Some studies have set up scenarios with and without reservoirs to compare runoff differences. For example, Tao et al. (2020) reconstructed a no-reservoir scenario to comprehensively assess the impact of the Three Gorges Project on the water temperature of the Yangtze River. Zeng et al. (2023) established scenarios including dam operation and scenarios without dam operation, to comprehensively evaluate the hydrological effects of the TGR in the Yangtze River. A modified SWAT model (SWAT-M) proposed by Wang et al. (2023) aims to assess the runoff impact of large multi-purpose reservoirs, which has practical significance. It addresses the limitation of the original SWAT reservoir (SWAT-O) module and performs well in simulating outflows for large reservoirs with multiple functions.

To quantify the impact of the TGR on runoff and water supply-demand balance in the Upper Yangtze River, this study conducted runoff simulations using the SWAT-M model. The main objectives are: (1) quantifying the characteristics of water body changes in the Upper Yangtze River from 2000 to 2020 to gain a preliminary understanding of the temporal variations in surface water bodies area. (2) Simulating the differences in runoff in the Upper Yangtze River under scenarios with and without the TGR. (3) Assessing the impact of the TGR on the water supply-demand balance in the upper Yangtze River. The flow chart of this study is displayed in Figure 1. This study primarily investigates the impact of the Three Gorges Dam by incorporating the reservoir parameters into the model while keeping other variables constant. Consequently, it is assumed that the effects of other dams are negligible. Additionally, this research does not examine the influence of land use changes, using only one year of land use data as the model input. Thus, it can be assumed that variations due to land use changes are not considered.

1 MATERIALS AND METHODS

1.1 Study Area and Data List

The Upper Yangtze River (from the river source to Yichang in Hubei Province) is located between 90°33'E–111°39'E and 24°21'N–35°52'N (Figure 2). This region covers more than half of the Yangtze River Basin, controlling approximately 1 million km² (Qin et al., 2020). The Upper Yangtze River flows through six provinces, autonomous regions, and municipalities, including Qinghai, Tibet, Sichuan, Yunnan, Chongqing, and Hubei. Due to the steep terrain, river gradients, and abundant rainfall, the Upper Yangtze River is rich in water resources, making it possible to develop hydropower in China. Based on the topography and river conditions, the Upper Yangtze River

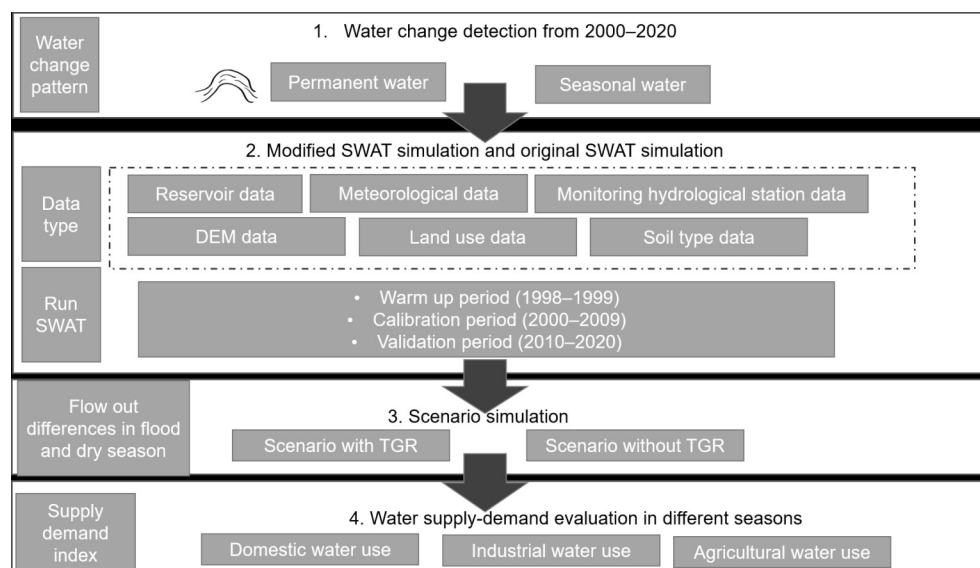


Figure 1. Flow chart of this study.

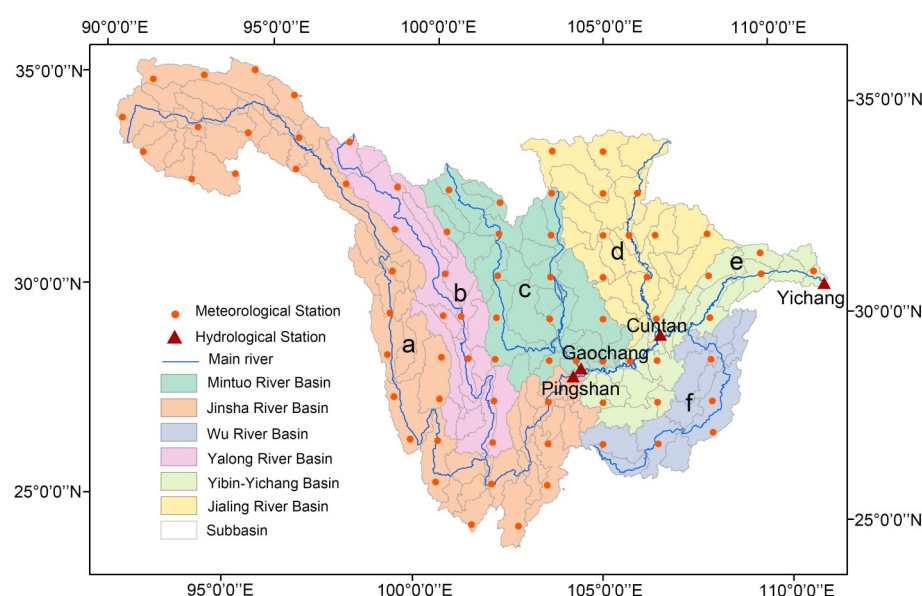


Figure 2. The delineated sub-basins in the Upper Yangtze River Basin and the selected CN05.1 meteorological stations in SWAT model.

is divided into six subbasins: the Jinsha River Basin, Yalong River Basin, Mintuo River Basin, Jialing River Basin, Wu River Basin, and the Yibin-Yichang section of the main stem of the Yangtze River. The construction of the TGR was from 1993 to 2009, and the total reservoir capacity is 39 300 km³. The reservoir has submerged 245 km² of farmland and orchards, approximately 35 km² of residential areas, and 824 km of roads (Xiao et al., 2020).

The input data of the SWAT model include meteorological data, soil data, and land use data (Table 1). Gridded daily climate data with a spatial resolution of 0.25° obtained from the CN05.1 dataset was used to establish a meteorological database (Wu and Gao, 2013). Finally, 77 meteorological sites (Figure 2) were selected in the Upper Yangtze River. There are 206 subsoil types in the Upper Yangtze River, which are reclassified into 12 categories according to soil phase (phases are subdivisions

of soil units based on characteristics). To obtain formula (1), the reservoir data including reservoir capacity and water level is acquired by referencing Li and Kuang (2009). The guaranteed output of the reservoir is 4.99 million kW·h. The annual drawdown water level, tailwater level, monthly ecological environment damage prevention line, monthly restricted power generation line, monthly power generation damage prevention line, and monthly flood limited water level are obtained from Bulletin of the Three Gorges Project.

1.2 Modified SWAT Model

1.2.1 Principle of the modified model

This study utilized the SWAT model for runoff simulation in the Upper Yangtze River. The SWAT model has undergone nine improvements since its initial application and has evolved into a widely used open-source hydro-

Table 1 Primary data used in this study

Data	Type	Source	Use	Resolution
Meteorological station data	Daily precipitation, average /maximum/minimum temperature, sunshine hours, average wind speed, and relative humidity from 1990 to 2020	CN05.1 dataset (Wu and Gao, 2013)		0.25°
Basic geographic data	Soil data	The Harmonized World Soil Database		1 km
	Land use/cover data	http://www.resdc.cn	Input data of SWAT model	1 km
	Dem data	http://www.resdc.cn		30 m
Hydrological data	Monthly observed streamflow data from 2000 to 2020 at Yichang and Cuntan stations, and from 2000 to 2015 at Gaochang and Pingshan hydrological stations. Measured daily outflow of the TGR from 2000 to 2020	The Changjiang Water Resources Commission (CWRC) and Qin et al. (2020)		/
Reservoir parameter	Reservoir capacity, water level, guaranteed output value, annual efficiency coefficients	Li and Kuang (2009) and data query	Input data of reservoir module	/
Water demand data	Domestic, industrial, and agricultural water use for 2005, 2010, 2015, and 2020	Provincial statistical yearbooks	Calculate the water supply demand	/
Global water body area data	Surface water seasonality data, encompassing seasonal water and permanent water from 2000 to 2020	Pekel et al. (2016)	Analyze surface water change	30 m

logical model. It divides an entire basin into several sub-basins, further subdivided into hydrological response units (hru). The fundamental basis of the model lies in the water balance equation (Arnold et al., 2012).

To simulate the flow out volume in different subbasins, the SWAT model runs at a monthly time step. To enhance the accuracy of the reservoir module, this study incorporated the SWAT-M model proposed by Wang et al. (2023). A reservoir scheduling chart is needed before utilizing the module (Figure 3). The modified principle and process of the SWAT-M model primarily involve three steps.

Step 1: Establish water level and storage formula. The reservoir water balance comprises inflow, outflow, precipitation, evaporation, seepage from the reservoir bottom, and water withdrawals. Water level is the main variable to develop a reservoir outflow framework that satisfies the multiple objectives of reservoir regulation. The formula between the water level and the storage volume is as follows.

$$H = \alpha_{res} \times V^{\beta_{res}} \quad (1)$$

where H is the water level (m); V is the reservoir storage volume (m^3); α_{res} and β_{res} is the regression coefficient between the water level and the storage capacity of the reservoir (no unit). If $\beta_{res} > 1$, the curve between the water level and storage volume is convex; if $\beta_{res} < 1$, the curve between the water level and storage volume is concave; if $\beta_{res} = 1$, the relationship between the water level and storage volume is linear (Wang et al., 2023). By referencing the water and storage formula of Li and Kuang (2009), we obtained that α_{res} and β_{res} of TGR is 0.59 and 0.23.

Step 2: Modify the formula of reservoir target storage volume and outflow. The original model uses a target release method for water discharge. The target release method is only used to simulate the reservoir release of floodwater. However, the TGR is a multi-purpose reservoir, combining functions such as flood control, power generation, and navigation. Thus, the original SWAT model should be modified when applied in large reservoirs with multipurpose. The target release correction formula of the modified model proposed by Wang et al. (2023) is as follows.

$$V_{tag} = V_m + \frac{1 - \min(\frac{SW}{FC}, 1)}{2} \times (V_f - V_m) \quad (2)$$

$$V_{flowout} = \frac{V - V_{tag}}{ND_{tag}} \quad (3)$$

where V_{tag} is the target volume of water in the reservoir at the end of the day (m^3); V_m is the minimum storage in the modified target release scheme (m^3); V_f is the flood control storage (m^3). V_m and V_f are the design parameters of the reservoir. SW is the average soil water content (mm) on that day; FC is the field capacity (mm). V_{tag} is obtained through the calibration of SW and FC . $V_{flowout}$ is the vol-

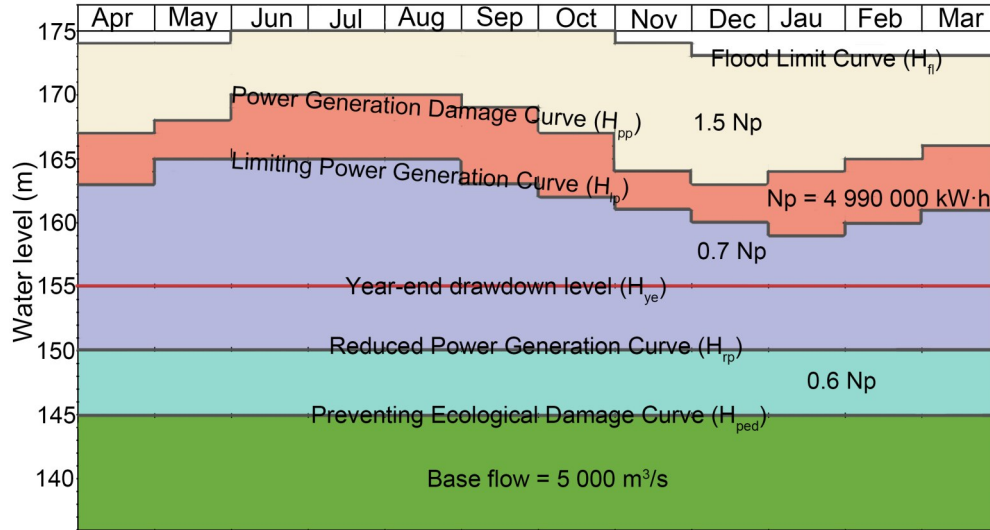


Figure 3. Established TGR scheduling chart, represents the water level (unit: m) in different months.

ume of water the reservoir releases during the day (m^3/d). ND_{tag} is the number of days to reach the target storage, need to be calibrated.

Step 3: Calculate reservoir outflow according to the reservoir outflow curve in the operation chart. According to Wang et al. (2023), the modified reservoir outflow calculation formula is as follows.

$$Q_{out} = \begin{cases} 0 (H_t \leq H_d) \\ \max \left[F(H_t), \frac{V_{flowout}}{86400} \right] (H_d < H_t \leq H_{fc}) \\ \frac{V_{flowout}}{86400} (H_{fc} < H_t) \end{cases} \quad (4)$$

where Q_{out} is the reservoir outflow (m^3/s); H_{fc} is the flood control limit water level. H_t is the real-time water level on day t . An established reservoir scheduling operation chart is necessary when calculating Formula (4). It mainly consists of different guide curves and corresponding operation zones. The reservoir's release target at the beginning of each month can be defined based on the respective zone in which the water level is located. Based on the water level and its range in the reservoir operation chart, including preventing power generation damage curve (H_{pp}), limiting power generation curve (H_{lp}), reduced power generation curve (H_{rp}), and preventing ecological damage curve (H_{ped}), the reservoir outflow in different zones can be calculated by Formula (5).

$$F(H_t) = \frac{\rho \times N_p}{(H_t - H_{out}) \times k} \quad (5)$$

$F(H_t)$ is the function of the reservoir release for utilizable capacity (H_d to H_{fc}), which is calculated according to the reservoir water level. ρ is the efficiency coefficient corresponding to different sections. N_p is the guaranteed output power generation capacity of the reservoir. H_{out} is the tailwater level of the reservoir, and k is the total power efficiency coefficient. The total annual electricity generation of the reservoir from 2003 to 2020 and the guaranteed

output were obtained from statistics data provided by the Ministry of Water Resources of the People's Republic of China. By averaging the ratios of the total annual electricity generation of the reservoir to the guaranteed output, the k value of the TGR was determined to be 0.9.

1.2.2 Calibration and validation

SWAT-CUP was employed for calibration and evaluation of the simulation results. Nash-Sutcliffe efficiency (NS), coefficient of determination (R^2), and percent bias (PBIAS) were selected to evaluate the simulation results of the model. The formula of NS, R^2 and PBIAS are as follows (Xu et al., 2011; Nash and Sutcliffe, 1970).

$$NS = 1 - \frac{\sum_{i=1}^n (Q_m - Q_s)_i^2}{\sum_{i=1}^n (Q_{m,i} - \bar{Q}_m)^2} \quad (6)$$

$$R^2 = 1 - \frac{[\sum_{i=1}^n (Q_{m,i} - \bar{Q}_m)(Q_{s,i} - \bar{Q}_s)]^2}{\sum_{i=1}^n (Q_{m,i} - \bar{Q}_m)^2 \sum_{i=1}^n (Q_{s,i} - \bar{Q}_s)^2} \quad (7)$$

$$PBIAS = 100\% \times \frac{\sum_{i=1}^n (Q_m - Q_s)_i}{\sum_{i=1}^n Q_{m,i}} \quad (8)$$

where Q_m is the measured flow out volume, Q_s is the simulated flow out volume, i and n represent the sample number and total sample size. NS reflects the overall fit between simulated and observed runoff but tends to give higher weight to peak flow. R^2 measures the goodness of fit between simulated and observed values; however, it may not indicate the response of the overall bias when the simulated values are consistently higher or lower. PBIAS captures the cumulative deviation between simulated and observed values. PBIAS is particularly effective in assessing the model's overall water balance accuracy when the simulated hydrological processes align well with the observed trends (Chen et al., 2022). The classification criteria of model performance evaluation is displayed in Table 2.

Table 2 Evaluation criteria for the model performance
(Chen et al., 2022)

Model performance	NS	R^2	$PBIAS$ (%)
Excellent	(0.75, 1]	(0.75, 1]	$ PBIAS \leq 10$
Good	(0.65, 0.75]	(0.65, 0.75]	$10 < PBIAS \leq 15$
Not good	(0.5, 0.65]	(0.5, 0.65]	$15 < PBIAS \leq 25$
Bad	(0, 0.5]	(0, 0.5]	$ PBIAS > 25$

1.3 Water Supply and Demand Index (SDI)

The SWAT model defines the total water provisioning service supply as the clean water that leaves the sub-basin and flows into the river within a time step (Arnold et al., 2012). The calculation formula is as follows.

$$WYLD = SURQ + LATQ + GWQ - TLOSS - PA \quad (9)$$

where $WYLD$ is the total water yield (mm); $SURQ$ is the surface runoff from a time step that flows into a river (mm); $LATQ$ is the lateral flow rate into the river (mm); GWQ is the amount of groundwater that flows into a river in a time step (mm); $TLOSS$ is the amount of loss caused by riverbed seepage (mm); and PA is the pond retention (mm). These values can be output by the SWAT model. By calculating $WYLD$ for each hru, the total water supply for each city (m^3) is obtained using ArcGIS's zonal statistics method.

Water demand data is obtained from the statistical yearbooks of 59 cities in the upstream Yangtze River for 2005, 2010, 2015,, and 2020. These specific years represent changes over time and have been chosen given data availability. The water consumption categories encompass domestic, industrial, and agricultural use. An equal distribution is applied in the allocation of water consumption for domestic and industrial for each season. The seasonal distribution of the agricultural water usage is determined based on the planting seasons of various crops in each season, calculated according to the proportional yield of crops (Zhou et al., 2024). The crops considered in this study primarily include rice, wheat, legumes, tuber crops, rapeseed, flax, sugarcane, tobacco, vegetables, and cotton.

We standardized the water use and supply values with uniform values between 0 and 1 using the FuzzyMembership tool of ArcGIS. Then The supply-demand balance index was used to calculate whether the water supply-demand situation was balanced. The supply-demand index was calculated by referencing Li et al. (2016). The formula is as follows.

$$SDI_i = \frac{S_i - D_i}{(S_{\max} + D_{\max})/2} \quad (10)$$

where SDI_i is the supply and demand index for city i ; S_i and D_i are the water supply and demand for city i . $S_{\max}$ and $D_{\max}$ are the maximum water supply and demand pixel values of a city, respectively. If SDI is greater than 0, the supply exceeds the demand. If SDI equals 0, it signifies a balance between supply and demand. If SDI is less than 0, the supply is less than the demand.

2 RESULTS

2.1 Change Pattern of Surface Water in the Upper Yangtze River

Understanding the changes in water resources in the upstream Yangtze River can provide knowledge for subsequent runoff simulations. We analyzed surface water body area changes in major basins over the past 20 years. There is a significant increasing trend ($P < 0.001$) in the permanent water body area in the six major basins (Figure 4). The Jinsha River Basin shows the highest increase in permanent water body area, increased by 37 $km^2/year$ while the seasonal water bodies increased by 46 $km^2/year$. Glacier meltwater is the primary contributor to the runoff in the Jinsha River Basin, constituting over 70% of the total runoff. Global warming played a crucial role in altering the speed of glacier meltwater thus the increase in water storage is mainly attributed to climate change (Wu et al., 2023). Following that is the mainstream of the Yangtze River from Yibin to Yichang, with an increasing rate of 27.8 $km^2/year$. However, there is a significant decreasing trend in seasonal water bodies of this basin ($P < 0.001$), decreasing by 0.26 $km^2/year$. This basin contains the TGR zone, since the impoundment of the TGR, the submerged area has reached 632 km^2 , leading to a significant increase in water body area in this basin. Therefore, large reservoirs such as the TGR are a crucial factor influencing regional changes in water storage. It is essential to consider further how to deduct and quantify the impact of the TGR on the Upper Yangtze River.

In the Jialing River Basin, Mintuo River Basin, Wu River Basin, and Yalong River Basin, the permanent water bodies increased annually by 17.4, 11, 5.8, and 4.8 km^2 , respectively. The seasonal water bodies increased by 6.9, 12.4, 9.8, and 5.8 km^2 annually. Overall, the water body area in the upper Yangtze River Basin showed a significant increasing trend from 2000 to 2020.

2.2 Evaluation of SWAT-M Simulation Results

In this study, The SUFI-2 algorithm was used to calibrate and validate the simulation accuracy. 22 parameters were selected for calibration in the Upper Yangtze River. Table 3 presents the range of values for the calibrated model parameters and the sensitivity analysis results. Nine sensitive parameters with P -values < 0.1 were selected. The sensitivity analysis result indicates that sol_k , $ALPHA_BNK$, $ALPHA_F$, $CANMX$, $NDTARGR$, $ESCO$, $CN2$, $GWQMN$, and $GW-DELAY$ are parameters of high sensitivity. Parameters related to groundwater have a significant impact on simulation results, as well as the soil-saturated hydraulic conductivity. The parameter ranges calibrated for SWAT-O and SWAT-M are different; therefore, the simulation results for the no-reservoir scenario in SWAT-M are not entirely consistent with those of SWAT-O. Additionally, to maintain consistency in variables, subsequent simulations for the reservoir and no-reservoir scenarios were conducted in the SWAT-M model, with parameters kept unchanged between the two scenarios.

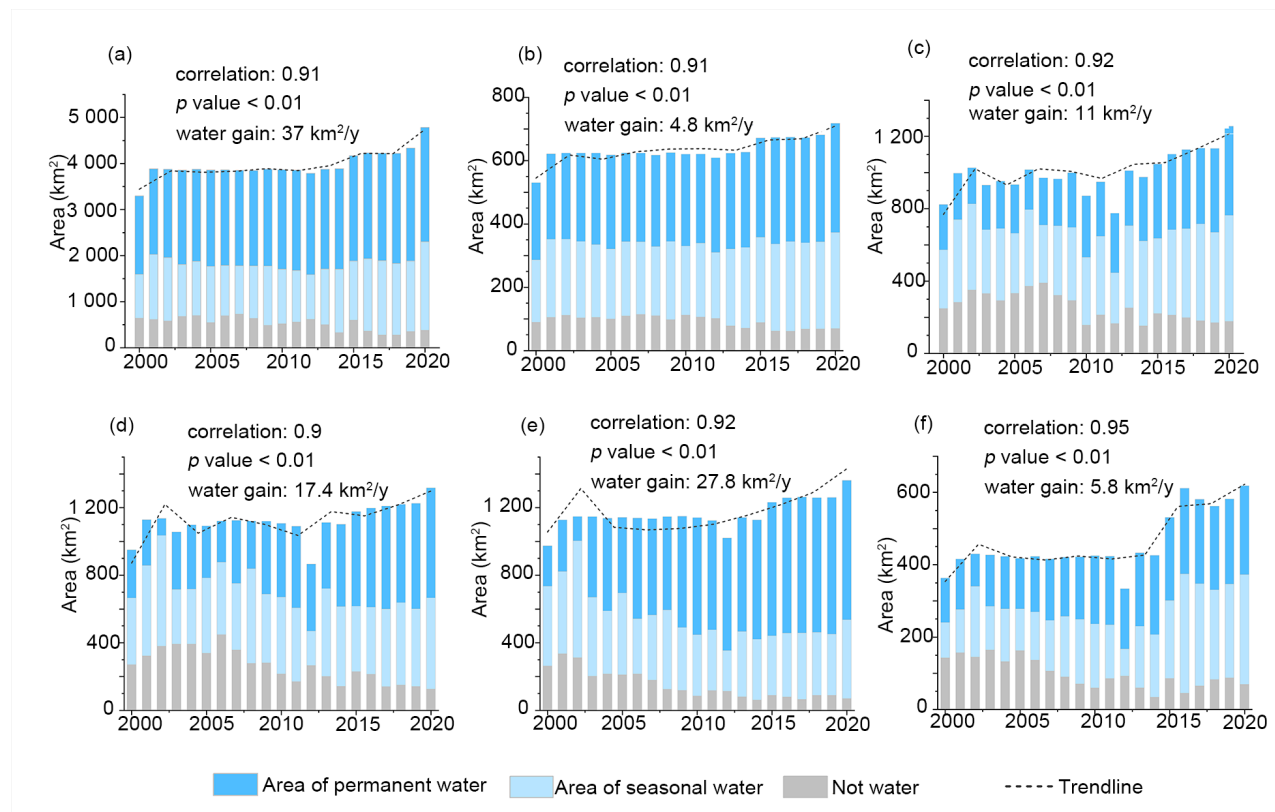


Figure 4. Trends in annual permanent and seasonal water body area in the Upper Yangtze River. (a) the Jinsha River Basin; (b) the Yalong River Basin; (c) the Mintuo River Basin; (d) the Jialing River Basin; (e) the Yangtze River Basin from Yibin to Yichang; (f) the Wu River Basin.

Table 3 The range of values for the calibrated parameters

Number	Parameters	Min	Max	File name	p-value
1	v_SOL_K().sol	0	2 000	sol	0.01
2	v_ALPHA_BNK.rte	-0.37	0.54	rte	0.02
3	v_ALPHA_BF.gw	0.47	1.42	gw	0.03
4	v_CANMX.hru	0	128.36	hru	0.04
5	v_NDTARGR.res	0	200	res	0.05
6	r_ESCO.hru	0.48	1.45	hru	0.06
7	r_CN2.mgt	58	106	mgt	0.06
8	v_GWQMN.gw	81.69	2 000	gw	0.07
9	v_GW_DELAY.gw	0	746.82	gw	0.08
10	v_SOL_AWC().sol	0	1	sol	0.12
11	r_CH_N2.rte	-0.1	0.17	rte	0.35
12	v_REVAPMN.gw	148.19	446.81	gw	0.45
13	v_CH_K2.rte	-224.34	259.32	rte	0.45
14	v_USLE_P.mgt	-0.37	1	mgt	0.44
15	v_GW_REVAP.gw	-0.01	0.13	gw	0.42
16	v_ESCO.bsn	0	1	bsn	0.54
17	v_SURLAG.bsn	3.31	17.14	bsn	0.57
18	v_RES_PSA.res	1	1 000	res	0.65
19	r_RES_K.res	0	1	res	0.75
20	r_EPCO.hru	0	1	hru	0.85
21	r_SLSUBBSN.hru	-52.8	82.6	hru	0.86
22	v_CH_COV1.rte	-0.35	0.28	rte	0.89

The Upper Yangtze River was divided into 181 sub-watersheds in the SWAT model. The warm-up period was from 1998 to 1999, the calibration period was from 2000 to 2009, and the validation period was from 2010 to 2020. Runoff results under the SWAT-M and SWAT-O were obtained by calibrating and revising model parameters in SWAT-CUP. The SWAT-M shows enhanced simulation accuracy for various stations compared to the SWAT-O (Table 4). During the calibration period, NS of the Yichang Station improved from 0.72 to 0.78, PBIAS decreased by 5, while R^2 remained at 0.87. NS of the Cuntan Station was improved from 0.73 to 0.86, PBIAS decreased by 15, and R^2 remained at 0.89. NS of the Gaochang Station improved from 0.85 to 0.89, PBIAS improved from 11.8 to 1.8, but R^2 decreased from 0.92 to 0.89. The simulation results at the Pingshan Station showed the most significant improvement, with R^2 increasing from 0.88 to 0.92, NS increasing from 0.68 to 0.9, and PBIAS decreasing from 38.7 to 6.8. In the calibration period, the NS at the Yichang Station improved from 0.55 to 0.68. Although R^2 at the Cuntan Station decreased by 0.1, NS increased from 0.61 to 0.8, and PBIAS decreased by 9. At the Gaochang Station, NS increased from 0.81 to 0.87, and PBIAS decreased to 1.4. The Pingshan Station showed significant improvements in three indicators, with NS increasing by 0.3, R^2 increasing by 0.02 and PBIAS improving by 22. Overall, the modified model exhibits a discernible improvement compared to the original model, with significant improve-

Table 4 The verification results for the SWAT-O and SWAT-M model

Period	Station	R^2	NS	PBIAS	R^2	NS	PBIAS
		SWAT-O			SWAT-M		
Calibration	Yichang	0.87	0.72	24.7	0.87	0.78	19.2
	Cuntan	0.89	0.73	26.2	0.89	0.86	11.7
	Gaochang	0.92	0.85	11.8	0.89	0.89	1.8
	Pingshan	0.88	0.68	38.7	0.92	0.90	6.8
Validation	Yichang	0.81	0.55	22.1	0.81	0.68	20.1
	Cuntan	0.86	0.61	23.6	0.85	0.80	14.4
	Gaochang	0.89	0.81	7.3	0.89	0.87	1.4
	Pingshan	0.87	0.58	27.3	0.89	0.88	5.4

underlining indicates that there has been no improvement in R^2 .

ments in NS and PBIAS, but a relatively smaller improvement in R^2 .

Figures 5a–5d displays various hydrological stations of the simulated monthly flow-out results in the validation period. The simulation results showed that the SWAT-M addressed the issue that SWAT-O simulated abnormal low and excessively high peak values. The variation in runoff values generally corresponds with the peaks and trends of precipitation. Yichang hydrological station is the outlet for the upstream Yangtze River Basin, controlling the entire upstream region. It has the highest flow, with monthly runoff reaching 40 000 m³/s. Cuntan Station, as the outlet of the Jialing River Basin, serves as a fundamental hydrological station established to explore the hydrological changes after the Jialing River flows into the Yangtze River and understand the hydrological characteristics of the river. The maximum flow at Cuntan reaches up to 35 000 m³/s. Gaochang Station serves as the outlet of the Mintuo River Basin, with a maximum flow reaching 8 000 m³/s. Pingshan Station is the outlet of the Jinsha River Basin, with a maximum flow reaching 15 000 m³/s.

The outflow values of the TGR simulated by the SWAT-O is too low or too high (Figure 5e), while there is an improvement in both low and high flow values of the SWAT-M, with the minimum ranging around 5 000 m³/s and the maximum around 35 000 m³/s. Therefore, the SWAT-M can improve the outflow simulation results of the TGR in terms of both peak and low values.

2.3 Runoff Differences with and without TGR under Flood Season and Dry Season

Since the measured data are station data and there is no spatial comparison of runoff, it is necessary to simulate the scenario with the reservoir in SWAT-M. To quantify the impact of the TGR on runoff in the Upper Yangtze River, scenarios with and without the reservoir were set and simulated. The Yichang hydrological station as the outlet of the basin, was analyzed to understand the differences in flow out across the entire basin under the two scenarios. The monthly average flow out differences displayed in Figure 6 indicate that from June to September, flow out with the reservoir scenario is lower than without

the reservoir. The flow out difference in June is 3 800 m³/s, in July, it exceeds 4 000 m³/s. In other months, the flow out with the reservoir scenario is higher than that without the reservoir scenario.

Annual flow out differences under flood and dry seasons are also shown in Figure 7. This study defined June, July, August, and September as the flood season, while December, January, February, and March as the dry season. The results show that the flow out without the reservoir during the flood season is generally higher than that with the reservoir scenario, indicating the flood control function of the TGR. Without the reservoir scenario, the flow out after 2010 is all above 30 000 m³/s. However, under the regulation of TGR, the flow out can be adjusted to below 30 000 m³/s, achieving a difference of 4 000 m³/s. During the flood season, except the flow values in 2006 and 2011 were below 25 000 m³/s, the flow values in other years were consistently around 30 000 m³/s. During the dry season, the flow out with the reservoir is significantly higher than the scenario without the reservoir, with the highest supplement of 1 400 m³/s. In 2006, 2008, 2009, 2011, 2013, 2016, 2019, and 2020, the increased flow value was above 1 000 m³/s. Moreover, there is an increase in the average annual flow out during the dry season. The results also further indicate that the TGR reduced seasonal differences in runoff.

The simulation result indicates that TGR significantly impacts the hydrology of the Three Gorges Reservoir area. Therefore, the TGR area was selected to analyze the spatial differences of flow out. We compared the runoff differences under the two scenarios during flood and dry seasons. The results (Figure 8) indicate that during the flood season, the reservoir can reduce the flow volume by up to 3 000 m³/s compared to the scenario without the reservoir. In the dry season, the reservoir scenario can supplement up to 1 000 m³/s more than the natural scenario. The areas with the largest flow differences are primarily the upstream of the Yichang Station, significantly affecting the sub-basins of the mainstream of the Yangtze River. Due to the inherently lower runoff volume in winter compared to summer, the magnitude of the runoff changes in the dry season is relatively small.

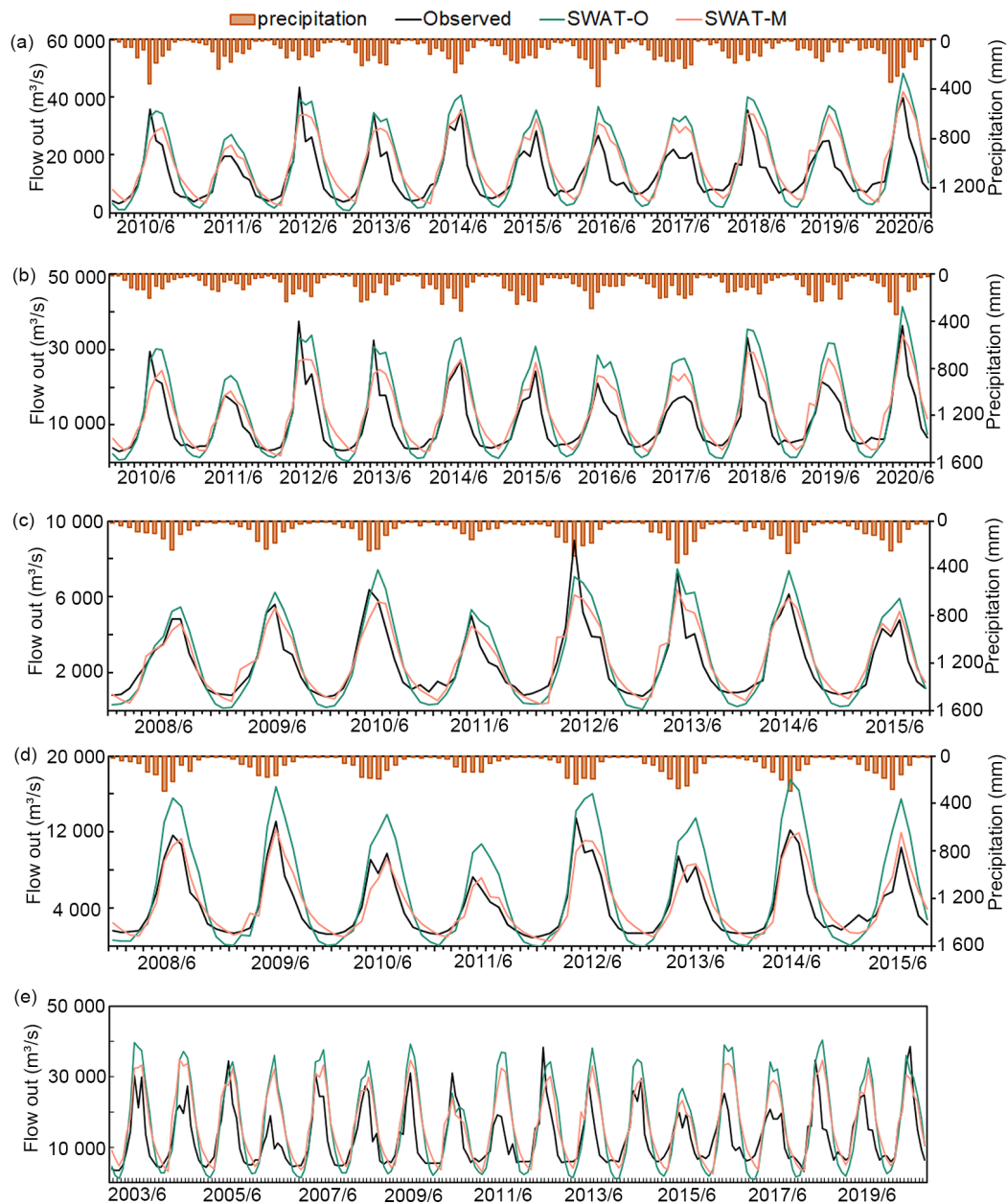


Figure 5. The monthly flow out simulation result in the validation period of four hydrology stations and the outflow of the TGR simulated by SWAT-O and SWAT-M. (a) Yichang; (b) Cuntan; (c) Gaochang; (d) Pingshan; (e) the TGR.

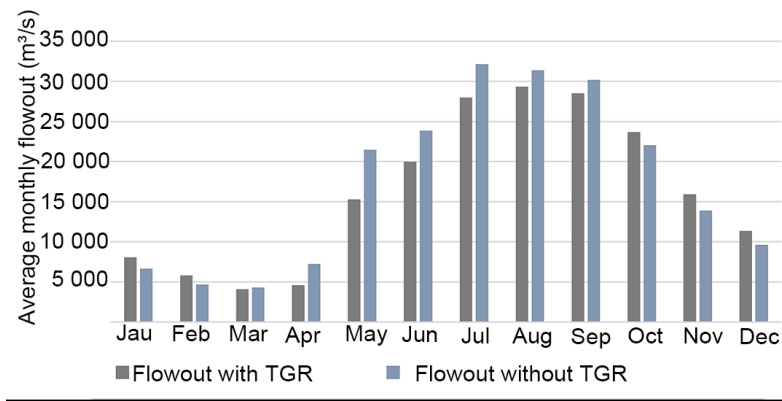


Figure 6. The monthly average flow under the simulated outflow with TGR operation and the natural flow without TGR operation from 2000 to 2020.

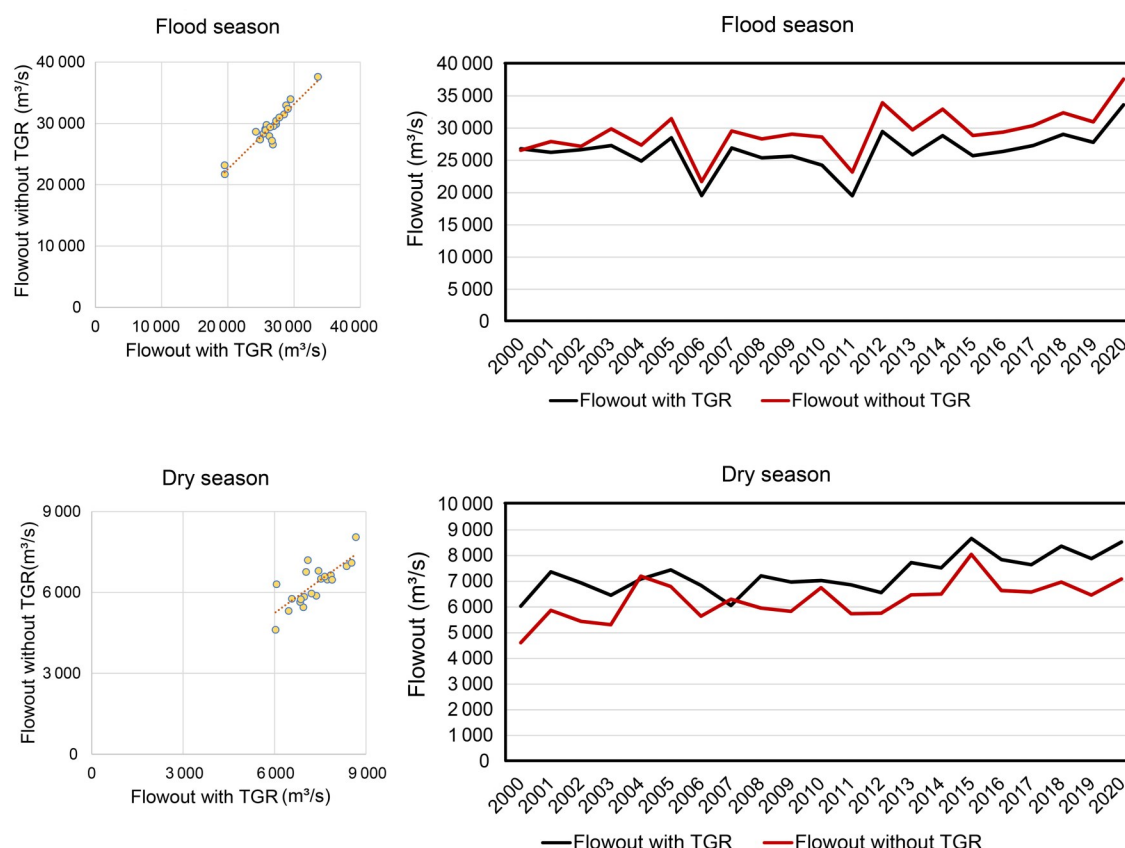


Figure 7. Comparison of flow out volume in flood and dry seasons from 2000 to 2020 (runoff with TGR minus the runoff without TGR) under scenarios with and without TGR.

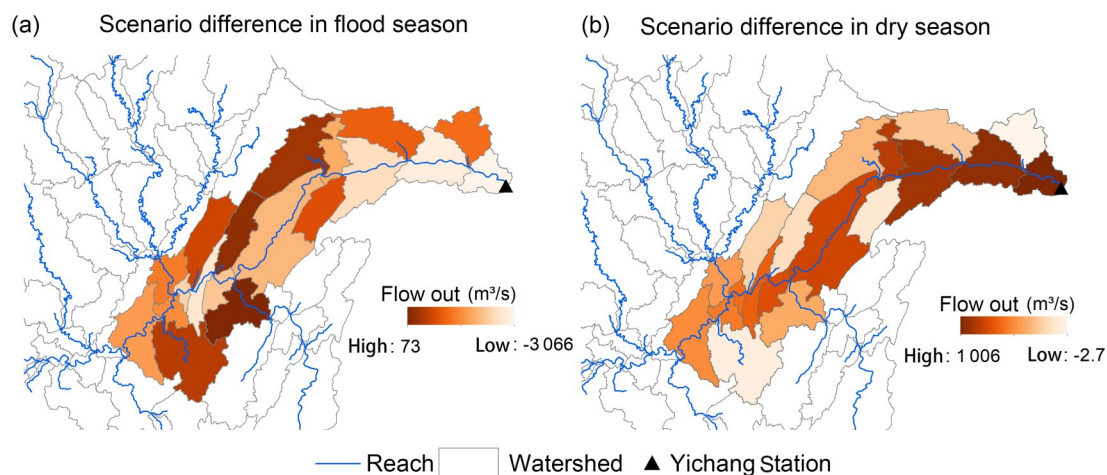


Figure 8. Differences (flowout with TGR minus flowout without TGR) in yearly average flow out under flood and dry seasons.

2.4 Impact of TGR on Water Supply and Demand

To understand the variation characteristics of the supply-demand index over time and consider data availability, years including 2000, 2005, 2010, and 2020 were chosen to make a supply-demand analysis. By comparing the seasonal differences in the supply-demand index under scenarios with and without the TGR, the impact of the reservoir on the supply-demand balance in the Upper Yangtze River is revealed (Figure 9). The results indicate that the water supply and demand imbalanced area in

the Upper Yangtze River is mainly concentrated in areas such as Chongqing, Chengdu, and Guizhou. Qinghai, Gansu, and Yunnan are regions where supply and demand are balanced or supply exceeds demand. In 2020, compared to 2005, the number of cities with supply-demand imbalance increased by 6 in spring, 5 in summer, and 3 in autumn and winter.

Scenarios with and without the reservoir indicate that the TGR has a minimal regional impact on supply-demand balanced areas, which remain largely unchanged

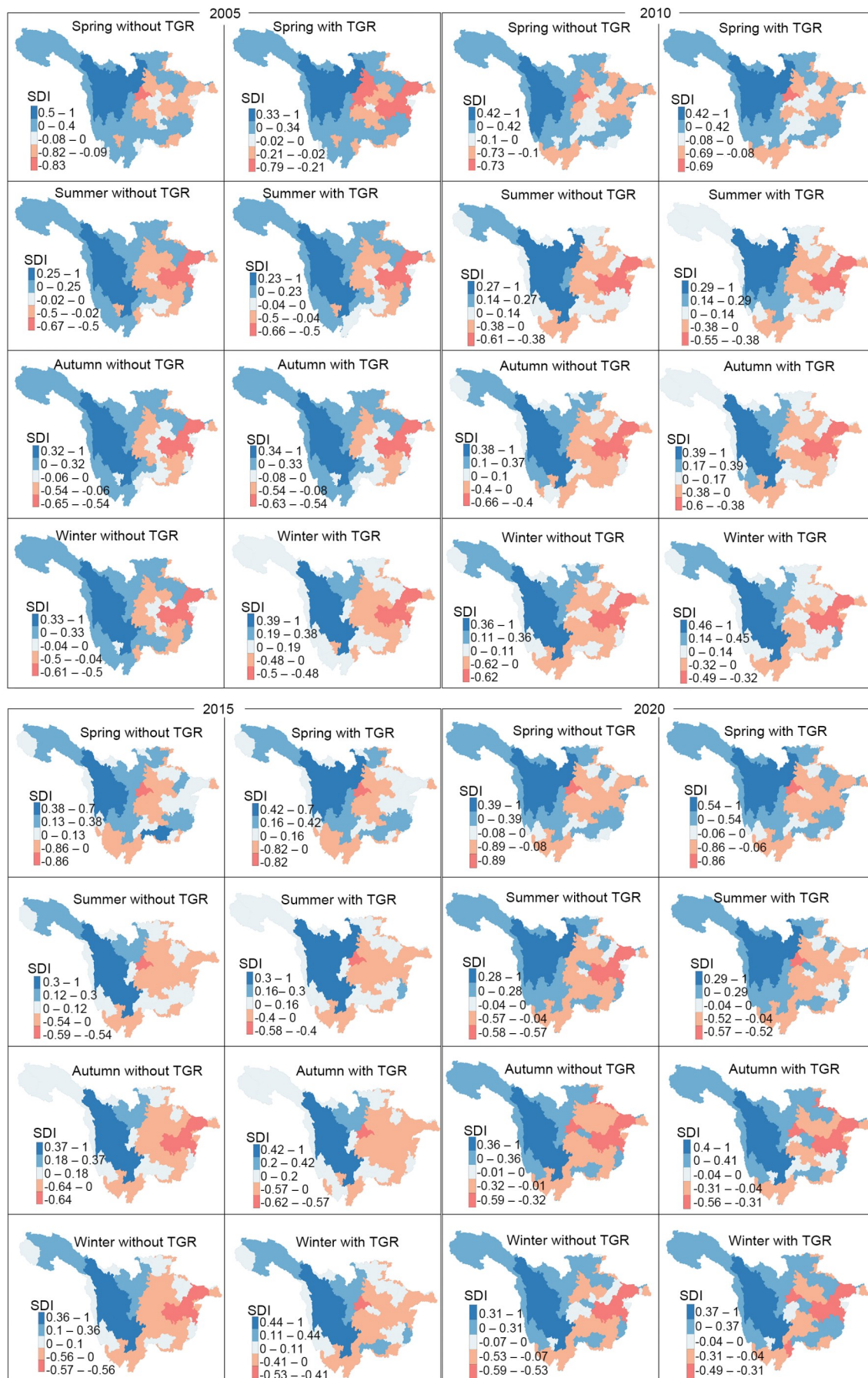


Figure 9. Disparities in water supply-demand balance in the Upper Yangtze River Basin under scenarios with and without TGR.

regardless of the reservoir. However, the TGR plays a notable role in mitigating supply-demand imbalances, particularly in Chongqing. For instance, in the winter of 2005, the SDI for Chongqing improved from -0.6 to -0.5, in spring it decreased from -0.3 to -0.22. Similar effects were observed in the winter of 2010 and the summer of 2015, with the SDI increasing by 0.12 and 0.14, respectively. In 2020, the SDI for Chongqing increased slightly in both autumn and winter. In contrast, the TGR has a relatively minor influence on Chengdu, where the spring SDI remains consistently low, ranging between -0.7 and -0.89. During summer, autumn, and winter, the SDI for Chengdu fluctuates between -0.5 and -0.6, indicating a less severe imbalance than spring.

3 DISCUSSION

3.1 Impact of TGR on Runoff and Water Supply-Demand

Before simulating runoff, analyzing the water change pattern in the Upper Yangtze River region is imperative. Due to climate change and frequent human activities, there has been a significant increase in the water body area in the Upper Yangtze River in recent years. Compared to the year 2000, the permanent water bodies in the Upper Yangtze River have increased by 2 195.83 km², while the seasonal water bodies have increased by 1 687.78 km². Zhang et al. (2023) found that since 2003, there has been an increasing trend in water storage in the Yangtze River Basin, with a rise of 2.75 ± 0.62 mm/year from January 2003 to July 2017. Changes in precipitation play a crucial role in altering the spatial distribution of the trend in water storage and the increase in water storage is attributed to climate change (Wu et al., 2023). Large reservoirs such as the TGR also influence regional water storage. It is essential to consider how to deduct and quantify the impact of the TGR on the upstream runoff.

The original model uses a target release method for water discharge, designed for reservoir release of floodwater, while the TGR is a multi-purpose reservoir. In SWAT-M, NDTARG is the same as the ND_{tag} in Eq. (3), calibrating NDTARG is important for simulating result. Besides, the minimum outflows of the TGR in SWAT-M is 5 000 m³/s. The reservoir outflows ensured the minimum water supply. Therefore, the model provides more realistic runoff values in the flood period and the lowest reservoir outflow during the dry season. Based on the NS and PBIAS, the modified model demonstrates better simulation performance than the original model. Therefore, when simulating multi-purpose reservoirs, the use of the SWAT-M model proposed by Wang et al. (2023) is recommended. Notably, the flow at each hydrological station experienced sudden reductions in 2006, 2011, 2015, and 2017. Some studies suggest that El Niño is the primary factor contributing to these anomalies in runoff (Yu and Kim, 2013). Therefore, the SWAT simulation results in these years are difficult to match with actual data.

By setting scenarios with and without the reservoir, the effects of the TGR on the upstream can be evaluated

quantitatively. Seasonal variations reveal a significant reduction in flow out volume during the flood season under the reservoir scenario, particularly in the mainstream of the Yangtze River, where flow differences can reach up to 3 000 m³/s. Conversely, during the dry season, flow levels in the reservoir scenario exceed those of natural runoff, with a maximum flow out of 1 000 m³/s also occurring in the mainstream. Previous studies (Cheng et al., 2024; Wang et al., 2023) have confirmed that TGR operations, which aim to store water in wet seasons and release water during dry seasons, effectively reduce high-flow peaks while enhancing low-flow flow conditions. Data from the Ministry of Water Resources also indicate that TGR's flood control measures reduced peak flows by 30 000 m³/s during July 2010, demonstrating its critical role in flood mitigation. Consequently, model simulations indicate that the reservoir operations reduce flows during flood seasons, whereas strategic water replenishment increases flows in dry seasons. It is a potential solution to future extreme climate events, such as severe droughts and extreme precipitation. Research indicates that future extreme climates will manifest as compound weather patterns, with rapid shifts between droughts and floods becoming increasingly common, particularly in the Yangtze River Basin of China (Wang et al., 2022). This implies that under the future climate, the TGR must simultaneously address the risks of floods and droughts, thereby increasing the complexity of its operation (Cheng et al., 2024). Determining the optimal operational level of the TGR to face future flood and drought risks is a critical issue worthy of in-depth exploration. The SWAT-M incorporates reservoir scheduling plans, and integrating future flood and drought warning systems will facilitate optimal scheduling in response to extreme weather events.

Moreover, this study discussed the social impacts of the TGR, particularly concerning water supply and demand balance. The imbalance of ecosystem services supply and demand can trigger cascading ecological and environmental challenges, threatening sustainable socioeconomic development (Tao et al., 2018). The TGR has significantly altered the natural flow regime, resulting in varied socio-economic impacts across the Upper Yangtze River Basin. Regions like Chongqing, Chengdu, and Guizhou face pronounced supply-demand imbalances, while areas such as Qinghai, Gansu, and Yunnan benefit from balanced or surplus conditions due to abundant water resources. In comparing scenarios with and without the reservoir, the TGR's influence is minimal in regions with an existing supply-demand balance. However, it plays a mitigating role in significant imbalances areas, particularly in Chongqing, where increased water supply has notably reduced the SDI by up to 0.14. Overall, the TGR has shown a notable effect on alleviating supply-demand imbalances, especially during the winter and spring seasons in Chongqing. We primarily focus on the impact of the TGR on the seasonal supply-demand relationship in water yield, which holds practical significance at the seasonal scale. It could guide watershed manage-

ment and sustainable agricultural production (Zhou et al., 2024). The spring and winter seasons represent low-flow periods with relatively limited water resources, however, it is time for irrigation and sowing, as crop growth requires substantial water. Consequently, the reservoir's water storage during low-flow periods alleviates this supply-demand imbalance to some extent.

3.2 Limitation and Future Work

Although this study quantitatively assessed the impact of the TGR on the upper reaches of the Yangtze River, certain limitations should be acknowledged. First, the inherent uncertainty of the model will cause some discrepancies in certain upstream river sections under different reservoir scenarios. This may be due to parameter issues rather than the reservoir scenarios. However, overall, the results for the sections closer to the reservoir are considered reliable. Although the influence of the TGR on surface runoff has been clarified, its impact on groundwater remains unclear. Another limitation is the absence of collaboration with the Three Gorges Corporation, preventing access to authentic reservoir operation parameter data. The reservoir scheduling chart used in this study does not entirely correspond to the real data, introducing a degree of uncertainty to the results. These limitations highlight potential improvement in future studies, such as incorporating more advanced models that better capture the complexities of groundwater interactions. As well as seeking closer collaboration with relevant authorities for detailed reservoir operation data.

4 CONCLUSION

This study mainly utilized the SWAT reservoir optimization module to simulate the runoff from 2000 to 2020 in the Upper Yangtze River. Two scenarios were set (with and without the TGR scenarios) to compare the differences in flow, runoff depth, and changes in water supply and demand relationships. The main conclusions are: (1) Over the past two decades, permanent water bodies in the Upper Yangtze River increased significantly. The Jinsha River Basin and the mainstream of the Yangtze River from Yibin to Yichang showed the highest increase at rates of 37 and 27 km²/year, respectively. (2) The optimized SWAT model improved the NS and PBIAS at the four hydrological stations. The NS increased by a maximum of 0.3, and the PBIAS increased by 22. (3) The scenario analysis with and without the TGR revealed significant seasonal variations in flow out value. In flood season, the reservoir scenario showed lower flow than the non-reservoir scenario, with a maximum decrease of 4 500 m³/s. In the dry season, the reservoir scenario exhibited higher flow, with a maximum increase of 1 500 m³/s. (4) The TGR had the most significant mitigating effect on the supply-demand imbalance in Chongqing, particularly alleviating the imbalance during the winter and spring seasons. The reservoir increased the supply-demand balance index by up to 0.16, but its impact on regions already in supply-demand balance was minimal.

This study can contribute to understanding the natural and socio-economic effects of the TGR.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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