Climate Risk Management 40 (2023) 100505

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Wetland-based solutions against extreme flood and severe drought: Efficiency evaluation of risk mitigation

Yanfeng Wu [a,*], Jingxuan Sun [a,b], Boting Hu [a,b], Guangxin Zhang [a], Alain N. Rousseau [c]

[a] *Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, Jilin 130102, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*
[c] *INRS-ETE / Institut National de la Recherche Scientifique – Eau Terre Environnement, 490 rue de la Couronne, G1K 9A9 Quebec City, Quebec, Canada*

A R T I C L E I N F O

Keywords:
Hydrological regulation services
Wetlands
Flood and drought
Multi-scenario simulation
Location and type

A B S T R A C T

The hydrological regulation services provided by wetlands have great potential to be used as a nature-based solution for improving basin resilience to hydrological extremes. However, the efficiency of wetlands in attenuating hydrological extremes and how this attenuation efficiency varies with the location and type of wetland are not well understood. Here, we used a distributed hydrological modeling platform coupled with isolated and riparian wetland modules (IWs and RWs) to (i) quantify the impacts of wetlands on extreme flood and severe drought and (2) investigate the influences of geographical location and types of wetlands on their regulation efficiency. The hydrological modeling was conducted with various wetland loss scenarios on the Nenjiang River Basin (NRB)- a large river basin where wetlands are abundant and play an important hydrological regulation function. Modeling results showed that RWs mainly decreased peak flow and reduced downstream flood volume. However, IWs predominantly decreased flood volume and slightly mitigated peak flow in the entire NRB. For severe drought, RWs overall alleviated drought while IWs could intensify drought deficit to some extent. In terms of geographical location, upstream wetland obviously amplified downstream flood risks whereas alleviated drought intensity by providing source water for downstream during drought period. Downstream wetland exerted strong hydrological influence on extreme floods and severe droughts and should be restored and conserved preferentially to promote basin hydrologic resilience in the NRB. The methodology in this study can also be applied to other study areas for decision and management when considering spatial distribution and types of wetland restoration for promoting basin hydrologic resilience.

1. Introduction

Extreme hydrological events, such as floods and droughts, are considered among the costliest type of natural disasters because they are the most frequent and serious disasters in the world (Stine, 1994; Hirabayashi et al., 2013; UNISDR, 2015). For instance, floods and droughts affected a larger number of people (excessed 2 billion and 1.5 billion respectively) globally in the period 1998–2017

* Corresponding author.
E-mail address: wuyanfeng@iga.ac.cn (Y. Wu).

https://doi.org/10.1016/j.crm.2023.100505
Received 19 April 2022; Received in revised form 1 February 2023; Accepted 2 April 2023
Available online 6 April 2023

(UNISDR, 2018), and caused considerable economic loss constituted a great proportion in natural disasters damages (Milly et al., 2002; Hirabayashi et al., 2013; Güneralp et al., 2015; Dottori et al., 2018; Ward et al., 2020). Furthermore, the frequency and severity of hydrological extremes have generally intensified on a global scale over the last century and are expected to continue to increase, resulting in increased flood risk, more severe droughts, and other negative impacts (Tabari et al., 2021; Zhang et al., 2021). With these circumstances, it has become imperative to manage floods and droughts and relieve their downstream impacts to improve basin adaptability to hydrological extremes.

Wetlands have a strong hydrologic regulation function, which could be considerate as a nature-based solution for improving basin resilience to hydrologic extremes and to support downstream hydrologic infrastructures (Mitsch et al., 1977; Thorslund et al., 2017; Ameli and Creed, 2019a; Elisa et al., 2021; Wu et al., 2020a,2020b). Common hydrological regulation services of wetlands are their influence on flow patterns, specifically, their reduction in flood volume and peak flow by storing surface runoff at hillslopes and excess water from river channels (Bullock and Acreman, 2003; Acreman and Holden, 2013), and relief on drought risks by supporting baseflow (Evenson et al., 2018; Wu et al., 2020a; 2023), and maintenance of water level by replenishing groundwater (Hefting et al., 2004; Thorslund et al., 2017; Ketcheson et al., 2017). Among these services, the flood mitigation function is critical for the attenuation of larger flood events (Acreman and Holden, 2013; Zhang and Song, 2014; Wu et al., 2020b; 2022), and the baseflow support function is of great importance for drought alleviation (Downard and Endter-Wada, 2013; Wu et al., 2020a; Golden et al., 2021). However, despite their importance, wetland area continues to be lost and are largely caused by agricultural reclamation and urban sprawl (McCauley et al., 2013; He et al., 2014) as well as river regulation (Hermoso et al., 2019; Talukdar and Pal, 2019; Chen et al., 2021; Wu et al., 2021). For instance, global wetlands were lost by 35 % from 1970 to 2015, with agriculture, urbanization contributing 25 % and 16.8 %, respectively (Davidson, 2018). This area loss impaired the effectiveness of hydrological regulation services of wetlands, such as increase in downstream flooding (Ahmed, 2017; Evenson et al., 2018), intensification of downstream runoff variability (Lee et al., 2018), and reduction in groundwater recharge and baseflow support (Yeo et al., 2019; Ameli and Creed, 2019b). Hence, the nature-based solutions could perform practically no function if wetland areas decline continuously. Restoration of lost wetlands and conservation of remaining wetlands have been put forward as necessary to improve their functions and aid nature-based solutions (Walters and Babbar-Sebens, 2016; Thorslund et al., 2017; Acreman et al., 2021).

Given limited land and financial resources, and spatial heterogeneity of basin landscape characteristics, it would be desirable to prioritize locations and types for wetland restoration to achieve a minimum cost and maximum effectiveness for mitigating hydrological extremes (Babbar-Sebens et al., 2013; Yang et al., 2016). Quantifying the hydrologic functions of wetlands could be helpful in the scientific and decision-makers communities (Kadykalo and Findlay, 2016). Because targeted evaluations of hydrologic benefits from wetland are a prerequisite and an essential part of wetland conservation and restoration (Babbar-Sebens et al., 2013; Wu et al., 2020a,b,c). In addition, the specific placement of wetlands in a basin greatly affects their efficiency in regulating floods (Ameli and Creed, 2019a; Gourevitch et al., 2020; Åhlén et al., 2022) as well as the benefits and costs of achieving specific targets (Ferrier, 2020). For instance, Fossey et al. (2016) assessed the impacts of spatiotemporal attributes of wetlands on stream flows in the Becancour River watershed of the St Lawrence Lowlands, Quebec, Canada, and showed that the more isolated wetlands are in the upper part of a watershed, the greater their effects on both on flow regulation seems to be. In addition, they found that the more riparian wetlands are connected to a main stream, the greater the hydrological connectivity of the riparian wetlands to the river, the greater their impact on runoff. Åhlén et al. (2022) analyzed impacts of wetland position on water storage and flood buffering using continuous observations of water levels in multiple wetlands throughout a growing season in Vattholma, Sweden, and found a distinct storage behavior depending on the position of the wetland within the landscape. Further, Ameli and Creed (2019a) estimated the hydrologic functions of lost wetlands and estimated the hydrologic functions of wetlands located at different distances from the main stream network in the Prairie Pothole Region of North America. They showed that wetlands close to the main stream network play a disproportionately important role in attenuating peakflow, while wetland location may not be important for regulating baseflow. However, there are still two important preliminary questions for wetland restoration and conservation: (i) how and to what extent do wetlands attenuate hydrological extremes with their current distribution; and (ii) which wetland types and where are wetlands prioritized for restoration and conservation to maximize hydrological resilience in a basin? Although some studies suggest that the geographical location of wetlands affects the function they provide (Fossey and Rousseau, 2016; Wu et al., 2020a,b,c; Blanchette et al., 2022), the efficiency of wetlands in attenuating hydrological extremes and how this attenuation efficiency varies with their location and type have not been assessed as extensively within a large river basin.

In this study, we used PHYSITEL/HYDROTEL modeling platform coupling with two wetlands modules (i.e., isolated and riparian wetlands) to assess the efficiency of risk reduction from wetlands on hydrological extremes. Using the modeling platform, this study was expected to elucidate two questions: 1) How effectively can wetlands mitigate extreme floods and drought? 2) Do and to what extent can wetland locations and types have an impact on extreme floods and droughts? The Neijiang River Basin was selected as a case study because it is abundant in wetlands and has experienced a strong land conversion from wetland to farmland over the last half-century, particularly as wetland restoration is being undertaken. Findings gained from this study can support the design of practical wetland restoration and conservation programs and maximize basin adaptability to hydrological extremes.

2. Materials and methods

2.1. Study area

The Nengjiang River Basin (NRB) is in the central-western part of northeastern China and is the largest tributary of the Songhua River in northeastern China (Fig. 1a). The NRB belongs to northern temperate zone, with geographical coordinates of 119°12′-

127°54′E, 44°02′-51°42′N (Feng et al., 2011). The basin drains a total area of 29.71 × 10^4 km^2 and has a total length of 1370 km, which belongs to the temperate continental monsoon climate (Li et al., 2016). The mean annual flow for the 1961–2021 period was 228 × 10^8 m^3 at the basin outlet. The average annual temperature of the NRB varied from −4.63 to 6.43 °C, and the average annual precipitation ranged from 322.5 to 537.4 mm (Li et al., 2014). The summer precipitation mainly concentrates from June to September, accounting for 70 %-80 % of the annual precipitation (Wu et al., 2020b). The northern, western, and southern parts of the NRB have high topography and are the boundary of water separation, while the southeastern part has low topography and forms the vast Songnen Plain. According to its topography, geomorphology, and river valley features, the NRB can be divided into three sections, namely the upper-, middle-, and lower-basin (Fig. 1a).

The NRB is one of the high wetland coverage areas in China. Land use and land cover (LULC) was 27.57 % agriculture, 27.96 % forested, 1.53 % developed/urban land, and 26.42 % wetland at the time of this study (Fig. 1c). There was generally more agricultural land use located downstream, and more forested and wetland land use in the upstream NRB including Ramsar Sites (Fig. 1b). In the lower basin, a large area of the lakes and swamps distributed around the tails of the Uyu'er River, Tao'er River, and the Huolin River. Theses wetlands are important natural water storage space and regulator of regional water balance as well as important ecological barrier to prevent desertification in the lower NRB (Feng et al., 2011; Meng et al., 2019; Wu et al., 2021). There are many international and national important wetland nature reserves, including Zhalong, Xianghai, and Momoge wetlands, which are more vulnerable than other ecosystems to climate change and anthropogenic disturbance (Feng et al., 2011; Feng et al., 2013; Liu et al., 2020). However, due to agricultural reclamation, irrigation water withdrawal and river regulation, 23.69 % (around 1.59 × 10^5 km^2) of wetlands were lost from 1978 to 2020. In particular, most of them were lost in the lower-basin.

The NRB experienced a 100-year flood in 1998. This flood in NRB and the downstream caused a 40-billion-yuan (RMB) loss, damaged 456 × 10^4 ha of cropland and 115 × 10^4 houses, and affected 131 × 10^4 people (Li et al., 2014; Chen et al., 2021). Likewise, NRB witnessed a severe drought in 2011 resulting in almost drying up in the riverbed (Song et al., 2015). The projected increasing

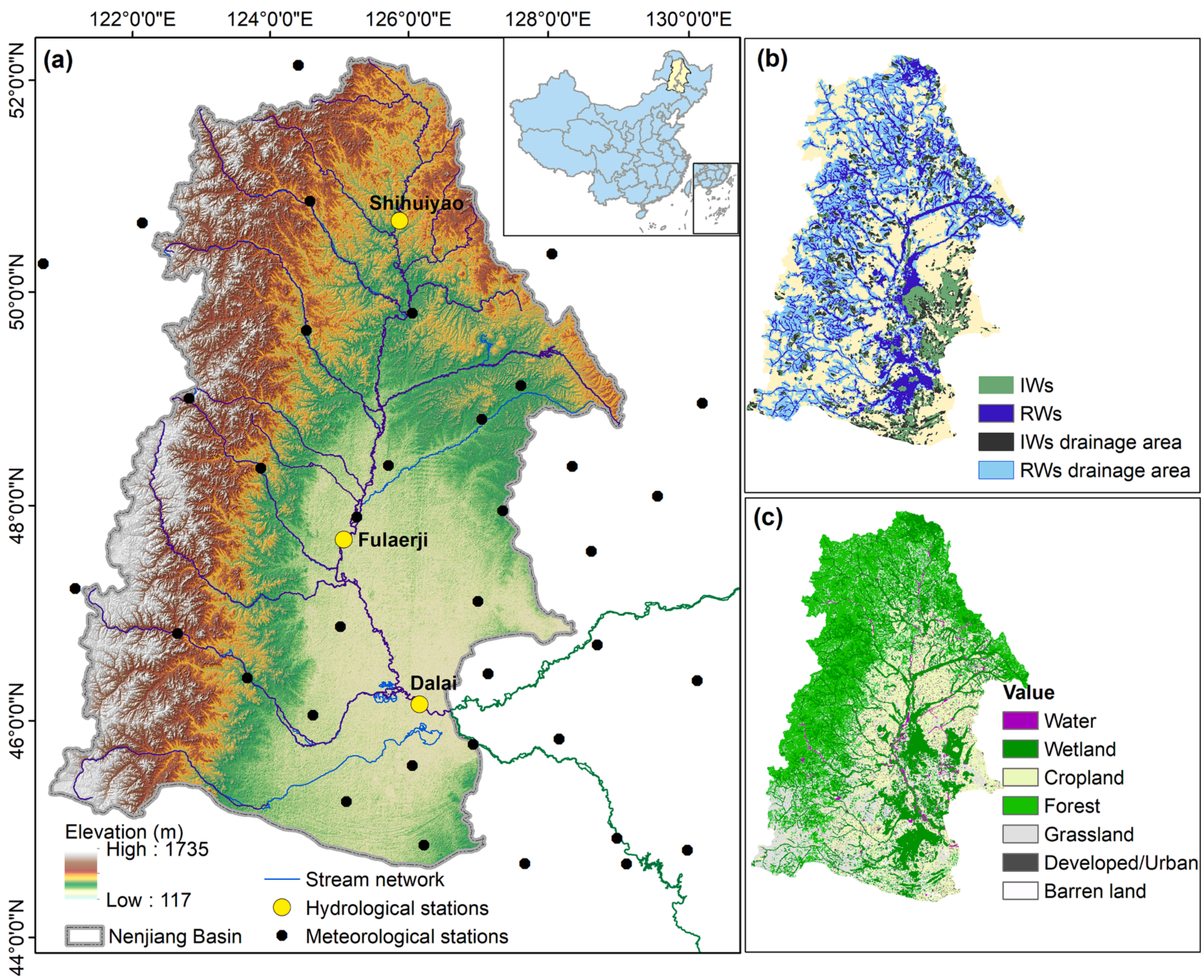

Fig. 1. (a) Location of the Nenjiang River Basin, (b) spatial distribution of isolated wetlands (IWs), riparian wetlands (RWs) and their drainage area, and (c) distribution of land use types.

flooding and drought risks in NRB (Wu et al., 2022) necessitate more solid eco-environment management plans and strategies, beyond current reservoirs and dams, to maintain the sustainability of the water system in the NRB.

2.2. Hydrological model

We used the PHYSITEL/HYDROTEL model platform coupled with wetland modules to carry out hydrological processes simulation and assess the regulation efficiency of wetlands on hydrological extremes. PHYSITEL/HYDROTEL is a hydrologic modeling platform and has been used for quantifying hydrological services of wetlands (Blanchette et al., 2019; Wu et al., 2020a,b,c, 2021, 2023; Blanchette et al., 2022). The modeling platform allows for a clear delineation of isolated (IWs) and riparian wetlands (RWs) (Fossey et al., 2015), using the Hydrologically Equivalent Wetland (HEW) concept (Liu et al., 2008; Wang et al., 2008). HYDROTEL is a continuous distributed hydrological model that executes various tasks and calculations in successive steps around six computational modules (Fortin et al., 2001; Turcotte et al., 2007). Application of PHYSITEL software is required prior to the application of the HYDROTEL model in order to prepare the basin physiographic database. PHYSITEL is a specialized GIS that makes it easy to segment watersheds and parameterize hydrological objects (RHHU, basic sub-basins or desired hillsides) (Turcotte et al., 2001; Rousseau et al., 2011). For a detailed description of the IWs and RWs modules and their integration into the PHYSITEL/HYDROTEL hydrological modeling platform as well as specific parameters, the reader should refer to Fossey et al. (2015). In this study, the NRB was subdivided into 3868 RHHUs using PHYSITEL, with an average area of 74.9 km^2 and 1551 river segments. Simultaneously, the area of IWs and RWs obtained from PHYSITEL were 458.4 km^2 and 4575.5 km^2, 2845.6 km^2 and 23417.1 km^2, 5511.7 km^2 and 22450.4 km^2 for upper-, middle- and lower-basin, respectively.

In this study, the hydrometeorological datasets including daily precipitation, maximum and minimum temperatures and observed flows were used to calibrate the HYDROTEL model. Daily precipitation and temperatures for 1970–2018 were obtained from thirty-nine weather stations including nineteen stations inside the basin and twenty stations nearby and operated by China Meteorological Administration (https://www.cmads.org/). The daily flows data spanning 1961–2018 for three hydrological stations installed at the mainstream, i.e., Shihuiyao, Fualerji and Dalai stations (Fig. 1a). The digital elevation model and raster maps of 2000 land use types (including wetlands) with the resolution of 1 km, and vectorial river network were obtained from the Chinese Resource and Environment Data Cloud Platform (https://www.resdc.cn). The spatial distribution data of soil texture types with the resolution of 500 m were obtained from the China Soil Dataset (v1.1) of the World Soil Database (HWSD) from the Cold and Arid Region Science Data Centre (https://westdc.westgis.ac.cn). All the raster datasets were uniformly adjusted to 1 km resolution to maintain the consistency of the model input. The observed daily flows at the three hydrological stations were used to calibrate HYDROTEL throughout 1989–2000 and validate against those of 2001–2010 after a 2-year warm-up period (1989–1990).

The SAFE (Sensitivity Analysis for Everybody) developed by Pianosi et al. (2015) was used to quantify the sensitivity of 18 parameters proposed by Foulon et al. (2018) and the 13 most sensitive parameters were selected to calibrate the model using the dynamically dimensioned search algorithm (DDS) (Tolson and Shoemaker, 2007). Automatic calibration was carried out based on the maximization of Kling-Gupta Efficiency (KGE) (Gupta et al., 2009) since it has been used and recommended in many studies (e.g., Kling et al., 2012; Fowler et al., 2018; Wu et al., 2021). KGE is a weighted combination of the three components (mean flow, flow variability, and daily correlation) and can improve model performance compared to specific objective functions such as Nash-Sutcliffe Efficiency (NSE). Flowing N. Moriasi et al. (2007) and Moriasi et al. (2015), the Nash-Sutcliffe efficiency (NSE_{log}) (Nash and Sutcliffe, 1970), Correlation Coefficient (CC), the root-mean-square error (RMSE), and the percent bias (Pbias) were selected to assess model performance on daily flow simulation. Numerous studies proved that NSE emphasizes high flow and potentially biased evaluation of model performance (Efstratiadis and Koutsoyiannis, 2010; Mizukami et al., 2018), while a logarithmic (e.g., NSE_{log}) would put more weight on low flows (Garcia et al., 2017). Therefore, the NSE and NSElog were used for assessing model performance on high flow and low flow respectively, representing flows during flood and drought periods.

2.3. Wetland loss scenarios

The calibrated hydrologic model was used to execute a series of wetland loss scenarios analyses to measure the efficiency of wetlands in mitigating hydrological extremes and assess how this mitigation efficiency varies with their location and types. The wetland condition in 2000, the most appropriate wetland map for flow simulation during the extreme flood (1998) and severe drought (2001), was set as the baseline scenario. For Scenario 1, all IWs were removed in the upper-NRB, regarding as an extreme IWs loss scenario, and only RWs existed. Conversely, in Scenario 2, all RWs were taken away as an extreme RWs loss scenario while all IWs remained. Scenario 3 denoted the impacts of wetlands by removing both IWs and RWs at the upper-NRB. From Scenario 4 to Scenario 15, we removed IWs or RWs or both located at middle-NRB, upper- and middle-NRB, lower-NRB, and the entire NRB, respectively. Note that the single wetland type loss scenarios, namely either removing IWs or RWs, were used to investigate how wetland types affect their hydrological services. Moreover, the wetland loss scenarios located at different sub-basins, i.e., the upper-, middle-, upper-middle- and lower-NRB, were used to examine changes in hydrological services caused by wetland geographical location. Three hydrographic stations, namely Shihuiyao, Fulaerji and Dalai (Fig. 1a), are located at the outlets of the upper-, middle-, and lower-NRB respectively. The specific geographical location and detailed area information for the baseline and fifteen wetland loss scenarios are presented in Fig. 2 and shown in Table 1.

2.4. Assessment of impacts of wetlands on extreme flood and severe drought

To examine the impacts of wetland on extreme floods and severe droughts, the drought and flood events were determined in the Shihuiyao, Fualaerji, and Dalai stations as shown in Fig. 3. Then the peak flow and flood volume were obtained from flood hydrography and the minimum flow and deficit were extracted from drought events. Flood characteristics can be described regarding peak flow and flood volume (Lobligeois et al., 2014; Xu et al., 2019; Wu et al., 2020a,b,c). To determine the beginning and the end of the flood events, the method of Lobligeois et al. (2014) adapted by Melsen et al. (2019) was applied, which is based on a specific threshold

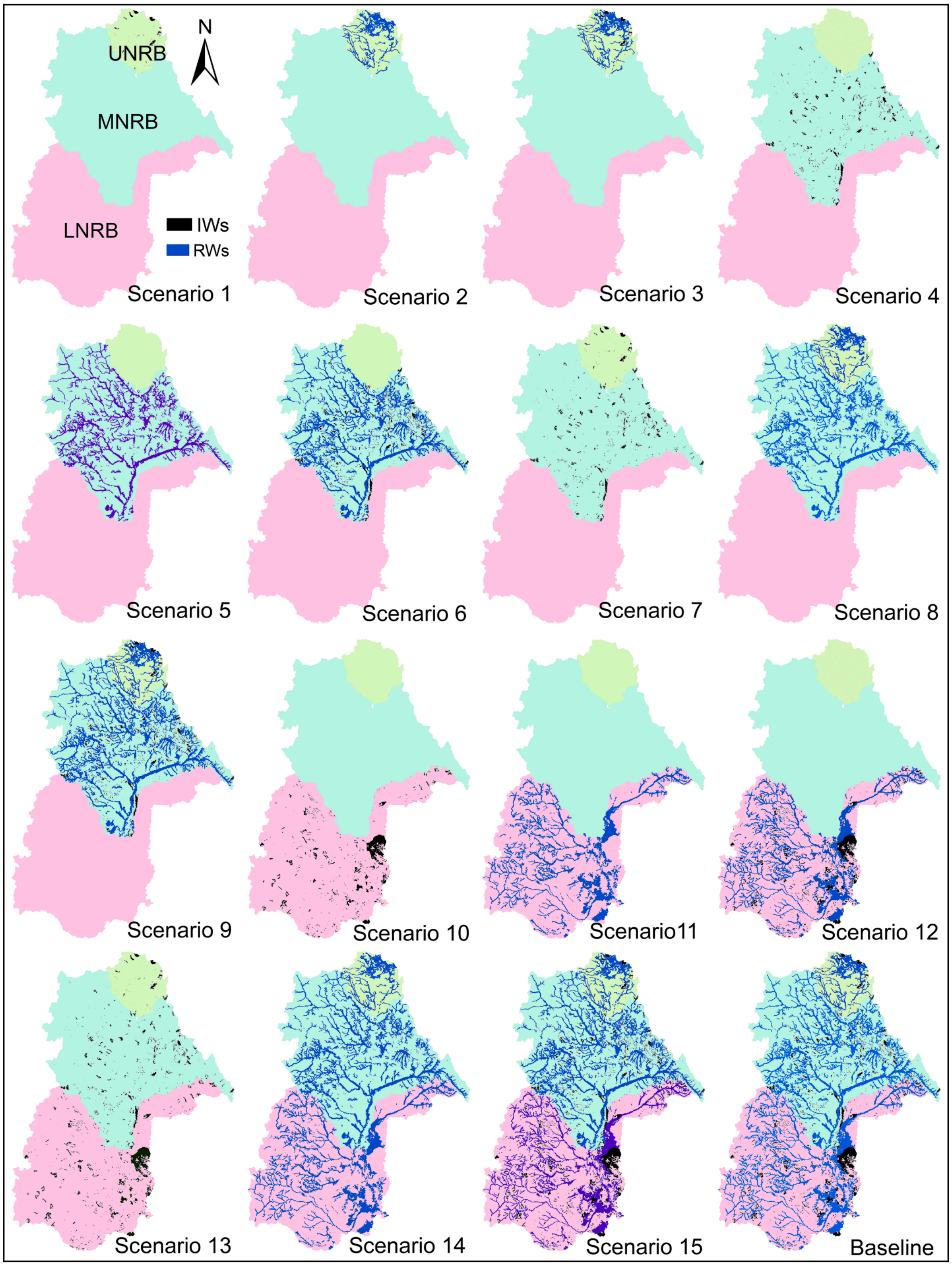

Fig. 2. Specific geographical location of wetland loss and baseline scenarios. IWs and RWs refer to isolated wetlands and riparian wetlands, respectively.

Table 1
Descriptive statistics of wetlands loss scenarios.

Scenario	Remove and remained area (km^2)						Remove location		
	IWs		RWs		Total removed	Total remained			
	Removed	Remained	Removed	Remained			UNRB	MNRB	LNRB
Sce.1	458	0	0	4575	458	58,800	■		
Sce.2	0	458	4575	0	457	54,683	■		
Sce.3	458	0	4575	0	5033	54,224	■		
Sce.4	2845	0	0	23,417	284	56,413		■	
Sce.5	0	2845	23,417	0	23,417	35,841		■	
Sce.6	2845	0	23,417	0	26,262	32,995		■	
Sce.7	3304	0	0	27,992	3303	55,954	■	■	
Sce.8	0	3303	27,992	0	27,992	31,266	■	■	
Sce.9	3304	0	27,992	0	31,296	27,962	■	■	
Sce.10	5512	0	0	22,450	551	53,747			■
Sce.11	0	5511	22,450	0	22,450	36,808			■
Sce.12	5512	0	22,450	0	27,962	31,296			■
Sce.13	8816	0	0	50,443	8815	50,443	■	■	■
Sce.14	0	8816	50,443	0	50,443	8815	■	■	■
Sce.15	8816	0	50,443	0	59,258	0	■	■	■
Baseline	0	8816	0	50,443	0	59,258			

Notes: IWs and RWs refer to isolated wetlands and riparian wetlands, respectively. UNRB, MNRB, and LNRB refer to the upper-, middle-, and lower-Nenjiang River Basin, respectively.

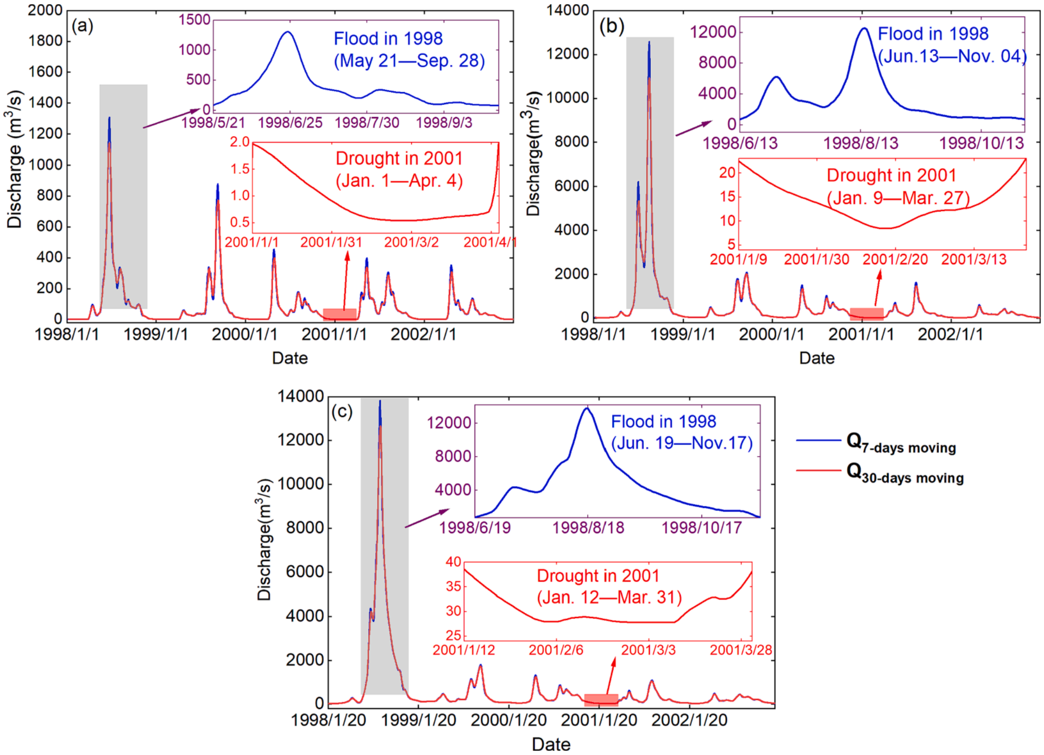

Fig. 3. Determination of the duration of the 1998 extreme flood and 2001 severe drought event at the (a) Shihuiyao, (b) Fualaerji, and (c) Dalai stations, respectively.

level. The threshold level, based on the defined $Q_{\min}$, was calculated by the following equations:

$$Q_f = \max_{t-1,t+4}(Q_p/4, Q_0 + 0.05 \cdot (Q_p - Q_0)) \tag{1}$$

The flood event initiates as soon as the flow surpass threshold level Q_f and ends when the flow falls below Q_f. Then the onset and the ending of the flood event for all the simulated scenarios were determined according to the identification results. Q_0 is the lowest flow determined from daily flow serious with a 7-day moving window. With this definition, the peak flow and flood volume for each simulated scenario were obtained in 1998 flood event.

In this study, a drought starts as the flow falls below the lowest 10 % (Q_{90}) of the observations following Melsen et al. (2019). The threshold level was ascertained based on 31-days moving average of daily flow serious spanning 1970–2018. Similar to the identification of flood events, a drought event begins when the flow lowered the Q_{90} and ends when the flow surpassed Q_{90}. Then, the minimum flow was obtained from drought events. The drought deficit was determined as the summation of flow during the drought events. In this study, the flood in 1998 and drought in 2001 were selected to estimate the effect of wetlands on extreme flood and severe drought, respectively. The hydrographs during 1998–2001 as well as drought in 1998 and flood in 2001 at the Shihuiyao, Fualaerji, and Dalai stations are shown in Fig. 3. Subsequently, the mitigation services of wetlands on peak flow, flood volume, minimum flow, and drought deficit were calculated and compared to the baseline wetland scenarios, and to examine the influences of geographical location and types of wetlands on their regulation efficiency.

The simulation scenarios with/without wetlands were performed for quantifying mitigation services of wetlands on extreme flood and severe drought. This methodology has been used in several studies such as Fossey et al. (2015), Evenson et al. (2015), Ameli and Creed (2019a), Wu et al., 2020a,b,c; 2022; 2023) and Blanchette et al. (2022). The wetland specific impact (*WSI*) metric was adopted to determine the hydrological impact of wetlands according to Fossey et al. (2016). This index provides a mean of normalizing the hydrological impact (increase or decrease in stream metrics) with respect to wetland area, as outlined in the following equation:

$$WSI_{ij_k} = \frac{Ire_{i_k} - Iw_{j_k}}{Ao_k - Are_k} \tag{2}$$

where *WSI* is the index of wetland impact expressed as flood or drought characteristic indicators (peak flow, flood volume, minimum flow, and drought deficit) reduction or increase per unit area of a considered wetland loss. Iw_{jk} and Ire_{ik} are flood and drought characteristic indicators obtained from simulated daily flow series under the baseline scenario and wetland loss scenario, respectively (see Fig. 2 and Table 1). Ao_k and Are_k (km^2) are the wetland area in a specific sub-basin k (i.e., the upper-, middle-, and lower-NRB) under the baseline scenario and wetland loss scenario, respectively. In this study, we calculated the *WSI* value for peak flow (WSI_{peak}, m^3/s·km^{-2}), flood volume (WSI_{volume}, m^3/km^2), minimum flow ($WSI_{\text{mini flow}}$, m^3/s·km^{-2}) and drought deficit ($WSI_{\text{drought deficit}}$, m^3·km^{-2}) of each flood event for the upper-, middle-, and lower-NRB.

3. Results and discussion

3.1. Model calibration and validation

Simulations were overall consistent with the observed flows during both the calibration and validation periods (Table 2). The KGE values are, for the same periods, both considered good. The NSE values from 0.61 to 0.73 underline a good match for high flow between the observed discharges and our simulations. Simultaneously, the $NSE_{\log}$ values calculated for the calibration and validation periods are comparable for three stations, indicating that both simulations offer a good depiction of the low flows. Moreover, RMSE indicated that simulation performed slight poor during the validation periods (9.01–13.12 m^3/s) than during calibration periods (range from −13.02 to 18.55 m^3/s). However, simulated flows overall achieved the acceptable performance criteria suggested by Gupta et al. (2009), N. Moriasi et al. (2007), and N. Moriasi et al. (2007), both for calibration and validation periods. These results demonstrated that the calibrated model succeeded in depicting flow patterns under a steady wetland while different climate driving conditions in the NRB.

3.2. Effect of wetlands on extreme flood

3.2.1. Overall impacts of wetlands on extreme flood

The impacts of wetlands on peak flow and flood volume (i.e., WSI) for different wetland loss scenarios at Shihuiyao, Fualaerji, and

Table 2
Statistics of model performance for calibration and validation periods for three hydrological stations in the Nenjiang River Basin.

Stations	Calibration period					–	Validation period				
	KGE	NSE	$NSE_{\log}$	RMSE (m^3/s)	Pbias		KGE	NSE	$NSE_{\log}$	RMSE (m^3/s)	Pbias
Shihuiyao	0.81	0.65	0.85	9.01	−2.08 %		0.75	0.63	0.81	12.65	4.59 %
Fualerji	0.82	0.70	0.87	7.64	−2.03 %		0.71	0.73	0.87	−13.02	−7.3 %
Dalai	0.71	0.63	0.84	13.12	2.32 %		0.69	0.61	0.83	18.55	11.5 %

Dalai stations are presented in Fig. 4 and Fig. 5, respectively. Most of the wetland loss scenarios resulted in increased peak flow with WSI values ranging from 0.03 to 37.36 $m^3/s{\cdot}km^{2-}$, and augmented flood volume with WSI values spanning from 0.014 to 7.38 $m^3{\cdot}km^{2-}$. Unexpectedly, the loss of both IWs and RWs (i.e., Scenario 3, 6, 9, 12, and 15) not produced less increase in peak flow and flood volume than the single loss. In addition, the regulation efficiency of wetlands on peak flow and flood volume was not proportional to the area loss. For example, the area losses of wetlands were 5033.4 km^2, 31296.6 $km^{2,}$ and 59258.6 km^2 under Scenarios 3, 9, and 15; while the peak flow in their outlets performed an increasing trend with the WSI values of 0.1016 $m^3/s{\cdot}km^{-2}$, 0.1860 $m^3/s{\cdot}km^{-2}$, and 0.0838 $m^3/s{\cdot}km^{-2}$ (Fig. 4). It should be noted that wetland loss can decrease peak flow and flood volume to some extent. Under Scenario 3, wetland loss decreased peak flow by −0.9963 $m^3/s{\cdot}km^{-2}$, and −1.6547 $m^3/s{\cdot}km^{-2}$ at the Fulaerji and Dalai stations, respectively. Simultaneously, the flood volume decreased by –-0.1523 $m^3{\cdot}km^{-2}$, −2.945 $m^3{\cdot}km^{-2}$ and −2.432 $m^3{\cdot}km^{-2}$ for the Fulaerji station under Scenarios 3, Scenarios 4 and Scenarios 6, and decreased by −3.1362 $m^3{\cdot}km^{2-}$ and −4.7061 $m^3{\cdot}km^{-2}$ under Scenario 3 and 6 respectively (Fig. 5). Although wetlands augmented peak flow and flood volume to some extent, wetlands mainly mitigated them for most scenarios.

3.2.2. Impacts of wetlands location on extreme flood

Scenario 3, 6, and 12 (wetland loss scenarios for both IWs and RWs located at the upper-, middle- and lower-NRB respectively) were selected to examine the spatial difference of wetland impacts on the extreme flood. It can be observed that wetland loss in the upper-NRB (i.e., Scenario 3) resulted in an obvious increase in peak flow (0.1016 $m^3/s{\cdot}km^{-2}$) and flood volume (1.1824 $m^3/s{\cdot}km^{-2}$) in their drainage basin, while led to a considerable decrease in peak flow and flood volume in the middle-NRB (-0.9963 $m^3/s{\cdot}km^{-2}$ and −2.9452 $m^3{\cdot}km^{-2}$ respectively) and lower-NRB (-0.6468 $m^3/s{\cdot}km^{-2}$ and −3.1362 $m^3{\cdot}km^{-2}$ respectively) (Fig. 4 and Fig. 5). For wetland loss under Scenario 6, an increase in the peak flow can be found in the middle-NRB (0.2051 $m^3/s{\cdot}km^{-2}$) and lower-NRB (0.1946 $m^3/s{\cdot}km^{-2}$). However, wetland loss in the middle-NRB (Scenario 6) caused a decrease in flood volume by −2.4321 $m^3{\cdot}km^{-2}$ and −4.7061 $m^3{\cdot}km^{-2}$ in the middle-NRB and lower-NRB, respectively. Similar to Scenario 3, peak flow and flood volume both increased due to wetland loss in the lower NRB (Scenario 12), with the WSI values of 0.0835 $m^3/s{\cdot}km^{-2}$ and 1.2826 $m^3{\cdot}km^{-2}$ respectively.

IWs loss (Scenario 1, 4, and 10) and RWs loss (Scenario 2, 5, and 11) simulation at UNRB (Scenario 1 and 2), MNRB (Scenario 4 and 5) and LNRB (Scenario 10 and 11) were selected to discern a spatial change in extreme flood caused by IWs and RWs, respectively. As shown in Fig. 4 and Fig. 5, due to IWs loss (Scenario 1), the peak flow increased slightly (0.0842 $m^3/s{\cdot}km^{-2}$) in the upper-NRB and reduced negligibly in the middle-NRB (0.0336 $m^3/s{\cdot}km^{-2}$) and lower NRB (0.0296 $m^3/s{\cdot}km^{-2}$) due to IWs loss. Similarly, flood volume had a minor increase in three river sections under Scenario 1. In terms of IWs loss in the middle-NRB (Scenario 4) and lower-NRB (Scenario 10), peak flow and flood volume also performed slightly increase. Similarly, RWs loss had a considerable impact on peak flow but slightly influences flood volume. Under Scenarios 2, 5, and 11, RWs loss substantially decreased peak flow at the lower-NRB with the value of 0.0871 $m^3/s{\cdot}km^{-2}$, 0.1902 $m^3/s{\cdot}km^{-2}$, and 0.0692 $m^3/s{\cdot}km^{-2}$, respectively. There was a slight increase in peak flow under Scenario 1 from the upper-NRB to the lower-NRB. The WSI values of peak flow under Scenarios 2, 5, and 11 also indicate that RWs mainly impacted peak flow in their drainage basin whereas exerted less influence on the downstream. When comparing peak flow at the Fulaerji (outlet in middle-NRB) and Dalai (outlet in lower-NRB) station under Scenario 5, the same results can be found in Fig. 4b and Fig. 4c. Conversely, little increase in the flow volume in the upper-NRB (0.0921 $m^3{\cdot}km^{-2}$) and middle-NRB (0.2444 $m^3{\cdot}km^{-2}$) can be found both under Scenario 2 and Scenario 5. However, RWs loss under Scenario 2, 5, and 11 led to an increase in the volume at the lower-NRB with the values of 3.3095 $m^3{\cdot}km^{-2}$, 1.0084 $m^3{\cdot}km^{-2}$, and 1.2498 $m^3{\cdot}km^{-2}$, respectively. Hence, RWs mainly decreased peak flow in their drainage basin and reduced flow volume of further downstream.

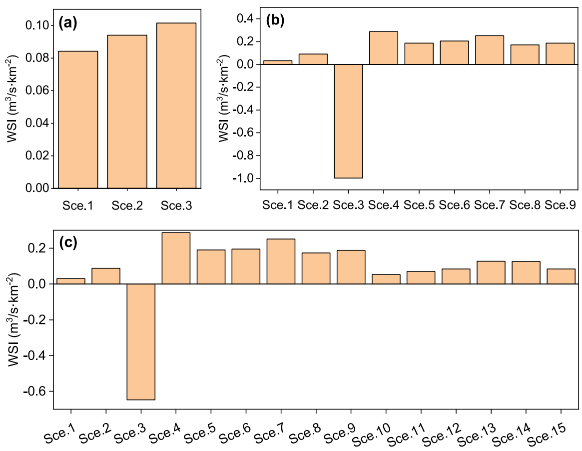

Fig. 4. Wetland specific impact (WSI) on peak flow at (a) Shihuiyao, (b) Fualaerji and (c) Dalai stations. Sce. refer to the Scenario. A positive WSI refer to the increase in peak flow due to a certain wetland loss scenario, and vice versa.

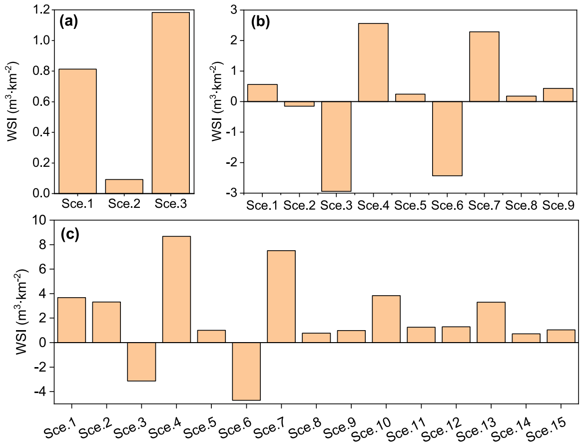

Fig. 5. Flood volume response for different wetland loss scenarios at (a) Shihuiyao, (b) Fualaerji and (c) Dalai stations. Sce. refer to the Scenario. A positive WSI refer to the increase in flood volume due to a certain wetland loss scenario, and vice versa.

3.2.3. Impacts of wetlands types on extreme flood

Five pairs of wetland loss scenarios were selected to comparably analyze the impacts of wetland types (IWs and RWs) on peak flow and flood volume. The five pairs of wetland loss scenarios are Scenario 1 and 2 at the upper-NRB, Scenario 4 and 5 at the middle-NRB, Scenario 7 and 8 at the middle-NRB, Scenario 10 and 11 in the lower-NRB, Scenario 13 and 14 for the entire basin (Fig. 4b and Fig. 4c). It can be observed that IWs showed a larger impact on peak flow than that of RWs across most scenarios. However, for the Scenario 1 and 2, IWs and RWs loss increased peak flow by 0.0842 $m^3/s{\cdot}km^{-2}$ and 0.0941 $m^3/s{\cdot}km^{-2}$, 0.0336 $m^3/s{\cdot}km^{-2}$ and 0.0902 $m^3/s{\cdot}km^{-2}$, 0.0297 $m^3/s{\cdot}km^{-2}$ and 0.0871 $m^3/s{\cdot}km^{-2}$, at the outlets of upper-, middle- and lower-NRB, respectively. In terms of flood volume, the regulation efficiencies provided by IWs and RWs were markedly different. IWs overall showed a stronger impact on flood volume than RWs. These results indicated that IWs contributed largely to the reduction of both peak flow and flood volume while upper RWs predominantly decreased peak flow in their basin.

3.3. Effects of wetlands on severe drought

3.3.1. Overall impacts of wetlands on severe drought

Fig. 6 and Fig. 7 show the changes in minimum flow and drought deficit response for different wetland loss scenarios at the

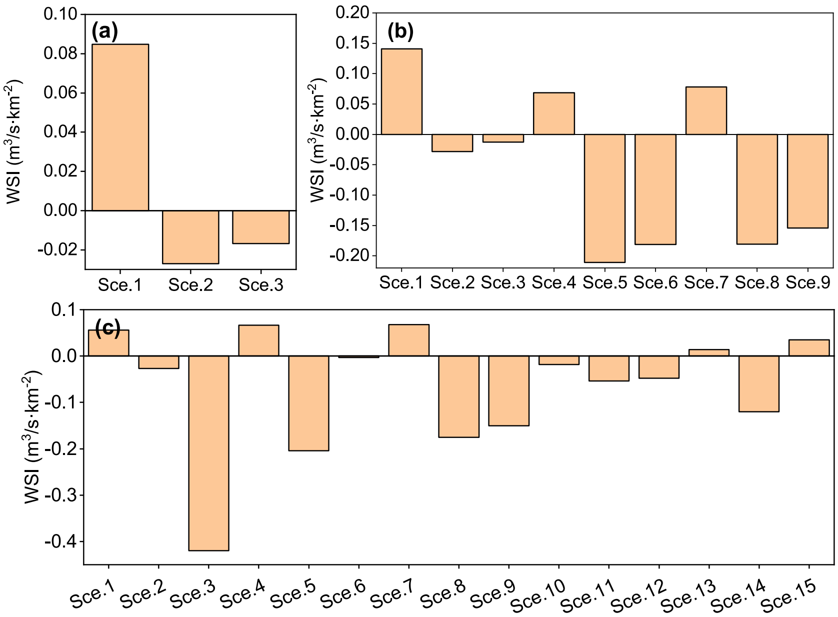

Fig. 6. Changes in minimum flow response for different wetland loss scenarios at (a) Shihuiyao, (b) Fualaerji and (c) Dalai stations. Sce. refer to Scenario. A positive WSI refer to the increase in minimum flow due to a certain wetland loss scenario, and vice versa.

Shihuiyao, Fualaerji, and Dalai, respectively. WSI values for the minimum flow and drought deficit were from −0.41957 $m^3/s\cdot km^{-2}$ to 0.1407 $m^3/s\cdot km^{-2}$ and from −19.1784$\cdot km^{-2}$ to 7.3848 $m^3\cdot km^{-2}$ due to wetland removal. However, for most scenarios, the decrease of minimum flow and drought deficit was greater than the increase caused by wetland removal, indicating that wetlands overall supported low flow during the severe drought in 2011. It is noteworthy that upstream wetland loss led to the largest decrease in minimum flow and drought deficit with the WSI values of −0.4196 $m^3/s\cdot km^{-2}$ and −19.1784 $m^3\cdot km^{-2}$, at the lower-NRB. In addition, the regulation efficiency of wetlands on drought showed a disproportional variation in the area loss of wetlands (Scenario 3, 9, and 15). The cumulative effect of both RWs and IWs on drought, unexpectedly, produced less decrease in minimum flow and drought deficit than RWs under most scenarios.

3.3.2. Impacts of wetlands location on severe drought

Similar to the aforementioned analysis on the extreme flood, the pairs of wetland loss scenarios concerning their spatial location were performed to investigate spatial changes in regulation efficiency on minimum flow and drought deficit. The pairs of wetland loss scenarios were: Scenario 3, 6, and 12 for the cumulative effect of both IWs and RWs, Scenario 1, 4, and 10 for IWs, Scenario 2, 5, and 11 for RWs in upper-NRB, middle-NRB, and lower-NRB, respectively. As illustrated by Fig. 6 and Fig. 7, wetland loss generally decreased minimum flow and drought deficit under Scenarios 3, 6, and 12. Specifically, wetlands loss under Scenario 3 resulted in a decrease in minimum flow and drought deficit in the upper-NRB (-0.0168 $m^3/s\cdot km^{-2}$ and −1.5249 $m^3\cdot km^{-2}$, respectively) and middle-NRB (-0.0128 $m^3/s\cdot km^{-2}$ and −1.2954 $m^3\cdot km^{-2}$, respectively). However, the loss scenario led to a considerable decrease in minimum flow and drought deficit in lower-NRB (-0.4195 $m^3/s\cdot km^{-2}$ and −19.1784 $m^3\cdot km^{-2}$, respectively). These results showed that wetlands in the headwater region potentially play an important role in providing source water for downstream during the drought period. Moreover, wetlands located at the middle-NRB had the great impact on drought deficit in their belonging sub-basin with WSI value of −0.1816 $m^3\cdot km^{-2}$ (Scenario 6 in Fig. 6b and Fig. 7b). However, the minimum flow almost kept unchanged due to wetland removal under the scenario.

Conversely, removing IWs (Scenario 1, 4, and 10) mainly led to an increase in minimum flow and drought deficit in the upper-NRB, middle-NRB, and lower-NRB, respectively. However, the WSI value of IWs varied from the upper-NRB to the lower-NRB for Scenario 1 and Scenario 4. Specifically, removing IWs increased minimum flow by 0.0848 $m^3/s\cdot km^{-2}$ in the upper-NRB, 0.1407 $m^3/s\cdot km^{-2}$ in the middle-NRB, and 0.0559 $m^3/s\cdot km^{-2}$ in the lower-NRB. For drought deficit, the WSI value of IWs for the upper-, middle, and lower-NRB were 7.3848 $m^3\cdot km^{-2}$, 6.5623 $m^3\cdot km^{-2}$, and 6.7224 $m^3\cdot km^{-2}$, respectively. This indicated that IWs affected drought both in their belonging sub-basin and downstream areas during the severe drought events.

For RWs, it can be observed that minimum flow and drought deficit overall decreased under Scenarios 2, 5, and 11, indicating an obvious drought alleviation function of wetlands. Fig. 6 and Fig. 7 also showed that RWs exhibited a slighter higher impact on a severe drought in the local basin than the downstream basin. For instance, under Scenario 5, the WSI values for minimum flow and drought deficit were −0.2109 $m^3/s\cdot km^{-2}$ and −12.9088 $m^3\cdot km^{-2}$ respectively in the middle-NRB.

RWs removing at the upper-NRB led to a slight decrease in minimum flow (-0.0281 $m^3/s\cdot km^{-2}$) and drought deficit (-2.0826 $m^3\cdot km^{-2}$) in the middle-NRB. However, the WSI values for minimum flow and drought deficit caused by RWs' removing were reduced

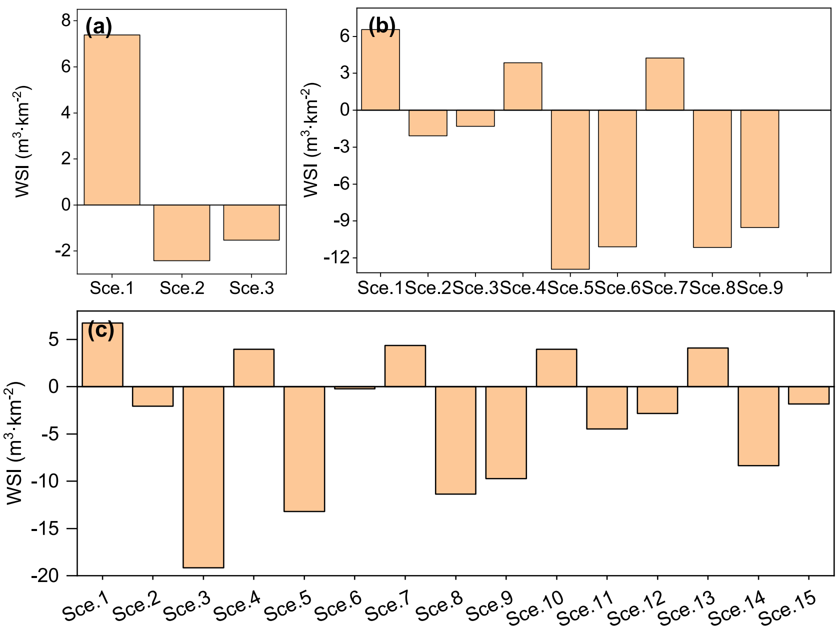

Fig. 7. Changes in drought deficit response for different wetland loss scenarios at (a) Shihuiyao, (b) Fualaerji and (c) Dalai stations. Sce. refer to Scenario. A positive WSI refer to the increase in drought deficit due to a certain wetland loss scenario, and vice versa.

and with the value of $-0.0265\ m^3/s{\cdot}km^{-2}$ and $-2.0789\ m^3{\cdot}km^{-2}$ in lower-NRB, respectively. In terms of the three scenarios with different geographical locations, Scenario 5 showed a higher absolute change of minimum flow and drought deficit than Scenarios 1 and Scenario 11, which indicated that the RWs located at the middle and lower-NRB play an important in alleviating severe drought in the NRB.

3.3.3. Impacts of wetlands types on severe drought

Based on the same pairs of wetland loss scenarios as aforementioned illustrated, the effect of wetland types on minimum flow and drought deficit were quantified and compared to the baseline scenario. For all the pairs of wetland loss scenarios (Scenario 1 and 2 in the upper-NRB, Scenario 4 and 5 in the middle-NRB, Scenario 7 and 8 in the upper- and middle-NRB, Scenario 10 and 11 in the lower-NRB, Scenario 13 and 14 in the entire basin), IWs removing led to an opposite change in minimum flow and drought deficit when comparing with RWs. Specifically, minimum flow and drought deficit showed a decreasing trend accompanied by RWs loss. However, except for Scenario 10 and 11 in the lower-NRB, RWs loss overall led to increasing in minimum flow and drought deficit. Therefore, RWs mainly contributed to the alleviation of drought while IWs mainly intensified drought deficit to some extent.

3.4. How wetlands regulate extreme flood and severe drought

Prior work has recognized that wetlands play an important role in regulating basin hydrological processes including a reduction in the flooding peaks and extension of flood return period; low flow supports; and reduction of runoff and streamflow (Acreman and Holden, 2013; Kadykalo and Findlay, 2016; Lee et al., 2018; Wu et al., 2020a,b,c). We found that the WSI of all wetlands (approximately 20 % of the NRB) were $-0.0838\ m^3/s{\cdot}km^{-2}$ and $-1.0483\ m^3{\cdot}km^{-2}$ for flood peak and volume, respectively. Our modeling results indicated that RWs mainly contribute to the decrease in peak flow in their basin and reduced flow volume for the downstream area. However, IWs predominantly decreased flood volume in their basin and slightly mitigate peak flow. In addition, RWs (especially those located at the middle- and lower-NRB) considerably contributed to the alleviation of severe drought deficit while IWs can intensify the deficit to some extent. Our results demonstrated that (i) wetlands overall mitigate extreme floods and alleviate severe drought in a basin; (ii) the types and spatial location of wetlands affect their regulation capacity (the degree of impacts) and behaviors (attenuation and amplification effects) within a large river basin.

Upstream wetland plays an important role in controlling hydrological processes and ecosystem integrity in the upper basin and, thus, downstream flow patterns (Yeo et al., 2019). In the NRB, wetland loss at the upper-NRB led to a considerable decrease in both peak flow and flood volume at the middle-NRB and the lower-NRB (Figs. 4 and 5), indicating upstream wetlands have a stronger role in enhancing flooding than in reducing it. This is comparable with Acreman and Holden (2013) who found that upland wetlands generally contribute to augmenting downstream flooding. In addition, a wetland located at the middle-NRB amplified flood volume at the lower-NRB (Fig. 5). Since the efficiency of wetlands flood regulation largely relies on their capacity of water storage. For instance, permanently saturated wetlands with little or no storage capacity may generate or augment floods compared to semi-saturated or

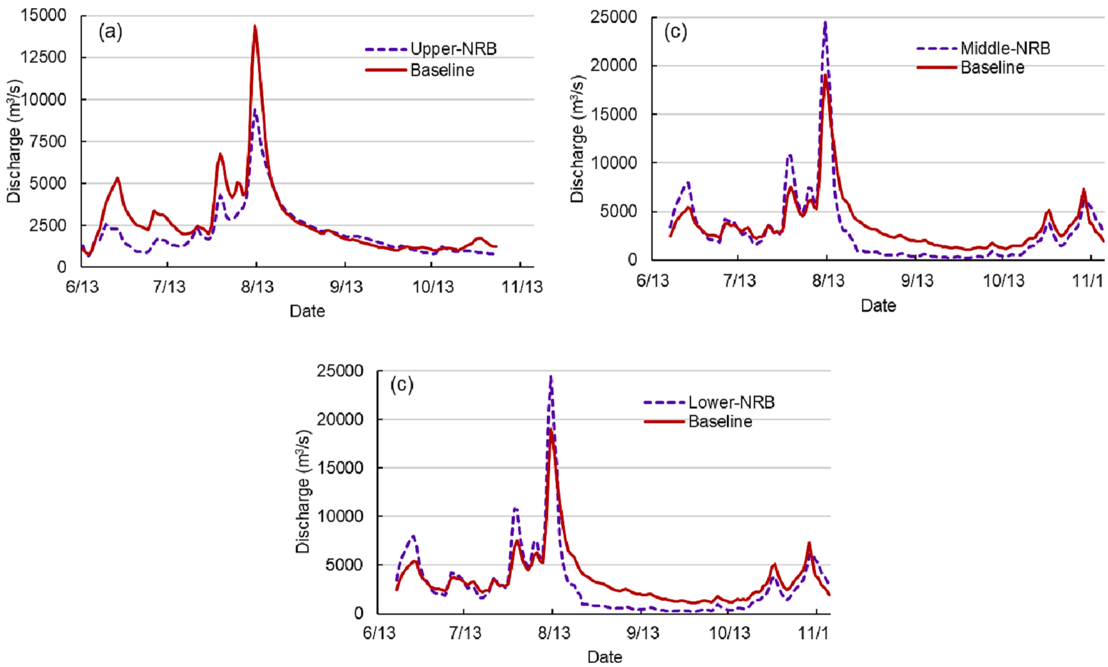

Fig. 8. Hydrography at the (a) Shihuiyao, (b) Fulaerji and (c) Dalai stations with and without wetland loss scenarios at the upper-, middle- and lower-NRB. The solid and dash lines refer to discharge with and without wetlands, respectively.

unsaturated wetlands (Morris and Camino, 2011; Kadykalo and Findlay, 2016; Wu et al., 2020a,b,c). As illustrated in Fig. 8, compared to baseline (with wetland), loss of wetland at the upper-NRB mainly decreased flood volume and peak flow during the rising stage and the early falling stage at the upper-NRB (Fig. 8a) and the middle-NRB (Fig. 8b). Therefore, headwater wetland amplified downstream flood by increasing both peak flow and flood volume during the rising stage in the NRB. For severe drought, wetlands at the upper-NRB overall alleviated drought intensity by providing source water for downstream during the drought period (Fig. 6 and Fig. 7). Therefore, upstream wetland exerts significant effects on basin hydrological processes and acts to regulate streamflow fluctuations in this region. However, wetland at the middle-NRB slightly influenced flood volume at the lower-NRB during the rising stage while considerably decreasing flood volume thereafter (Fig. 8c). These discrepancies in amplification efficiency provided by wetlands at the upper-NRB also demonstrated that the spatial location of wetland affects their hydrological regulation benefits.

What is surprising is that the regulation efficiency of wetlands on flood and drought was not proportional to the area loss of wetlands in the NRB. We found that the relative change of peak flow from the upper- and the lower-NRB performed a decreasing trend with the increase of wetland area loss (Fig. 4 and Fig. 5). In addition, the capacity of drought mitigation intensified with the area increase of wetland from the upper-NRB to the middle-NRB; while the capacity rendered the severity of drought to some extent in the lower-NRB (Fig. 6 and Fig. 7). This finding is contrary to previous studies which have suggested that the more wetlands, the greater their influence on water transport mechanisms and routing processes that generate streamflow. A possible explanation for this might be that a variety of factors (e.g., soil properties, vegetation characteristics and initial hydrological conditions) affect the cumulative hydrologic effects of wetlands, resulting in a disproportionate relationship between wetland area and their function (Ameli and Creed, 2019; Wu and Zhang, 2021). Another possible explanation for this might be that the agricultural reclamation and water infrastructures has directly changed the hydrological and hydraulicly between wetland landscapes and other hydrological units such as rivers, lakes, and groundwater (Meng et al., 2019; Chen et al., 2021; Wu et al., 2021). This change could alter the hydrological connection mechanism between wetlands and ground/surface water in the lower-NRB. This hydrological connection mechanism is one of the deterministic factors governing flow regulation services of wetlands (Golden et al., 2014).

Our simulation results indicated that RWs overall mitigated more peak flow than IWs while exerting comparable effect on flood volume in the NRB (Fig. 4 and Fig. 5). This is also true for the regulation services of wetlands on drought (Fig. 6 and Fig. 7). Lee et al. (2018) found that IWs loss caused a greater fluctuation of downstream flow than all RWs loss for the Tuckahoe Creek Basin. This is because of the larger area of IWs (3527 ha) and less coverage of RWs (1437 ha) in the study area. Conversely, a larger area of RWs can be found at the middle-NRB and the lower-NRB (Fig. 1), which generated a stronger regulation service from RWs than IWs for our study site. As illustrated by Fossey et al. (2015), the more wetlands are in the upper part of the basin, the greater their mitigation on high flow and support on low flow seems to be. In addition, the higher connectivity between RWs and adjacent main stream, the greater the RWs' effect. Therefore, the regulation magnitude of either IWs or RWs partially depends on their area of a basin. In addition, the great majority of floodplain wetlands located at the lower-NRB are RWs which have a strong connection with groundwater, stream, river, and lake (Li et al., 2018; Lane et al., 2018), showing valuable and substantial regulation services on flood and drought.

Previous studies showed that wetlands contribute to recharging groundwater, support baseflow, and reduction in drought (Lee et al., 2018; Ameli and Creed, 2019a; Ameli and Creed, 2019b; Wu et al., 2020a,b,c). However, we found that IWs amplified drought severity to some extent in the NRB (Fig. 5 and Fig. 6). And this amplification weakened the cumulative efficiency of wetlands (both IWs and RWs) and led to an overall less alleviative function on drought than RWs under most scenarios. Due to the relative weaker hydrologic connections with surface water such as river channels, the hydrology of IWs is primarily governed by the change in water table level controlled by precipitation, evapotranspiration, and basin contribution (Evenson et al., 2015; Evenson et al., 2016; Golden et al., 2016; Leibowitz et al., 2018). It is possible that the ecological water requirements for wetland ecosystems could account for some aspects of these results. Since wetlands need certain amount of water to maintain their natural hydro-ecological healthy and services, such as protecting biodiversity, supporting human activities, and improving environmental sustainability (Yuan et al., 2014; Agha-Kouchak et al., 2015). IWs would lose their flow regulation services and consume certain water to conserve an appropriate ecosystem regime when experiencing severe drought (Bond et al., 2008; Middleton and Souter, 2016). Moreover, the consumptive water of wetland rather than recharging groundwater could directly lead to a reduction in water yield to the river when experiencing a severe drought event.

3.5. Implication for wetland protection and restoration

The hydrological services of wetlands can potentially offer a nature-based solution for addressing a variety of environmental, social, and economic challenges (Mitsch et al., 1977; Wu et al., 2020a,b,c; Acreman et al., 2021; Holden et al., 2022). However, wetland protection and restoration are often subject to many constraints regarding where and which type of wetlands can be restored (e.g., ownership of the wetlands, owner's willingness to restore the wetland, benefits of wetlands, etc.) (Clare and Creed, 2014; Walters and Babbar-Sebens, 2016; Ameli and Creed, 2019a; Gourevitch et al., 2020). The various wetland loss scenarios and comparative analysis allowed us to identify prioritized types and locations of wetlands to maximum hydrological services provided by wetlands. In recent years, the management is gradually carrying out multi-purpose water resource management to make the Songhua River Plain a major grain production base in China and a wetland reserve in the downstream NRB (Meng et al., 2019; Zhang et al., 2020). Therefore, it is necessary and valuable to conserve current wetlands and restore lost wetlands for curbing the potential effects of climate variability on hydrological extremes in this region. Our simulated results suggest that if managers are primarily focused on adaptation strategies for flooding, both IWs and RWs should be prioritized because the fact that both are highly effective in mitigating flood peak and volume. If managers are primarily concerned with drought adaptation strategies, RWs at the middle- and lower-NRB should be effectively protected and restored. Although wetlands in the upper-NRB could increase the risk of flood in the middle-NRB and the lower-NRB (Fig. 4 and Fig. 5), their overall mitigation of flood and drought also can produce numerous benefits, such as providing source water for downstream river channels during the severe drought. Such methodology can also be applied to other study areas for decision and management on restoration and conservation of wetlands to promote basin resilience to hydrologic extremes. This study has important implications for the mitigation on hydrological extremes with respect to wetland-based solution, i.e., the flow regulation services of wetlands.

Several limitations to this study need to be acknowledged. Acreman and Holden (2013) concluded that the further downstream one is, the more difficult it is to quantify the effects of upstream wetland restoration and loss on flood risk, as these effects can be overwhelmed by other processes in the watershed. In addition, various factors, such as landscape geographic location and spatial configuration, soil matrix characteristics, topography, soil moisture conditions and characteristics of a rainfall event, can affect the efficiency of wetlands in regulating floods and droughts. For example, the distances of wetland from the main stream network (Fossey and Rousseau, 2016; Ameli and Creed, 2019a), landscape characters of wetland (Gao et al., 2016) and anthropogenic activities (Wu et al., 2021) can modify the regulation efficiency of wetland. Particularly, the total amount, intensity, duration and concentration of rainfall events affect the processes of vegetation retention, depression filling, infiltration, and flow yield in wetlands and their contribution areas, ultimately modifying the flow regulation services provided by wetlands (Dubreuil, 1985; Evans et al., 1999; Burt 2001; Wu and Zhang, 2021). For example, McCauley et al. (2015) discovered that wetlands can completely storage rainfall during a rainfall event if the rainfall intensity is small and long-lasting; while wetlands will directly perform the water transfer function by storing the full amount of yield flow if the rainfall intensity is strong and concentrated. Moreover, we only addressed the effect of wetlands on the extreme flood in 1998 and severe drought in 2011 with respect to change in volume, peak flow, deficit, and minimum flow. It is unclear how and to what extent the long-term intensity–durationfrequency of droughts and floods altered regarding changes in wetlands types, geographical location, and area. These are important issue for future research.

4. Summary and conclusion

A hydrological modeling platform integrated with wetland modules were used to simulate hydrological processes and to assess wetland impacts on extreme flood and severe drought. Fifteen wetland loss scenarios including area change and geographical location scenarios were developed to quantify how and to what extent can wetlands mitigate extreme flood and drought in the NRB. The modeling results showed that the cumulative regulation efficiency of all wetlands (approximately 20 % of the basin area) were $-0.0838\ m^3/s{\cdot}km^{-2}$ and $-1.0483\ m^3{\cdot}km^{-2}$ for flood peak and flood volume respectively, as well as a slight alleviation effect on drought. Moreover, wetland types and spatial location affected their regulation efficiency. Although wetland in the upstream increased the risk of flood for the downstream, their overall mitigation on flood and drought also can produce numerous benefits, such as providing source water for downstream during the severe drought. Wetland located at low basin exerted strong hydrological influence on extreme flood and severe drought in the NRB. Conservation and restoration of middle- and lower-basin's wetland (both RWs and IWs) are more likely to largely promote basin resilience to extreme flood in the NRB. In addition, RWs located at lower-NRB should be highlighted for alleviating drought. This study demonstrated that wetlands can mitigate extreme floods and alleviate severe droughts in a basin and they can serve as an efficient nature-based solution for improving basin resilience to hydrological extremes.

CRediT authorship contribution statement

Yanfeng Wu: Conceptualization, Writing – original draft. **Jingxuan Sun:** Conceptualization, Software, Formal analysis, Investigation. **Boting Hu:** Software, Investigation, Visualization. **Guangxin Zhang:** Conceptualization, Supervision. **Alain N. Rousseau:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the Postdoctoral Science Foundation of China (2021M693155), National Natural Science Foundation of China (42101051 and 41877160) and Strategic Priority Research Program of the Chinese Academy of Sciences, China (XDA28020501 and XDA28100105).

References

Acreman, M., et al., 2021. Evidence for the effectiveness of nature-based solutions to water issues in Africa. Environ. Res. Lett. 16 (6), 063007.
Acreman, M., Holden, J., 2013. How wetlands affect floods. Wetlands 33 (5), 773–786.

AghaKouchak, A., et al., 2015. Water and climate: Recognize anthropogenic drought. Nature 524 (7566), 409–411.
Åhlén, I., et al., 2022. Wetland position in the landscape: Impact on water storage and flood buffering. Ecohydrology 15 (7), e2458.
Ahmed, F., 2017. Influence of Wetlands on Black-Creek Hydraulics. J. Hydrol. Eng. 22 (1), D5016001.
Ameli, A.A., Creed, I.F., 2019a. Does Wetland Location Matter When Managing Wetlands for Watershed-Scale Flood and Drought Resilience? JAWRA J. Am. Water Resour. Assoc. 55 (3), 529–542.
Ameli, A.A., Creed, I.F., 2019b. Groundwaters at risk: wetland loss changes sources, lengthens pathways, and decelerates rejuvenation of groundwater resources. JAWRA J. Am. Water Resour. Assoc. 55 (2), 294–306.
Babbar-Sebens, M., Barr, R.C., Tedesco, L.P., Anderson, M., 2013. Spatial identification and optimization of upland wetlands in agricultural watersheds. Ecol. Eng. 52, 130–142.
Blanchette, M., Rousseau, A.N., Foulon, É., Savary, S., Poulin, M., 2019. What would have been the impacts of wetlands on low flow support and high flow attenuation under steady state land cover conditions? J. Environ. Manage. 234, 448–457.
Blanchette, M., Rousseau, A.N., Savary, S., Foulon, É., 2022. Are spatial distribution and aggregation of wetlands reliable indicators of stream flow mitigation? J. Hydrol. 127646.
Bond, N.R., Lake, P.S., Arthington, A.H., 2008. The impacts of drought on freshwater ecosystems: an Australian perspective. Hydrobiologia 600 (1), 3–16.
Bullock, A., Acreman, M., 2003. The role of wetlands in the hydrological cycle. Hydrol. Earth Syst. Sci. 7 (3), 358–389.
Burt, T.P., 2001. Integrated management of sensitive catchment systems. Catena 42, 275–290.
Chen, L., Wu, Y., Xu, Y.J., Guangxin, Z., 2021. Alteration of flood pulses by damming the Nenjiang River, China – Implication for the need to identify a hydrograph-based inundation threshold for protecting floodplain wetlands. Ecol. Ind. 124, 107406.
Clare, S., Creed, I.F., 2014. Tracking wetland loss to improve evidence-based wetland policy learning and decision making. Wetl. Ecol. Manag. 22 (3), 235–245.
Davidson, N.C., 2018. Ramsar convention on wetlands: scope and implementationThe Wetland Book I: Structure and function, management, and methods. Springer 451–458.
Dottori, F., et al., 2018. Increased human and economic losses from river flooding with anthropogenic warming. Nat. Clim. Chang. 8 (9), 781–786.
Downard, R., Endter-Wada, J., 2013. Keeping wetlands wet in the western United States: adaptations to drought in agriculture-dominated human-natural systems. J. Environ. Manage. 131, 394–406.
Dubreuil, P.L., 1985. Review of field observations of runoff generation in the tropics. J. Hydrol. 80 (3–4), 237–264.
Efstratiadis, A., Koutsoyiannis, D., 2010. One decade of multi-objective calibration approaches in hydrological modelling: a review. Hydrol. Sci. J. 55 (1), 58–78.
Elisa, M., Kihwele, E., Wolanski, E., Birkett, C., 2021. Managing wetlands to solve the water crisis in the Katuma River ecosystem, Tanzania. Ecohydrol. Hydrobiol. 21 (2), 211–222.
Evans, C., Davies, T.D., Murdoch, P.S., 1999. Component flow processes at four streams in the Catskill Mountains, New York, analysed using episodic concentration/discharge relationships. Hydrol. Process. 13 (4), 563–575.
Evenson, G.R., et al., 2018. A watershed-scale model for depressional wetland-rich landscapes. J. Hydrol. X 1, 100002.
Evenson, G.R., Golden, H.E., Lane, C.R., Amico, D., E.,, 2015. Geographically isolated wetlands and watershed hydrology: A modified model analysis. J. Hydrol. 529, 240–256.
Evenson, G.R., Golden, H.E., Lane, C.R., D'Amico, E., 2016. An improved representation of geographically isolated wetlands in a watershed-scale hydrologic model. Hydrol. Process. 30 (22), 4168–4184.
Feng, X., Zhang, G., Yin, X., 2011. Hydrological Responses to Climate Change in Nenjiang River Basin, Northeastern China. Water Resour. Manage. 25 (2), 677–689.
Feng, X.Q., Zhang, G.X., Jun, X.u., Y., 2013. Simulation of hydrological processes in the Zhalong wetland within a river basin, Northeast China. Hydrol. Earth Syst. Sci. 17 (7), 2797–2807.
Ferrier, S., 2020. Prioritizing where to restore Earth's ecosystems. Nature 586 (7831), 680–681.
Fortin, J., et al., 2001. Distributed Watershed Model Compatible with Remote Sensing and GIS Data. I: Description of Model. J. Hydrol. Eng. 6 (2), 91–99.
Fossey, M., Rousseau, A.N., Bensalma, F., Savary, S., Royer, A., 2015. Integrating isolated and riparian wetland modules in the PHYSITEL/HYDROTEL modelling platform: model performance and diagnosis. Hydrol. Process. 29 (22), 4683–4702.
Fossey, M., Rousseau, A.N., 2016. Assessing the long-term hydrological services provided by wetlands under changing climate conditions: A case study approach of a Canadian watershed. J. Hydrol. 541, 1287–1302.
Foulon, E., Rousseau, A.N., Gagnon, P., 2018. Development of a methodology to assess future trends in low flows at the watershed scale using solely climate data. J. Hydrol. (Amsterdam) 557, 774–790.
Fowler, K., Peel, M., Western, A., Zhang, L., 2018. Improved Rainfall-Runoff Calibration for Drying Climate: Choice of Objective Function. Water Resour. Res. 54 (5), 3392–3408.
Gao, J., Holden, J., Kirkby, M., 2016. The impact of land-cover change on flood peaks in peatland basins. Water Resour. Res. 52 (5), 3477–3492.
Garcia, F., Folton, N., Oudin, L., 2017. Which objective function to calibrate rainfall-runoff models for low-flow index simulations? Hydrol. Sci. J. 62 (7), 1149–1166.
Golden, H.E., et al., 2014. Hydrologic connectivity between geographically isolated wetlands and surface water systems: A review of select modeling methods. Environ. Model. Softw. 53, 190–206.
Golden, H.E., et al., 2016. Relative effects of geographically isolated wetlands on streamflow: a watershed-scale analysis. Ecohydrology 9 (1), 21–38.
Golden, H.E., Lane, C.R., Rajib, A., Wu, Q., 2021. Improving global flood and drought predictions: integrating non-floodplain wetlands into watershed hydrologic models. Environ. Res. Lett. 16 (9), 091002.
Gourevitch, J.D., et al., 2020. Spatial targeting of floodplain restoration to equitably mitigate flood risk. Glob. Environ. Chang. 61, 102050.
Güneralp, B., Güneralp, O., Liu, Y., 2015. Changing global patterns of urban exposure to flood and drought hazards. Global Environ. Change, 31: 217-225.
Gupta, H.V., Kling, H., Yilmaz, K.K., Martinez, G.F., 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. J. Hydrol. 377 (1–2), 80–91.
He, C., Liu, Z., Tian, J., Ma, Q., 2014. Urban expansion dynamics and natural habitat loss in China: A multiscale landscape perspective. Glob. Chang. Biol. 20 (9), 2886–2902.
Hefting, M., et al., 2004. Water table elevation controls on soil nitrogen cycling in riparian wetlands along a European climatic gradient. Biogeochemistry 67 (1), 113–134.
Hermoso, V., Clavero, M. and Green, A.J., 2019. Dams: Keep wetland damage in check. Nature, 568(7751): 171-171.
Hirabayashi, Y., et al., 2013. Global flood risk under climate change. Nat. Clim. Chang. 3 (9), 816–821.
Holden, P.B., et al., 2022. Nature-based solutions in mountain catchments reduce impact of anthropogenic climate change on drought streamflow. Commun. Earth Environ. 3 (1).
Kadykalo, A.N., Findlay, C.S., 2016. The flow regulation services of wetlands. Ecosyst. Serv. 20, 91–103.
Ketcheson, S.J., et al., 2017. The hydrological functioning of a constructed fen wetland watershed. Sci. Total Environ. 603, 593–605.
Kling, H., Fuchs, M., Paulin, M., 2012. Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. J. Hydrol. 424–425, 264–277.
Lane, C.R., Leibowitz, S.G., Autrey, B.C., LeDuc, S.D., Alexander, L.C., 2018. Hydrological, Physical, and Chemical Functions and Connectivity of Non-Floodplain Wetlands to Downstream Waters: A Review. JAWRA J. Am. Water Resour. Assoc. 54 (2), 346–371.
Lee, S., et al., 2018. Assessing the cumulative impacts of geographically isolated wetlands on watershed hydrology using the SWAT model coupled with improved wetland modules. J. Environ. Manage. 223, 37–48.
Leibowitz, S.G., et al., 2018. Connectivity of Streams and Wetlands to Downstream Waters: An Integrated Systems Framework. JAWRA J. Am. Water Resour. Assoc. 54 (2), 298–322.
Li, F., Zhang, G., Xu, Y.J., 2014. Spatiotemporal variability of climate and streamflow in the Songhua River Basin, northeast China. J. Hydrol. 514, 53–64.
Li, F., Zhang, G., Xu, Y., 2016. Assessing Climate Change Impacts on Water Resources in the Songhua River Basin. Water (Basel) 8 (10), 420.

Li, Y., Zhang, Q., Lu, J., Yao, J., Tan, Z., 2018. Assessing surface water–groundwater interactions in a complex river-floodplain wetland-isolated lake system. River Res. Appl. 35 (1), 25–36.
Liu, Q., et al., 2020. Vegetation dynamics under water-level fluctuations: Implications for wetland restoration. J. Hydrol. (Amsterdam) 581, 124418.
Liu, Y., Yang, W., Wang, X., 2008. Development of a SWAT extension module to simulate riparian wetland hydrologic processes at a watershed scale. Hydrol. Process. 22 (16), 2901–2915.
Lobligeois, F., Andréassian, V., Perrin, C., Tabary, P., Loumagne, C., 2014. When does higher spatial resolution rainfall information improve streamflow simulation? An evaluation using 3620 flood events. Hydrol. Earth Syst. Sci. 18 (2), 575–594.
McCauley, L.A., Jenkins, D.G., Quintana-Ascencio, P.F., 2013. Isolated wetland loss and degradation over two decades in an increasingly urbanized landscape. Wetlands 33 (1), 117–127.
McCauley, L.A., Anteau, M.J., van der Burg, M.P., Wiltermuth, M.T., 2015. Land use and wetland drainage affect water levels and dynamics of remaining wetlands. Ecosphere 6 (6), 1–22.
Melsen, L.A., et al., 2019. Subjective modeling decisions can significantly impact the simulation of flood and drought events. J. Hydrol. 568, 1093–1104.
Meng, B., Liu, J., Bao, K., Sun, B., 2019. Water fluxes of Nenjiang River Basin with ecological network analysis: Conflict and coordination between agricultural development and wetland restoration. J. Clean. Prod. 213, 933–943.
Middleton, B.A., Souter, N.J., 2016. Functional integrity of freshwater forested wetlands, hydrologic alteration, and climate change. Ecosyst. Health Sustainability 2 (1), e01200-n/a.
Milly, P.C.D., Wetherald, R.T., Dunne, K.A., Delworth, T.L., 2002. Increasing risk of great floods in a changing climate. Nature 415 (6871), 514–517.
Mitsch, W.J., Dorge, C.L. and Wiemhoff, J.R., 1977. Forested wetlands for water resource management in southern Illinois.
Mizukami, N., et al., 2018. On the choice of calibration metrics for high flow estimation using hydrologic models. Hydrol. Earth Syst. Sci. Discuss. 43 (1), 1–16.
Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: Performance measures and evaluation criteria. Trans. ASABE 58 (6), 1763–1785.
Moriasi, N., D., et al., 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Trans. ASABE 50 (3), 885–900.
Morris, J., Camino, M., 2011. Economic assessment of freshwater, wetland and floodplain (FWF) ecosystem services. UK National Ecosystem Assessment Working Paper, Cranfield University.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. J. Hydrol. 10 (3), 282–290.
Pianosi, F., Sarrazin, F., Wagener, T., 2015. A Matlab toolbox for Global Sensitivity Analysis. Environ. Model. Softw. 70, 80–85.
Rousseau, A.N., et al., 2011. PHYSITEL, a specialized GIS for supporting the implementation of distributed hydrological models. Water News-Official Mag. Can. Water Resour. Assoc. 31 (1), 18–20.
Song, X., et al., 2015. Recent changes in extreme precipitation and drought over the Songhua River Basin, China, during 1960–2013. Atmos. Res. 157, 137–152.
Stine, S., 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. Nature 369 (6481), 546–549.
Tabari, H., Hosseinzadehtalaei, P., Thiery, W. and Willems, P., 2021. Amplified drought and flood risk under future socioeconomic and climatic change. Earth's Future, 9(10): e2021EF002295.
Talukdar, S., Pal, S., 2019. Effects of damming on the hydrological regime of Punarbhaba river basin wetlands. Ecol. Eng. 135, 61–74.
Thorslund, J., et al., 2017. Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management. Ecol. Eng. 108, 489–497.
Tolson, B.A., Shoemaker, C.A., 2007. Dynamically dimensioned search algorithm for computationally efficient watershed model calibration. Water Resour. Res. 43 (1).
Turcotte, R., Fortin, J.P., Rousseau, A.N., Massicotte, S., Villeneuve, J.P., 2001. Determination of the drainage structure of a watershed using a digital elevation model and a digital river and lake network. J. Hydrol. (Amsterdam) 240 (3–4), 225–242.
Turcotte, R., Fortin, L.G., Fortin, V., Fortin, J.P., Villeneuve, J.P., 2007. Operational analysis of the spatial distribution and the temporal evolution of the snowpack water equivalent in southern Québec, Canada. Hydrol. Res. 38 (3), 211–234.
UNISDR, C., 2015. The human cost of natural disasters: A global perspective.
UNISDR, C., 2018. Economic Losses, Poverty, & Disasters 1998-2017. CRED-UNISDR.
Walters, K.M., Babbar-Sebens, M., 2016. Using climate change scenarios to evaluate future effectiveness of potential wetlands in mitigating high flows in a Midwestern US watershed. Ecol. Eng. 89, 80–102.
Wang, X., Yang, W., Melesse, A.M., 2008. Using Hydrologic Equivalent Wetland Concept Within SWAT to Estimate Streamflow in Watersheds with Numerous Wetlands. Trans. ASABE 51 (1), 55–72.
Ward, P.J., et al., 2020. Natural hazard risk assessments at the global scale. Nat. Hazards Earth Syst. Sci. 20 (4), 1069–1096.
Wu, Y., et al., 2022. Projection of future hydrometeorological extremes and wetland flood mitigation services with different global warming levels: A case study in the Nenjiang river basin. Ecol. Ind. 140, 108987.
Wu, Y., et al., 2023. Wetland mitigation functions on hydrological droughts: From drought characteristics to propagation of meteorological droughts to hydrological droughts. J. Hydrol. 128971.
Wu, Y., Zhang, G., Rousseau, A.N., Xu, Y.J., 2020a. Quantifying streamflow regulation services of wetlands with an emphasis on quickflow and baseflow responses in the Upper Nenjiang River Basin, Northeast China. J. Hydrol. 583, 124565.
Wu, Y., Zhang, G., Rousseau, A.N., Xu, Y.J., Foulon, É., 2020b. On how wetlands can provide flood resilience in a large river basin: A case study in Nenjiang river Basin, China. J. Hydrol. 587, 125012.
Wu, Y., Zhang, G., Rousseau, A.N., 2020c. Quantitative assessment on basin-scale hydrological services of wetlands. Sci. China Earth Sci. 63 (2), 279–291.
Wu, Y.F., Zhang, G.X., 2021. A review of hydrological regulation functions of watershed wetlands. Advance in Water Science 32 (3), 458–469.
Wu, Y., Zhang, G., Xu, Y.J., Rousseau, A.N., 2021. River Damming Reduces Wetland Function in Regulating Flow. J. Water Resour. Plan. Manag. 147 (10), 05021014.
Xu, X., et al., 2019. Evaluating the impact of climate change on fluvial flood risk in a mixed-use watershed. Environ. Model. Softw. 122, 104031.
Yang, W., et al., 2016. Integrated Economic-Hydrologic Modeling for Examining Cost-Effectiveness of Wetland Restoration Scenarios in a Canadian Prairie Watershed. Wetlands 36 (3), 577–589.
Yeo, I., et al., 2019. Mapping landscape-level hydrological connectivity of headwater wetlands to downstream waters: A catchment modeling approach-Part 2. Sci. Total Environ. 653, 1557–1570.
Yuan, Y., Yan, D., Wang, H., Wang, Q., Weng, B., 2014. Quantitative assessment of drought in a lacustrine wetland based on a water balance model. Nat. Hazards 70 (1), 693–703.
Zhang, L., Hou, G., Li, F., 2020. Dynamics of landscape pattern and connectivity of wetlands in western Jilin Province, China. Environ. Dev. Sustain. 22 (3), 2517–2528.
Zhang, X., Song, Y., 2014. Optimization of wetland restoration siting and zoning in flood retention areas of river basins in China: A case study in Mengwa, Huaihe River Basin. J. Hydrol. 519, 80–93.
Zhang, J., Xu, W., Liao, X., Zong, S., Liu, B., 2021. Global mortality risk assessment from river flooding under climate change. Environ. Res. Lett. 16 (6), 064036.