



Dam Effects on Downstream Riparian Wetlands: The Nenjiang River, Northeast China

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Abstract: Many studies have found that damming a river can change downstream hydrology, sediment transport, channel morphology, and fish habitat. However, little is known about river dam effects on downstream riparian wetland dynamics and their quantitative relationship with hydrological alterations. In this study, hydrological time series and wetland distribution data spanning nearly 40 years (1978–2016) before and after the construction of a large dam in 2005 across the Nenjiang River in Northeast China were used to reveal the impact of dam on the downstream discharge regime and wetland degradation. Hydro-statistical and stepwise multiple regression analyses were performed to quantify the relationship of riparian wetland area with a metrics of 33 hydrological indicators. Dam construction caused decline in peak discharge, flood frequency, and magnitude. Moreover, 150 km riparian wetlands along the downstream of the dam was largely reduced. The count and duration of high flow pulses, 1-day maximum, and date of maximum discharge changed significantly after the dam construction. The hydrological changes have made a significant contribution to the 44% reduction in riparian wetlands following the dam construction. Our results indicated that hydrological alterations caused by dam regulation led to the area reduction of downstream riparian wetlands. The findings provide relevant information for developing best dam operation practices to protect and restore downstream wetland ecosystems.

Keywords: riparian wetlands; river dam; dam operation; indicators of hydrological alteration; the Nenjiang River

1. Introduction

The construction by damming rivers has considerably altered downstream hydrologic regimes around the world [1–5]. Considering that 85% of the total rivers were controlled and fragmented by dams [6], many downstream hydrologic effects of dams are noticeable and direct. For example, dams have been found to decrease maximum discharge and flow variability, while they can increase minimum discharge and homogenize flow in different hydro–climatic regions [7]. In arid regions, dams are built for regulating discharge to ensure water supply [8]. On the other hand, damming rivers can help flood control, which can reduce intensity of downstream inundation [9] and make the channel occasionally or enduringly dry or at least significantly reduce discharge, which can alter the floodplain and river channel [10]. Dam operations often result in trapping sediment upstream and



reducing sediment delivery downstream, affecting fish habitat, spawning, and migration [11]. Studies have found that river dams can reduce sediment, nutrients, and organic matter inputs downstream, altering physical, chemical, and biological characteristics of riparian soils [12,13].

Hydrological processes play a decisive role in the formation, development, succession, and extinction of riparian wetlands. Changes in floodplain sediment and riparian soils could reduce the abundance of nitrogen-fixing plants and reduce nitrogen input [14–18], potentially altering structure and ecological functions of the riparian wetlands and exacerbating degradation and destruction of the wetland ecosystems [19–22]. Riparian wetland areas are exceedingly sensitive to the hydrological alterations by way of favorable indicators of the ecological variation that is caused by dam operations [23–26]. Over the past several decades, more than 70% of riparian wetlands in the world have gradually been changed into other land use types [27]. Facing these pressing challenges, quantifying the relationship of riparian wetland loss with hydrological alterations caused by dam operations is gaining attention from both the research community and the general public [28–31]. Although many studies on river dam effects on downstream changes in hydrology, geomorphology, vegetation, and fish have been conducted [32–34], less is known about dam effects on downstream wetland dynamics [35–37].

With this in mind, this study focuses on how hydrologic changes following a dam construction can affect downstream riparian wetlands. As an example, the study utilizes long-term hydrologic data and wetland areal assessment along a 150-km river reach downstream of a dam constructed across the Nenjiang River in Northeast China. Specifically, the study aims to: (1) identify downstream discharge changes after the dam construction in 2005; (2) determine riparian wetland changes along the river reach from 1978 to 2016; and (3) investigate the relationship between riparian wetland changes and altered hydrological indicators. The primary goal of the study is to provide scientific information for developing ecological management strategies and plans for dam operation to protect downstream riparian wetlands.

2. Study Area

This study assessed changes in riparian wetlands along a 150-km reach downstream of the Nierji (NEJ) Dam in the middle Nenjiang River Basin, Northeast China (Figure 1). The region has a mean annual precipitation of 448 mm [38], approximately 80% of which occurs from June to September. This river basin is one of the most important wetland regions and commodity grain bases in China. Large areas of wetlands in the basin, including Zhalong, Xianghai, Momog, and Nanweng (Ramsar Recognized Wetland Sites of International Importance) have important hydrological functions such as water storage, recharging groundwater, and flood mitigation. In recent years, the decrease in area and hydrological functions of wetlands has been detrimental to the agriculture and economic development in the Nenjiang River Basin. It is necessary to examine how wetlands changed and their relationship with hydrological alteration. The NEJ Dam, built in 2005, is a large reservoir across the Nenjiang River, approximately 585 km upstream from its confluence with the Songhua River. It is the only flow control structure in the mainstream of the Nenjiang River, playing an important role in flood control. The dam creates a reservoir with a total storage capacity of 86.1×10^8 m³, and the drainage area to the reservoir is 6.64×10^4 km², accounting for 22.4% of the total drainage area of the Nenjiang River Basin [39].



Figure 1. Geographical locations of the Nenjiang River Basin, meteorological and hydrological stations, and the Nierji–Fulaerji (NEJ–FLEJ) river reach, where the present study focuses.

3. Methods

3.1. Data Collection

We collected daily discharge records for 1968–2016 from the Fulaerji (FLEJ) gauge station, which is the first station downstream of the NEJ Dam. River stage records at the station were also collected for 1972–1981 and 2003–2016. Wetland distribution maps in the years of 1978, 1990, 2000, 2005, 2010, and 2015 were obtained from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. The datasets used moderate-resolution imaging spectroradiometer (MODIS) time series data to map wetland distribution in China [40,41] and have been widely used in assessment on wetland development and wetland ecological service functions [42]. The original data resolution of DEM is 30 m \times 30 m, which was obtained from geospatial data cloud (http://www.gscloud.cn/). The precipitation data (1968–2016) used to remove the underlying influence of climate alteration on hydrological progression came from 40 Meteorological Stations by National Meteorological Information Center (http://data.cma.cn/).

3.2. Break Point Determination Time Series Division

Given that NEJ operation considerably altered hydrological regimes in downstream Nenjiang River, we divided the 48-year period (1968–2016) into two time windows: (1) before dam construction: 1968–2004 and (2) after dam construction: 2005–2016.

3.3. Removal of Latent Impacts of Climate Change on Hydrological Process

It is necessary to separate the combination of dam construction and climatic variety [43,44]. In the present study, we used the precipitation data during the 1968–2016 period to define wet and dry years for hydrologic time-series. Generally, the dry and wet years directly characterize a relative lower and higher discharge in a given year, respectively [45]. Yang [46] suggested that the optimal periods in which annual river precipitation is more than $P_{\text{mean+0.75stdv}}$ ($P \ge P_{\text{mean+0.75stdv}}$) are considered as the wet years, while periods of annual river precipitation less than $P_{\text{mean+0.75stdv}}$ ($P \le P_{\text{mean+0.75stdv}}$) can be regarded as the dry years. Therefore, annual precipitation between $P_{\text{mean+0.75stdv}} \le P \le P_{\text{mean-0.75stdv}}$ serve as normal years. Therefore, hydrological changes in normal years are attributable to factors other than precipitation (Figure 2).



Figure 2. Hydrologic year separation of the streamflow time-series in the lower Nenjiang River, Northeast China.

3.4. Indicators and Range of Hydrologic Alteration

We used indicators of hydrologic alteration (IHA) metrics and the range of variability approach (RVA) described by Richter and others [47,48] to analyze discharge regime changes before and after dam construction. The metrics are comprised of 33 hydrologic parameters including five groups, namely magnitude of monthly discharges, magnitude, and duration of annual extreme flows, frequency and duration of high and low pulses, and the rate and frequency of discharge change (Table 1) [49]. We split the 48-year study period (1968–2016) into two-time windows: (1) the pre-dam period: 1968–2000; (2) the post-dam period: 2005–2016. We did not consider the construction period (2001–2005) in this study because the dam was not in complete operation. For further comparative analysis of hydrologic alteration caused by the NEJ dam, we divided the year into three periods: pre-monsoon season (March–May), monsoon period (June–September) and post-monsoon season (October–February). The IHA metrics at the FLEJ gauge station was calculated using daily river discharge data. Changes in the IHA metrics between the pre and post NEJ periods were classified into three groups with respect to the hydrologic alteration degree, as follows: 0–35% (no altered or minimally altered), 35–75% (moderately altered), and 75–100% (highly altered) [50].

Table 1. Indicators of h	ydrologic alteration	and their definitions	used in this study.
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Parameter Group	Regime Features	Hydrologic Parameters		
1. Magnitude of monthly median discharge	Magnitude, timing Median discharge for each calend			
2. Magnitude of annual extreme flows	Magnitude, duration	Annual minimum 1-day medians		
		Annual minimum 3-day medians		
		Annual minimum 7-day medians		
		Annual minimum 30-day medians		
		Annual minimum 90-day medians		
		Annual maximum 1-day medians		

Parameter Group	Regime Features	Hydrologic Parameters
		Annual maximum 3-day medians
		Annual maximum 7-day medians
		Annual maximum 30-day medians
		Annual maximum 90-day medians
		Number of zero-flow days
		Base flow (7-day minimum discharge divided by median discharge for year)
3. Duration of annual extreme flows	Timing	Julian date of each annual one-day maximum discharge
		Julian date of each annual one-day minimum discharge
4. Frequency and duration of the high and low pulses	Magnitude, frequency	Number of high pulses for each year
		Number of low pulses for each year
		Medians duration of high pulses for each year
		Medians duration of low pulses for each year
5. Rate of change and frequency	Frequency, rate of change	Number of rises
		Number of falls
		Number of flow reversals

Table 1. Cont.

3.5. Quantifying Relationship of Riparian Wetland Change with Hydrologic Alteration

First, the riparian wetland areas were calculated from each wetland distribution map. The hydrologic alteration of 33 hydrologic parameters and overall hydrologic alteration were presented during the pre-dam and post-dam operation periods. Secondly, we used a principal component analysis (PCA) [51–53], to determine the relevance of various hydrologic parameters obtained by the IHA and selected those that have a cumulative contribution rate of 70–90%. These parameters serve as indicators related to the area of riparian wetlands. Finally, a stepwise multiple regression analysis was performed for further recognizing the most relevant hydrological indicators. The relationship between the wetland areas and the hydrological indicators was then determined using linear regression.

4. Results

4.1. The Alteration of Hydrological Regime Downstream of the Dam

River stage records were assessed for pre-dam and post-dam (for pre-monsoon season (March–May) and post monsoon season (October–February)). In the post dam period, the average, maximum and minimum river stage records reduced 0.02 m; 0.54 m; 0.01 m and 0.47 m; 0.43 m; 1.05 m during the pre-monsoon season and post-monsoon season, respectively (Table 2). In the pre and post dam periods, the average and maximum river stage decreased significantly from 139.58 m to 139.11 m and from 140.45 m to 140.02 m. The coefficient of variation decreased from 0.77% to 0.32%, from 0.39% to 0.22% and from 0.21% to 0.20% for maximum, average, and minimum river stage during pre-monsoon season, respectively.

After the dam construction, average discharge reduced from 512 m³/s to 406 m³/s (Figure 3). Before damming, except for the flood years of 1969 and 1998, the monthly maximum discharge reached 4041 m³/s. In the post dam period, the monthly mean discharge maintained below 2245 m³/s except for the flood year of 2013.

Table 2. River stage record gaps in pre and post monsoon seasons in reference to maximum, minimum and average river stage records. Before and after dam construction have been considered. (Note: A significant difference of river stage (pre-monsoon season and post-monsoon season) between before and after dam construction is marked by an asterisk (Welch's *t*-test—*p* < 0.05)).

River Stage Records Type	Season .	River Stage Records(m)				CV in %	
		Before Dam Construction	After Dam Construction	Gap	% of Gap	Before Dam Construction	After Dam Constructior
Average	Pre monsoon	139.74	139.52	0.22	0.16	0.39	0.22
	Post monsoon	139.58	139.11	0.47 (*)	0.34	0.31	0.44
Maximum	Pre monsoon	140.56	140.02	0.54	0.38	0.77	0.32
	Post monsoon	140.45	140.02	0.43 (*)	0.31	0.59	0.37
Minimum	Pre monsoon	139.01	139.00	0.01	0.01	0.21	0.20
	Post monsoon	139.00	137.95	1.05	0.76	0.28	1.46

Figure 3. Monthly mean discharge at the Fulaerji (FLEJ) gage station on the Nenjiang River in Northeast China, showing the impact of the Nierji (NEJ) Dam construction in 2005.

When compared with the pre-dam period, the discharge variability has decreased during the post-dam period for the pre-monsoon season (279–270 m^3 /s) (Figure 4a), post monsoon season (186–180 m^3 /s) (Figure 4b), and monsoon season (1049–851 m^3 /s) (Figure 4c).

Dam construction reduced flood frequency in high discharge groups (Figure 5a), for instance, floods with a peak discharge of >5000 m³/s with the percentage of 10% before the dam construction and only 5% afterwards. Simultaneously, floods with a peak discharge between 2000 and 4000 m³/s showed a 53% occurrence before dam construction and 34% afterwards. A once-in-50-year event occurred in 1998 (15,400 m³/s) (Figure 5b). However, the flood recurrence interval is maintained within once-in-two-years event after the dam construction.

Figure 4. Discharge fluctuation at the Fulaerji (FLEJ) gage station on the Nenjiang River in the (**a**) pre-monsoon, (**b**) post-monsoon seasons, and (**c**) monsoon season before and after the Nierji (NEJ) dam construction. The average discharge is calculated by normal year (Figure 2).

Figure 5. Changes in flood frequency before and after dam construction (**a**) and discharge–recurrence interval distribution (**b**) in Fulaerji station.

As shown by the results of the range of IHA (Table 3 and Figure 6), the monthly mean discharges during January and June increased after the dam construction. The monsoon season discharge decreased from July to September, the monthly mean discharges decreased after October in the post-dam period and the maximum discharge decreased during the entire study period. However, the minimum discharges increased to some extents. Apparently, the operation of the NEJ Dam weakened the hydrological extremes. Moreover, the frequency and duration of high and low pulse discharge are important parameters for the construction of the river eco-environment. The low pulse count decreased with a decrease in duration. The operation of the dam has a great influence on the low pulse count and high pulse count. It can be observed that the regulation of the dam has weakened the peak discharge and flood volume. The overall hydrological alteration is 66%, namely, a moderate alteration.

Indicators	Pre-Imp	act Period	Post-Imp	act Period	Hydrologic Alteration		
Monthly Median Discharge	Median (m ³ ·s ^{−1})	Coeff. of Dispersion	Median (m ³ ·s ^{−1})	Coeff. of Dispersion	(%)		
January	22	6.46	96	0.62	87 (H)		
February	15	10.51	84	0.82	87 (H)		
March	20	9.11	78	0.81	87 (H)		
April	124	1.53	216	1.18	34 (L)		
May	262	1.12	356	1.31	24 (L)		
June	317	0.99	413	2.09	48 (M)		
July	373	1.40	332	1.29	73 (M)		
August	861	2.04	762	1.25	73 (M)		
September	543	1.15	470	1.66	97 (H)		
October	419	0.78	350	1.09	73 (M)		
November	122	1.05	172	1.19	34 (L)		
December	51	2.49	114	0.75	60 (M)		
	Mag	nitude of annual ext	reme flows (m ³ ·s ⁻	-1)			
1-day minimum	13	8.15	60	0.86	75 (H)		
3-day minimum	13	8.12	66	0.82	87 (H)		
7-day minimum	13	8.10	71	0.75	87 (H)		
30-day minimum	14	7.69	76	0.78	87 (H)		
90-day minimum	21	6.63	86	0.73	87 (H)		
1-day maximum	2245	1.41	1570	0.80	87 (H)		
3-day maximum	2142	1.40	1557	0.83	87 (H)		
7-day maximum	1977	1.38	1517	0.83	87 (H)		
30-day maximum	1531	1.43	1222	0.79	87 (H)		
90-day maximum	945	1.10	788.2	0.92	75 (H)		
Number of zero days	0	0	0	0	0		
Base flow index	0.02	13.75	0.18	0.91	73(L)		
Duration of annual extreme flows							
Date of minimum	58	0.39	41	0.10	75 (H)		
Date of maximum	234	0.15	220	0.17	87 (H)		
Frequency and duration of the high and low pulses							
Low pulse count	3	1	1	0	100 (H)		
Low pulse duration	16	0.21	2	8.18	100 (H)		
High pulse count	4	2.00	1	1.50	100 (H)		
High pulse duration	55	1.70	7	1.50	100 (H)		
Rate of change and frequency of flow							
Rise rate	12	1.54	7	1.63	6 (L)		
Fall rate	-8	-1.79	-8	-1.08	57 (M)		
Number of reversals	29	1.41	72	0.29	100 (H)		

Table 3. Results of indicators of hydrologic alteration (IHA) non-parametric range of variabilityapproach (RVA) for the Nierji (NEJ) dam.

Figure 6. Alteration of monthly discharge before and after dam construction in Fulaerji station.

4.2. Riparian Wetland Loss after Dam Construction

The riparian wetland area in the study area decreased 91.68 km² from 1978 to 2005 (Figure 7). After the NEJ dam construction (from 2005 to 2015), the wetland area further and largely decreased by 590.01 km² (or 44%). The average wetland areas before and after the dam construction were 1415.35 km² and 1057.01 km², respectively, suggesting a clear association of wetland loss with the dam construction.

Figure 7. Area change of riparian wetlands along the 150-km Nierji–Fulaerji (NEJ–FLEJ) reach of the Nenjiang River in Northeast China from 1978 to 2015.

4.3. Relation of Riparian Wetland Loss with Hydrological Indicators

Principal component analysis between the riparian wetland areas and the 33 hydrological indicators isolated five principal components. Eighteen hydrological variables were selected (High pulse count, High pulse duration, Date of maximum, March, June, July, August, September, 1-day minimum, 3-day minimum, 7-day minimum, 30-day minimum, 90-day minimum, 1-day maximum, 3-day maximum, 7-day maximum, 30-day maximum, 90-day maximum), which are the 18 most relevant hydrological indicators for the change of riparian wetlands.

Our stepwise multiple regression analysis between riparian wetland area and the 18 hydrological indicators showed that wetland area is mostly associated with the count of high pulse (Pearson correlation > 0.6, p < 0.05), the duration of high pulse (Pearson correlation > 0.7, $\rho < 0.05$), date

of maximum (Pearson correlation > 0.7, ρ < 0.05), and 1-day maximum (Pearson correlation > 0.6, ρ < 0.05), which can be numerically described as follows:

Riparian wetland areas = $880.93 + 16.34 \times$ high pulse count + $4.31 \times$ high pulse count duration + $1.15 \times$ 1-day maximum + $7.08 \times$ date of maximum

For further illustration of how the four most relevant hydrological indicators were altered by dam construction, violin plots were used to comparatively analyze high pulse count, high pulse duration, 1-day maximum, and date of maximum during the pre-dam and post-dam periods (Figure 8). High pulse count and 1-day maximum values were reduced compared to pre-dam conditions. Date of maximum and high pulse duration variation of post dam were significantly lower compared to pre-dam period (p < 0.05). The mean value of high pulse count decreased from two times to one, the mean discharge of 1-day maximum reduced from 2617 m³/s to 1782 m³/s, the date of maximum occurring time reduced from 224 to 219 days, and the high pulse duration decreased significantly from 78 to 23 days. These alterations contribute to the decrease of wetlands from 1338.76 km² to 748.75 km² in the post-dam period.

Figure 8. Variety characteristics of four hydrologic indicators (high pulse count, high pulse duration, 1-day maximum and date of maximum) for pre-dam (red) vs. post-dam (blue) conditions. The dashed line represents the range of quartiles between the first and third quartiles, and the horizontal line represents the mean value. Differences between pre-dam vs. post-dam conditions were based on paired permutation tests. (Note: A significant difference of four hydrologic indicators between before and after dam construction is marked by an asterisk (Welch's *t*-test—p < 0.05)).

5. Discussion

5.1. Hydrological Alterations Caused by Dam Construction

Analysis of the discharge between pre-monsoon season and post-monsoon season in the downstream indicated that the magnitude of two periods' discharges presented a difference caused by dam operation. Extreme low/high discharges were both altered in the post-dam period. Dam impoundment reduced the discharge and peak flow during the pre-monsoon season. In addition, after the post monsoon season, a large amount of water released by the dam can sustain water requirements during dry period, so as to increase the minimum discharge. Furthermore, dams can seasonally alter

the river stage records. Therefore, the operation of NEJ dam reduced the frequency and magnitude of high flow and diminished extreme discharge in the downstream basin. The results are consistent with those reported in previous studies [54,55].

5.2. Spatiotemporal Dynamics of Riparian Wetlands Downstream of Dam

The results of this study show that riparian wetland areas in the Nenjiang River decreased by 590.01 km² in the period of 2005–2016 when compared with those in the period of 1978–2004 (Figure 7). Because riparian wetlands were mainly located at floodplain areas where the terrain is relatively flat, any decline in water stage can considerably alter the river–riparian wetland connectivity [56,57]. For example, although precipitation showed a rapid increasing trend during the post dam period (Figure 2), the decreasing trend of wetlands area also can be found in the study area, indicating that dam contribute substantially to the areal change of riparian wetlands in the downstream. Specifically, the water stage decreased and the maximum difference between the pre-dam and post-dam periods were 0.54 m and 0.43 m, respectively (Table 2). This slight reduction in water stage can lead to a hydrological regime transformation in riparian wetlands, namely, from frequently flooding to scarce flooding. This indicated that water stage variation caused by the dam contributed substantially to the areal change of riparian and influenced the connectivity between riparian wetlands and rivers.

5.3. Major Hydrological Indicators Reflecting Downstream Riparian Wetland Loss

In addition to hydrological conditions, other factors such as topography, river bank elevation, and the promenade along the river can also play an important role in regulating water exchange (hydrological connectivity) between wetlands and their river channel. These changes could have an important impact on water level and wetland water recharge during flooding [58–60] (Figure 9). For example, after damming, the peak flow decreased by 32% (Figure 8), and the flow velocity decreased with the decrease of peak flow. Simultaneously, the maximum and the average water level were 140.56 and 139.74 m before the dam (Figure 9a), while decreased to 140.02 and 139.52 m after the dam (Figure 9b). This can considerably reduce the water exchange between river channel and riparian wetlands, namely surface and subsurface water exchange, and eventually lead to area loss and functional degeneration of wetlands. Previous studies have shown that the reduction of peak flow decreases the frequency and area of floodplain flooding in the Atreyee River by 28% after construction of the dam [61]. Therefore, the slowing down of moving flood wave has a greater impact on the flood inundation area and frequency of riparian wetlands. The antecedent date of maximum flow, and the decreasing times and duration of high pulse flow also can lead to a shorter duration of the connection between wetland and surrounding water bodies, and to the reduction of water supply from rivers to wetlands, which extensively change the transformation mode and distribution of wetland types [35,62,63]. For example, the peak flow time is 15 days earlier and the duration is 55 days shorter after damming, which results in a considerable reduction in the interaction time between river and wetland, and the corresponding reduction in water volume. The total area of riparian wetlands decreased by 590.01 km², of which 397 km² transformed into marsh (Figure 10). The finding indicates the importance of maintaining hydrological connectivity for river corridor wetlands.

Figure 9. Conceptual model of interaction between river stage and riparian wetland water volume (pcp: Precipitation; Rwse: Riparian water surface exchange; Rwge: Riparian water groundwater exchange).

Figure 10. Conversion types of riparian wetlands along the 150–km Nierji–Fulaerji (NEJ–FLEJ) reach of the Nenjiang River in Northeast China from 2005 (when a dam was constructed) to 2016. The numbers denote to the changed areas from riparian wetlands to other types and vice versa.

Few studies have looked at the downstream effects of dams on wetland ecosystem development. Our results provide a clear quantification between alteration to hydrological indicators and wetland loss downstream of a river dam. Exploring the relationship between hydrology and wetland ecology from the perspective of hydrologic regime can be used to better understand the characteristics of wetland development. However, the discharge serious used in the post-dam period is relatively shorter than that in the pre-dam period. This will influence the degree of fitting to some extent when developing the multiple regression between wetlands area and flow indictors. In addition, the reduction in flood peak discharge can change the frequency and area of inundation [64]; but, in this study, we have only investigated the impact of hydrological conditions on wetland degradation. Further studies are needed to assess the characteristic changes of wetlands under different flood intensities.

6. Conclusions

In this study, we investigated hydrologic alteration and riparian wetland changes after dam construction in the middle Nenjiang River, Northeast China. Our results show that the dam construction has decreased the peak discharge, flood frequency, and the count and duration of high flow pulses. Dam construction has significantly decreased the riparian wetland areas along a 150-km river reach downstream of the dam. Many previous riparian wetlands have become separated from the river channel and have changed to marsh due to hydrological alterations caused by the dam operation.

The reduction in the count and duration of high flow pulses, date of maximum, and 1-day maximum discharge have been found to be the key factors responsible for the wetland area decline. The information gained from this study may have useful implications, not only for the Nenjiang River but also for other dammed rivers in the world, in developing best dam operation practices to protect and/or restore riparian wetland ecosystems downstream of river dams.

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