

# Geophysical Research Letters®

## RESEARCH LETTER

10.1029/2025GL119131

## Water Storage Changes of Lakes and Reservoirs Across Asia (2018–2023) and Their Effects in Flood Control



### Key Points:

- Fusion of altimetry satellite and meteorological data reconstructed a 5-year monthly water level series for 7,433 water bodies across Asia
- The annual water level change rate of reservoirs exceeds that of lakes, indicating a significant intervening influence on regional surface hydrology across Asia
- Lakes' limited self-regulation increases flood risk, while reservoir networks effectively reduce flood frequency and intensity

### Supporting Information:

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

### Correspondence to:

Z. Li,  
zhao.li@whu.edu.cn

### Citation:

An, Z., Li, Z., Jin, T., Jiang, W., Yuan, P., Liu, K., et al. (2026). Water storage changes of lakes and reservoirs across Asia (2018–2023) and their effects in flood control. *Geophysical Research Letters*, 53, e2025GL119131. <https://doi.org/10.1029/2025GL119131>

Received 3 SEP 2025

Accepted 6 DEC 2025

### Author Contributions:

**Conceptualization:** Zhao Li, Weiping Jiang  
**Data curation:** Taoyong Jin, Jian Wang  
**Formal analysis:** Peng Yuan, Kai Liu, Jian Wang, Peng Chen  
**Investigation:** Taoyong Jin, Kai Liu  
**Methodology:** Zhao Li  
**Resources:** Peng Chen  
**Software:** Taoyong Jin, Weiping Jiang  
**Validation:** Zhao Li, Peng Chen  
**Visualization:** Weiping Jiang  
**Writing – review & editing:** Peng Yuan

Zhiyuan An<sup>1</sup> , Zhao Li<sup>2</sup> , Taoyong Jin<sup>1</sup> , Weiping Jiang<sup>1,2</sup> , Peng Yuan<sup>3</sup> , Kai Liu<sup>2</sup> , Jian Wang<sup>2</sup> , and Peng Chen<sup>4</sup> 

<sup>1</sup>School of Geodesy and Geomatics, Wuhan University, Wuhan, China, <sup>2</sup>GNSS Research Center, Wuhan University, Wuhan, China, <sup>3</sup>Space Geodetic Techniques, GFZ Helmholtz Centre for Geosciences, Potsdam, Germany, <sup>4</sup>College of Geomatics, Xi'an University of Science and Technology, Xi'an, China

**Abstract** Monitoring lake and reservoir water levels is critical for water resource management and flood risk mitigation. We integrate Sentinel-3A/B and ICESat-2 altimetry to reconstruct monthly water levels (2018–2023) for 7,433 lakes and reservoirs (>5 km<sup>2</sup>) across Asia and estimate their storage variations. Reservoirs exhibit a median annual water level change of 0.36 m/yr, far exceeding the 0.05 m/yr observed for lakes, highlighting their dominant role in surface water dynamics. Eight Asian basins flood events reveal that insufficient self-regulation capacity of lakes is the primary flood trigger, while large reservoirs effectively mitigate flood frequency and intensity through regulation. These findings emphasize the importance of high-precision satellite altimetry in surface water assessments and the critical role of reservoirs in modulating hydrological extremes under climate change.

**Plain Language Summary** Obtaining high-precision, long-term water level time series for reservoirs is a necessary prerequisite for understanding how reservoirs regulate regional hydrological cycles. In this study, we used multi-source satellite altimetry data to retrieve water level and storage changes for 7,433 lakes and reservoirs across Asia, and compared the observations with traditional water level measurements. Based on this, we assessed the overall impact of reservoirs on Asia's hydrological cycle. The results demonstrate that human activities exert significant intervention on the natural water cycle, especially in low-latitude and coastal regions. Reservoirs dominate water storage changes in Asian basins and provide the main seasonal water level variations within these basins. Proper management of reservoirs can effectively reduce the frequency and intensity of flooding in local areas.

## 1. Introduction

Surface water bodies are one of the essential components sustaining diverse and complex ecosystems (Gleick, 2003; Tranvik et al., 2009), with lakes and reservoirs serving as the primary storage forms of surface water, holding approximately 87% of the planet's surface freshwater (Bonnema et al., 2022). Formed by natural forces, lakes exhibit long water exchange cycles, low mobility, and are greatly influenced by natural climate conditions, making them prone to natural disasters such as floods (Downing et al., 2006). Reservoirs are formed by human-made dams on rivers, which influence the hydrological cycle by regulating regional surface water for purposes such as hydropower generation, irrigation, water supply, and flood control (Han et al., 2024). Asia is the most densely populated continent in the world, where human activities have a particularly significant impact on the hydrological system (Wang et al., 2022). Over the past decades, to meet the growing demands for energy and environmental regulation, the water volume in Asian reservoirs has increased exponentially, accounting for 60.04% of the global total reservoir storage capacity (Lehner et al., 2011; Li et al., 2023; Timpe & Kaplan, 2017; Zarfl et al., 2015). Improper utilization of reservoirs can cause downstream water shortages, flood disasters, and other related problems (Deemer et al., 2016; G. Zhao et al., 2022). Therefore, continuous monitoring of water level and storage changes in reservoirs and lakes is crucial for water resource management and hydrological cycle studies in Asia.

Due to political and economic factors, long-term, high-precision water level observation data for lakes and reservoirs are severely poor, resulting in a very limited understanding of the extent of human impact on regional hydrological cycles (P. Chen et al., 2022; Duan & Bastiaanssen, 2013; Ryan et al., 2020). Satellite altimetry technology can obtain high-precision, long-term water level time series for individual water bodies without relying on ground monitoring stations and operates all-weather. However, due to fixed orbits and revisit cycles,

© 2026. The Author(s).

This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

the continuity of the acquired water level time series is limited (Yang et al., 2024). Therefore, global water body changes based on altimetry satellites mainly focus on annual and seasonal variations, making it difficult to capture water level changes at shorter time scales (T. Chen et al., 2021; Song et al., 2014). The KF-MFWL (Kalman Fusion–MissForest Water Level) algorithm can fuse altimetry data and meteorological data to reconstruct high-precision, continuous monthly water level time series for lakes and reservoirs (Jiang et al., 2024), providing a theoretical basis for obtaining long-term, high-precision water level variations of lakes and reservoirs in the Asian region.

On the other hand, reservoir water level variations not only drive regional lake water levels but also play an important role in flood regulation. Lake water level changes are primarily influenced by natural factors (such as temperature, evaporation, and precipitation) and human factors (such as reservoirs). For example, permafrost thaw induced by global warming has caused rapid lake expansion on the Tibetan Plateau (Ji et al., 2025), while decreased rainfall and increased evaporation on the Indian Peninsula have led to sustained lake level declines (Rodell et al., 2018). Globally, lake water level changes are positively correlated with reservoir water level variations within the basin (Cooley et al., 2021). However, the aforementioned studies only investigated the impact of natural factors on lake changes, without quantifying the continuous variation characteristics of reservoirs and lakes, nor further exploring the extent of human activities' influence on lakes. Furthermore, flood disasters caused by rising lake water levels due to extreme rainfall, snowmelt, and other factors result in significant annual economic losses (B. Zhao et al., 2024). While individual reservoirs play a notable role in flood control within small areas (Ryan et al., 2020), there is limited research exploring the regulatory role of reservoirs in flood mitigation over larger regions. Therefore, it is essential to obtain high-precision, long-term water level variation data for reservoirs and lakes, to distinguish between reservoir and lake changes, to quantify their continuous variation characteristics, so as to explore the impact of reservoirs on lakes, and investigate the regulatory role of reservoirs in flood disaster management.

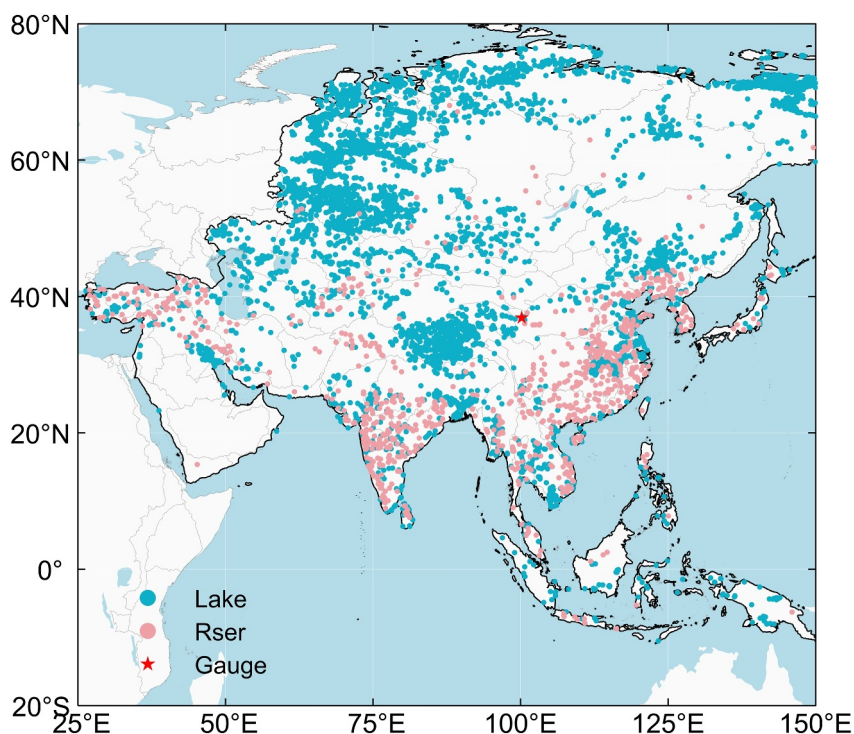
Therefore, we employ the KF-MFWL algorithm, integrating ICESat-2, Sentinel-3A/B satellite data, global mask data (Pi et al., 2022a), and meteorological data to reconstruct monthly water level and storage time series for 7,433 water bodies across Asia from August 2018 to August 2023. Reservoirs and lakes were classified based on the water body type labels provided by the GLAKE data set (in general, water bodies influenced by human activities are classified as reservoirs, while those unaffected by human interventions are categorized as lakes; in the GLAKE database, reservoirs are labeled as “1” and lakes as “0”). Building on this data set, this study conducted an in-depth investigation of the impact of human activities' impact on the hydrological cycle in Asia, categorized by river basins. Finally, by integrating data from the International Disaster Database, the spatial and temporal relationship between reservoirs and flood disasters in the Asian region were discussed. Our work would provide more comprehensive and accurate data support for water resource management, ecological protection, and disaster prevention in Asia, while also offering new insights and methodologies for hydrological studies under the context of global change.

## 2. Data and Methods

### 2.1. Water Level Retrieval Based on Altimetric Satellite Data

To obtain the water level time series of inland water bodies in Asia, we used the global lake data set provided by Pi et al. (2022a) as a mask. Water level time series from August 2018 to August 2023 were retrieved for 7,433 water bodies larger than 5 km<sup>2</sup>—including 6,517 lakes and 916 reservoirs—based on Sentinel-3A/B Level-2B products corrected with the Improved Narrow Primary Peak Threshold Retracking (INPPTR) retracking algorithm and the ATL13 (ICESat-2 ATL13-Inland Water Surface Height) product from the ICESat-2 satellite (Figure 1). The 5-year monthly water level data set enables the analysis of seasonal patterns and interannual variations, offering valuable insights into mid- to long-term hydrological dynamics and reservoir operations influenced by human regulation. However, this time span is insufficient for evaluating long-term climate-driven trends—particularly those associated with multi-decadal oscillations such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO)—which require longer observation records for robust assessment.

The GLAKES (global lake) data set was developed based on the Global Surface Water Occurrence (GSWO) (Pekel et al., 2016) data set and a deep learning semantic segmentation model (U-Net), resulting in a global water body boundary data set that includes approximately 3.4 million water bodies with surface areas  $\geq 0.03$  km<sup>2</sup>. Sentinel-3A/B is a satellite constellation consisting of two satellites: Sentinel-3A, which became operational on



**Figure 1.** The spatial distribution of lakes and reservoirs across Asia is shown. Light blue dots indicate the locations of lakes, light pink dots represent the locations of reservoirs, and the pentagram denotes the location of the in situ observation station at Qinghai Lake. Since HOBO gauges are deployed for dynamic monitoring rather than as fixed long-term observation stations, their locations are not shown in the figure.

26 February 2016, and Sentinel-3B, which was launched on 25 April 2018 (Peng et al., 2025). Due to the application of delay-Doppler technology and the increased range migration, their along-track spatial resolution has been improved from 2 to 10 km (as in Low Resolution Mode [LRM], altimeters) to approximately 300 m. Moreover, they possess strong capabilities for minimizing land contamination (Boy et al., 2017). ICESat-2 satellite was launched in September 2018 and, compared to radar altimetry satellites, can provide higher spatial resolution and denser sampling frequency, with a footprint diameter of 17.5 m, enabling the monitoring of small to medium-sized lakes (Liu et al., 2019; Neumann et al., 2019; Xiang et al., 2021).

## 2.2. Water Level Time Series Reconstruction and Water Storage Estimation

Due to the limitations of satellite altimetry, such as orbit and revisit cycles, continuous long-term observation of a single water body is not feasible. However, continuous high-precision water level time series are crucial for monitoring the hydrological cycle. ERA5 (European Centre for Medium-Range Weather Forecasts [ECMWF] Reanalysis v5) is the fifth-generation atmospheric reanalysis data set from ECMWF, covering global climate data from January 1950 to the present (Muñoz-Sabater et al., 2021). It has a spatial resolution of 0.1° and provides hourly estimates of atmospheric, land, and ocean climate variables. By combining meteorological data with water level data from satellite altimetry, a model can be built to reconstruct water level time series. Therefore, this study uses the KF-MFWL algorithm to reconstruct water level time series, combining satellite-observed water levels with ERA5 meteorological data to obtain monthly resolution water level time series (Jiang et al., 2024).

Landsat provides continuous water body area change since 1979. The GLAKE database derives accurate global water body areas using Landsat data. Therefore, in this study, water storage variation is approximated as the product of water level change and the surface area defined by the water body mask, thereby converting water level change into storage change. Basin-scale water storage variation is calculated as the sum of water storage changes for all water bodies (using the same method for both reservoirs and lakes). The proportion of reservoir storage change is calculated as reservoir storage change divided by the sum of lake and reservoir storage changes (Cooley et al., 2021).

### 2.3. In Situ Water Level

To validate the accuracy of the water level time series obtained by the method used in this study, continuous daily in situ measurements were compared, including data from the Xiasha Hydrological Station in Qinghai Province, China, for Qinghai Lake from January 2019 to August 2020, as well as continuous in situ data provided by the National Tibetan Plateau Data Center (<https://data.tpdc.ac.cn/home>) for Lumajiangdong Co from January 2019 to August 2020, Longyangxia Reservoir from January 2018 to August 2022, and Xiashan Reservoir from August 2022 to August 2023. The in situ water levels for Longyangxia Reservoir and Xiashan Reservoir were obtained using Onset HOBO Water Level Data Logger (HOBO) measurements, without fixed observation locations provided.

### 2.4. Flood Disaster Data

To investigate the relationship between reservoir water level changes and flood disasters, we obtained area and location data for 191 flood events in Asia from 2018 to 2021 from the Global Active Archive of Large Flood Events, 1985–Present (Dartmouth Flood Observatory). The Global Active Archive of Large Flood Events contains the timing and locations of 5,130 large-scale flood disasters from 1985 to August 2021.

## 3. Results and Discussion

### 3.1. Accuracy Validation of the KF-MFWL Algorithm

We validated the accuracy of the water level retrieval method based on Kalman filtering and multi-source altimetry satellite fusion water level (KFWL) and KF-MFWL algorithms (In Figure S1c in Supporting Information S1, KFWL refers only to the 12 red points and does not represent a continuous line overlapping with the KF-MFWL results. This is because KFWL is derived solely from the fusion of multi-source satellite observations. Due to satellite orbit and revisit cycle limitations, it cannot provide a continuous monthly water-level time series for relatively small water bodies. KF-MFWL, in comparison, is built upon KFWL by employing a machine learning approach that combines multi-source altimetry water levels with meteorological data to reconstruct a continuous time series. Therefore, in Figures S1b and S1c in Supporting Information S1, KFWL appears as discrete points, (whereas KF-MFWL constitutes a complete water-level time series.) using in situ water level from two lakes and two reservoirs (Table S1 and Figure S1 in Supporting Information S1). Qinghai Lake and Lumajiangdong Co have complete satellite-observed water level time series, with the KFWL and KF-MFWL time series fully comparable. Therefore, accuracy comparisons between KFWL and KF-MFWL were conducted only for Longyangxia Reservoir and Xiashan Reservoir. The RMSE values of KFWL for Qinghai Lake and Lumajiangdong Co were 0.08 and 0.10 m, respectively, with correlation coefficients ( $R$ ) of 0.96 and 0.92. These results demonstrate that the KFWL algorithm can obtain high-precision water level time series (Table S1 and Figure S1 in Supporting Information S1). At Longyangxia Reservoir, although the RMSE of KF-MFWL (1.17 m) is higher than that of KFWL (1.05 m) and the correlation coefficient  $R$  (0.80) is lower than that of KFWL (0.98), KF-MFWL provides a more complete and continuous water level time series (Figure S1c in Supporting Information S1). At Xiashan Reservoir, since KFWL and the in situ water level data overlap for only 1 month, RMSE and  $R$  could not be calculated. The KF-MFWL algorithm achieved an RMSE of 0.12 m and an  $R$  of 0.83, showing a high level of agreement with the observed water levels (Figure S1d and Table S1 in Supporting Information S1). In Figure S1c in Supporting Information S1 (July 2021) and Figure S1d in Supporting Information S1 (August 2022), the KF-MFWL is higher than the observed minimum water level, indicating an overestimation of the reservoir's lowest level. This issue was not observed in Figures S1a and S1b in Supporting Information S1. Therefore, KF-MFWL may overestimate the minimum reservoir level and underestimate the amplitude of water level variation, potentially leading to an underestimation of the reservoir's regulation capacity in subsequent analyses. The results demonstrate that the KF-MFWL algorithm provides stable and reliable monthly water level time series, effectively capturing both long-term trends and seasonal (monthly) variations in water storage. However, this study is based on a 5-year data set with monthly resolution, which limits its ability to capture high-frequency (e.g., daily or event-driven) short-term dynamics. This represents an important limitation. Future work should integrate multiple data sources—including higher temporal resolution remote sensing products and regional water storage observations—to enhance the characterization of short-term hydrological processes, extreme flood events, and reservoir operation dynamics.

### 3.2. Assessment of Reservoir Impacts on Surface Hydrological Changes in Asian River Basins

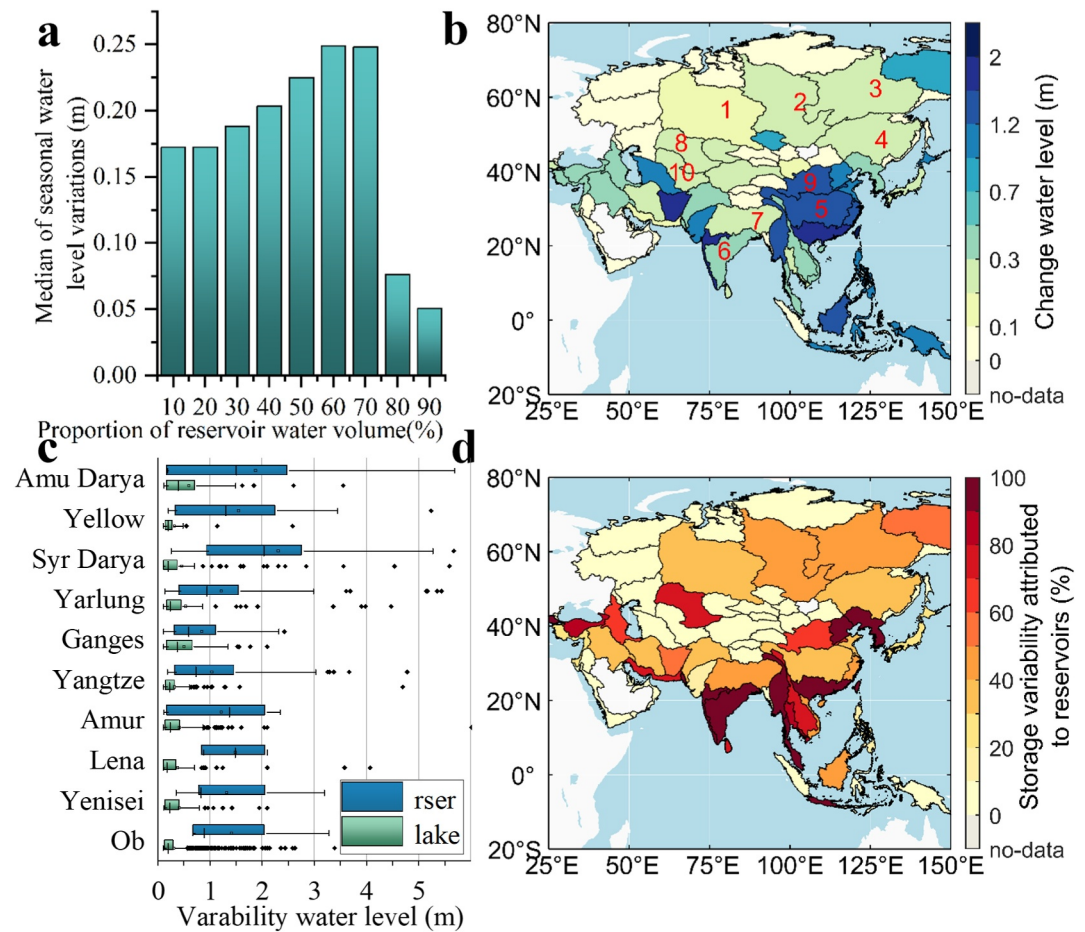
During the 5-year period from August 2018 to August 2023, human-managed reservoirs dominated surface water changes across Asia. Among Asian river basins, the median annual water level change rate of 916 reservoirs larger than 5 km<sup>2</sup> was 0.36 m/yr, whereas the median annual change rate for 6,517 lakes larger than 5 km<sup>2</sup> was only 0.05 m/yr, significantly lower than that of the reservoirs. A total of 80 reservoirs (8.73%) exhibited an annual water level change rate greater than 1 m, and 29 reservoirs (3.17%) exceeded 2 m per year. In contrast, only 53 lakes (0.81%) had an annual water level change rate above 1 m, and 25 lakes (0.38%) exceeded 2 m annually. These findings indicate that the seasonal water level fluctuations in reservoirs are much greater than those in lakes, and that reservoir operations—such as power generation, irrigation, and storage—have a far greater impact on basin water volume changes than natural factors.

We also utilized a global watershed data set (Lehner & Grill, 2013) to obtain the boundaries of 83 river basins in Asia and quantified the impact of human activities on surface hydrology across the continent. This data set classifies basins into 12 levels based on size, with level 3 used as the standard for river basin classification in this study. The results show that within Asia, the higher of reservoir water volume in a basin, the greater the median seasonal water level variation in lakes. Specifically, for every 10% increase in the proportion of reservoir storage volume relative to the total basin storage, the median seasonal water level variation in lakes rises by 0.02 m (Figure 2a). Reservoirs exhibit higher seasonal water level variability, and basins with greater reservoir seasonal water level fluctuations also show higher seasonal lake water levels (Figure 2b and Figure S2 in Supporting Information S1). This indicates that reservoirs contribute significantly to the main seasonal water level fluctuations within basins, reflecting a notable human intervention in the natural water cycle. This phenomenon is especially pronounced in coastal basins (Figure S2 in Supporting Information S1, Figures 2b and 2d). Even in northern high-latitude regions abundant in surface water resources, human management—primarily through hydropower operations—still accounts for half of the surface water variations in some basins (Cooley et al., 2021). For the 10 largest river basins in Asia, the median seasonal water level variation of reservoirs is significantly higher than that of lakes (Figure 2c). Among them, the Indus Basin (1.45 m) and the Ob Basin (1.36 m) exhibit the highest median reservoir water level changes, highlighting the substantial impact of human engineering on regional hydrological dynamics. Overall, from August 2018 to August 2023, reservoirs exerted a strong intervening influence on surface water changes across Asia, particularly in coastal regions. It should be noted that since the algorithm used in this study may overestimate the minimum reservoir water levels, the actual impact of reservoirs on basin surface water variations could be even greater than the results presented here.

### 3.3. Assessment of Reservoir Impacts on Flooding

The reservoir, while influencing the water volume changes in the main drainage basin, can also alleviate the frequency and intensity of flooding in localized areas (K. Zhang et al., 2023). By analyzing water level data alongside flooding data sets, the relationship between reservoirs and flooding in the Asian region can be further understood and assessed. Most reservoirs release water in advance before the rainy season to empty storage capacity and reduce flood peak flows. Their water level variations differ significantly from those of natural water bodies such as lakes, thereby decreasing the likelihood and severity of flooding. For example, in China's Yangtze River basins, summer rainfall is concentrated, but since the large-scale development of hydraulic infrastructure from 1991 to 2020, the death toll, economic loss rate, and affected area rate have all shown significant declining trends (Table S2 and Figure S3 in Supporting Information S1). The increasingly well-developed cascade reservoir systems have further strengthened flood control capabilities in the Pearl River region (Wang et al., 2023).

Across Asia, flooding is strongly correlated with climatic conditions, with a higher frequency of events observed between 20° and 40° latitude, primarily driven by monsoonal circulation and rainfall distribution (Figure 3). Overall, the extent of flooding is negatively correlated with the number of reservoirs; areas with higher reservoir density generally exhibit smaller affected areas (Figure S4 in Supporting Information S1), although this relationship is influenced by multiple factors such as climate, topography, and human activities. The Indian Peninsula features numerous reservoirs and significant seasonal variation in reservoir water volume Figure 2d. Compared to southeastern China and the Southeast Asian Peninsula at similar latitudes, however, the Indian Peninsula experiences a higher frequency of flooding (with the Yarlung Zangbo River experiencing 24 major flood events in 5 years) and a larger affected area.

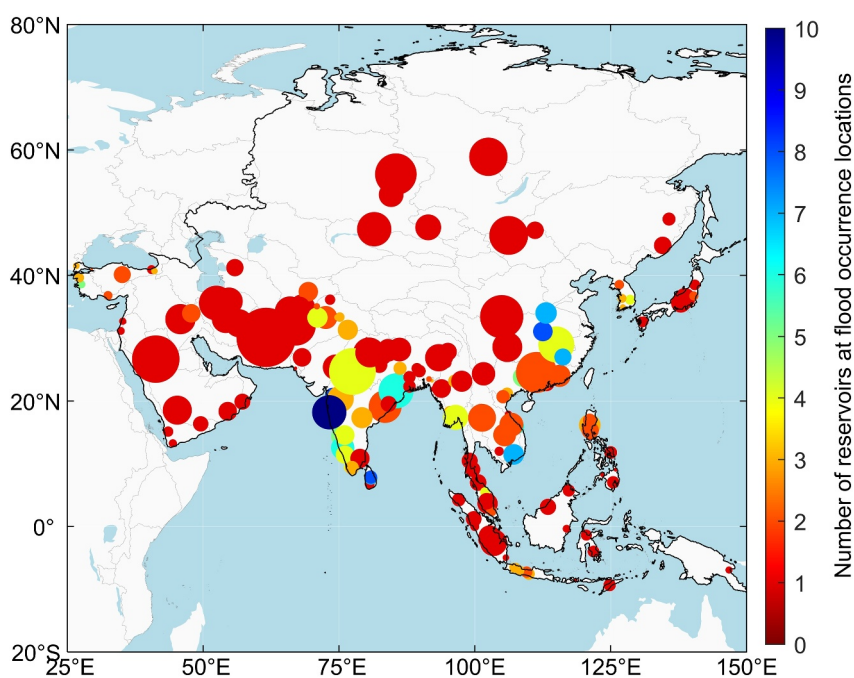


**Figure 2.** Impact of reservoirs on different river basins in Asia. (a) Relationship between the proportion of reservoir storage variation and the median seasonal water level variation of lakes across different Asian river basins. (b) Median seasonal water level variation of water bodies in various Asian basins; darker colors indicate larger seasonal variations, while lighter colors indicate smaller variations. Regions are numbered as (1) Amu Darya, (2) Yellow, (3) Syr Darya, (4) Yarlung Zangbo, (5) Yangtze, (6) Ganges, (7) Amur, (8) Lena, (9) Yenisei, and (10) Ob. (c) Comparison of water level change rates for the 10 largest basins in Asia. The boxplot displays the upper quartile, median, and lower quartile; whiskers extend to 1.5 times the interquartile range, while outliers are shown as small diamonds. (d) Proportion of annual reservoir water storage variation across different Asian basins. Darker colors indicate a greater influence of human-managed reservoirs on surface water storage, while lighter colors indicate less influence. Gray areas represent basins where no water body data were observed or where only one type of water body (lake or reservoir) was observed within the basin.

### 3.4. Potential Causes and Driving Forces of Regional Flooding

By analyzing the spatial distribution of affected areas together with reservoirs and lakes, the potential causes and driving forces of regional flood occurrences can be further understood and assessed. Changes in lake and reservoir water levels reflect the capacity of reservoirs to regulate flooding. Both lakes and reservoirs show interannual fluctuations, while floods often coincide with peak lake levels. The sharp rise in lake levels during floods indicates their limited capacity to buffer short-term heavy rainfall, making them prone to overflow or breaching (Figure 4).

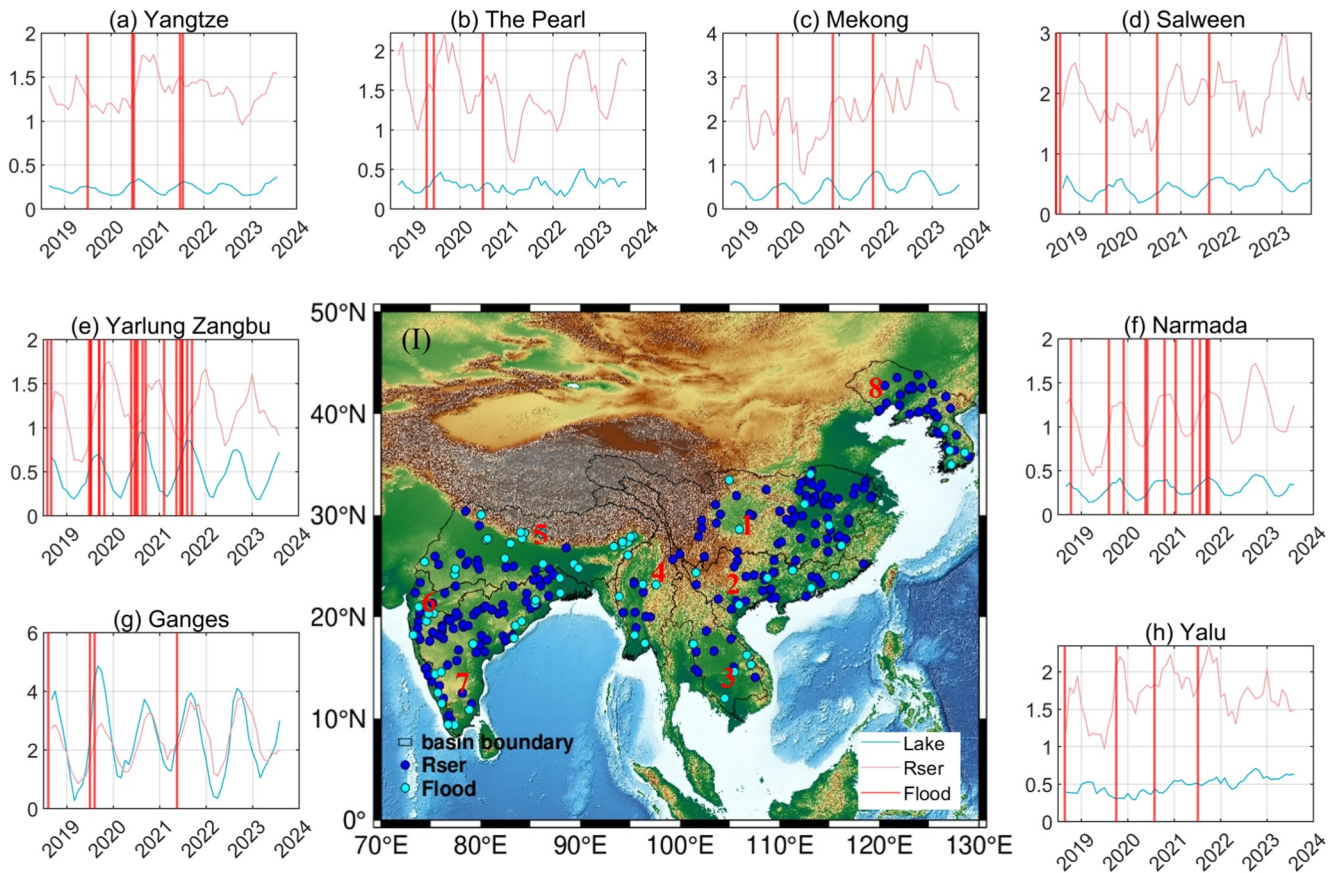
From Figure 4, we can see that flooding are concentrated in the rainy season, and under comparable rainfall conditions, the frequency of flood events in the Indian Peninsula is significantly higher than in other basins. Reservoirs in southern China, Southeast Asia, and the Korean Peninsula play a prominent regulatory role, with reservoir levels fluctuating much more than lake levels. In the Yangtze and Pearl River basins, reservoir levels dropped significantly after floods, which may reflect water releases for flood control (Figures 4a and 4b). In Southeast Asia and the Korean Peninsula, reservoir and lake levels exhibit a clear lagged response (lake levels rise rapidly during intense rainfall and floods, whereas reservoirs, due to their storage capacity and artificial



**Figure 3.** Locations and extents of flooding in the Asian region from 2018 to 2023. Solid circles represent flooding locations during this period, larger circles indicate greater flooding areas, and cooler colors signify a higher number of reservoirs at the flooding location.

regulation, increase more gradually with delayed peaks). After each flood event, reservoir levels rise substantially, while lake levels increase sharply for a short period and then begin to fall (Figures 4c, 4e, 4f, and 4h). Specifically, in the Ganges basin, reservoir water level variations are lower than those of lakes, indicating insufficient reservoir regulation capacity within the basin. In the Narmada and Ganges basins, reservoir and lake water level changes are nearly synchronous, lacking the lag effect observed in other basins. This suggests that reservoirs in these basins are likely not primarily used for flood control (Figures 4f, 4g, and 4i). In contrast, the Yarlung Zangbo River basin shows reservoir water level variations significantly exceeding those of lakes, with a certain lag relative to lake levels. However, this basin experiences the highest frequency of flood events among all basins (Figure 4e and Figure S5 in Supporting Information S1). The causes of this phenomenon include both natural and human factors. Natural factors involve intense monsoon rainfall that frequently subjects reservoirs to flood discharge pressures, as well as sudden events such as the glacier collapse in February 2021 that led to dam failure. Notably, a flooding occurred between August 2018 and August 2023 during the only instance when both reservoir and lake water levels dropped to their lowest points (Dash et al., 2023).

During each flood event, lake water levels were generally similar, whereas reservoir water levels varied and continued to rise for some time after the occurrence of floods. This suggests that the excessive rise in lake levels, resulting from their limited self-regulation capacity, may be one of the triggers of flooding (Figure 4). We used the difference between the minimum lake water level during flood events and the minimum lake water level as the maximum allowable rise in water level, based on which the maximum storage capacity was estimated for the eight basins mentioned above (Table S4 in Supporting Information S1). It was found that both the number of reservoirs and their theoretical storage capacity are important indicators affecting local water resource management. The Yangtze River Basin has the largest storage capacity, totaling  $19.69 \text{ km}^3$ , while the Ganges Basin has the smallest, at only  $1.6 \text{ km}^3$ . The number and capacity of reservoirs in the Yarlung Zangbo River Basin are much smaller than those of lakes, accounting for only 21% of lake capacity. This may be a key reason for the frequent occurrence of flooding in the region, suggesting that increasing the number of reservoirs could effectively reduce the frequency of flood events.



**Figure 4.** Timing of flooding and median relative water Levels compared to historical lows for lakes and reservoirs in South Asia (a–h), with vertical lines indicating the timing of flood events in the figure. Map of the geographic locations of eight South Asian River basins, reservoirs, and flood sites (I), where numbers 1–8 correspond to subplots (a–h). In panels (a–h), the water level time series are constructed as follows: (1) Each individual water level time series is normalized with respect to its minimum value using the formula  $x'(t) = x(t) - \min(x)$ , where  $x'$  is the normalized water level and  $x$  is the original water level; (2) Based on the normalized series from step (1), the median water level across all reservoirs within the same basin is calculated at each time step. This results in a basin-level reservoir water level time series. The same method is applied to lakes.

#### 4. Conclusions

This study reconstructed monthly water level time series for 7,743 inland water bodies (including lakes and reservoirs) across Asia from August 2018 to August 2023 by applying the KF-MFWL algorithm, through integrating multi-source satellite altimetry data (ICESat-2, Sentinel-3A/B) and meteorological data. The impacts of reservoirs on Asia's hydrological cycle and flooding are also quantified. We find that the median annual water level change rate of reservoirs (0.36 m/yr) is significantly higher than that of lakes (0.05 m/yr). Within the same basin, a higher proportion of reservoir storage is associated with larger seasonal lake water level variations. Particularly in coastal regions, seasonal reservoir storage changes account for more than 80% of basin-scale variability, reflecting strong human intervention in the natural hydrological cycle. In regions with higher maximum adjustable reservoir storage, the system is likely more resilient to extreme hydrological conditions, thereby reducing the frequency and intensity of such floods. The regulatory capacity of reservoirs is positively correlated with the number of reservoirs and their storage volume proportion within a basin. Increasing the number of reservoirs in the Yarlung Zangbo River Basin can effectively mitigate the likelihood and extent of flooding. Our work highlights the role of reservoir regulation in regional hydrological cycles and provides high-resolution data support for water resource management in Asia. Future research will integrate multi-source observational data such as SWOT, GNSS, and GRACE to obtain water level time series for water bodies smaller than 5 km<sup>2</sup>, enabling analysis of reservoir impacts on regional water level changes at finer spatial scales.

## Conflict of Interest

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

## Data Availability Statement

The authors gratefully thank the data distribution agencies who provided the publicly released data used in this work. The ATLAS/ICESat-2 L3A Inland Water Surface Height (ATL13) data were provided by the NASA National Snow and Ice Data Center Distributed Active Archive Center (Jasinski et al., 2025). The Sentinel-3A/B SRAL Level-2 WAT data were provided by Copernicus Open Access Hub (<https://browser.dataspace.copernicus.eu/>). Water surface mask data is provided by the GLAKES data set (Pi et al., 2022b). The Global Surface Water Occurrence (GSWO) data set (<https://global-surface-water.appspot.com/>). The ERA5 meteorological data were provided by the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2023). The Qinghai Lake gauge data were provided by the National Tibet Plateau Data Center (G. Zhang & Duan, 2021). The Lumajiangdong co Lake gauge data were provided by the National Tibet Plateau Data Center (Yanbin, 2022). The flood disaster data were provided by The Global Active Archive of Large Flood Events (<https://floodobservatory.colorado.edu/Archives>). The Global watershed boundaries data were provided by the HydroSHEDS database (<https://www.hydrosheds.org/>). Time series reconstruction is processed using the KF-MFWL algorithm (Jiang et al., 2024). The monthly water level time series of lakes and reservoirs can be accessed at An et al. (2025).

## References

- An, Z., Li, Z., Jin, T., Jiang, W., Yuan, P., Liu, K., et al. (2025). Water storage changes of lakes and reservoirs across Asia (2018–2023) and their effects in flood control [Dataset]. <https://doi.org/10.5281/zenodo.15742935>
- Bonnema, M., David, C. H., Frasson, R. P. D. M., Oaida, C., & Yun, S. H. (2022). The global surface area variations of lakes and reservoirs as seen from satellite remote sensing. *Geophysical Research Letters*, *49*(15), e2022GL098987. <https://doi.org/10.1029/2022gl098987>
- Boy, F., Desjonqueres, J.-D., Picot, N., Moreau, T., & Raynal, M. (2017). CryoSat-2 SAR-mode over oceans: Processing methods, global assessment, and benefits. *IEEE Transactions on Geoscience and Remote Sensing*, *55*(1), 148–158. <https://doi.org/10.1109/tgrs.2016.2601958>
- Chen, P., An, Z., Xue, H., Yao, Y., Yang, X., Wang, R., & Wang, Z. (2022). INPPTR: An improved retracking algorithm for inland water levels estimation using Cryosat-2 SARin data. *Journal of Hydrology*, *613*, 128439. <https://doi.org/10.1016/j.jhydrol.2022.128439>
- Chen, T., Song, C., Ke, L., Wang, J., Liu, K., & Wu, Q. (2021). Estimating seasonal water budgets in global lakes by using multi-source remote sensing measurements. *Journal of Hydrology*, *593*, 125781. <https://doi.org/10.1016/j.jhydrol.2020.125781>
- Cooley, S. W., Ryan, J. C., & Smith, L. C. (2021). Human alteration of global surface water storage variability. *Nature*, *591*(7848), 78–81. <https://doi.org/10.1038/s41586-021-03262-3>
- Dash, S., Shekhar, M. S., Bhardwaj, P., Swain, M., Satyawali, P. K., & Mohanty, U. C. (2023). Chamoli disaster 2021, Uttarakhand: A study on the role of a hidden meteorological parameter. *Journal of Earth System Science*, *132*(4), 193. <https://doi.org/10.1007/s12040-023-02207-w>
- Deemer, B. R., Harrison, J. A., Li, S., Beaulieu, J. J., DelSontro, T., Barros, N., et al. (2016). Greenhouse gas emissions from reservoir water surfaces: A new global synthesis. *BioScience*, *66*(11), 949–964. <https://doi.org/10.1093/biosci/biw117>
- Downing, J. A., Prairie, Y. T., Cole, J. J., Duarte, C. M., Tranvik, L. J., Striegl, R. G., et al. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and oceanography*, *51*(5), 2388–2397. <https://doi.org/10.4319/lo.2006.51.5.2388>
- Duan, Z., & Bastiaanssen, W. G. M. (2013). Estimating water volume variations in lakes and reservoirs from four operational satellite altimetry databases and satellite imagery data. *Remote Sensing of Environment*, *134*, 403–416. <https://doi.org/10.1016/j.rse.2013.03.010>
- Gleick, P. H. (2003). Global freshwater resources: Soft-path solutions for the 21st century. *Science*, *302*(5650), 1524–1528. <https://doi.org/10.1126/science.1089967>
- Han, Z., Zhang, H., Fu, J., Wang, Z., Duan, L., Zhang, W., & Li, Z. (2024). Dynamic assessment of the impact of compound dry-hot conditions on global terrestrial water storage. *Remote Sensing of Environment*, *315*, 114428. <https://doi.org/10.1016/j.rse.2024.114428>
- Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., et al. (2023). ERA5 hourly data on single levels from 1940 to present [Dataset]. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. <https://doi.org/10.24381/cds.adbb2d47>
- Jasinski, M., Stoll, J., Hancock, D., Robbins, J., Nattala, J., Pavelsky, T., et al. (2025). ATLAS/ICESat-2 L3A along track inland surface water data, version 7 [Dataset]. *NASA National Snow and Ice Data Center Distributed Active Archive Center*. <https://doi.org/10.5067/ATLAS/ATL13.007>
- Ji, S., Wu, P., Chen, L., Yang, Y., Pi, X., McKenzie, J. M., & Liang, X. (2025). Quantifying permafrost thawing and its impact on lake storage dynamics in the Qinghai-Tibet Plateau. *Journal of Hydrology*, *650*, 132529. <https://doi.org/10.1016/j.jhydrol.2024.132529>
- Jiang, W., An, Z., Jin, T., Chen, P., & Zou, X. (2024). KF-MFWL: A high-resolution time series construction algorithm for lake water levels based on multisource altimeter satellites and meteorological data fusion. *IEEE Transactions on Geoscience and Remote Sensing*, *62*, 1–12. <https://doi.org/10.1109/tgrs.2024.3491859>
- Lehner, B., & Grill, G. (2013). Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. *Hydrological Processes*, *27*(15), 2171–2186. <https://doi.org/10.1002/hyp.9740>
- Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., et al. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494–502. <https://doi.org/10.1890/100125>
- Li, Y., Zhao, G., Allen, G. H., & Gao, H. (2023). Diminishing storage returns of reservoir construction. *Nature Communications*, *14*(1), 3203. <https://doi.org/10.1038/s41467-023-38843-5>
- Liu, Z., Yao, Z., & Wang, R. (2019). Evaluation and validation of CryoSat-2-derived water levels using in situ lake data from China. *Remote Sensing*, *11*(8), 899. <https://doi.org/10.3390/rs11080899>
- Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., et al. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349–4383. <https://doi.org/10.5194/essd-13-4349-2021>

- Neumann, K., Schecker, H., & Theyßen, H. (2019). Assessing complex patterns of student resources and behavior in the large scale. *The Annals of the American Academy of Political and Social Science*, 683(1), 233–249. <https://doi.org/10.1177/0002716219844963>
- Pekel, J. F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, 540(7633), 418–422. <https://doi.org/10.1038/nature20584>
- Peng, F., Deng, X., & Shen, Y. (2025). Assessment of an adaptive subwaveform coastal retracker (ASCR) over global coastal oceans for SAR altimetry. *Remote Sensing of Environment*, 316, 114495. <https://doi.org/10.1016/j.rse.2024.114495>
- Pi, X., Luo, Q., Feng, L., Xu, Y., Tang, J., Liang, X., et al. (2022a). Mapping global lake dynamics reveals the emerging roles of small lakes. *Nature Communications*, 13(1), 5777. <https://doi.org/10.1038/s41467-022-33239-3>
- Pi, X., Luo, Q., Feng, L., Xu, Y., Tang, J., Liang, X., et al. (2022b). Mapping global lake dynamics reveals the emerging roles of small lakes: Code and data [Dataset]. <https://doi.org/10.5281/zenodo.7016548>
- Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., & Lo, M. H. (2018). Emerging trends in global freshwater availability. *Nature*, 557(7707), 651–659. <https://doi.org/10.1038/s41586-018-0123-1>
- Ryan, J. C., Smith, L. C., Cooley, S. W., Pitcher, L. H., & Pavelsky, T. M. (2020). Global characterization of inland water reservoirs using ICESat-2 altimetry and climate reanalysis. *Geophysical Research Letters*, 47(17), e2020GL088543. <https://doi.org/10.1029/2020gl088543>
- Song, C., Huang, B., Ke, L., & Richards, K. S. (2014). Seasonal and abrupt changes in the water level of closed lakes on the Tibetan Plateau and implications for climate impacts. *Journal of Hydrology*, 514, 131–144. <https://doi.org/10.1016/j.jhydrol.2014.04.018>
- Timpe, K., & Kaplan, D. (2017). The changing hydrology of a dammed Amazon. *Science Advances*, 3(11), e1700611. <https://doi.org/10.1126/sciadv.1700611>
- Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., et al. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and oceanography*, 54(6part2), 2298–2314. [https://doi.org/10.4319/lo.2009.54.6\\_part\\_2.2298](https://doi.org/10.4319/lo.2009.54.6_part_2.2298)
- Wang, X., Meng, X., & Long, Y. (2022). Projecting 1 km-grid population distributions from 2020 to 2100 globally under shared socioeconomic pathways. *Scientific Data*, 9(1), 563. <https://doi.org/10.1038/s41597-022-01675-x>
- Wang, X., Xia, J., & Li, Q. (2023). Spatiotemporal variation of flood distribution and influencing factors in provinces in middle and lower reaches of Yangtze River. *Water Resources Protection*, 39(2), 78–86. <https://doi.org/10.3880/j.jssn.10046933.2023.02.010>
- Xiang, J., Li, H., Zhao, J., Cai, X., & Li, P. (2021). Inland water level measurement from spaceborne laser altimetry: Validation and comparison of three missions over the great lakes and lower Mississippi River. *Journal of Hydrology*, 597, 126312. <https://doi.org/10.1016/j.jhydrol.2021.126312>
- Yanbin, L. E. I. (2022). In-situ observations of lake level on the western Tibetan Plateau (2016–2021) [Dataset]. <https://doi.org/10.11888/Terre.tpdc.272314>
- Yang, H., Liang, B., Gao, H., & Shao, Z. (2024). Adaptive temporal resolution fusion method for peak significant wave height capture using multi-satellite data in large wave processes. *Physics of Fluids*, 36(11), 117153. <https://doi.org/10.1063/5.0236155>
- Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Sciences*, 77(1), 161–170. <https://doi.org/10.1007/s00027-014-0377-0>
- Zhang, G., & Duan, S. (2021). Qinghai Lake climate and hydrology data [Dataset]. *All Earth*, 33(1), 161–165. <https://doi.org/10.1080/27669645.2021.2015870>
- Zhang, K., Yuan, X., Lu, Y., Guo, Z., Wang, J., & Luo, H. (2023). Quantifying the impact of Cascade reservoirs on streamflow, drought, and flood in the Jinsha River basin. *Sustainability*, 15(6), 4989. <https://doi.org/10.3390/su15064989>
- Zhao, B., Sui, H., Liu, J., Shi, W., Wang, W., Xu, C., & Wang, J. (2024). Flood inundation monitoring using multi-source satellite imagery: A knowledge transfer strategy for heterogeneous image change detection. *Remote Sensing of Environment*, 314, 114373. <https://doi.org/10.1016/j.rse.2024.114373>
- Zhao, G., Li, Y., Zhou, L., & Gao, H. (2022). Evaporative water loss of 1.42 million global lakes. *Nature Communications*, 13(1), 3686. <https://doi.org/10.1038/s41467-022-31125-6>