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Special Issue

Characteristics of water level fluctuations at Shuanglian Reservoir Wetland

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ABSTRACT: Wetland hydrology plays a critical role in the formation and sustainability of wetland ecosystems, as fluctuations in water levels directly affect habitats and ecosystems. This study focuses on the Shuanglian Reservoir Wetland to explore the primary drivers of water level fluctuations and the influence on the surface water area and hydrological regime due to the extreme flood events in the wetland through rainfall-runoff process simulation and statistical analysis. A strong positive correlation ($r = 0.9$) was observed between daily precipitation and water levels, showing the direct impact of precipitation on water level fluctuations in the wetland. However, the changes in the surface water area and hydrological regime of the Shuanglian Reservoir Wetland during extreme flood events remain minimal due to the steep shorelines and flat topography across the wetland. There are 94.5% of the wetland's surface remains permanently flooded, with water level fluctuations restricted to approximately 0.3 meters. The findings enhance the understanding of the characteristics of water level fluctuations and water regime features in the wetland and thus provide insights to inform future wetland management strategies of water level fluctuation patterns for the Shuanglian Reservoir Wetland. The insights gained from this study enhance the understanding of the hydrological characteristics at Shuanglian Reservoir Wetland and contribute valuable knowledge to the broader wetland conservation and management issues, particularly for similar reservoir-type wetland systems.

KEY WORDS: Shuanglian Reservoir Wetland, water level fluctuation, water regime, wetland conservation and management.

INTRODUCTION

Wetlands provide essential ecosystem services, including climate change mitigation, water cycling, biodiversity preservation, and so on (Kuo and Wang, 2018; Xu *et al*., 2019). However, the natural climate phenomenon and human activities pose significant threats to the wetland ecosystems, causing substantial damage to their functionality and leading to wetland loss (Finlayson *et al*., 2018). Understanding the environmental characteristics of wetlands is crucial for evaluating their ecological functions and guiding effective management and restoration strategies. Among these characteristics, wetland hydrology is critical in forming and sustaining wetland ecosystems (Mitsch *et al*., 2015). Fluctuations in water levels directly impact wetland habitats and ecosystems and are strongly influenced by hydrological factors, including rainfall, evaporation, infiltration, upstream and downstream flows, and surface runoff (Hu *et al*., 2015; Reis *et al*., 2019; Krasnostein and Oldham, 2004; Rezaeianzadeh *et al*., 2017). Besides, human activities such as land use change and hydraulic engineering structures operations also affect water level fluctuations within wetlands (Holden *et al*., 2004; Liu *et al*., 2017).

The impact of water level fluctuations on wetlands is complex. Werner *et al*. (2005) observed that rapid water level fluctuations due to climate change, such as severe droughts, can lead to the mass mortality of shallow-water bivalves, reducing available food sources for waterbirds. Similarly, Liu *et al*. (2020) found that flood and drought drive water level fluctuation significantly influence wetland vegetation distribution, creating foraging challenges for certain species. According to Huang and Hwang (2022), the lack of variability for water level distribution in coastal artificial wetlands may substantially reduce habitat suitability for species like *Anas crecca*. These findings highlight the importance of a habitat-oriented water management plan in wetland conservation.

Several studies have demonstrated that water level fluctuations promote habitat diversity, leading to an increase in species richness and abundance in wetlands (Abhilash *et al*., 2008; Hsu and Severinghaus, 2011; Shah *et al*., 2017; Yin and Yan, 2020; Gownaris *et al*., 2018; Wang *et al*., 2020). Minimizing extreme water level changes and maintaining water availability during dry seasons are suggested to help mitigate climate change impacts (Coops *et al*., 2003). Furthermore, water management in wetlands should account for the connection between rivers and wetlands, as upstream artificial structures may influence downstream water level fluctuations (Kingsford, 2000). Clarifying the relationship between wetland water level fluctuations and wetland ecosystems is essential for developing effective water management plans (Liu *et al*., 2020), with long-term monitoring of water level fluctuations forming a critical foundation (Herath *et al*., 2023).

Given the importance of water level fluctuations in wetland ecosystems and their management implications, this study examines the Shuanglian Reservoir Wetland as

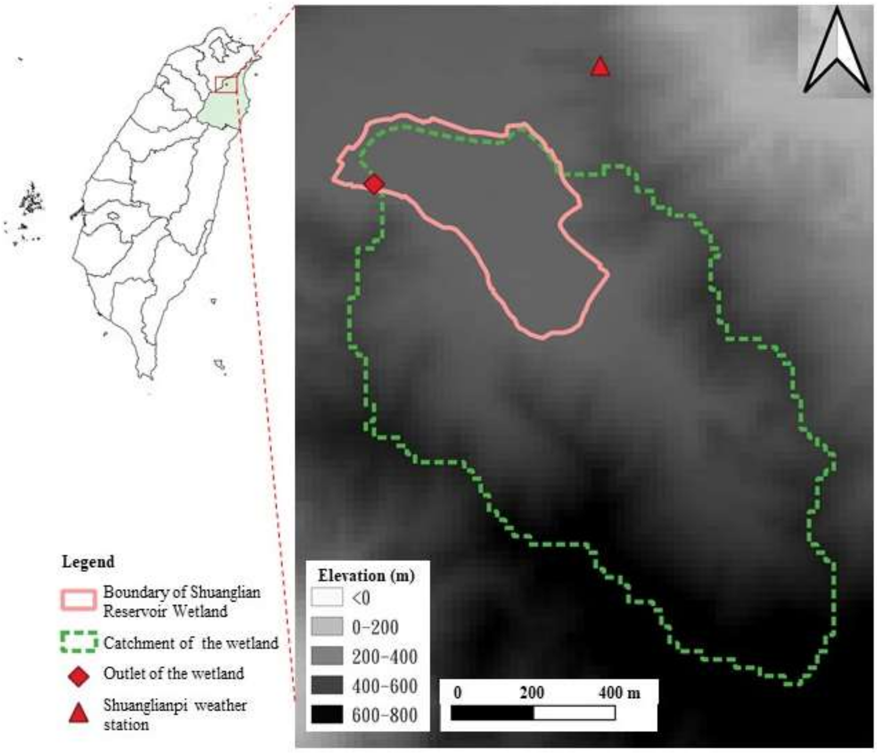

Fig. 1. Study area. The Shuanglian Reservoir Wetland is located on a suburban hill in northeastern Taiwan, covering an area of 17 ha. It collects surface runoff from a catchment of 98 ha, with water exiting through a culvert in the northwestern part of the wetland.

a case study to investigate the response to water level fluctuations characteristics and water regime types under the climate conditions shift with the seasons and extreme flood events. The research addresses two key questions: (1) What are the primary drivers of water level fluctuations in the Shuanglian Reservoir Wetland? and (2) How do extreme flood events influence the surface water area and hydrological regime in the Shuanglian Reservoir Wetland? Understanding the patterns and drivers of water level fluctuations is scientifically valuable and thus could provide crucial insights for managing the wetland.

MATERIALS AND METHODS

Study Area

The Shuanglian Reservoir Wetland (雙連埤濕地), located in Yilan County, northeastern Taiwan, spans an area of 17 ha on a suburban hill at an altitude of approximately 460 meters. It is designated as a nationally important wetland under the Wetland Conservation Act and a wildlife refuge under the Wildlife Conservation Act in Taiwan. The wetland collects surface runoff from the catchment of 98 ha, with water flowing out through a culvert in the northwestern part of the area (Figure 1). The culvert outlet is positioned 2.2 m above the bottom of the wetland, allowing water to flow out automatically when the water depth exceeds 2.2 m, functioning similarly to a reservoir with a spillway mechanism.

Before the 2000s, the Shuanglian Reservoir Wetland featured diverse habitats, including deep-water zones, shallow-water zones, and various vegetation communities, which support high biodiversity and rare species. Plant diversity was abundant in the wetland because the migratory birds introduced different plant species and grew up in these diverse habitats. However, in the 2000s, private landowners altered the landscape of the wetland, causing extensive habitat destruction. Shallow-water areas were deepened, and embankments were raised, resulting in steep shorelines and a homogenized water depth across the wetland. Moreover, the landowners introduced invasive fish species, which led to the disappearance of aquatic vegetation and the eutrophication of the water quality (Yilan County Government, 2021).

The current water depth in the Shuanglian Reservoir Wetland ranges from one to two meters, with a surface water area of 12.9 ha and a storage capacity of approximately 13×10^4 m^3 (Ministry of the Interior, 2018). Water level fluctuations in the wetland may be influenced by precipitation and hydrologic processes within the catchment. According to rainfall records from the Shuanglianpi weather station (2014–2023) recorded by the Central Weather Administration of Taiwan, the annual precipitation from 2014 to 2023 ranged from 2,658 mm in 2023 to 4,614 mm in 2022. The average monthly rainfall ranges from 146 mm in April to 648 mm in October, with the primary rainy season occurring in the fall and winter due to the influence of the winter monsoon.

Hydrologic Modeling

The rainfall-runoff process was simulated using the HEC-HMS model (Hydrologic Modeling System), developed by the U.S. Army Corps of Engineers, to model the complete hydrologic processes within the catchment of Shuanglian Reservoir Wetland. The HEC-HMS model consists of three main components: the basin model, the meteorological model, and control specifications (Hydrologic Engineering Center, U.S. Army Corps of Engineers, 2016). In the simulation, rainfall data from the Shuanglianpi weather station recorded by the Central Weather Administration of Taiwan, on-site DEM (Digital Elevation Model) data in 2020, and information on hydraulic engineering structures were used to create the rainfall-runoff model. Historical water level records from three flood events (Typhoon Haikui at 01:00 on September 2 to 23:00 on September in 2023, Typhoon Gaemi at 01:00 on July 23 to 23:00 on July 27 in 2024, and Typhoon Krathon at 01:00 on October 2 to 23:00 on October 6 in 2024) were utilized for model calibration and validation based on the Nash-Sutcliffe model efficiency coefficient (NSE) at Eq. 1(Nash and Sutcliffe, 1970). Following the validated model, hourly water levels and outflows from 2019 to 2021 were simulated, providing a foundation for further analysis.

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_s^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \quad \text{Equation 1}$$

Where

Q_o^t: observed data at time t

Q_s^t: simulated data at time t

$\overline{Q_o}$: mean of the observed data

Water Level Fluctuation and Water Regime Analysis

We applied descriptive and inferential statistics, Weibull's method, and Cowardin's wetland classification system (Cowardin *et al*., 1979) to analyze the water level characteristics and features of the water regime based on the simulated water levels from 2019 to 2021. Descriptive statistics summarized the distribution of water level fluctuations, while inferential statistics, including the T-test and F-test, were used to examine statistically significant differences of mean and variance in water level fluctuations across different years. The significance level for the T-test and F-test was set at α=0.05. Weibull's method (Eq. 2) calculated the inundation exceedance probability of daily water levels in 2019, 2020, and 2021. The areas associated with different water regimes were determined by linking the water levels corresponding to the inundation exceedance probabilities in a year with the wetland's water level-to-surface water area relationship created by the DEM (Figure 2). For water regime classification, we followed the Cowardin wetland classification system (Table 1). Seven types of hydrological regimes—permanently flooded, intermittently exposed, semi-permanently flooded, seasonally flooded, temporarily flooded, saturated, and intermittently flooded—were discussed based on the inundation exceedance probabilities of daily water level in a year with 100%, 99%, 90%, 66%, 33%, 10%, and 1%, respectively.

$$P = \left(\frac{\mathrm{m}}{\mathrm{n}+1}\right) \times 100\% \quad \text{Equation 2}$$

Where

P(%): inundation exceedance probability of daily water levels in a year

M : the ranked position on the listing from minimum to maximum

N : the number of water level data

RESULTS

The rainfall-runoff process from 2019 to 2021 was simulated using the validated HEC-HMS model (NSE=0.82). According to the precipitation recorded at the Shuanglianpi weather station (Figure 3), the annual rainfall ranged from 3,148 mm in 2021 to 3,720 mm in 2020, with the standard deviation of daily rainfall rangingfrom 19.4 mm in 2019 to 23.6 mm in 2020. The highest daily precipitation in 2019, 2020, and 2021 was recorded on October 31 with 192.0 mm, October 12 with 263.0 mm, and October 11 with 163.5 mm, respectively. The highest 10-day precipitation was recorded in late September for 2019 (443.5 mm), mid-October for 2020 (805.5 mm), and mid-October for 2021 (455.5 mm). In contrast, the lowest 10-day precipitation occurred in mid-March for 2019 (8.0 mm), mid-June for 2020 (3.0 mm), and early September for 2021 (1.5 mm). The differences in the mean of daily rainfall were insignificant (P-value > 0.05) based on the T-test. However, the F-test revealed a significant difference in the variance of daily rainfall in 2020 compared to 2019 and 2021 (P-value < 0.05).

The rainfall-runoff process simulation results indicated that the daily water level at Shuanglian Reservoir Wetland ranged from 463.33 to 463.79 m in 2019, 463.33 to 463.83 m in 2020, and 463.33 to 463.75 m in 2021, with the differences between the highest and lowest water levels of 0.42 to 0.45 m. The average daily water levels were 463.378 m with a standard deviation of 0.054 m in 2019, 463.378 m with a standard deviation of 0.065 m in 2020, and 463.373 m with a standard deviation of 0.057 m in 2021 (Figure 4). The highest daily water levels across the three years were recorded on October 31, 2019, October 12, 2020, and October 11, 2021, aligning with the dates of the highest daily precipitation. There are no significant differences (P-value > 0.05) in the mean of daily rainfall and a significant difference in the variance of daily water levels in 2020 compared to 2019 and 2021 (P-value < 0.05), consistent with the analysis results for

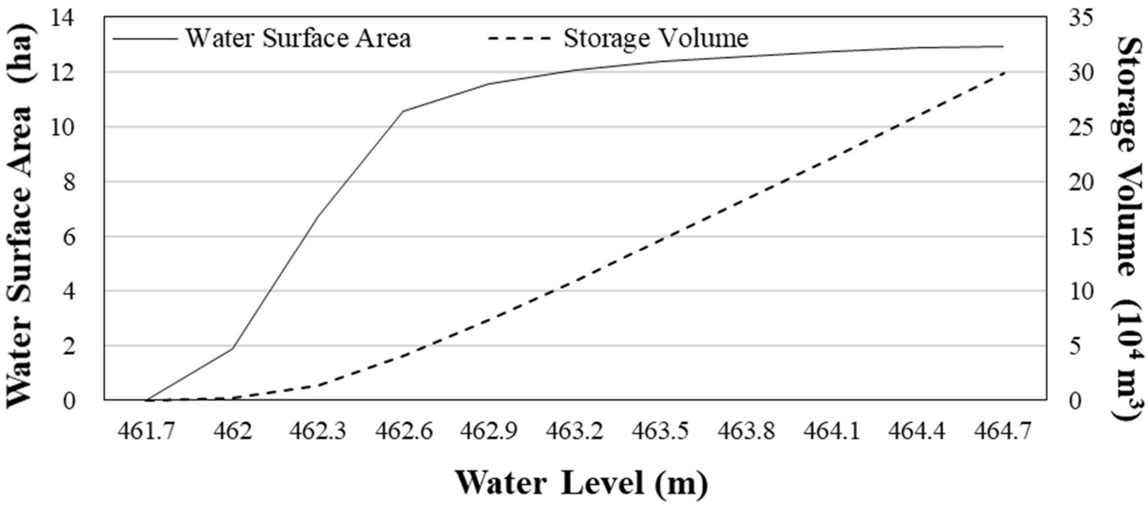

Fig. 2. Water level-to-surface water area and storage volume relationship. The data shows the relationship between water level, surface water area, and storage volume created by the DEM to understand how changes in water level affect both the surface water area and the storage volume.

Table 1. Classification of the water regime (Cowardin *et al*., 1979)

Water Regime	Definition
Permanently Flooded	Water covers the land surface throughout the year. (The area with the inundation exceedance probabilities of 100% in a year.)
Intermittently Exposed	Surface water is present throughout the year except in years of extreme drought. (The area with the inundation probabilities of between 99% to 100% in a year.)
Semi-permanently Flooded	Surface water persists throughout the growing season in most years. (The area with the inundation probabilities of between 90% and 99% in a year.)
Seasonally Flooded	Surface water is present for extended periods, especially early in the growing season, but is absent by the end of the season in most years. (The area with the inundation probabilities of between 66% and 90% in a year.)
Temporarily Flooded	Surface water is present briefly during the growing season, but the water table usually lies well below the soil surface for most of the season. (The area with the inundation probabilities of between 33% and 66% in a year.)
Saturated	The substrate is saturated to the surface for extended periods during the growing season, but surface water is seldom present. (The area with the inundation probabilities of between 10% and 33% in a year.)
Intermittently Flooded	The substrate is usually exposed, but surface water is present for variable periods without detectable seasonal periodicity. (The area with the inundation exceedance probabilities of 1% to 33% in a year.)
Artificially Flooded	The amount and duration of flooding are controlled using pumps or siphons in combination with dikes or dams.

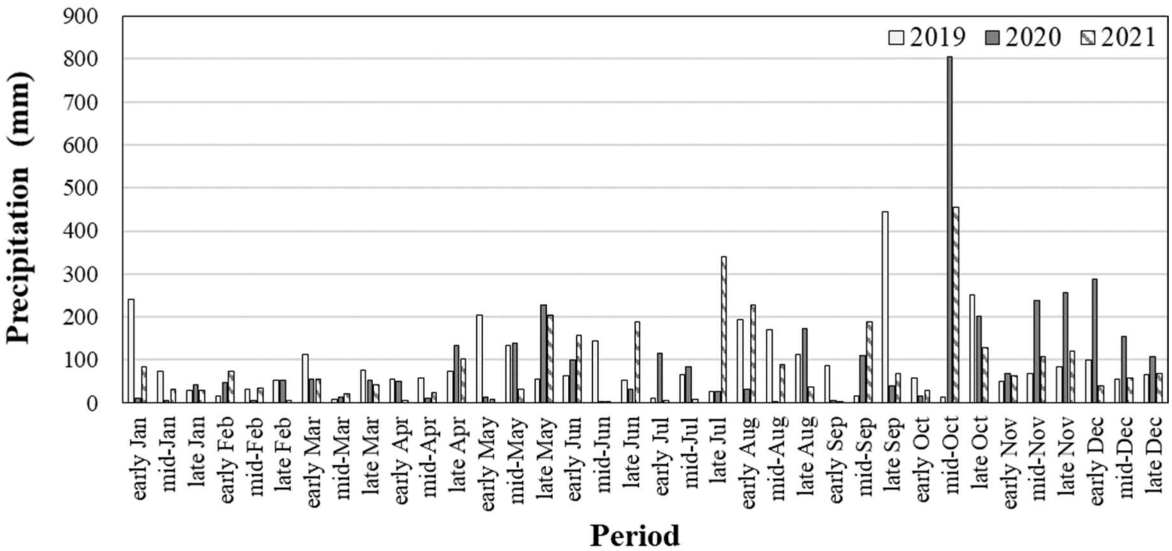

Fig. 3. 10-Day precipitation at Shuanglianpi weather station from 2019 to 2021 (Data Source: Central Weather Administration, Taiwan). The highest 10-day rainfall was recorded in late September for 2019, mid-October for 2020, and mid-October for 2021, while the lowest 10-day precipitation occurred in mid-March for 2019, mid-June for 2020, and early September for 2021.

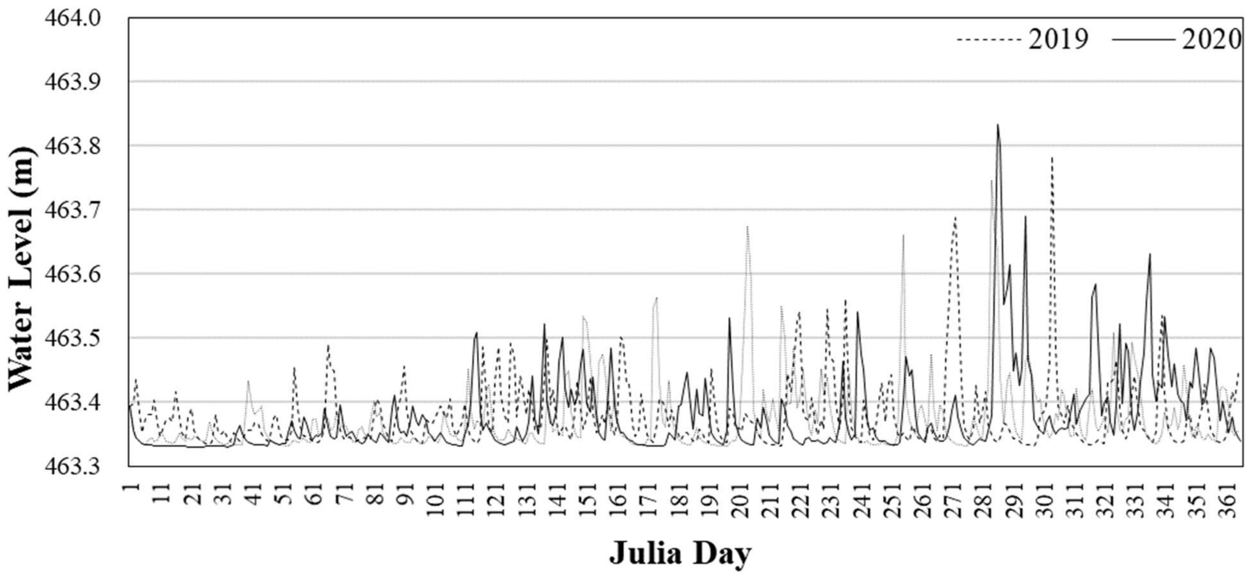

Fig. 4. Simulated daily water level from 2019 to 2021. The highest water levels were consistently observed in October across all three years (2019, 2020, and 2021), while the lowest water levels occurred in August for 2019, January for 2020, and July for 2021. The differences between the highest and lowest water levels were 0.45 m, 0.50 m, and 0.42 m for 2019, 2020, and 2021, respectively.

Table 2. The water levels corresponding to the inundation exceedance probabilities from 2019 to 2021.

Exceedance Probability (%)	2019		2020		2021	
	Water Level (m)	Surface Water Area (ha)	Water Level (m)	Surface Water Area (ha)	Water Level (m)	Surface Water Area (ha)
1	463.64	12.451	463.65	12.458	463.67	12.471
10	463.44	12.298	463.46	12.317	463.44	12.298
33	463.38	12.240	463.37	12.231	463.37	12.231
66	463.35	12.212	463.34	12.202	463.34	12.202
90	463.34	12.202	463.33	12.192	463.34	12.202
99	463.33	12.192	463.33	12.192	463.33	12.192
100	463.33	12.192	463.33	12.192	463.33	12.192

daily rainfall. Additionally, the correlation coefficients between daily precipitation and daily water level were 0.91 in 2019, 0.93 in 2020, and 0.93 in 2021, indicating a strong positive correlation between rainfall and water level.

The water levels and surface water areas corresponding to inundation exceedance probabilities for 2019, 2020, and 2021 are presented in Table 2. As the inundation exceedance probabilities increased from 1% to 90%, the associated water levels decreased by 0.30 m in 2019, 0.32 m in 2020, and 0.33 m in 2021. This indicates that the change in water level between extreme flood events (inundation exceedance probability = 1%) and normal conditions (inundation exceedance probability = 90%) ranged from 0.30 m to 0.33 m over the study period. Meanwhile, the surface water areas increased by 0.10 ha (0.75% of the surface water areas) in 2019, 0.13 ha (0.97% of the surface water areas) in 2020, and 0.10 ha (0.75% of the surface water areas) in 2021 as the inundation exceedance probabilities increased from 1% to 90%. It represents less than a 1% increase in the total surface water area between extreme flood events and normal conditions during the study period.

We further analyzed the areas associated with different water regimes from 2019 to 2021, as summarized in Table 3. The results indicate that the majority of the water regime type is permanently flooded areas, characterized by inundation exceedance probabilities of 100% in a year, covering 94.5% of the surface water area consistently across all three years. Fluctuations in other water regime types were minimal. The intermittently flooded areas slightly decreased from 1.2% in 2019 to 1.1% in 2020, followed by an increase to 1.3% in 2021. These variations are likely attributable to changes in water levels driven by differing precipitation patterns across the years.

DISCUSSION

According to the rainfall-runoff process modeling and statistical analysis, precipitation is confirmed as the primary driver of water level fluctuations in the Shuanglian Reservoir Wetland with a correlation coefficient of 0.9. This finding is consistent with Herath *et al.* (2023), which identified precipitation as the primary

Table 3. The areas associated with different water regimes from 2019 to 2021.

Water Regime	2019		2020		2021	
	ha	%	ha	%	ha	%
Permanently Flooded	12.192	94.5	12.192	94.5	12.192	94.5
Intermittently Exposed	0.000	0.0	0.000	0.0	0.000	0.0
Semi-permanently Flooded	0.010	0.1	0.000	0.0	0.010	0.1
Seasonally Flooded	0.010	0.1	0.010	0.1	0.000	0.0
Temporarily Flooded	0.029	0.2	0.029	0.2	0.029	0.2
Saturated	0.058	0.4	0.087	0.7	0.067	0.5
Intermittently Flooded	0.153	1.2	0.140	1.1	0.173	1.3
Others*	0.455	3.5	0.449	3.5	0.435	3.4

* Others means the inundation exceedance probability is less than 1%.

driver of wetland water level variations and associated challenges to wetland ecosystem stability. However, changes in the surface water area and hydrological regime of the Shuanglian Reservoir Wetland during extreme flood events remain minimal. The limited spatial and temporal variability in surface water area and hydrological regime may be attributed to the steep shorelines and flat topography across the wetland, which private landowners modified in the 2000s. This observation aligns with Liu *et al*. (2020), who emphasized the critical role of topography in wetland hydrological dynamics. These findings demonstrate the impact of anthropogenic modifications to natural topography on wetland hydrological and ecosystem responses, highlighting how human interventions affect wetland ecosystem functions and underscoring the need to consider topographical features in wetland management and restoration efforts carefully. Besides, given the terrain constraints, future conservation efforts should focus on reconstructing and operating the outlet culvert and implementing terrain adjustments to create diverse habitats.

The Shuanglian Reservoir Wetland is characterized by extensive permanent flooding, with 94.5% of its surface area remaining continuously inundated. This hydrological condition, coupled with limited water level fluctuations of only 0.3 m during flood events due to the flat terrain, significantly constrains vegetation distribution and ecological processes. Previous research has demonstrated that water level variations are crucial in shaping wetland ecosystems. Liu *et al*. (2020) found significant effects of water level variations on vegetation growth and coverage, particularly for species such as *Phragmites australis* and *Bolboschoenus planiculmis*, whose distribution and biomass vary considerably under different hydrological conditions. Similarly, Hu *et al.* (2015) established that flood duration and frequency significantly influence the distribution and developmental stages of wetland vegetation. The slight water level variations observed in the Shuanglian Reservoir Wetland may negatively impact vegetation diversity and ecological structure, contrasting with findings by Coops *et al*. (2023) that moderate water level fluctuations enhance wetland ecosystem diversity. Furthermore, Gownaris *et al*. (2018) demonstrated that appropriate water level amplitude and frequency are essential for improving the ecological stability and maturity of lake ecosystems. To address these considerations of water level fluctuations, future wetland management strategies should implement several key measures to enhance habitat and biological diversity: (1) increasing the amplitude and frequency of water level fluctuations within habitat requirements of native species, (2) incorporating seasonal water level adjustments based on the seasonal precipitation patterns, and (3) considering the impact of climate change on precipitation patterns and hydrological conditions. These adaptive management approaches enhance the wetland's ecological function, promote biodiversity, and build long-term ecosystem resilience.

CONCLUSION

This study employed rainfall-runoff process simulation and statistical analysis to investigate the hydrological characteristics of the Shuanglian Reservoir Wetland. The results revealed that precipitation is the primary driver of water level fluctuations. At the same time, the distinct topographical features in the wetland, characterized by steep shorelines and flat topography, contribute to limited spatial and temporal variability in hydrological patterns. There are 94.5% of the wetland's surface remains permanently flooded, with water level fluctuations restricted to approximately 0.3 meters. These constrained hydrological dynamics may lead to reduced habitat heterogeneity and vegetation diversity, potentially impacting ecological functions in the wetland, implying the need for hydraulic engineering structures operation, terrain adjustments, and water level fluctuations moderation.

The crucial role of moderate water level fluctuations in maintaining wetland ecosystems is emphasized in the study, and the key management strategies considering the water level fluctuation are recommended. This should include careful adjustment of fluctuation amplitude and frequency considering ecological demands and implementing seasonal water level variations that better mimic natural wetland hydrology. Furthermore, given the increasing challenges of global climate change, management plans should incorporate robust climate change adaptation measures, mainly focusing on anticipated shifts in precipitation patterns and their potential effects on wetland hydrology. Integrating these management approaches will be essential for maintaining ecosystem resilience and ensuring long-term wetland sustainability. The insights gained from this study enhance the understanding of the hydrological characteristics at Shuanglian Reservoir Wetland and contribute valuable knowledge to the broader wetland conservation and management, particularly for similar reservoir-type wetland systems.

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