Can the combining of wetlands with reservoir operation largely reduce the risk of future flood and droughts?

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Abstract. Wetlands and reservoirs are important water flow and storage regulators in a river basin; therefore, they can play a crucial role in mitigating flood and hydrological drought risks. Despite the advancement of river basin theory and modeling, our knowledge is still limited about the extent that these two regulators could have in performing such a role, especially under future climate extremes. To improve our understanding, we first coupled wetlands and reservoir operations into a semi-spatially explicit hydrological model and then applied it in a case study involving a large river basin in Northeast China. The projection of future floods and hydrological droughts was performed using the hydrological model during different periods (near-future: 2026-2050, mid-century: 2051-2075, and end-century: 2076-2100) under five future climate change scenarios. We found that the risk of future floods and hydrological droughts can vary across different periods, in particular, will experience relatively large increases and slight decreases. This large river basin will experience longer duration, larger peak flows and volume, and enhanced flashiness flood events than the historical period. Simultaneously, the hydrological droughts will be much more frequent with longer duration and more serious deficit. Therefore, the risk of floods and droughts will overall increase further under future climate change even under the combined influence of reservoirs and wetlands. These findings highlight the hydrological regulation function of wetlands and reservoirs and attest that the combining of wetlands with reservoir operation cannot fully eliminate the increasing future flood and drought risks. To improve a river basin's resilience to the risks of future climate change, we argue that implementation of wetland restoration and development of accurate forecasting systems for effective reservoir operation are of great importance. Furthermore, this study demonstrated a wetland-reservoir integrated modeling and assessment framework that is conducive to risk assessment of floods and hydrological droughts, which can be used for other river basins in the world.

Keywords: Climate change; Hydrologic projection; Floods and droughts; Wetland hydrological services; Reservoir operations; Model integration

1. Introduction

Floods and droughts have produced some of the most frequent and serious disasters in the world (Diffenbaugh et al., 2015; Hirabayashi et al., 2013; UNISDR, 2015). Globally, they account for 38% of the total number of natural disasters, 45% of the total casualties, more than 84% of the total number of people affected, and 30% of the total economic damage caused by all-natural disasters (Güneralp et al., 2015) in the past. As climate change has been accelerating the hydrological cycle, causing more frequent and stronger weather extremes, more floods and droughts have been projected to increase at both global (Chiang et al., 2021; Jongman, 2018) and regional scales (Hallegatte et al., 2013; Wang et al., 2021). Concurrently, the disaster-related loss of ecosystems (e.g., wetlands, forest, and grassland) and their services can mitigate the flood and drought risks to a great extent (Gulbin et al., 2019; Walz et al., 2021). Given this, grey infrastructure such as dams, dikes, and reservoirs, which have often been used to attenuate flood and drought hazards because of their rapid and visible effects, can play an important role in ensuring the water security of a river basin (Alves et al., 2019; Casal-Campos et al., 2015). However, relying solely on grey infrastructure to attenuate floods and droughts has some inadequacies, such as large investments to build and maintain in addition to adverse effects on downstream ecosystems (Maes et al., 2015; Schneider et al., 2017). In this context, Nature-based solutions (NBS) for hydrometeorological hazards mitigation are becoming increasingly popular (Kumar et al., 2021), because NBS can effectively reduce or even offset the hydrological processes driving floods and droughts (Nika et al., 2020), while making least disturbance to the environment as well as delivering co-benefits which grey infrastructure cannot provide (Anderson and Renaud, 2021; Nelson et al., 2020). Therefore, it is urgent to integrate NBS into the current water management practices to increase basin resilience to hydrological extremes under climate change.

Wetlands have the potential to be used as a NBS for improving water storage and hence the resilience of a river basin to hydrological extremes along with grey infrastructures (Thorslund et al., 2017). This is because, similar to man-made dams and reservoirs, wetlands can attenuate flow and alter basin hydrological processes (Lee et al., 2018), such as floods (Wu et al., 2020a) and baseflows (Evenson et al., 2015; Wu et al., 2020b). However, unlike man-made grey infrastructures, wetlands are integral in landscapes and they are connected laterally and vertically with the surrounding terrestrial and aquatic environments through the hydrological cycling of water and waterborne substances (Ahlén et al., 2020), making their water storage and cycling fundamental to estimate a watershed's water balance (Golden et al., 2021; Shook et al., 2021). To understand how and to what extent wetlands can mitigate hydrological processes, two approaches are commonly used: (i) description of individual wetland service at the field scale (e.g., Park et al., 2014) or wetlandscape scale (e.g., Åhlén et al., 2022); (ii) assessment of wetland hydrological services at the regional/watershed scale (Fossey et al., 2016; Wu et al., 2020a, 2020b). However, the former approach only be achieved with field instruments and is mainly used to provide key parameters of wetland processes for model calibration (Fossey and Rousseau, 2016). Recently, several wetland modules have been development and coupled to hydrological (e.g., Soil and Water Assessment Model, HYDROTEL model) to quantify hydrological function of wetlands, particularly the mitigation services on floods and droughts (Evenson et al., 2018; Evenson et al., 2016; Fossey et al., 2015a; Zeng et al., 2020). These wetland hydrological models not only consider the general water budget of a river basin but also consider the perennial and intermittent hydrological interactions between wetlands-to-wetlands and wetlands-to- surrounding landscapes. It is of both scientific and practical interest to project wetland capability in mitigating floods and droughts in response to a changing climate.

Reservoirs redistribute large amounts of surface water, thus altering natural hydrological processes, such as flow range, flood and drought patterns, and basin water balances (Boulange et al., 2021; Chen et al., 2021; Manfreda et al., 2021; Zhao et al., 2016). So far, throughout the world, there are 57, 985 reservoirs registered by the International Commission on Large Dams and their total volume has been reached 14, 602 km^3 (Eriyagama et al., 2020). Such numerous reservoirs and their large storage capacity should not be neglected in water hazard assessment and hydrological projection because of their significant modification on flood and drought patterns (Boulange et al., 2021; Brunner et al., 2021). For that reason, scholars called for the need to integrate reservoirs in model-based impact analysis of flood exposure under climate change (Dang et al., 2020a; Yassin et al., 2019). Therefore, there is a growing need in incorporating reservoir operations into basin hydrologic simulations and predictions.

Despite the well-established knowledge of flow regulation and water storage functions that wetlands and reservoirs can provide in a river basin, most modeling assessments on floods and droughts at the basin scale do not take the two components into account, or give little emphasis on the combined benefits of them (Brunner et al., 2021; Golden et al., 2021). Nor are the hydrological processes associated with these features implicitly included in the calibration of hydrologic models. Recent studies have suggested that disregarding of the wetlands or reservoir operation would add significant error and larger uncertainties to simulate hydrologic processes (Brunner et al., 2021; Ward et al., 2020). Because wetlands are often abundant across many landscapes, making their water storage and cycling fundamental to estimating a watershed's water balance (Rains et al., 2016; Lee et al., 2018). Therefore, missing this component of water balances could potentially lead to disproportionately large model errors (Rajib et al., 2020). Consequently, integrating the wetlands (Fossey et al., 2015a; Golden et al., 2021; Rajib et al., 2020) or reservoir operation (Dang et al., 2020; Yassin et al., 2019; Zhao et al., 2016) alone into watershed-scale hydrologic models may largely minimize uncertainties and improve model performance. Furthermore, on a global scale, most river basins have wetlands and their river flow has or will experience reservoir regulation (Muller, 2019; Schneider et al., 2017), which elicits a thought-provoking concerns: What will be the changes of future floods and droughts under the combined influence of wetlands and reservoirs? Such concern is important because the omission of wetlands and reservoirs can cause the policy-making process to be imprecise at best and ineffective at worst. However, a reservoir operation and wetland services, integrated basin-scale model rarely exist in the literature. Furthermore, although few studies (e.g., Rajib et al. (2020; Chen et al., 2021; Wu et al., 2021) provide insights into modeling and understanding the flow regulation functions provided by wetlands and reservoirs, however, is it still unclear whether the combining of wetlands with reservoir operation can largely reduce the risk of future floods and droughts.

Considering the above-introduced scientific challenges and management deficiencies, we first developed a framework of hydrological modeling coupled with wetland modules and reservoir operation scenarios. We then applied it to a large river basin with abundant wetlands and a large reservoir, the Nenjiang River Basin in northeast China, to address a central question: Can the combining of wetlands with reservoir operation largely reduce the risk of future flood and droughts? The Nejinang River Basin was selected as a case study here because it has abundant wetlands and a large reservoir, and has undergone intensive anthropogenic activities in the past half century, particularly in the increasing agricultural water consumption and conversion of wetlands to agricultural and other land uses. Our framework and results are expected to bring new insights into future floods and droughts and provide a basis for decision-making to curb the growing impacts of unprecedented and future hydrological extreme conditions.

2. Methodology

2.1 Study area and datasets

We conducted this analysis in the Nenjiang River Basin (NRB), a large river basin (291,700 km^2) located in the Northeast China (Fig. 1). Long-term annual average runoff depth and volume from the NRB are 97.4 mm and 22.7 billion m^3. The river basin is located in the middle-high latitudes and can be characterized by a temperate semi-humid continental monsoon climate. Inter-annual differences in temperature and precipitation are large, i.e., disparate hot and cold periods, and uneven dry and wet conditions (Meng et al., 2019). The average annual temperature across the basin ranges between 2.1-4.5°C. The annual total precipitation within the basin fluctuates from 323.1 to 537.6 mm. Precipitation is mainly concentrated during June-September, which accounts for about 85% of the annual precipitation (Li et al., 2014).

The NRB is one of the pivotal wetland areas in China. The basin contains several important wetland conservation areas, among which Zhalong and Nanweng River Wetlands have been designated as a Ramsar Site of International Importance. The wetlands and their contributing drainage areas (see Section 2.2.1 for specific definition) within the subbasins monitored by the ten hydrological stations range from 14 to 23% and from 39 to 56% respectively, demonstrating the large wetland coverage of the NRB and its sub-basins (Table 1). The lower NRB is an important agricultural area of the Songnen Plain, which is one of the three major plains (including the Sanjiang, Songnen and Liaohe Plains) in northeast China. Therefore, understanding potential floods and hydrological droughts under future climate change is crucial for ensuring regional food security and wetland ecological integrity. During the past 60 years, land use and land cover types have drastically changed owing to large-scale development of intensive agriculture and water resources management (Meng et al., 2019). The area of wetlands in the NRB decreased by nearly 23% from 1978 to 2000 (Chen et al., 2021), with only 16.34% remaining today (Table 1), which largely degraded their services (Wu et al., 2021). Along with the reduction in wetland area, the hydrological functions of wetlands in the NRB, such as water storage, flood mitigation and baseflow support, have been considerably reduced (Wu et al., 2021). These wetland services are closely related to flood and drought risks, such as the 1998 mega-flood. In order to effectively deal with the risk of floods and droughts, the Nierji Reservoir was constructed along the mainstream NRB (Fig. 1); it started normal operation in 2006. The drainage area of the reservoir accounts for 22.8% of the NRB. The Nierji Reservoir, located in the upper Nenjiang River (Fig. 1), has flood control and water supply as the primary purposes and hydropower generation and navigation as secondary purposes, thus playing an important role in the distribution of water resources for the lower NRB.

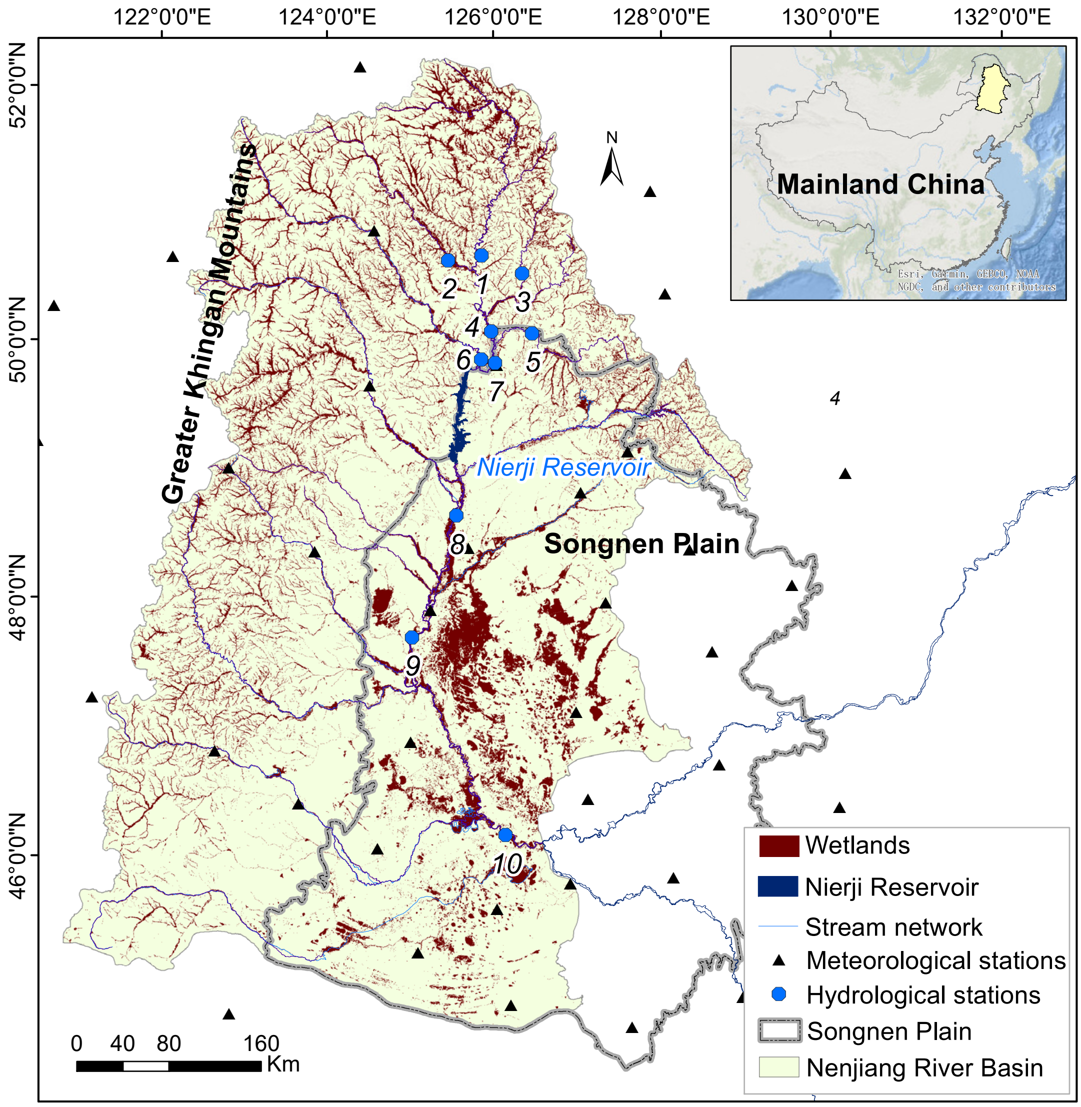

Figure 1. Location of the Nenjiang River Basin and the distribution of wetlands, river networks, Nierji Reservoir, and hydrological and meteorological stations within the basin.

Table 1 The drainage area of the ten hydrological stations used in this study, area ratios of wetlands and their contributing areas to the drainage area of the Nenjiang River Basin, northeast China.

ID	River	Hydrological stations	Drainage area (km^2)	Wetland area ratio (%)	Wetland contribution area ratio (%)
1	Mainstream	Shihuiyao	17205	22.2	54.7

2	Duobukuli River	Guli	5490	16.3	57.1
3	Menlu River	Huolongmen	2151	20.8	50.7
4	Mainstream	Kumotun	32229	20.4	54.3
5	Keluo River	Kehou	7310	23.4	56.2
6	Gan River	Liujiatun	19665	13.2	49.9
7	Mainstream	Nenjiang	61249	18.3	54.1
8	Mainstream	Tongmeng	108029	13.1	47.5
9	Mainstream	Fulaerji	123911	13.7	39.0
10	Mainstream	Dalai	221715	16.3	42.4

The driving datasets used in this study include meteorological data, land-use/land-cover types, soil texture, digital elevation models, drainage network, and observed discharge data. The land-use/land-cover types for 2015 (including wetland types), digital elevation models and digital elevation models with 1 km resolution were obtained from Resource and Environment Science and Data Center (https://www.resdc.cn/). The river network was collected from the Geographical Information Monitoring Cloud Platform (https://www.dsac.cn/DataProduct/Index/30). Historical daily meteorological datasets including precipitation and air temperature for the period 1963-2020 were obtained from 39 weather stations administered by the National Meteorological Information Centre of China (http://data.cma.cn) and 49 weather stations in the upper NRB (Fig. 1) administered by the Nenjiang Nierji Hydraulic and Hydropower Ltd. Company (http://www.cnnej.cn). The hydrological data from ten hydrological stations (see Fig.1 and Table 1) were obtained from the Songliao Water Resources Commission, Ministry of Water Resources (http://www.slwr.gov.cn/), with the time series extending from 1963 to 2020.

In this study, we drove hydrological model using five GCM projections (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) under three Socioeconomic Pathways (SSPs) from the latest CMIP6 (O'Neill et al., 2016). Each of these specific SSPs represents a development model that includes a corresponding combination of development characteristics and influences. The three SSPs that were used herein include SSP126, SSP370 and SSP585, which represent potential futures characterized by green-fueled growth (van Vuuren et al., 2017), high inequality between the countries (O'Neill et al., 2016) and fossil-fueled growth (Kriegler et al., 2017), respectively. We chose the five GCM projections because their high resolution (0.25°) and wide application in previous studies. Given the data requirements of the hydrological model, we downloaded the SSP outputs including daily precipitation, maximum and minimum temperature. We then performed bias correction and spatial downscaling of the SSP outputs. The bias correction of SSP outputs was carried out using the CMhyd software (https://swat.tamu.edu/software/cmhyd), in which the widely used Delta Change method in the CMhyd software was used. Delta Change bias-corrects the projected SSP outputs based on the historical statistics and thus conserves the linear spatial-, temporal-, and multi-variable dependence structure in the future climate (Bosshard et al., 2011; Maraun, 2016; Moore et al., 2008; Shafeeque and Luo, 2021). The ANUSPLIN package developed by (Hutchinson and Xu, 2004) was then used to uniformly downscale the output from five bias-corrected GCMs to a resolution of 1-km based on the DEM. Following previous studies (Hagemann and Jacob, 2007; Zhao et al., 2021), the multi-model ensemble means (M_{GCM}) of the daily precipitation, and the maximum and minimum temperature under the SSPs scenarios were then obtained to diminish the uncertainties inherited in a single GCM. MEM was calculated using an equally-weighted average:

$$M_{GCM} = \frac{1}{N}\sum_{i=1}^{N} P_i \tag{1}$$

where M_{GCM} is the multi-model ensemble means, N is the number of ensemble members (5 in this study); and P_{i} is the projected climate data of an ensemble member. In this study, the M_{GCM} of five GCMs were used to drive hydrological modeling.

2.2. Framework of hydrological modeling coupled with wetland modules and reservoir operation scenarios

We developed a spatially-explicit hydrological modeling framework that considers wetland hydrological processes and reservoir operations based on HYDROTEL model and reservoir simulation algorithms (Fig.2). Such a modeling framework was based on a distributed coupling implementation at watershed scale from upstream to downstream. Observed streamflow from seven hydrological stations (see hydrological stations 1-7 in Fig.1) located upstream of the Nierji Reservoir and three hydrological stations (see hydrological stations 8-10 in Fig.1) installed at downstream of the reservoir, respectively, were used to calibrate the HYDROTEL model. For the upstream Nierji Reservoir, we calibrated the HYDROTEL model against observed streamflow of seven hydrological stations with consideration of wetlands (i.e., hydrologic-wetlands model). Among the seven hydrological stations, the Nenjiang Station is located at the end of the upstream, where the simulated streamflow was taken as the inflow of the reservoir. We then computed the reservoir outflow using the simulated inflow, estimated lateral inflow and reservoir simulation algorithms (see Section 2.2.2), thereby integrating reservoir operation into the hydrologic-wetlands model to build a hydrologic-wetlands-reservoir model. Based on the calibrated hydrologic-wetlands-reservoir model, we simulated the outflow of the reservoir (Sect. 2.2.2), which was used as the input streamflow for downstream model calibration. For the downstream reservoir, we calibrated the hydrologic-wetlands-reservoir model against observed streamflow of Tongmeng, Fulaerji and Dalai Stations. Based on this framework, the simulation of basin hydrological processes coupled with basin scale wetlands and reservoir operations were realized.

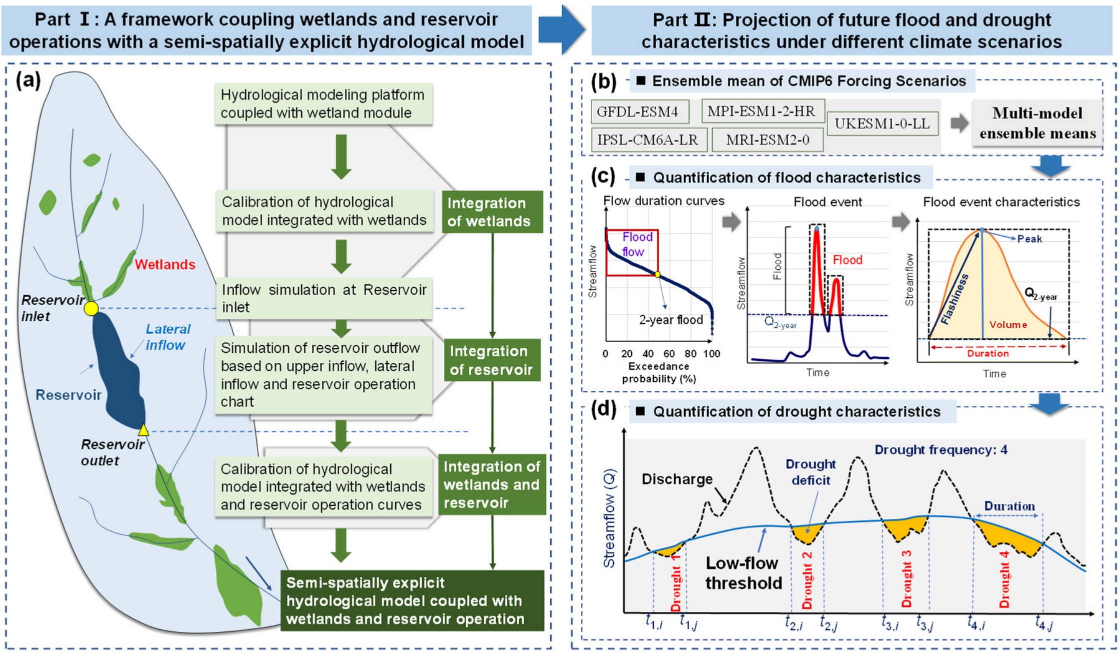

Figure 2. Framework for projecting future flood and hydrological droughts based on a semi-spatially

integrating wetlands and reservoir operation into a hydrological model: (a) a framework coupling wetlands and reservoir operations with a semi-spatially explicit hydrological model; (b) multi-model ensemble means from five GCM projections used for driving modeling framework; (c) methodology for determining a flood threshold, defining flood events, and extracting flood characteristics, and (d) a sequence of runs with examples of drought deficit, duration, and frequency.

2.2.1. A semi-distributed hydrological model platform coupled with wetland modules

The PHYSITEL/HYDROTEL modeling platform coupled with two wetland modules (isolated and riparian wetlands) (Fossey et al., 2015b), has been used to quantify hydrological function of wetlands (e.g., Fossey and Rousseau, 2016; Blanchette et al., 2019; Wu et al., 2023). PHYSITEL is a Geographic Information System based pre-processing platform for managing hydrological modeling data (Noël et al., 2014; Rousseau et al., 2011). Using general basin data (a digital elevation model, vectorized river network and lacustrine water bodies, and raster-based land use and soil matrix distribution maps), PHYSITEL divides the basin into more detailed hydrological response units, i.e., relatively homogeneous hydrological units (RHHUs) (Fortin et al., 2001). The RHHUs were defined using the algorithm for delineating and extracting hillslopes proposed by (Noël et al., 2014). The hillslopes with same characteristics (e.g., physical geography and hydrological response) were then aggregated within each RHHUs. In addition, the PHYSITEL platform distinguishes wetlands from other land-use types, and then classifies both isolated and riparian wetlands based on an adjacency threshold (i.e., percentage of pixels in contact) between the wetlands and the river network (Fossey et al., 2015b). Specifically, if more than adjacency threshold (e.g., 1%) of wetland pixels are connected to the river network, they are considered as pixels of a riparian wetlands; otherwise, they are referred to as isolated wetlands. It subsequently generates data pertaining to isolated and riparian wetlands and their contributing areas. The contributing area of wetlands is defined as the sum of the area of all wetland RHHUs and upland RHHUs within their immediate catchment areas situated along active fill-spill pathways to the stream network (Evenson et al., 2016). The PHYSITEL platform uses the concept of a hydrologically equivalent wetland (HEW) proposed by (Wang et al., 2008) to integrate isolated and riparian wetlands at the RHHU scale. These typically large RHHUs contain large wetland complexes consisting of various wetland categories such as bogs, fens, marshes, and forested peatlands. After defining the hydrological and wetland parameters, PHYSITEL can directly export the database as part of the input data to HYDROTEL; these data can also be used for other watershed hydrological models.

HYDROTEL is a physically-based and semi-distributed hydrological model (Bouda et al., 2014; Bouda et al., 2012; Turcotte et al., 2007) that requires wetland parameter data, land-use type maps, soil texture maps, meteorological data (e.g., daily temperature and precipitation) and daily flows as input. The HYDROTEL model couples the hydrological processes associated with both isolated and riparian wetlands (i.e., the isolated and riparian wetlands modules) at the RHHU scale and calculates the wetland water balance with respect to the surface area of the HEW, contribution area and RHHU. Specifically, for isolated wetlands, the hydrogeological processes are integrated in the vertical water budget (Fortin et al., 2001) at the RHHU scale. For riparian wetlands, the water balance is partially integrated in the vertical water budget of an RHHU and directly connected to the associated river segment via the kinematic wave equation (Beven, 1981). Based on this, the isolated wetlands modules can realize the vertical water balance processes of hillslope wetlands with land surface runoff processes, while the riparian wetlands modules can realize the interaction of hydrological processes between riparian wetlands and river channels. It should be mentioned that the HEW concept developed by Wang et al (2008) served as the foundation for the integration of riparian wetlands and isolated wetlands into the modeling framework. This concept contends that the features of one HEW (also known as an isolated wetland or riparian wetland) are equivalent to the sum of the characteristics of each wetland inside a RHHU (which could either be hill slopes or elementary sub-watersheds related to one river segment). The following premises apply to this concept: (i) only one isolated and/or riparian HEW per RHHU; (ii) one HEW can be fully integrated within a RHHU; (iii) isolated HEW parameters must be numerically integrated; and (iv) riparian HEW parameters must be numerically integrated and spatially integrated (i.e., located in a specific location on the river segment). Therefore, isolated wetlands and riparian wetlands do not appear to have direct hydrological connection within a RHHU. However, isolated wetlands also have hydrological interactions with riparian wetlands through vertical water balance processes and fill-spill processes (Fossey et al., 2015). Nevertheless, such representations provide a modelling approach that can simulate water balances at the wetland scale while considering their interactions with the surrounding environment (contributing drainage area and hydrological connectivity) (Fossey et al., 2015b). But the hydrological interactions between riparian wetlands and isolated wetlands are not considerate in this study.

2.2.2. Simulation of Nierji reservoir operations

Based on the simulated runoff at the inlet (the Nenjiang Station), lateral inflow, and the schemes of reservoir operation, we estimated the reservoir outflow using the ResSimOpt-Matlab software package developed by (Dobson et al., 2019) was used to simulate the operation of the Nierji Reservoir. ResSimOpt-Matlab contains three algorithms for reservoir simulation. The first algorithm considers a case when we want to always release a constant amount over the simulation period. This constant amount is the target release that would cover all downstream demand for water, for instance for domestic use and/or irrigation. The second consider a case when we still want to release the target demand but we would also like to (1) apply some hedging (that is, an intentional reduction of the release - even if it would still be feasible to release the target demand - aimed at saving more water and thus facing smaller deficits at later time); and (2) attenuate downstream peak flows for flood control purpose. The third algorithm, which was used in this study, dynamizes the operation rules. A dynamic operation schemes was used in this study to achieve the simulation. Specifically, following (Dobson et al., 2019) and according to actual hydrological conditions, we defined two seasons: the wet season (from June to September) when the risk of flooding is higher and we wanted to release the target demand and provide some storage space for flood control, and the dry season when the risk of flooding is low and the main objective is to sustain ecological baseflows. The required input data to the algorithm includes reservoir inflow (Q_{in}) (m^3/s), the minimum environmental flow (E_{env}), (m^3/s) initial storage (S_{o}) (m^3), minimum (S_{min}) and maximum (S_{max}) storage (m^3), estimated evaporative losses (E_{vap}) (mm), released discharge (Q_{out}) (m^3/s) and the simulation time-step length (day). Based on the required data, we performed reservoir simulation by implementing the mass balance equation at each simulation time step t:

$$\begin{cases} S_{(t+1)} = S_{(t)} + Q_{in(t)} - E_{vap(t)} - Q_{out(t)} \quad or \quad S_{(t)} + Q_{in(t)} - E_{\min(t)} - E_{vap(t)} \\ 0 \le S_{(t)} \le S_{\max} \\ 0 \le R_{(t)} \le \min\left(S_{(t)} + Q_{in(t)} - E_{\min(t)} - E_{vap(t)}, Q_{\max}\right) \end{cases} \tag{2}$$

where S_t is the reservoir storage at time t. S_t and Q_{out} are constrained by the design specifications and operation rules of a reservoir. Specifically, S_t cannot exceed the reservoir capacity S_{max}, while Q_{out} (m^3/s) is constrained by the operation schemes and capacity of the turbines Q_{max} (m^3/s). The excess water, if any, is spilled:

$$Q_{spill(t)} = \max\left(S_{(t)} + Q_{in(t)} - E_{vap(t)} - Q_{out(t)}\right) \tag{3}$$

Based on this, the dynamic Q_{out} can be represented using the equation (1) and (2).

We collected information on the reservoir operation including reservoir capacity, control water levels, outflow, the storage-area-water level relationship, the tailwater level-discharge relationship, and the maximum release, along with other data necessary to estimate the outflow. The reservoir inflow is the simulated streamflow at the Nengjiang Hydrological Station, which is at the inlet of the Nierji Reservoir. The minimum storage and maximum storage are 4.9 billion m^3 and 86.1 billion m^3, respectively. Based on the available data for the study area, the Karrufa method (Kharrufa, 1985) was used to estimate daily evaporative losses from the reservoir. We convert days to seconds so that it would correspond to the flow data. During the wet season, the actual operation schemes for the Nierji Reservoir are as follows: The pre- and post-flood periods are June 1-20 and September 6-30, respectively, with a flood limited water level of 216.0 m; The main flood period is from June 21 to August 25, and the reasonable flood limited water level ranges from 213.4 m to 216.0 m and can be gradually increased. During the dry season, the environmental flow was defined as 25.3% of the daily streamflow during the dry season over the years based on the designed operating curves of the reservoir operation chart.

2.2.3. Model calibration, validation and performance assessment

For all above scenarios, we calibrated the HYDROTEL model against observed streamflow at a daily time step over 8 years, including a 1-year warm-up (2010.10.01-2011.09.30) and a 7-year calibration (2011.10.01-2018.09.30) periods. The same model settings (i.e., key parameters, simulation periods, fitting algorithm, and objective function, etc.) were used for the calibration processes under the both presence and absence scenarios. Following (Arsenault et al., 2018), the model was calibrated using full-time observations without additional validation, as the former allows for more reliable parameters and maximizes the accuracy of the model. The dynamically dimensioned search algorithm (DDS) developed by (Tolson and Shoemaker, 2007) was used to calibrate the 13 most sensitive parameters of the model as proposed by (Foulon et al., 2018). Based on the maximizing of Kling-Gupta efficiency (KGE) (Gupta et al., 2009), automatic calibrations using DDS were carried out utilizing 10 optimization trials (250 sets of parameters per trial). Then, the best set of parameter values out the 10 trials were selected following (Foulon et al., 2018). The KGE was chosen as the objective function because previous research has shown that it can improve flow variability estimates when compared to the NSE (Fowler et al., 2018; Garcia et al., 2017).

It should be noted that we calibrated the HYDROTEL model against observed streamflow under with and without wetland scenarios. For the without wetland scenarios are defined as follows: When the wetland modules are turned off in HYDROTEL, wetland areas are not removed, but they are treated as the land cover of saturated soils. Such a saturated soil is fixed and does not participate in hydrological processes such as water yielding and runoff routing, and thus their explicit storage properties are not accounted for in the modeling. This is a basic assumption that has been used in several studies using models such as SWAT (Liu et al., 2008; Wang et al., 2008; Evenson et al., 2015), Mike 11 (Ahmed, 2014) and HYDROTEL (Fossey et al., 2016; Fossey and Rousseau, 2016a, b; Wu et al., 2019, 2020a, 2021), to quantify the hydrologic services provided by wetlands (flood mitigation, flow regulation and baseflow support etc.).

To determine whether coupling the wetland module and the reservoir can improve the model performance, we compared (1) the efficiency of the model in simulating daily flow processes; and (2) the capability of the model to simulate floods and hydrological droughts in the presence or absence of the wetlands and the combination of wetlands and reservoir. Following the recommendations of (N. Moriasi et al., 2007) and (Moriasi et al., 2015), four performance criteria were selected to assess model performance with regards to simulated daily flows with and without the presence of the wetland modules and reservoir operation, namely the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), Correlation Coefficient (CC), the root-mean square error (RMSE) and the percent bias (Pbias). We used multiple performance criteria because it may be unreliable to rely on a single objective function to determine whether the model performs well (Fowler et al., 2018; Pool et al., 2018; Seibert et al., 2018). It should be noted that although NSE as an objective function has shortcomings in model calibration, it can still provide an important reference for the evaluation of simulation results as a performance criterion as suggested by Moriasi et al. (2007, 2015). In addition, we compared model performance considering daily hydrograph changes. Furthermore, flood and drought features were extracted (see Sect. 2.4.2 and 2.4.3) and used to discern whether, and to what extent, the coupled wetland modules and reservoir simulations could improve the model's ability to simulate droughts and floods.

2.3. Projection of future flood and drought characteristics under different climate scenarios

The calibrated hydrologic-wetland-reservoir model was used to simulate streamflow driven by multi-model ensemble means from the latest CMIP6 and to derive drought and flood characteristics. The flood and drought characteristics were then compared against historical periods to discern how future hydrological extremes will be changed under the influence of wetlands and reservoirs (see Part II in Fig.2).

The future simulated streamflow at the Nenjiang and Dalai hydrological stations driven by the ensemble mean of bias-corrected CMIP6 Forcing Scenarios (see Section 2.1) were selected to derive drought and flood characteristics. The Nenjiang Station was chosen because it is located at the outlet to (mouth of) the upper NRB and the inlet to the Nierji Reservoir, whose flood and drought patterns are mainly driven by wetlands and climate change. Moreover, changes in drought and flood characteristics of the Nenjiang Station are critical to the operation of the reservoir immediately lower reach. The Dalai Station, located at the outlet of the entire NRB, was used as a proxy to characterize future flood and drought evolution for the whole basin under the combined influence of the wetlands and reservoir. Using the calibrated hydrologic-wetland-reservoir model, we carried out the simulation of hydrological processes for the historical period (1971-2020) and under the constraints of the SSP126, SSP370 and

SSP585 scenarios. We then extracted flood and hydrological drought characteristic indices from the simulations to conduct a comparative analysis of their temporal evolution for the near-future (2026-2050), mid-century (2051-2075) and end-century (2076-2100). The purpose of subdividing the analysis into three time periods was to compare whether, or to what extent, flood and drought characteristics increase or decrease for different future time periods as compared to a historical period.

In this study, we characterized floods in terms of four indices consisting of flood peak, flood volume, duration, and flashiness (Fig. 2c). The 2-year flood streamflow was used as a threshold for defining flood events, as it has been often used as a substitute of the threshold for bankfull discharge in previous studies (Cheng et al., 2013; Wu et al., 2020; Xu et al., 2019). Daily streamflows that were greater than the 2-year flood threshold were considered as flood flows. Flood flows occurring on multiple consecutive days were considered as a single flood event. The flood indices, i.e., flood peak, volume, duration, and flashiness were derived with respect to event hydrographs. Flood volume is the cumulative flow from the initial to the end of a flood event with respect to the 2-year flood streamflow level, and represents the flood intensity for different flood events (Wang et al., 2015). The annual total flood volume is the total amount of water associated with all flood events during a water year. We calculated the annual total flood volume based on flood duration and the average amount of streamflow per event in a water year. Flood duration varies for different floods and is, therefore, an important characteristic of a flood event. We summed the flood duration of each event in a water year to obtain the annual flood days. In addition, the annual maximum peak flow was derived from the daily flows to investigate changes in the characteristics of extreme floods. We extracted the 2-year flood threshold for a hydrological station based on the streamflow-exceedance probability curve. Flashiness is a measure of flood severity and is defined as the difference between the peak discharge and action stage discharge normalized by the flooding rise time (Saharia et al., 2017).

We characterized hydrological drought characteristics using four indices consisting of the number of droughts, annual drought days, drought duration and deficit (Fig. 2d). A threshold method was used to define hydrological drought events because it can determine the start and end of a hydrological drought event, which allows further assessment of drought characteristics, such as frequency, duration, and intensity of a drought event (Cammalleri et al., 2017). It is based on defining a flow threshold (discharge, Q, m^3/s), below which a hydrological drought event is considered to occur (also known as a low flow spell). A daily variable threshold, defined as an exceedance probability of the 365 daily flow duration curves was used to derive drought events from daily streamflow records (Fleig et al., 2006; Hisdal and Tallaksen, 2003). For rivers with perennial flow, relatively low streamflows ranging from Q_{70} to Q_{95} have been used as a reasonable threshold (Tallaksen and van Lanen, 2004; Zelenhasić and Salvai, 1987). In this study, we chose the 90th percentile (Q_{90}-n) streamflow as the daily threshold, which also used as the threshold for identifying droughts in future climate change scenarios. The Q_{90}-n of all days was determined based on the observed historical daily streamflow.

To enable the comparison across different modeling scenarios (i.e., historical scenarios and future climate change scenarios), we derived drought days, deficit, duration, and number from identified hydrological drought events to characterize their patterns. Drought volume deficit was calculated by subtracting daily streamflow from the threshold level (Q_{90}-n) during a drought event, and it presents the severity of the drought compared to the normal streamflow conditions. Drought duration was the cumulative number of days during a drought event, i.e., the number of days from the beginning to the end of the drought. Annual drought days were then the cumulative drought duration in a year. The number of droughts is expressed by the number of drought events during a study period. In addition, the annual minimum flows of each water year were extracted and used to determine the model's ability to simulate very low flows. The drought volume deficit was calculated as:

$$D_k = \sum_{t_i}^{t_j} \left(Q_{90,t} - Q_n \right) \cdot 60 \cdot 60 \cdot 24 \tag{4}$$

where D_k is the drought volume deficit (m^3) of a drought event k at a hydrological station and $t_{\mathrm{k,i}}$ and $t_{\mathrm{k,j}}$ are the initial and final time steps of the run, respectively. Q_n is the daily streamflow of n day of the year (1-365). The corresponding drought duration is computed as t_j-t_i +1.

For hydrological drought events that occur relatively close in time, the inter-event time method introduced by (Zelenhasić and Salvai, 1987) was used to separate events. This method defines a minimum gap period, t_c, and assumes that if the inter-event time (t_j-t_i+1) < t_c, then the consecutive events are interdependent and merged. In this case, the total drought deficit volume is the sum of the individual deficit values, and the event duration is the so-called real drought duration (sum of the single event duration, excluding excess periods). For this study, t_c was set equal to 7 days as recommended by (Cammalleri et al., 2017).

3. Results

3.1 Model performance on daily streamflow and hydrography

Fig. 3 depicts model performances for calibration results in the presence or absence of the wetlands and the combination of wetlands and reservoir at the ten hydrological stations in the NRB. In the case of whether the wetlands were present or absent, the simulated daily streamflow results all achieved the acceptable performance criteria (NSE > 0.5 and Pbias ≤±15%) suggested by (Moriasi, 2007) and (Moriasi et al., 2015) at the Shihuiyao, Guli, Huolengmen, Kumotun, Kehou, Liujiatun and Kumotun stations. However, compared with the calibrated results of the model without wetlands, the simulation efficiency under with wetland scenario improved to varying degrees. Specifically, the relative improvement (i.e., the relative change) of KGE values at Shihuiyao, Guli, Huolengmen, Kumotun, Kehou, Liujiatun, Kumotun, Tongmeng, Fulaerji and Dalai were 44%, 24%, 2%, 6%, 5%, 3%, 4%, 46%, 47% and 67%, respectively. In addition, the NSE and CC values were generally larger in the presence of wetlands than those in the absence of wetlands, and the RMSE and Pbias values are generally smaller than those in the absence of wetlands, showing that integrating wetlands into the hydrological model can slightly improve the model calibration results.

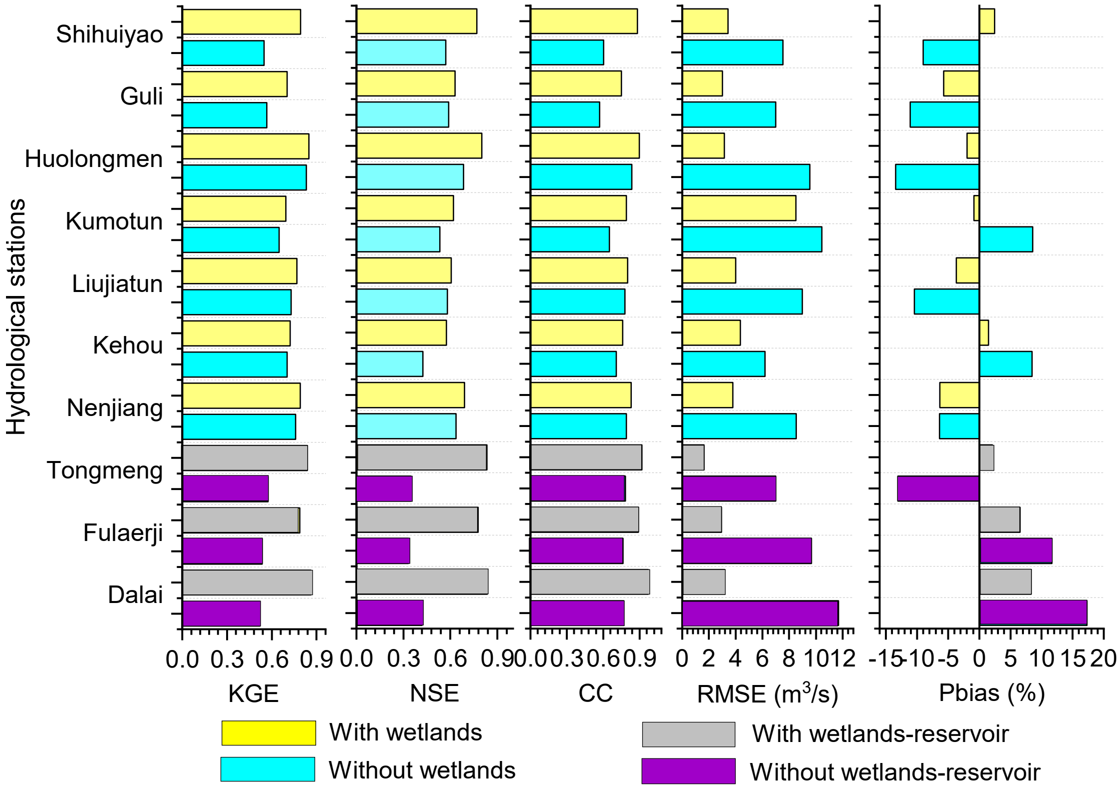

Figure 3. Model performances for calibration results for the with/without wetlands and reservoir scenarios at the ten hydrological stations in the Nenjiang River Basin. The KGE, NSE, CC, KGE, RMSE and Pbias refer to Kling-Gupta efficiency, Nash-Sutcliffe efficiency, Correlation Coefficient, Root Mean Square Error, and the percentage bias, respectively.

For the lower reaches of Nierji Reservoir (i.e., the Tongmeng, Fulaerji and Dalai stations, representing inclusion of the wetlands and the reservoir operation into hydrological modeling), the NSE and CC values were greatly higher and RMSE and Pbias values were substantially lower when the wetlands and reservoir were considered, in comparison to the case without wetlands-reservoir (Fig. 3). In fact, in the scenario without wetlands-reservoir, the simulated daily streamflow results failed the acceptable performance criteria (NSE > 0.5 and Pbias ≤±15% as suggested by Moriasi (2007) and Moriasi et al. (2015). In addition, the simulated daily streamflow in the no-wetland and no wetlands-reservoir scenarios both overestimated the high flows, especially those during the flood periods; during the low flow periods, the low flows were underestimated (Please refer to Fig. S1 in Supplementary materials).

Further, the simulated hydrographs under the wetland and wetlands-reservoir scenario were in much better agreement with the hydrographs of observed streamflow, especially during floods and the low-flow period (Please refer to Fig. S2 in Supplementary materials). These results indicate that inclusion of the wetlands and the operation of reservoirs can greatly improve model capacity to replicate basic hydrograph characteristics and capture hydrological extremes (e.g., high and low flows).

3.2 Model capacity to replicate flood and drought characteristics

The simulated annual minimum streamflow for the wetlands/wetlands-reservoir scenarios were, in general, slightly overestimated or approximately equivalent to the observations compared to the scenarios that did not include the wetlands/wetlands-reservoir (Fig. 4 and 5). However, the simulation results without wetlands clearly underestimated minimum streamflow (Fig. 4a), distinctly overestimated annual drought days (Fig. 4b) and drought deficit (Fig. 4c) compared to the simulation results for the scenario with wetlands at the ten hydrological stations. In addition, the simulated annual maximum peak flow (Fig. 5a), flood days (Fig. 5b) and volume under (Fig. 5c) the with/without wetland scenarios are, in general, approximately comparable to observations at the Guli, Kumotun, Kehou, Liujiatun and Nenjiang hydrological stations (Fig. S4). Specifically, for the upstream Nierji Reservoir, it is apparent that if wetlands are not considered, the number of annual flood days will be overestimated, whereas flood volume will be substantially underestimate at the Huoloengmen Station. For the lower reach of Nierji Reservoir, lack of integrating the wetlands and reservoir into the simulation can lead to a notable underestimation of annual flood days, and a substantial overestimation of the annual maximum peak flow and flood volume. These results demonstrate that integrating wetlands and the combination of wetlands and the reservoir into the model can help improve model performance with regards to flow during the calibration process, and enhances the model’s capability of depicting streamflow processes as well as capturing flood and drought characteristics.

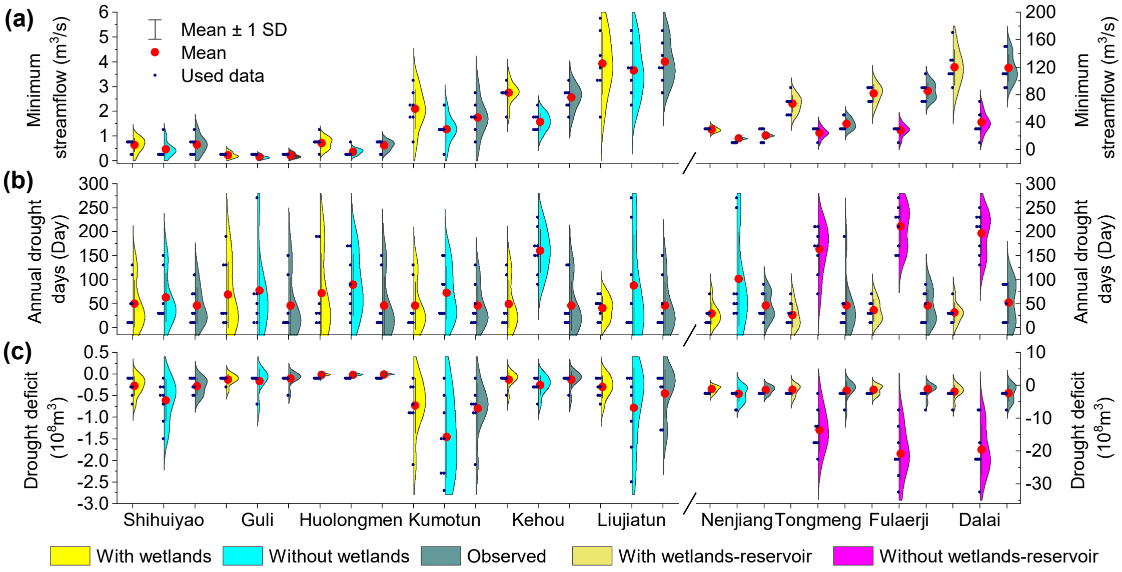

Figure 4. Annual minimum streamflow, drought days and deficit derived from observed records and simulated streamflow at ten hydrological stations in the Nenjiang River Basin. The with and without wetlands/wetlands-reservoir refers to streamflow simulation based on the presence or absence of wetlands/wetlands-reservoir.

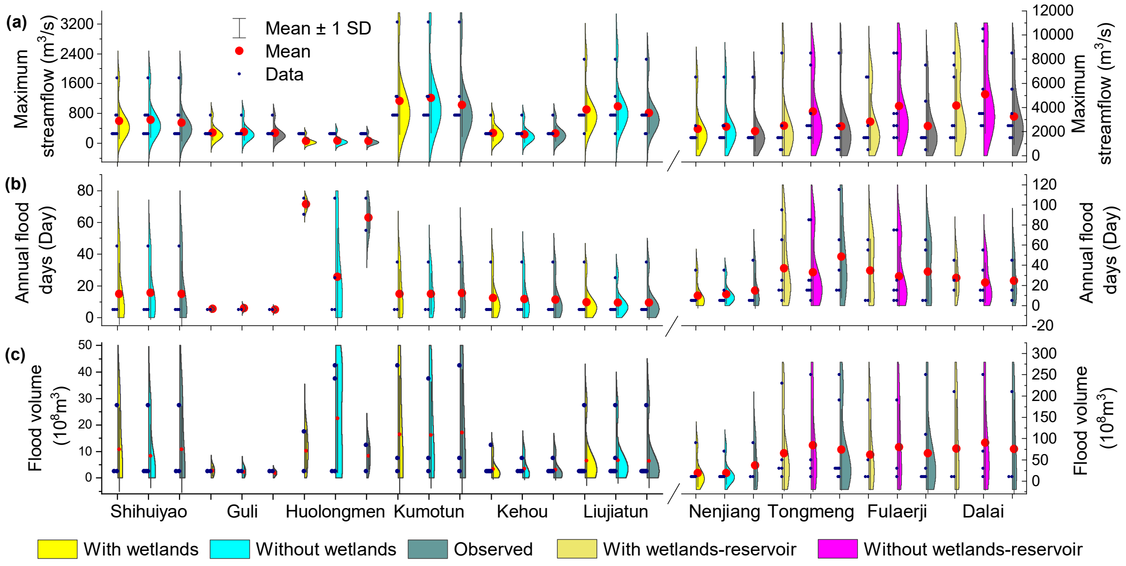

Figure 5. Annual maximum peak flow, flood days and volume derived from observed records and simulated streamflow at ten hydrological stations in the Nenjiang River Basin. The with and without wetlands/wetlands-reservoir refers to streamflow simulation based on the presence or absence of wetlands/wetlands-reservoir.

3.3 Projection of future floods

A comparison between historical and projected flood characteristics at the Nenjiang Station (representing inclusion of wetlands into hydrological modeling) shows an overall increase in flood risks in the upper NRB. The flood duration, peak flow, volume and flashiness generally exhibit larger fluctuations in most of the scenarios (different SSPs and three periods as shown in Fig. S3 and Table S1). In addition, the averaged increase in flood duration, peak flow, volume and flashiness ranges from 0.9 to 1.2%, from 16 to 33%, from 8 to 111% and from 26 to 55%, respectively (Fig.6). Specifically, the extreme values of flood duration are much larger during the near future and end-century under the SSP126 scenario, the end-century under the SSP370 scenario and the mid- and end-century under the SSP585 scenario (Fig. 6a). Apart from a slight decrease during the near future and mid-century under the SSP585 scenario, peak flow will increase through time in the SSP126, SSP370 and SSP585 scenarios (Fig. 6b). Simultaneously, the flood volume will experience the greatest increase of 68% during the near future under the SSP585 scenario, followed by a 22% increase during the mid-century under the SSP126 scenario (Fig. 6c). In terms of flashiness, the floods will be more severe under the constrains inherent in the SSP126 and SSP585 scenarios and less severe given the conditions in the SSP370 scenario, as compared to the historical period (Fig. 6d).

It should be noted that the flood duration, peak flow, volume and flashiness can decrease in the future, as compared to the historical period (Fig.6). For example, flood duration will slightly decrease during the near future and end-century under the SSP126 scenario, largely decrease during the near future under the SSP585 scenario, respectively. Under the SSP585 scenario, the flood peak flow will experience a decrease with the percentage change values of 15% during the mid-century and the volume will reduce 26% during near future. In addition, future flood flashiness will be reduced by 49% and 28% in the near future and the end-century under the SSP370 scenario respectively, and by 21% at mid-century under the SSP585 scenario.

The changes in the historical and future flood duration, peak flow, volume and flashiness at the Dalai Station (representing inclusion of downstream wetlands and reservoir operation into hydrological modeling) is shown in Fig.S3 and Fig.4 e-h. Similar to the Nenjiang station, the flood duration, peak flow, volume and flashiness at the Dalai station also exhibit divergent change trends across different SSPs and three periods, as compared to the historical periods. Flood duration is projected to increase largely in the near-future period for the SSP126 scenario, both in the mid-century and end-century for the SSP370 scenario (Fig.6e). The peak flow will broadly decrease for the SSP126 scenario, and increase for the SSP370 and 585 scenarios (Fig.6f). Flood volume shows divergent change trends under the three SSPs (Fig.4g). For the SSP126 scenario, flood volume will grow in the near-future and diminish in the mid- and end-century. Flood volume will decrease in the near-future, increase in the mid-century, and increase slightly in the end-century under the SSP370 scenario. However, following an apparent reduction in the near-future, flood volume is anticipated to have no discernible change trend in the mid-century and a clear increasing trend in the end-century for the SSP585 scenarios. Flashiness will be reduced in the near future and will increase in the mid-century and end-century for the SSP126 scenario (Fig.6h). For the SSP370 scenario, flashiness will increase substantially with percentage changes of 204% in the near-future, Moreover, for the SSP585 scenario, flashiness will experience a considerable increase with percentage changes of 109% in the end-century respectively. In terms of the averaged percentage change values, the peak flow and flood flashiness will overall increase; the flood volume will reduce in the near future and rise in the mid-century and end-century; and flood duration will experience a slight increase to a minor decrease.

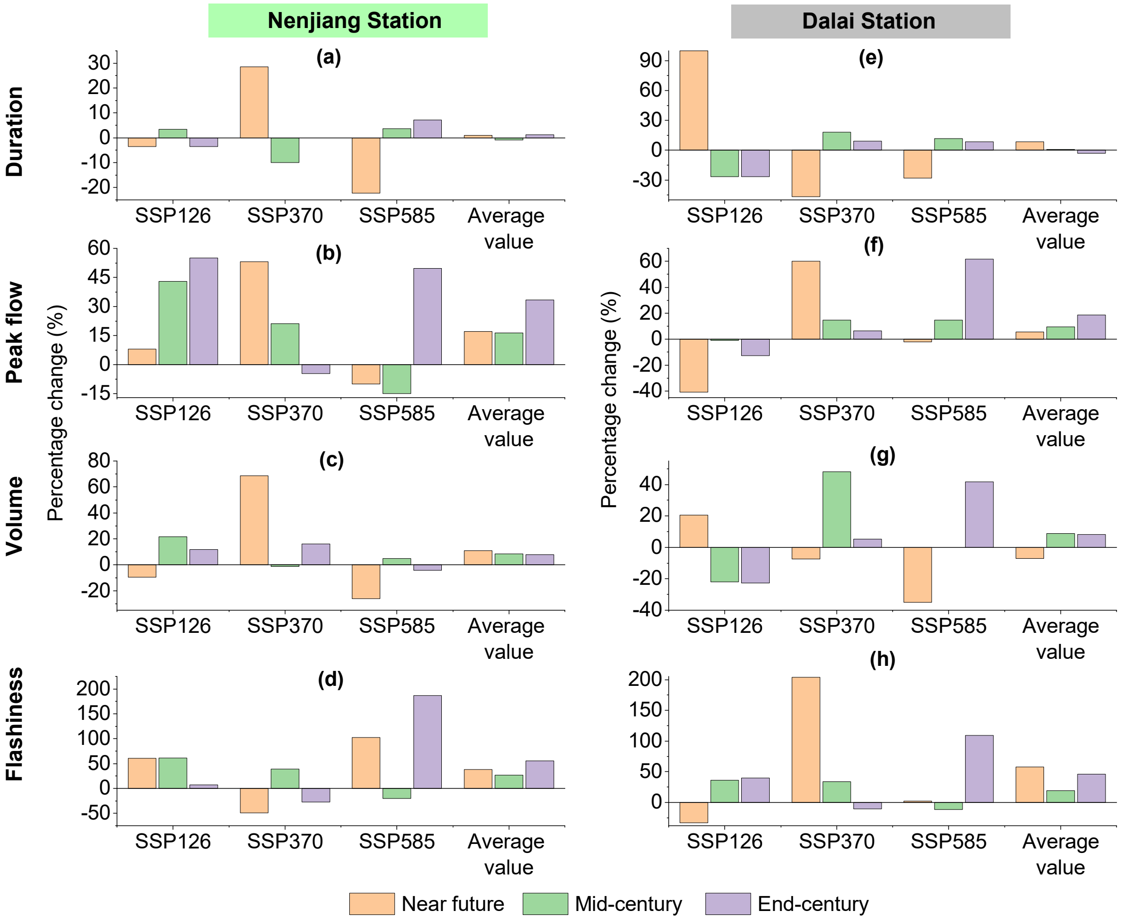

Figure 6. Projected percentage changes (relative to historical period during 1971-2020) in flood duration, peak flow, volume and flashiness at the Nenjiang (the left column) and Dalai (the right column) Station. The near-future, mid-century and end-century refer to the 2026-2050, 2051-2075 and 2076-2100 under the Socioeconomic Pathways (SSP) 126, SSP370 and SSP585 scenarios. The average values were calculated based on the projected percentage changes in the three SSP scenarios.

To further investigate flood risks in the NRB under future climate change, the flood duration-peak flow-flow volume relationships at the Nenjiang and Dalai stations for the SSPs were compared to those of the historical period and analyzed (Fig. 7a-c). Compared with historical flood risk, extreme flood events with longer and larger volumes will occur more frequently at the Nenjiang Station for the SSP126 and SSP585 scenarios (Fig. 7a and 7c). It is noteworthy that the flood peak-volume-duration relationships between the historical period and SSP370 scenario are approximate equal, with the exception that longer duration and larger volume floods will occur during the end-century period (Fig. 5b). In addition, extreme flood events will occur mainly in the near-future for the SSP126 scenario and during the mid- and end-century for the SSP585 scenario. Moreover, for the SSP370 and SSP585 scenarios, floods will become shorter in duration, and possess a lower peak flow and flood volume in the near-future. Thus, the upper NRB will experience more severe flood events to a large extent under most future climate change.

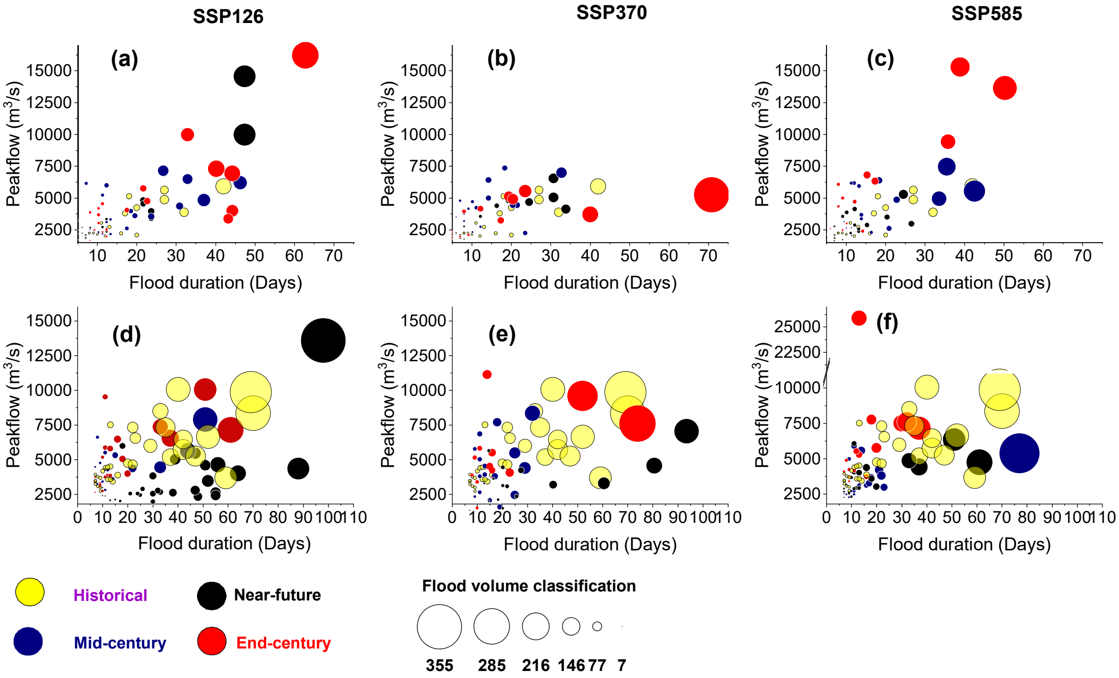

Figure 7. Historical and projected flood duration-peak flow-volume relationships at the Nenjiang (the first row) and Dalai (the second row) Station. The historical period refers to 1971-2020 and the near-future, mid-century and end-century refer to the 2026-2050, 2051-2075 and 2076-2100 under the Socioeconomic Pathways (SSP) 126 (the first column), SSP370 (the second column) and SSP585 (the

third column) scenarios.

The duration-peak flow-volume relationships of extreme flood events under future climate change scenarios are closer to those of the historical period at the Dalai Station than at the Nenjiang Station (Fig. 7d-f). For the three future SSPs, the flood events with longer duration, higher peak flows or larger volume than the historical period will occurred infrequently, and the duration, flood volume and peak flow of the other shorter and lower magnitude flood events will generally be attenuated. However, very extreme flood events are projected to occur in the near-future under the conditions of scenario SSP126 (Fig. 7d). Likewise, future climate change under the SSP370 scenario and 585 scenarios are projected to result in longer flood events in the near-future and mid-century, respectively (Fig. 7e and 7f). Therefore, the future flood risk can be effectively attenuated to a great extent by the combined influence of wetlands and reservoir. However, the fact that extreme flood events that will still occur in the future.

3.4. Prediction of future hydrological droughts

The comparison between historical and projected hydrological drought indices shows that the risks of hydrological droughts will be increased to some extent under future climate change for both Nenjiang and Dalai stations. Specifically, in addition to a reduction in the number of droughts and annual drought days in the near future for the SSP126 scenario, the number of droughts (Fig. 8a and 8e), annual drought days (Fig. 8b and 8f) and drought deficit (Fig. 8d and 8h) will overall increase in other periods for three scenarios (Fig. S4 and Table S2). It is clear that the number of droughts will be equivalent to the historical period in the mid-century and end-century for the SSP126 scenario and in the mid-century for the SSP585 scenario. For all other scenarios, the number of droughts will increase. In terms of the mean percentage change values, there is a general trend towards an increase in the number of droughts and annual drought days, which indicate that future drought events will be more frequent and there will be more days per year affected by drought. The predicted extreme values show that the future duration of drought at Nengjiang station may shorter than the historical period, but the degree of shortening presented in different SSP scenarios varies (Fig. 8c and 8g). For the Dalai station, the longest drought durations would all exceed historical extremes in the end-century for the SSP126 and SSP585 scenario, and in the near future for the SSP370 scenario. The percentage change values display that drought duration will be reduced at the Nenjiang station and will be extended at the Dalai station for all the SSP scenarios. Drought deficit at the Dalai station will increase by 39%, 36% and 36% and in the near future, mid-century and end-century. For the Dalai station, drought deficit will increase further in the three periods with 39%, 36% and 36%, respectively.

A comparison of the percentage change values between the Nengjiang and Dalai stations shows that, apart from a reduction of the number of drought events, the risk of drought to be experienced at Dalai is considerably stronger than at Nengjiang. Specifically, the percentage change in the annual drought days, drought duration and deficit will increase from 85-97% to 89-134%, from -17- -17% to 21%, and from 36-39% to 171-247%, respectively.

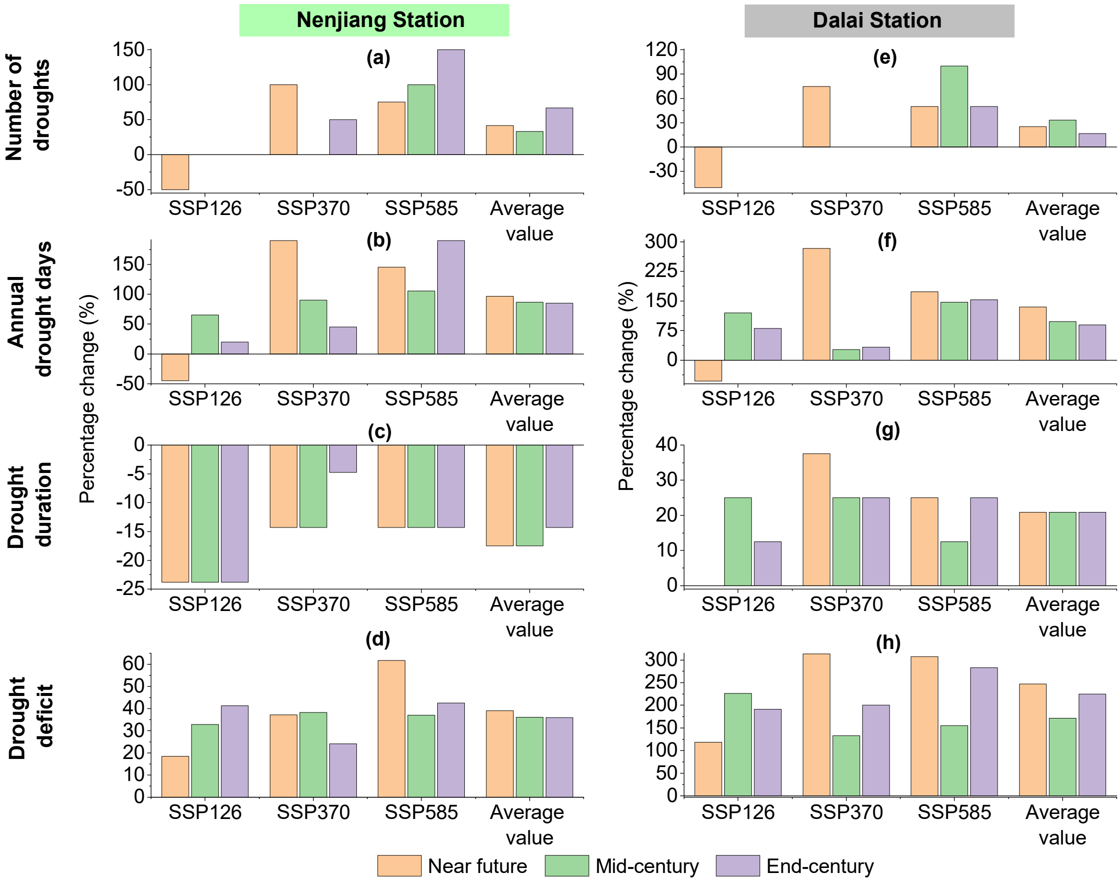

Figure 8. Projected percentage changes (relative to historical period during 1971-2020) in hydrological

drought characteristics at the Nenjiang (the left column) and Dalai (the right column) Station. The near-future, mid-century and end-century refer to the 2026-2050, 2051-2075 and 2076-2100 under the Socioeconomic Pathways (SSP) 126, SSP370 and SSP585 scenarios. The average values were calculated based on the projected percentage changes in the three SSP scenarios.

To further analyze the temporal evolution of droughts in the Nengjiang River Basin under future climate change, drought events were classified into four types in terms of duration and deficit, i.e., short-term light droughts, long-term light droughts, short-term severe droughts, and long-term severe droughts (see Fig. 9 for details). This four-part classification was then used to compare and analyze the changes in the temporal characteristics of drought events under the different SSP scenarios. Similar to the drought characteristics during the historic historical period, the majority of drought events for the SSP126, SSP370 and SSP585 scenarios are short-term light droughts (Fig. 9a-c), i.e., the upper NRB will still be dominated by short-term light droughts under future climate change. However, these droughts will be slightly aggravated and marginally longer. In addition, long-term light droughts will occur rarely under the conditions inherent in scenarios SSP126 (Fig. 9a) and SSP370 (Fig. 9b), and occur relative frequently in the SSP585 scenario (Fig. 9c). However, compared with the historical period, the overall number of long-term light droughts will largely decrease, but the deficit will increase slightly under future climate change. In addition, short-term severe droughts will increase substantially, along with their deficit. The number of long-term severe droughts for the SSP126 scenario is approximately the same as in the past, but the duration will be substantially reduced. For scenarios SSP370 and SSP585, the number of long-term severe droughts will increase more than during the historical period, but the duration will be markedly less, and the deficit will be reduced to some extent. In terms of the different the sub-periods, severe droughts in the upper NRB will be more severe during the near-future and end-century periods, and relatively less severe in the mid-century period in comparison to the historical period. However, overall, the droughts will be of shorter duration and characterized by an increased deficit under future climates.

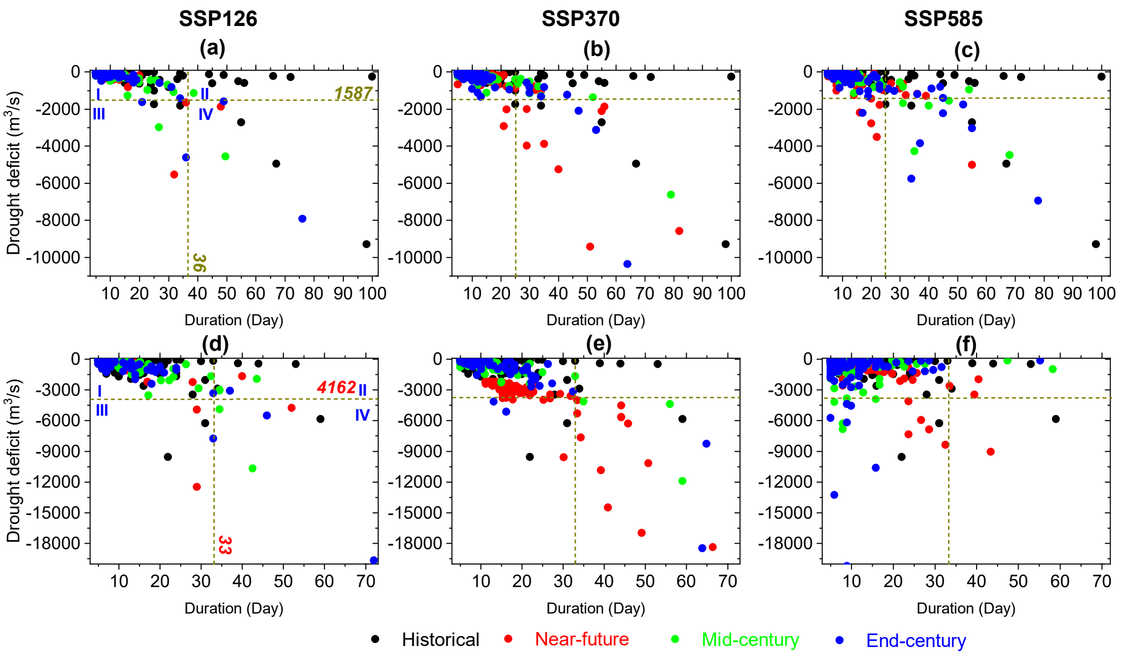

Figure 9. Historical and projected duration-deficit relationship of each hydrological droughts at the Nenjiang (the first row) and Dalai (the second row) Station. The historical period refers to 1971-2020 and the near-future, mid-century and end-century refer to the 2026-2050, 2051-2075 and 2076-2100 under the Socioeconomic Pathways (SSP) 126 (the first column), SSP370 (the second column) and SSP585 (the third column). The dark yellow lines in the horizontal and vertical directions refer the 95% threshold lines for drought deficit and duration values, respectively. I, II, III and IV refer to short-term light droughts, long-term light droughts, short-term severe droughts, and long-term severe droughts, respectively.

Droughts brought about by future climate change at the Dalai Station located along the lower reaches of the NRB will continue to be dominated by short-term slight droughts (Fig. 9d-f). For the SSP126 scenario, the duration and deficit of the short-term slight droughts will be approximately the same as those during historical times (Fig. 9d). However, the duration and deficit of short-term slight droughts will increase given the conditions specified in the SSP370 (Fig. 9e) and SSP585 (Fig. 9f) scenarios. The duration of short-term slight droughts will increase the most for scenario SSP370. In addition, under all three SSP scenarios, long-term slight droughts will, in general, be reduced. In fact, under the SSP370 scenario, long-term slight droughts will not occur. The number of short-term severe droughts will generally tend to increase, with the most pronounced increase under the SSP585 scenario, followed by the SSP370 scenario. A slight increase will occur under the SSP126 scenario. However, long-term severe droughts will increase substantially under the SSP126 and SSP370 scenarios. In particular, under the SSP370 scenario, the duration of long-term severe droughts will be exceptionally prolonged, and the severity will be extraordinarily increased, indicating that the risk of droughts of long duration and with a severe deficit will climb abnormally in some year. For example, under the conditions set by the SSP370 scenario, the deficit of long-term severe droughts will reach -18,169 m^3 and -18,457 m^3 during the near-future and end-century periods. For the SSP585 scenario, long-term severe drought will occur only once in the near-future, which is equivalent to the historical period. These results indicate that the risk of future hydrologic droughts along the lower NRB will further increase even under the combined influence of reservoirs and wetlands.

4. Discussion

4.1. Integrating wetlands and reservoir operation into basin hydrologic modeling and basin water management

A series of studies have shown that the simulation and prediction of floods and droughts faces many challenges, such as the scarcity of hydrometeorological driven data (Foulon et al., 2018), model errors (Golden et al., 2021; Smakhtin, 2001; Staudinger et al., 2011) and anthropogenic disturbances (e.g., reservoir operation) (Brunner, 2021; Brunner et al., 2021). In this study, we developed a spatially explicit hydrological model that considers wetland hydrological processes and reservoir operations through coupling a distributed hydrological modeling platform with wetland modules and reservoir simulation algorithms. We found that coupling wetland alone or coupling wetlands and reservoir with hydrological model can improve model calibration results and model performance of capturing flood and drought characteristics in a large river basin. Such model performance improvement can provide important information for developing downstream water resources management. Previous studies have shown that climate change is further exacerbating the risk of hydrological extremes, leading to an expanding of flood and drought affected area (Diffenbaugh et al., 2015; e.g., Hirabayashi et al., 2013; Wang et al., 2021), which increase the complexity of accurate prediction and the challenge for effective mitigation. Give that, projecting flood and drought risks in response to a changing climate requires robust hydrologic models that take into account the important factors within a watershed that can largely influence basin hydrological processes (Golden et al., 2021).Therefore, in basins that coexist with high-coverage wetlands and multiple reservoirs, it is necessary to integrate wetlands and reservoir operation into basin hydrological simulation, thus providing practical support for extreme hydrological risk mitigation and water resource management under a changing climate.

Although our developed framework demonstrates good modeling results, uncertainties could exist in the assessment. Aspects such as the accuracy and error of the input data (Lobligeois et al., 2014), the choice of the objective function (Fowler et al., 2018), the length of the period considered during calibration (Arsenault et al., 2018), and the model structure (Melsen et al., 2019) can all affect the performance of a model to replicate streamflow, thus impacting flood and drought predictions and water management under future climate change. In addition, due to a lack of wetlands water balance monitoring data, this study only used river station data (which only considered the cumulative hydrologic effect of upstream wetlands) for model calibration. Therefore, there are ongoing efforts to obtain sufficient observations on wetland area dynamics and evapotranspiration, water depth and volume, soil water content and actual observations to better calibrate/validate watershed hydrological models, which are expected to better provide key parameters for further improving the model's capacity to capture flood and drought patterns and better serve basin water management. In addition, the several SPPs employed to drive the simulation framework, including SSP126, SSP370, and SSP585 scenarios, can introduce uncertainty into future flood and drought risk projections. Because of the internal variability and uncertainties inherent in the existing climate models (Qing et al., 2020; Martel et al., 2022), the projection findings under different scenarios were inconsistent, creating a challenge for pro-active management and mitigation decisions. Despite the climate models' recognized flaws and uncertainties, the general concordance between models and observations over many regions suggests some improved confidence in their utility for understanding and mitigating future drought and climate change (Cook et al., 2020).

4.2. The combining mitigation efficiency of wetlands and reservoir operation

The relative changes (compared with historical periods) of future flood and drought indices (Fig. 6 and 8), duration-peak flow-volume relationships (Fig. 7) and duration-deficit relationship (Fig. 9) differ between the Nenjiang and Dalai stations under the same SSP scenario or in the same period, indicating that reservoirs and downstream wetlands can modify the continuous propagation of upstream flood and hydrological drought risks to the downstream. First, reservoirs and downstream wetlands can help to reduce the risks of future floods and droughts to some extent, namely partially reduce flood peak flow and flashiness, and decrease the number of droughts, annual drought days and drought deficit. Second, reservoirs and downstream wetlands cannot completely eliminate flood and drought risks. Because the flood duration and volume will overall increase at the Dalai station, especially that the extreme floods will be more frequent in the future (Fig.7). Further, in addition to the number of droughts, the percentage change values of the annual drought days, drought duration and deficit relative change at the Dalai Station are greater than those of Nenjiang Station (Fig.8). This imply that the mitigation effects on hydrological droughts is minimal. Such findings suggest that future climate change will lead to an increase in the risk of hydrologic failure of existing reservoir and wetlands, thus posing large challenges for future socio-and eco-hydrological systems in the downstream NRB.

Wetlands are typically viewed as green infrastructures and reservoirs are generally regarded as important gray infrastructures. Although our study showed that the combining of reservoirs and wetlands does not completely eliminate the risk of future hydrological extremes, they continue to play an important role that cannot be ignored. The reservoir's inherent constraints are one factor contributing to this likelihood of hydrological failure. This is because reservoirs only control floods and droughts that occur downstream of them, limiting their effects to the regional scale (Brunner, 2021). The regulation becomes less effective with distance increased due to "dilutions" effect caused by inflows from downstream tributaries (Guo et al., 2012). Reservoirs cannot, however, play a considerable role in basins where tributaries exist downstream, particularly those sub-basins prone to drought and flooding. From these perspectives, widely distributed wetlands can provide a complementary and vital function by providing biological function and hydrological regulation in regions where reservoirs are unable to have an impact. On the other hand, the limited capacity of existing wetlands to regulate hydrology increases the risk of hydrological failure to some extent. This is because, compared with the historical period, the existing wetlands in the NRB have been seriously degraded, such as the weakening of the connectivity between riparian wetlands and the river channel, and the increased fragmentation of wetlands, among other changes (Chen et al., 2021). These degraded wetlands cannot play an effective role in mitigating floods and droughts under future climate change.

4.3. Implications for flood and drought risk management under climate change

This modeling study predicts higher flood and drought risks in the NRB under the combined influence of wetlands and reservoirs. This could impose a great challenge to the operation of the Nierji Reservoir dam, i.e., to its effective operation for flood mitigation and drought alleviation. To curb the flood and drought risks caused by future climate change in the NRB, it is urgent to improve the water regulation capacity of the lower NRB. Although the Nierji Reservoir, as previously argued, plays an important role in reducing floods and droughts, the potential for extreme hydrological events in the future necessitate the application of various combinations of measures with different scales of implementation (i.e., hybrid measures). We insist that the first remedial measure to be undertaken should be the implementation of wetland restoration and protection projects, because studies have demonstrated that wetland coverage and their spatial pattern can affect both basin physical conditions and human decision-making attitudes toward risk (Gómez-Baggethun et al., 2019; Javaheri and Babbar-Sebens, 2014; Martinez-Martinez et al., 2014; Zedler and Kercher, 2005). Given that the spatial location of wetlands within a river basin is also important in determining the efficiency of their mitigation services (Gourevitch et al., 2020; Li et al., 2021; Zhang and Song, 2014), optimization of wetland spatial patterns should be considered and can be carried out to further enhance the role of wetlands in flood and drought defense.

In our view, the second important remedial measure that should be implemented is to improve the existing reservoir operation schemes based on accurate hydrological forecasting. This requires, on one hand, coupling of wetlands with hydrological processes and models to improve the simulation accuracy of the upstream incoming water (i.e., runoff from the Nenjiang Station) to provide scientific support for reservoir operation decisions. Concomitantly, it is necessary to modify the existing schemes for optimal reservoir operation to improve the system's capacity to deal with extreme flood and drought risks. Because the percentage increase in flood (Fig. 6) and drought indicators (Fig. 8) demonstrated that the existing reservoir operation schemes are not effective in mitigating the risks associated with future climate change-induced floods and droughts. Therefore, we need to re-examine and evaluate the flood and drought risks in the NRB under future climate change and propose optimal operation schemes that can maximize the reduction of flood and drought risks by the Nierji Reservoir. Traditionally, the water level of a reservoir should be maintained at the designed flood limited water level during the flood season, which does not consider river flow forecast. (Ding et al., 2015) analyzed a concept that provides a dynamic control of the maximum allowed water level during the flood season, for the Nierji Reservoir dam. A reasonable approach to tackle this issue could be to considerate forecast uncertainty and acceptable flood risk to minimize the total loss caused by flood and drought. Further modeling studies with multi-objective optimization algorithm can help identify an optimum reservoir operation for best economic and ecological outcomes.

5. Conclusions

This study projected future flood and drought risks by considering the combined impacts of wetlands and reservoirs. To achieve this, we developed a hydrological modeling framework coupled wetlands and reservoir operations and then applied it in a case study involving a 297,000-km^2 large river basin in northeast China. With this framework, we found that coupling wetlands and reservoir operations can slightly increase model calibration results and efficiently improve model capacity to capture both flood and hydrological drought characteristics in a river basin. The upper NRB will experience more severe flood and hydrological droughts and can impose a great challenge to the effective operation of downstream reservoir under the predicted future climate change scenarios. The risk of future floods and hydrologic droughts along the lower NRB will further increase even under the combined influence of reservoirs and wetlands. These results demonstrated that the risk of floods and droughts will overall increase further under future climate change even under the combined influence of reservoirs and wetlands, showing the urgency to implement wetland restoration and develop accurate forecasting systems. To fully understand how wetland and reservoir operations may be influential and maintain an acceptable level of risk, it is therefore necessary to consider an optimization of wetland spatial patterns and reservoir operations simultaneously, thus achieving a collaborative optimization management to maximum basin resilience to floods and hydrological droughts. Further, the effects of combining NBS (e.g., wetlands) with traditional engineering solutions (e.g., reservoir) should both be useful and necessary in the future for management decisions.

Data Availability

The data used in this study are openly available for research purposes. The five GCM outputs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-L) used in this study are publically available and were provided by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (https://esg.pik-potsdam.de/search/isimip/). The CMhyd software is available at https://swat.tamu.edu/software/cmhyd. The land-use/land-cover types, soil texture, and digital elevation model for China can be downloaded from https://www.resdc.cn/. Data from the 88 weather stations administered by National Meteorological Information Centre of China can be download at http://data.cma.cn.

Author contribution

Yanfeng Wu: Conceptualization, Writing, Data analysis, Methodology, Software. **Jingxuan Sun**: Formal analysis, Investigation, Data analysis and Plotting. **Boting Hu**: Software, Visualization, Data analysis. **Y. Jun Xu**: Writing - review &editing. **Alain N. Rousseau**: Writing - review & editing. **Guangxin Zhang**: Conceptualization, Supervision, review &editing.

Competing interests

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.

Acknowledgments

We are grateful to Jan Seibert for his valuable comments on the manuscript. The authors express their gratitude to the three anonymous reviewers for their constructive comments and suggestions that have helped improve the paper. We thank Anna Feist-Polner, Lorena Grabowski, Polina Shvedko and Sarah Buchmann for their efforts in the processing of the manuscript.

Financial support

This work was supported by the National Natural Science Foundation of China (42101051), the Postdoctoral Science Foundation of China (2021M693155), the Strategic Priority Research Program of the Chinese Academy of Sciences, China (XDA28020501, XDA28020105), and The National Key Research and Development Program of China (2021YFC3200203). During preparation of this manuscript, YJX received a grant from U.S. Department of Agriculture Hatch Fund (project number, LAB94459).

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