

# Spatiotemporal Variability of Non-Point Source Pollution and Water Quality Response in a Typical Shallow Lake Basin

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**Abstract.** Shijiu Lake is a typical transboundary shallow lake connected to the Yangtze River in the lower Yangtze region, where water environmental management faces practical challenges due to complex pollution sources and difficulties in cross-jurisdictional coordination. This study systematically analyzed the spatiotemporal variability of non-point source (NPS) pollution loads in the Shijiu Lake basin and investigated the response relationships between major inflowing rivers and lake water quality at monitoring sections. The results indicated that: (1) the total annual total nitrogen(TN) load entering the lake was 2924.20 t and the total annual total phosphorus(TP) load was 109.68 t, of which trans-basin water conveyed through the Zhongliu River accounted for 69% and 67% of the total TN and TP inputs, respectively, representing the dominant source of pollutants entering the lake; (2) high TN load areas were mainly distributed in the eastern zones with dense population and industrial activities and in the southwestern agricultural areas, whereas high TP load areas were concentrated in the northeastern zones with intensive livestock farming and the southwestern agricultural areas; and (3) the Zhongliu River inflow significantly influenced water quality at the Shijiu Lake center, Gaochun, Dangtu, and Bowang monitoring sections, the Xinqiao River primarily affected the Lishui section, and the remaining inflowing rivers had limited influence confined to river-mouth areas.

## 1 Introduction

Shallow lakes are vital freshwater resources and important ecosystem components in China. With rapid socioeconomic development in lake basins, non-point source (NPS) pollution has become a key factor limiting the improvement of lake water quality[1–5]. For cross-jurisdictional shallow lakes, the diversity of pollution sources within the basin, the complexity of inflow pathways, and the mismatch between administrative boundaries and natural catchment boundaries have compounded the difficulty of water environmental management.

Currently, research on the coupled analysis of NPS pollution and water quality response for cross-boundary shallow lakes connected to rivers remains relatively limited. Shijiu Lake, located at the border between Jiangsu and Anhui provinces, possesses multiple attributes including cross-boundary, river-connected, and shallow-water characteristics [6–7]. Its water quality management requires not only clarification of pollution contributions from various inflowing rivers but also analysis of the differentiated impacts of different inflow pathways on water quality across lake zones.

Accordingly, the present study took Shijiu Lake as the research subject and employed a coupled modeling approach using the distributed hydrological model SWAT (Soil and Water Assessment Tool) and the two-dimensional hydrodynamic water quality model MIKE21

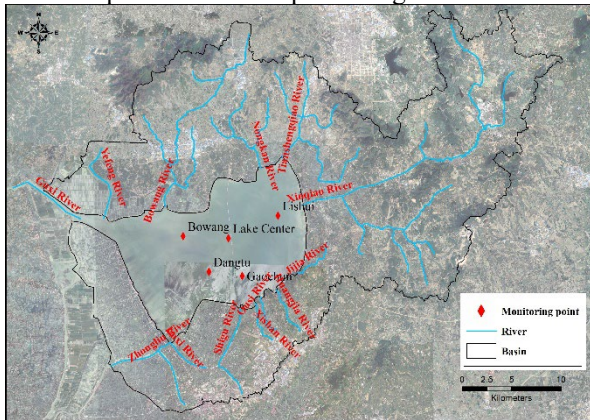
to conduct the following research: (1) construct a basin-scale NPS pollution load estimation framework and analyze the spatiotemporal distribution patterns of total nitrogen(TN) and total phosphorus(TP) loads; (2) couple the SWAT and MIKE21 models to simulate the transport and diffusion of pollutants within the lake; and (3) examine the influence of individual inflowing rivers on water quality at lake monitoring sections. The findings provide a scientific basis for pollution source identification and zoned management of inflowing rivers in Shijiu Lake and other similar transboundary shallow lakes.

## 2 Study Area

Shijiu Lake is located at the border between Jiangsu and Anhui provinces and is a typical river-connected shallow lake in the lower Yangtze River region, possessing multiple attributes as a cross-boundary lake, flow-through lake, and seasonally shallow lake. The lake surface area is approximately 207.65 km<sup>2</sup>, jointly managed by Gaochun District and Lishui District of Nanjing and by Dangtu County and Bowang District of Ma'anshan (Fig. 1). Major inflowing rivers include the Nongkan, Tianshengqiao, Xinqiao, Jijia, Huangjia, Ousi, Xishan, Shigu, Luxi, and Zhongliu rivers, as well as Yefeng River and the Bowang River; the Guxi River is the only outflowing channel connecting to the Yangtze River. Among these, the Xinqiao River has the largest catchment area on the Nanjing side, and the Zhongliu River serves as the

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primary channel conveying trans-basin water into the lake. Under the combined influence of agricultural NPS pollution, riparian domestic sewage, livestock farming pollution, and cross-boundary trans-basin inflows, TN and TP concentrations in the lake have remained at relatively elevated levels in recent years, exhibiting typical compound pollution characteristics involving both external inputs and internal pollutant generation.



**Fig. 1.** Geographic location and river system of the Shijiu Lake basin.

### 3 Data and Methods

#### 3.1 Data Sources

The data used in this study encompassed multiple categories, including topography, land use, soil, meteorology, hydrology and water quality, and socioeconomics. Topographic data were derived from a 1:50,000-scale DEM; land use classification data were obtained from the Global Land Cover spatial distribution dataset; soil data were sourced from the Harmonized World Soil Database (HWSD); meteorological data included daily precipitation, temperature, relative humidity, wind speed, and other observations from the study area and surrounding weather stations during 2013–2018; and river network data were digitized from Sentinel-2 satellite imagery. All geospatial data were projected using the CGCS2000 coordinate system.

#### 3.2 NPS Pollution Model Construction and Calibration

The SWAT model was employed to estimate NPS pollution loads in the Shijiu Lake basin. SWAT is a distributed hydrological model developed by the USDA Agricultural Research Service, capable of simulating watershed runoff, sediment, and nutrient transport processes at daily and monthly time scales [8,9]. In this study, the basin was divided into 59 sub-basins, and the runoff generation, pollutant production, and transport processes were simulated for each sub-basin.

Due to the lack of continuous discharge monitoring data in the Shijiu Lake basin, calibration and validation data were obtained through a proxy-basin transposition method [10–14]. Measured discharge data from the Shijie Hydrological Station on the Ruishui River in Guangde County, Xuancheng City, Anhui Province, located within

a comparable precipitation isoline region, were used and converted through catchment area ratios to derive discharge processes for the Shijiu Lake sub-basins. The model warm-up period was set to 2013, with 2014 serving as the calibration and validation period. The Nash–Sutcliffe efficiency coefficient (NSE) and relative error (RE) were selected as model performance indicators. Calibration results (Table 1) demonstrated that the model performed satisfactorily in nutrient load simulation and could provide reliable boundary conditions for the coupled hydrodynamic water quality model.

The Ruishui River basin was selected as the proxy basin based on its similarity to the validation sub-basin used in this study. Both regions are located in the northern subtropical monsoon climate zone and share generally comparable climatic conditions. Specifically, the mean annual precipitation in Guangde City, where the Ruishui River basin is located, is approximately 1328 mm, whereas that in Gaochun District, where Sub-basin 47 used for model validation is located, is about 1160 mm, suggesting broadly similar regional precipitation conditions. Moreover, the two regions are geographically close, being separated by only about 50 km, which further supports their climatic similarity. Hydrologically, they fall within the same precipitation isoline region and exhibit similar runoff generation mechanisms. In addition, the Shijie Hydrological Station in the Ruishui River basin provides long-term continuous discharge records, making it a reliable reference for proxy-basin transposition.

However, the proxy-basin transposition method inevitably introduces uncertainty due to differences in underlying surface conditions, soil properties, and local hydrological characteristics between the two basins. Moreover, the catchment area ratio method assumes a linear scaling relationship, which may not fully represent non-linear hydrological responses. These uncertainties were partially mitigated through model calibration, as indicated by the acceptable NSE and RE values in Table 1. Nevertheless, future studies should incorporate direct monitoring data from the Shijiu Lake basin to further reduce uncertainty and improve simulation accuracy.

**Table 1.** Model calibration results.

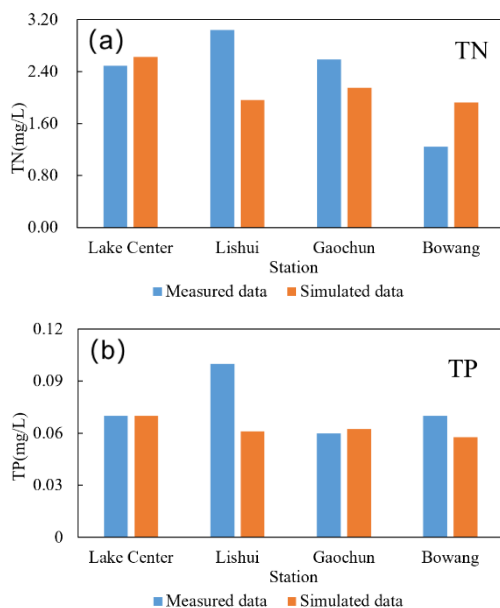
Sub-basin	Parameter	RE	NSE
47	TN	16.7%	0.68
	TP	5.8%	0.75

#### 3.3 Hydrodynamic Water Quality Model Construction and Validation

The MIKE21 model was adopted for hydrodynamic and water quality simulation of the lake. MIKE21 is a two-dimensional shallow-water equation hydrodynamic model developed by the Danish Hydraulic Institute (DHI) [15,16]. The required modeling data included Shijiu Lake bathymetric data, lake water level boundaries, and discharge and pollution load time series of 14 inflowing rivers (provided by SWAT model outputs).

Model parameter calibration and validation were conducted using measured water quality data from Shijiu

Lake in 2018. The water level boundary was set to the February 2018 mean water level of 3.532 m (Yellow Sea elevation datum). The Manning roughness coefficient ranged from 0.023 to 0.028, with slightly different values assigned to the main channel and the floodplain. The turbulent viscosity coefficient was calculated using the Smagorinsky formulation. The degradation coefficients of pollutants were determined based on relevant previous studies and model calibration results. Specifically, the degradation coefficients for TP and TN were set to 0.002 d<sup>-1</sup> and 0.03 d<sup>-1</sup>, respectively. To account for the influence of water temperature on degradation, the temperature correction coefficients were set to 1.073 for TP and 1.043 for TN. The sediment release rates were 0.0003 g m<sup>-2</sup> d<sup>-1</sup> for TP and 0.02 g m<sup>-2</sup> d<sup>-1</sup> for TN. Discharge and pollution load time series of the 14 inflowing rivers were all derived from SWAT model calculations. Validation was performed by comparing simulated and measured TP and TN concentrations at five monitoring sections (Shijiu Lake center, Lishui center, Gaochun center, Bowang center, and Dangtu center) in February 2018. The results showed that the mean relative errors for TP and TN were 15.3% and 28.0%, respectively, both below 30%, indicating that the model adequately reproduced the spatial distribution of lake water quality (Fig.2). February 2018 was selected for model validation because it represented dry-season low-flow conditions comparable to those of the design scenario. Under such conditions, reduced water level, storage volume, and dilution capacity make the lake more sensitive to external pollutant inputs. Therefore, satisfactory model performance during this period is essential for demonstrating the reliability of the simulation under critical conditions.



**Fig. 2.** Comparison between simulated and observed TN (a) and TP (b) concentrations at the monitoring sections.

### 3.4 Model Coupling Strategy and Design Scenarios

The SWAT and MIKE21 models were coupled using a one-way approach. Daily discharge and TN/TP load time

series output by the SWAT model for each inflowing river were reformatted and input as boundary conditions for the MIKE21 model. This coupling strategy leveraged SWAT's strengths in basin-scale NPS pollutant load estimation while utilizing MIKE21's capabilities in two-dimensional hydrodynamic and mass transport simulation, thereby enabling end-to-end simulation from the basin scale to the lake scale encompassing "pollutant generation–transport–response". For the design scenario, the mean storage volume during the driest month over the past 15 years was selected as the hydrological design condition to reflect the impact of unfavorable hydrological conditions on water quality. This corresponded to a water level of 5.02 m at the Sheshan Station of Shijiu Lake in February 2014, equivalent to 3.13 m above the Yellow Sea datum. Meteorological data from the concurrent period were used, with wind speed set to the Nanjing multi-year average of 3.5 m/s from the northeast.

The driest-month scenario was selected as the design condition because it reflects the most unfavorable water quality situation for management. During this period, reduced inflow, weakened flushing, and prolonged hydraulic residence time enhance pollutant accumulation in the lake. Consequently, even low pollutant loads may result in relatively high concentrations. Assessment under this scenario thus provides a conservative basis for evaluating the effectiveness of pollution control measures.

## 4 Results and Analysis

### 4.1 Spatial Distribution of Basin Pollution Loads

Based on the calibrated and validated SWAT model, combined with 2018 basin precipitation data, the annual TN and TP loads of each inflowing river to Shijiu Lake were calculated (Table 2). The total annual TN load entering the lake was 2924.20 t, and the total annual TP load was 109.68 t. Among all inflowing rivers, the Zhongliu River contributed a TN load of 2030.10 t/a (69% of the total) and a TP load of 73.63 t/a (67% of the total), ranking first by a substantial margin. The Xinqiao River had the largest TN load among intra-basin rivers (397.45 t/a), whereas the TP load of the Bowang River (9.58 t/a) was comparable to that of the Xinqiao River (9.21 t/a). By administrative region, the Nanjing section contributed TN of 726.26 t/a (25%) and TP of 26.05 t/a (24%); the Anhui section contributed TN of 167.85 t/a (6%) and TP of 10.0 t/a (9%); and trans-basin water through the Zhongliu River contributed TN of 2030.10 t/a (69%) and TP of 73.63 t/a (67%). Trans-basin water input was clearly the dominant source of pollutants entering the lake.

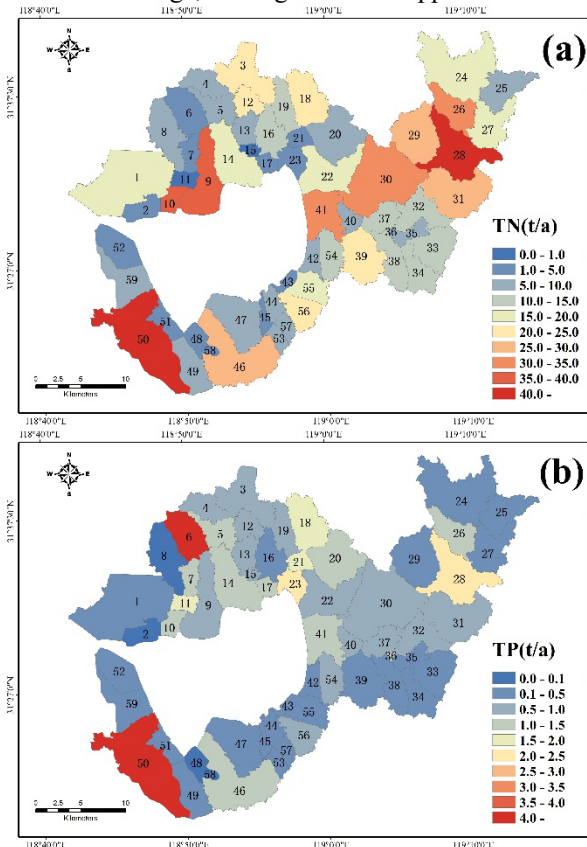
**Table 2.** Annual TN and TP loads of inflowing rivers to Shijiu Lake in 2018.

River	TN/t	TP/t	River	TN/t	TP/t
Yefeng River	18.49	0.16	Ousi River	11.58	0.38
Bowang River	141.97	9.58	Xishan River	14.29	0.54

Nongkan River	89.96	4.45	Shigu River	38.27	1.65
Tianshengqiao River	102.73	7.16	Luxi River	5.85	0.16
Xinqiao River	397.45	9.21	Zhongliu River	2030.10	73.63
Jijia River	19.86	0.94	Dangtu coast	7.39	0.26
Huangjia River	46.28	1.56	Total	2924.20	109.68

The spatial distribution of TN loads is shown in Fig. 3(a). The TN load in the Shijiu Lake basin ranged from 0.21 to 2024.28 t/a, with the maximum occurring in sub-basin No. 50. TN entered Shijiu Lake primarily through the Zhongliu River in the Anhui section and the Xinqiao River in the Nanjing section. High-value zones were mainly located in Jingqiao Town and Baima Town of Lishui District and Huyang Town of Dangtu County, where industrial activities were concentrated and population density was high.

The spatial distribution of TP loads is shown in Fig. 3(b). The TP load ranged from 0.03 to 46.73 t/a, with the maximum also occurring in sub-basin No. 50. TP entered Shijiu Lake mainly through the Bowang River and the Zhongliu River in the Ma'anshan section and through the Nongkan, Tianshengqiao, and Xinqiao rivers in Lishui District, Nanjing. These areas were characterized by heavy rural domestic sewage discharge, extensive farmland coverage, and high fertilizer application rates.



**Fig. 3.** Spatial distribution of annual TN (a) and TP (b) pollution loads in the Shijiu Lake basin.

## 4.2 Lake Water Quality Assessment

Under the driest-month scenario over the past 15 years, the water quality at five monitoring sections simulated by the coupled model is presented in Table 3. TN concentrations at the monitoring sections ranged from 1.736 to 1.885 mg/L, with all sections failing to meet the Class III standard (TN ≤ 1.0 mg/L), indicating that TN was the primary factor constraining water quality compliance in Shijiu Lake. TP concentrations ranged from 0.043 to 0.056 mg/L; most monitoring sections essentially met Class III water quality standards, except for the Dangtu Lake center, which fell into Class IV.

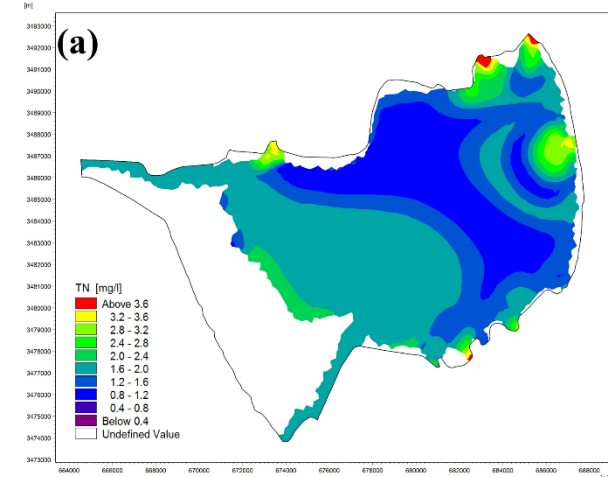
**Table 3.** Average TP and TN concentrations at monitoring sections under dry-season conditions.

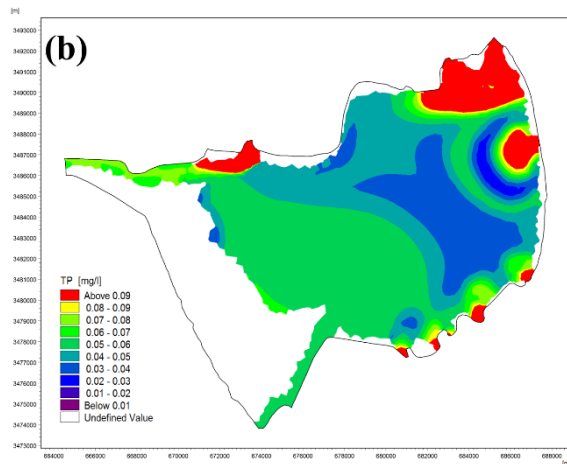
Parameter	Lake Center	Lishui	Gaochun	Bowang	Dangtu
TN (mg/L)	1.845	1.736	1.885	1.834	1.884
TP (mg/L)	0.047	0.043	0.050	0.050	0.056

## 4.3 Spatial Influence of Inflowing Rivers on Lake Water Quality

Based on the model simulation results, the spatial influence of each inflowing river on water quality at different lake monitoring sections was analyzed. The results indicated that during the dry season, lake water quality was primarily governed by trans-basin water input from the Zhongliu River and inflow from the Xinqiao River, which constituted the two dominant inflowing rivers affecting lake water quality (Fig. 4).

The Zhongliu River, located in the southwestern part of Shijiu Lake, is the main channel for receiving trans-basin water, carrying the largest discharge and the highest pollution load among all inflowing rivers. Simulation results showed that the Zhongliu River inflow significantly influenced the Shijiu Lake center, Gaochun center, Dangtu center, and Bowang center sections, serving as the key external input channel that determined overall lake water quality.





**Fig. 4.** Spatial distribution of TN (a) and TP (b) concentrations in Shijiu Lake.

The Xinqiao River, located on the northeastern side of the lake, is the inflowing river with the largest catchment area in the Nanjing section. Simulation results showed that among intra-basin inflows, the Xinqiao River exerted the most pronounced influence on the Lishui center section, whereas its impact on other lake sections was relatively minor.

In comparison, the remaining inflowing rivers, owing to their relatively small discharges, had generally limited influence ranges despite some exhibiting pollutant concentrations exceeding standards. Their effects were mainly confined to the respective river-mouth areas and adjacent nearshore zones of Shijiu Lake, with negligible impact on water quality at the lake center monitoring sections.

## 5 Discussion

This study revealed significant spatial variability in NPS pollution loads across the Shijiu Lake basin. The formation of high TN load zones was primarily influenced by population density and industrial activity intensity—in the eastern areas of Jingqiao Town, Baima Town, and Huyang Town, where urban–industrial activities and population were concentrated, domestic sewage and industrial wastewater discharge were the main causes of elevated TN loads. High TP load zones were more closely associated with livestock farming and agricultural fertilizer application; areas with heavy rural domestic sewage discharge, extensive farmland coverage, and high fertilizer application rates generally exhibited higher TP loads. Overall, the spatial variability of TN loads was driven by both urban–industrial and agricultural activities, whereas TP load variability was primarily controlled by livestock farming and agricultural fertilization [17–22].

As the main input channel for trans-basin water, the Zhongliu River’s TN and TP loads accounted for 69% and 67% of total inputs, respectively, far exceeding the combined contributions of intra-basin rivers (Nanjing section: 25% and 24%; Anhui section: 6% and 9%). This indicates that the water quality problems of Shijiu Lake do not originate solely from pollution discharge within the basin; trans-basin water input is the dominant factor

determining total pollutant loads in the lake. This finding has important implications for formulating lake management strategies.

Several methodological limitations and sources of uncertainty should be acknowledged. First, the proxy-basin transposition method used for SWAT calibration may introduce systematic bias because unavoidable differences remain in soil properties and land management practices between the Ruishui River basin and the study area. Second, the one-way coupling between SWAT and MIKE21 does not consider potential feedback effects of lake water level fluctuations on tributary discharge processes. Future studies should focus on establishing long-term monitoring stations within the Shijiu Lake basin and developing a two-way coupling framework to reduce these uncertainties and improve model performance.

## 6 Conclusions

This study employed a coupled SWAT–MIKE21 modeling approach to systematically analyze the spatiotemporal variability of NPS pollution loads in the Shijiu Lake basin and the spatial response relationships between major inflowing rivers and lake water quality. The main conclusions are as follows:

(1) The total annual TN and TP loads entering Shijiu Lake in 2018 were 2924.20 t and 109.68 t, respectively. The Zhongliu River was the dominant pollutant input channel, contributing 69% of TN and 67% of TP. The Nanjing section accounted for 25% and 24% of TN and TP loads, respectively, whereas the Anhui section accounted for 6% and 9%. Trans-basin water input was the dominant factor determining total pollutant loads in the lake.

(2) High TN load zones were mainly distributed in the eastern areas with dense population and industrial activities (Jingqiao Town, Baima Town, and Huyang Town) and the southwestern agricultural areas. High TP load zones were concentrated in areas with heavy rural domestic sewage discharge, extensive farmland, and high fertilizer application. Under the driest-month scenario, TP at monitoring sections generally met Class III water quality standards (except Dangtu center, which was classified as Class IV), whereas all TN sections failed to meet standards (1.736–1.885 mg/L). TN was the primary factor constraining water quality compliance.

(3) The Zhongliu River inflow significantly influenced water quality at the Shijiu Lake center, Gaochun, Dangtu, and Bowang monitoring sections. The Xinqiao River primarily affected the Lishui section. The remaining inflowing rivers had limited influence, confined to river-mouth areas. It is recommended to prioritize coordinated cross-boundary management of the upstream Zhongliu River basin and source reduction of NPS pollution in the Xinqiao River basin.

## References

1. Y. Tian, J. Shen, J. Feng, T. Wang, Y. Jiao, X. Wang, *Ecol. Indic.* 178, 113981 (2025)

2. W. Zhang, D. Zhang, X. Jin, B. Shan, *Ecol. Indic.* 178, 113914 (2025)
3. X. Zhang, S. Zhang, L. Fang, C. Zhang, X. Li, *Sci. Total Environ.* 957, 177843 (2024)
4. X. Yan, Y. Xia, C. Ti, J. Shan, Y. Wu, X. Yan, *Sci. Total Environ.* 914, 169821 (2024)
5. B. Qin, Y. Zhang, G. Zhu, G. Gao, *Sci. Total Environ.* 881, 163494 (2023)
6. Y. Liang, W. He, X. Xue, T. Zhang, J. Ma, Y. Bai, D. Fang, Z. Kuang, *Mar. Pollut. Bull.* 222, 118656 (2026)
7. C. Ren, M. Jiang, C. Jiang, T. Liu, Y. Wang, K. Liu, *Glob. Ecol. Conserv.* 65, e03998 (2026)
8. J.G. Arnold, R. Srinivasan, R.S. Muttiah, J.R. Williams, *J. Am. Water Resour. Assoc.* 34(1), 73-89 (1998)
9. P.W. Gassman, M.R. Reyes, C.H. Green, J.G. Arnold, *Trans. ASABE* 50(4), 1211-1250 (2007)
10. S.A. Archfield, R.M. Vogel, *Water Resour. Res.* 46, W10513 (2010)
11. C. Shu, T.B.M.J. Ouarda, *Water Resour. Res.* 48, W02523 (2012)
12. J. Samuel, P. Coulibaly, R.A. Metcalfe, *J. Hydrol. Eng.* 16(5), 447-459 (2011)
13. K. Ergen, E. Kentel, *J. Environ. Manag.* 166, 309-320 (2016)
14. Q. Li, Y. Peng, G. Wang, H. Wang, B. Xue, X. Hu, *Water* 11(5), 1104 (2019)
15. I.R. Warren, H.K. Bach, *Environ. Softw.* 7(4), 229-240 (1992)
16. A.D. McCowan, E.B. Rasmussen, P. Berg, in *Proc. 6th Conf. Hydraulics in Civil Engineering* (Hobart, 2001)
17. G. Xu, J. Xiao, D.M. Oliver, Z. Yang, K. Xiong, Z. Zhao, L. Zheng, H. Fan, F. Zhang, *Ecol. Indic.* 133, 108453 (2021)
18. Z. Wei, Y. Yu, Y. Yi, *J. Environ. Manag.* 345, 118662 (2023)
19. M. Choi, S. Nam, J. Choi, J. Hwang, S. Lee, *J. Hydrol. Reg. Stud.* 55, 101958 (2024)
20. L. Hua, W. Li, L. Zhai, H. Yen, Q. Lei, H. Liu, T. Ren, Y. Xia, F. Zhang, X. Fan, *J. Hydrol.* 571, 322-331 (2019)
21. D. Fu, Y. Gong, C. Chen, X. Gui, H. Liu, S. Chen, J. Ren, B. Hou, *Water* 15(19), 3503 (2023)
22. B. Yan, Y.Y. Li, Z.W. Gao, Y.H. Fang, Y.Q. Zhu, Z.B. Song, *Ecol. Indic.* 178, 113995 (2025)