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Simulation of hydrological processes in the Zhalong Wetland within a river basin, Northeast China

X. Q. Feng[1,2], G. X. Zhang[1], and Y. Jun Xu[3]

[1]Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, 130012, China
[2]Liaoning Province Hydrology and Water Resources Survey Bureau, Shenyang, 110003, China
[3]School of Renewable Natural Resources, Louisiana State University and LSU Agricultural Center, Baton Rouge, LA 70803, USA

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Correspondence to: G. X. Zhang (zhgx@neigae.ac.cn)

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Abstract

Zhalong National Nature Preserve is a large wetland reserve on the Songnen Plain in Northeast China. Wetlands in the preserve play a key role in maintaining regional ecosystem function and integrity. Global climate change and intensified anthropogenic activities in the region have raised great concerns over the change of natural flow regime, wetland degradation and losses. In this study, two key hydrologic components in the preserve, open water area and storage, as well as their variations during the period 1985–2006 were investigated with a spatially-distributed hydrologic modeling system, SWAT. A wetland module was incorporated into the SWAT model to represent hydrological linkages between the wetland and adjacent upland areas. The modified modeling system was calibrated with streamflow measurements from 1987 to 1989, in a Nash efficiency coefficient (E_{ns}) of 0.86, and was validated for the period 2005–2006, in an E_{ns} of 0.66. In the past 20 yr, open water area in the Zhalong Wetland fluctuated from approximately 200 km^2 to 1145 km^2 with a rapid decreasing trend through the early 2000s. Consequently, open water storage in the preserve decreased largely, especially in the dry seasons. The situation changed following the implementation of a river diversion in 2001. Overall, the modeling yielded plausible estimates of hydrologic changes in this large wetland reserve, building a foundation for assessing ecological water requirements and developing strategies and plans for water resources management within the river basin.

1 Introduction

Wetlands cover 6 % of the Earth's land surface and are important ecosystems. Hydrological regimes and water resources in the wetlands around the world have been greatly altered by human activities and global climate change, which has raised great concerns from the scientific communities, general public, and government agencies (Burkett and Kusler, 2000; Acreman et al., 2009; Milzow et al., 2010; Moradkhani et al.,

HESSD

9, 14035–14063, 2012

2010). The Zhalong Wetland, a 2100-km^2 wetland preserve designated as one of the Wetlands of International Importance by the Ramsar Convention, plays an important role in maintaining the ecosystem balance within the Songnen Plain in Northeast China (Yin et al., 2006). Since the1950s, precipitation and riverine inflow in the area have declined, resulting in the change of average open surface water depth in the Zhalong Wetland from about 0.75 m in September 1998 to less than 0.05 m in April 2001 (Tong et al., 2012). Consequently, the change has caused degradation and loss of many wetlands in the Zhalong Wetland preserve (Han et al., 2007). In 2001, the Chinese government launched an "ecological water diversion" project to bring water from the Nenjiang River into the Zhalong Wetland. However, it is not clear when and how much water should be diverted. A good understanding of hydrological variability in the Zhalong Wetland is needed to develop effective management strategies and plans.

Hydrology is a key factor driving wetland ecosystem functions and processes. Information on hydrologic characteristics is therefore fundamental for effective ecosystem restoration, which demands knowledge of wetland's geomorphological, biological, physical and chemical characteristics (Mitsch and Gosselink, 2000). In the Zhalong Wetland, field monitoring of long-term hydrologic conditions does not exist and spatial coherence between open water surface and wetland water storage is unknown. On the other hand, collection of such data across the vast wetland preserve will be time-consuming and costly. Hydrological modeling provides an alternative means to understanding wetland hydrological processes of this area under the influence from human activities and climate changes.

In their study conducted in the North Dakota Maple River and Wile Rice River watersheds in the United States, Padmanabhan and Bengtson (2001) applied the HEC-1 model (USACE, 1982) to assess the influence of wetlands on flooding. Vining (2002) incorporated a wetland hydrology subroutine into the PRMS model (Carey and Simon, 1984) to simulate the hydrological processes and the water stored in the wetlands of the Starkweather Coulee subbasin from 1981 to 1998. Bradley (2002) used a model, which is developed using MODFLOW, to simulate the annual water table of a floodplain wetland. Wang et al. (2010) modified the wetland module in SWAT (Arnold et al., 1998) to simulate the artificial water input to the QingDianWa depression. Wang et al. (2008) incorporated wetlands into the SWAT model using a "Hydrologic Equivalent Wetland (HEW)" concept and simulated the streamflow in the upper portion of the Otter Tail River watershed with abundant wetlands. In these studies, the wetlands were aggregated as a subbasin or a Hydrologic Response Unit (HRU), and were deemed as flow diversions, synthetic wetlands or hydrologic equivalent wetlands. The simulation results demonstrated that the aggregation on a HRU level using the HEW concept was a useful approach.

This study utilized this approach, taking into account of flow exchanges between wetlands and river channels, and modified the wetland module in the SWAT model to simulate hydrological processes of the Zhalong Wetland. Using the simulated streamflow, we established the hydrological connectivity between watershed drainage areas and wetlands, and analyzed the wetland hydrological responses to watershed hydrological processes. Through building a GIS framework in a form conducive to spatial analysis on a sub-watershed scale, the modeling system provides the basis for future assessment of ecological water requirements and effective river water diversion for the entire Zhalong Wetland area.

2 Zhalong Wetland

2.1 Description of the study area

The Zhalong Wetland is located on the west Songnen Plain, in the lower reaches of the Wuyuer and Shuangyang Rivers, Northeast China (Fig. 1). Covering an area of about 2100 km^2 the Zhalong Wetland is the largest national nature reserve in Northeast China. Marsh, lake and paddy field are the main wetland types in Zhalong, with marshes occupying 80 %–90 % of the entire area (Han et al., 2007). These wetlands are important to the well-being of a number of wildlife species, especially endangered crane and waterfowl species. For conservation management, the Zhalong Wetland is divided into a central zone, a buffer zone and an experimental zone based on their ecological and environmental functionalities.

The topography of the area is very flat in the south, gentle to slightly rolling in the center, and somewhat more rolling in the north. The average elevation of this area is approximate 144 m above sea level. Soils in the Zhalong Wetland are dominated by swamp soil (45 %), meadow soil (46 %) and aeolian sandy soil (6 %). The study area contains four different vegetation communities, among which reed marsh covers 80~90 percent of the total area with thousands of wetlands scattering across the landscape.

Climate of the Zhalong Wetland is characterized by a temperate, continental monsoon climate with occasional extremes of temperature and precipitation. Average monthly temperatures range from −19.5 °C in January to 23.0 °C in July with an annual mean of 3.9 °C. Annual mean temperature showed a significant increasing trend ($Z_c = 4.4$) from 1951 to 2010, especially in the spring season (Feng et al., 2011). Average annual precipitation is about 411 mm, of which about 85 percent occurs during the months from June to September. Annual precipitation had an insignificant decreasing trend ($Z_c = -0.06$) over the past 50 yr (Feng and Zhang, 2010). During 1999–2002, average annual precipitation decreased to about 350 mm. Multi-annual means evaporation from water surface and evapotranspiration from reed are 1280 mm and 897 mm, respectively. Annual streamflow of the study area decreased since 1970s, affected by the climate change and human activities (Feng and Zhang, 2010).

2.2 Hydrological characteristics of the Zhalong Wetland

Hydrological characteristics of the Zhalong Wetland have been well documented (Liu and Xu, 2006; Zhou et al., 2008; Xu et al., 2008; Wang et al., 2006). In this paper, some relative hydrological processes are presented. Precipitation in the area is the main source sustaining the wetlands. In addition to precipitation input, the Zhalong Wetland receives inflow from the upstream Wuyuer River as well as diverted water from the Nenjiang River. Quantity of the inflow from river diversion is highly variable affected by management decisions, for instance, with no supply during 1989–2000. Up to 2008, a total of 931.9 million cubic meters of external water resource have been brought to the Zhalong Wetland through the Nenjiang River diversion project since the spring of 2001. Flow of the Wuyuer River that naturally feeds the Zhalong Wetland is also regulated by water management measures in the basin. The river enters into the wetland area at Long'anqiao station, with a variable velocity ranging from 0.01 to 0.39 $m s^{-1}$ and a variable stream width of 4–28 m, which affects wetland conditions in the area. Channels in the wetlands are flanked by vegetation (reeds and sedges), which may retain and store the water flows, and there are free exchanges between channels and surrounding wetlands. Channels in the study area are not developed especially in the lower reach where the channels lose their continuity and integrity, and take the form of often disconnected stretches with variable width and length.

Pedologically, much of the Zhalong Wetland is gleization mire. The upper portion of gleization mire is a sod layer that consists of plants roots and residues. This layer has few mineral particles, high porosity, and a sponge-like texture with high saturated water content and available water capacity. These wetlands act as spongy reservoirs capable of absorbing water during the rainy seasons and releasing it slowly during the dry seasons (Krecek and Haigh, 2006). According to previous studies (Wang and Zhang, 2007; Xu et al., 2008), groundwater are mainly recharged by river and surface water. The substrates of the wetlands have higher viscosity and low permeability (typically 0.5 $mm d^{-1}$), which makes the exchange between surface water and groundwater slow. Surface water flow is also slow due to the flat topography and surface storage. These characteristics determine the important hydrological functions of conveyance, storage and retention of the wetlands.

HESSD
9, 14035–14063, 2012

3 Materials and methods

3.1 Data acquisition

High resolution Digital Elevation Model (DEM) is the basic data for simulation of hydrological processes, which provides topographic information for the delineation of subbasins and extraction of the channel network. We created a 30 m spatial resolution DEM using 3229 elevation points extracted from 1 : 10 000 topographic maps. The minimal elevation interval of these points is 0.1 m, which satisfies the resolution needed in the plain area. Due to the flat terrain in the Zhalong Wetland, water flow disperses after entering wetlands, with variable flow velocity and direction, and the hydrological connectivity in these wetlands is complex. In order to better partition hydrological units, the channel network was created by digitalizing real flow path acquired by field monitoring (Fig. 1). The digitized channel network was then used as the reference surface water drainage network for subbasin delineation.

Climate data requirements for the SWAT model include daily precipitation, daily maximum and minimum temperature, daily relative humidity, daily wind speed and daily solar radiation. These data were collected from the Qiqihaer weather station for the period from 1985 to 2006. Additional daily precipitation data were obtained from three national rainfall gauge stations including Yantongtun, Nianshikeshu, and Long'anqiao (Fig. 1). Spatially-referenced data on land use, soils and hydrologic characteristics of the study area were derived from Landsat™ images (Figs. 2 and 3), soil survey publications, and other sources of digital data and field monitoring. Stream inflow and outflow were obtained from records at the Long'anqiao station (inflow), Shuangyang station (inflow), and Binzhouxian station (outflow). Long'anqiao station and Binzhouxian station had disconnected monitoring periods with available data for 1968–1977 and 1971–1989, respectively, and after 2005 when the two stations resumed monitoring. For the missing period, simulated streamflow of the Long'anqiao station was used as inflow to the Zhalong Wetland, as a previous study (Feng et al., 2010) found that the SWAT model produced reasonable results in simulating the streamflow change in the Wuyuer River Basin.

3.2 Development of the wetland module in SWAT

SWAT is a physically based model developed to continuously simulate hydrological processes over long periods (Arnold et al., 1998). SWAT partitions a watershed or river basin into subbasins that are connected by surface flows (Neitsch et al., 2002). Each subbasin is further divided into one or more hydrological response units (HRU) according to topography, land-use, and soil types. HRU is the basic spatial unit of hydrological simulation and water budget for surface, soil, and ground water. SWAT treats wetlands as water bodies within subbasins (Arnold et al., 2001; Neitsch et al., 2002) and allows one wetland to be modeled for each subbasin, which does not consider the unique hydrological characteristics of wetlands and flow exchanges between wetlands and river channels. Wetland is the dominant land cover type in the study area and serves important hydrological functions. Therefore, we modified the wetland module and incorporated it into SWAT to simulate hydrological processes of the entire study area, including wetlands and other land cover types.

3.2.1 Partition of hydrological units

High resolution DEM and digital river network were used to delineate the boundary of the study area and its subbasins. Watershed and subbasins boundaries were determined by trial and error to ensure that delineated drainage channels closely matched digital channel network. Because of the flat terrain and the difficulty in automatic boundary delineation, actual boundaries of the subbasins in the Zhalong Wetland were defined manually. There was some inconsistence between actual boundary and the boundary defined by DEM, which, however, did not significantly influence the hydrological simulation. Considering the topography, functional regionalization, and channel network, we adjusted the outlets of subbasins in the discretization process to avoid

HESSD
9, 14035–14063, 2012

creating excessive subbasins. Long'anqiao and Shuangyang stations were added to model as outlets of upstream draining watersheds. Wenghai drainage engineering and Nenjiang River diversion project were treated as point source discharges. The entire Zhalong Wetland was subdivided into 14 subbasins, with a size ranging from 75 to 419 km^2. Furthermore, land use and soil data were used to define multiple HRUs for each of the 14 subbasins by specifying thresholds for the land use and soil data, and 24 HRUs were created for the study area (Fig. 1).

3.2.2 Treatment with wetlands

Thousands of marshes and ponds exist in the Zhalong Wetland. However, because of model constraints and the complexity of describing each wetland, these wetlands were aggregated on the HRU basis, and only one wetland per HRU was considered. Therefore, 24 wetlands were modeled within the study area, and each of them represented a combined area and storage of all wetlands within the respective HRU. This large-scale simplification may lead to inaccuracies about the interactions of multiple wetlands, but the simulation of hydrological processes was deemed satisfactory. Individual wetland water area, water depth and storage were determined by the DEM and ArcGIS analyses. It was assumed that surface water depths of the wetlands within the same HRU were identical, mainly attributing to the same weather, topography, land use, soil type and channel characteristics.

The wetland in each HRU is partitioned into two types, an open wetland and a closed wetland. A parameter was used to determine the proportion of the open wetland and closed wetland in the HRU wetland. The open wetland was defined as having an outlet and would spill when the storage of the open wetland exceeded a spillage threshold that was equal to a fraction of total storage without an outlet. The closed wetland was defined as not having an outlet and spill would not occur. All closed wetlands were allowed to increase storage beyond their maximum to simulate the expansion of wetlands areas within the study area. The open and closed wetland gain and lose water in the same manner.

HESSD
9, 14035–14063, 2012

3.2.3 Water balance calculation

The model assumes that precipitation, evapotranspiration, soil seepage, wetland inflow and wetland outflow are the only significant hydrologic inputs and outputs and thus, there are no net contributions of water to wetlands from groundwater. The dynamic water balance equation for the wetland is expressed as:

$$V_T = V_{T-1} + P + I - \mathrm{ET} - S - O \tag{1}$$

where V_{T-1} and V_T are the water storage of the wetland at the beginning and end of the day; P, I, ET, S and O denote precipitation, inflows (including upstream inflow and diverted water), evapotranspiration, soil seepage and channel outflow during the day, respectively. All variables in Eq. (1) have units of m^3.

Water flows were routed into wetlands through drainage channels, using a user-defined fraction of inflows. The remaining water was transported along channels. In order to better analyze the wetland hydrological response to variable inflows; it is essential to couple the watershed model with the wetland module. In this study, the wetland module and watershed hydrological model are coupled through the upstream inflow in order to better represent the actual hydrological processes of the wetlands. Available streamflow were imported into the model by specified input files.

Water was lost from the wetland system through evapotranspiration, groundwater recharge and outflow. Evapotranspiration (ET) is the primary loss of open surface water and soil water. The actual evapotranspiration flux is mainly driven by water availability. In this study, water supply in the wetlands was sufficient and therefore, actual evapotranspiration was approximately equal to potential evapotranspiration. Potential evapotranspiration was calculated with the Penman-Monteith equation. Groundwater recharge was set to vary directly with wetland water depth.

In addition, the open wetland releases water whenever the storage exceeds the spillage threshold, while the closed wetland does not have spillage. Spillage volumes from the open wetland, namely outflows, are directly proportional to the difference between the wetland storage and spillage threshold. Spillage volumes are routed into the channel network. The monthly spillage volume is different, as a result of winter freezing and spring unfreezing. We adopted outflow coefficient to reflect the effects of freezing and unfreezing on the outflow process. When the winter comes in November, the water freezes slowly, and the outflow coefficient decreases. The outflow coefficient is 0 during total freezing periods. The outflow coefficient increases with the increase of temperature and melting of snow and ice after April, and the outflow coefficient equals to 1.0 when snow and ice are totally melt. The wetland outflow is calculated as:

$$O = \begin{cases} 0 & V \leq V_{\text{spill}} \\ \text{Ka} \cdot (V - V_{\text{spill}}) & V \geq V_{\text{spill}} \end{cases} \tag{2}$$

where O is daily outflow of the wetland, Ka is outflow coefficient, V is the water storage of the open wetland, and V_{spill} is the spillage threshold of the open wetland. All the variables except Ka have the same units of m^3.

4 Model calibration and validation

Model runs were made for the years 1985–2006 with input data including DEM, weather parameters, soil parameters, land use/land cover data and the confirmations of wetland-related parameters. Based on the principle of reflecting the actual characteristics of wetlands, the fraction of wetlands on each HRU, fraction of closed wetland an open wetland, surface area of wetlands at maximum water levels, and storage of wetlands when filled to maximum water level were confirmed by ARCGIS spatial analysis of high resolution DEM. Parameters related to physical processes, such as seepage coefficient was determined by the available research results in the Zhalong Wetland. While the open wetland fraction volume at spillage was adjusted during the simulation in order to attain to goodness of fit of wetland module.

Monthly streamflow data from the period 1987–1989 were used for model calibration and monthly streamflow from the period 2005–2006 was used for model validation. SMTMP, SMFMX, TIMP, SURLAG, CH_L1, CH_N1, CH_N2, SOL_AWC, ESCO, CH_K2

HESSD
9, 14035–14063, 2012

were identified as sensitive parameters by sensitive analysis module of ArcSWAT2005 model. These parameters better reflected the underlying surface and hydrological condition, and were sensitive to the simulation of hydrological processes (Vassilios et al., 1998). Considering the special soil physical properties, weather conditions and unique hydraulic characteristics of the wetlands, the calibration was primarily implemented by adjusting 4 watershed-level, 3 subbasin-level, and 3 HRU-level sensitive parameters. Table 1 summarizes the initial values, ranges and calibrated values of these 10 sensitive parameters.

The calibrated parameters of the SWAT model were then used to simulate monthly streamflow for the validation period. The accuracy of simulated values was examined using the Nash efficiency coefficient, E_{ns} (Nash and Sutcliffe, 1970), the coefficient of determination, R^2, and the performance virtue, PV (Eq. 3) (Wang and Melesse, 2005).The performance virtue PV is computed as:

$$\mathrm{PV} = \omega_1 E_{\mathrm{ns}} + \omega_2 \left(1 - \left|D_{\mathrm{v}j}\right|\right) \tag{3}$$

where $D_{\mathrm{v}j}$ is the deviation of volume, ω_1 and ω_2 are the weights reflecting the priorities of simulating the silhouette and volume of the streamflow hydrograph observed at the station. A higher weight indicates a higher priority, and the weights must sum to 1. The deviation of volume ($D_{\mathrm{v}j}$) is computed as:

$$D_{\mathrm{v}j} = \frac{\sum_{i=1}^{n} Q_p - \sum_{i=1}^{n} Q_m}{\sum_{i=1}^{n} Q_m} \times 100\,\% \tag{4}$$

where Q_p and Q_m are the simulated and observed streamflow, respectively, and n is the number of observed data. According to Wang and Melesse (2005), a simulation can be judged to have a "poor" performance when PV is less than 0.60, an "acceptable" performance, when PV is between 0.60 and 0.80, and a "good" performance when PV is greater than 0.80.

HESSD
9, 14035–14063, 2012

5 Results and discussion

5.1 Goodness of fit of the model

Table 2 shows indices of PV, E_{ns}, and R^2 for evaluating the simulated values during the calibration and validation periods. For the calibration period, all the indices indicated that monthly simulated streamflow were consistent with the observed values (PV > 0.80, $E_{ns} > 0.75$). The simulated values reflected some ups and downs of annual streamflow (Fig. 4), and the model had a satisfactory performance in the simulation of streamflow. Whereas, there are certain differences between the simulated and observed streamflow, and the model had an acceptable performance during the validation period (PV > 0.80, $E_{ns} > 0.36$) (Table 2). Overall, the model better simulated the streamflow in the Zhalong Wetland, and would be a useful tool for the hydrological study in data-limited wetlands.

Compared to the calibration period, the poor prediction of the outlet streamflow in the validation period might be attributable to the simplification of complex channel network and the altered outlets, as indicated by the underestimate of outflows. Meanwhile, the limited observed data also decreased the accuracy of simulated values during the validation period.

Xu et al. (2008) conducted a hydrologic modeling study in the Zhalong Wetland using a reservoir approach. Although their study provides information on hydrological cycle processes in the wetlands, the model is semi-distributed model, ignoring the land surface hydrological processes in the preserve. In this study using a distributed hydrological model coupled with a wetland module, we were able to simulate several major components in the surface hydrological processes of Zhalong as discussed below.

5.2 Temporal change of open water area and storage

Simulated monthly water area and storage for the years 1985–2006 are shown in Fig. 5. Simulated monthly water area is the sum of the open and closed wetland area, which is

HESSD
9, 14035–14063, 2012

characterized by permanent or temporary inundation. Comparing the simulated water area with the results of image interpretation (Zhao et al., 2009; Gong et al., 2010; Tong et al., 2008), there were less differences in the water area. Simulated water area increased during wetter periods, but decreased during drier periods, mostly in the spring season. From the intra-annual variation of water area, the maximum monthly water area and storage usually occurred in October, not in August. The intra-annual variation of water area accorded with changing patterns of climatic and hydrological conditions. Because the upstream inflows and runoff generated in the HRUs were stored and cumulated in the wetlands during the summertime, the water area and storage increased and reached their maximums through October. In winter, the water area and storage decreased slightly, this was caused by freezing of water and largely reduced evapotranspiration. Generally, the minimum occur in June accompanying with high temperature, low precipitation, and strong evapotranspiration.

The maximum of water area occurred in October 1985, about 1145 km^2 (50 %) of the study area was inundated. The simulated water storage in the open and closed wetlands reached the maximum of $14 \times 10^8\,m^3$ at the same time. Time synchronization of the maximums reveals that the closed wetland plays a key role in the expansion of open water area and storage. The minimum value of simulated monthly water area happened in June 1996, with the water area of less than 200 km^2, while the minimum water storage of the wetlands occurred in June 2003. The inconsistency in occurrence of the minimum water area and storage was arisen by different relationships between water area and water storage in the individual wetlands. Water area and water storage of wetlands decreased during 1985–2001, which were in agreement with the findings by Gong et al. (2010). Since the 21st century, both open water area and water storage increased, when compared with those in the 1990's, due to the implementation of ecological water-supply engineering.

HESSD
9, 14035–14063, 2012

5.3 Dynamics of outflow in the Zhalong Wetland

The simulated outflows in the Zhalong Wetland from 1985 to 2006 are shown in Fig. 6. The interannual variation of outflow was highly variable, from zero in dry years (e.g. 1999 or 2001) to nearly 200 $m^3 s^{-1}$ in wet years, which was in agreement with the feature of the results simulated by Xu et al. (2008). In terms of monthly variation, the outflow was relatively small in the spring, due to the slight effects of snowmelt on outflows. During the rainy season, the outflows increased with the conveyance of flows, generally reached their maximum in September or October. After that, the outflows decreased and turned zero when water were totally frozen. On the whole, simulated outflows were in accordance with natural conditions. Maximum water area and storage corresponded to the maximum outflow, which was largely affected by wetland hydrological characteristics of conveyance, storage and retention.

5.4 Variation of water depth in wetlands

Water depth is a key factor affecting wetland ecosystem function and health. The central zone of the Zhalong Wetland, as a typical wetland environment, is the main habitat for waterfowls. Therefore, we focused our analysis on the variability of water depth in this zone.

Measured wetlands water levels from 3 plots in the central zone were available for evaluating the simulated water depths in 2005 and 2006. Simulated water depth in each subbasin equals to the average value of wetlands surface water depth in their respective subbasin. In general, the highest monthly water depth occurred in August, while the lowest appeared in June. Figure 7 compares the observed surface water level with the simulated water depth in the same HRUs. There were good agreement between the simulated water depth and observed water level, though with slight difference in ranges. So the model is credible for the simulation of wetland hydrological components.

HESSD
9, 14035–14063, 2012

Figure 8 presents the simulated water depth in the central zone, including subbasin 5, 7, and 8. Regarding interannual variation, the water depth decreased from the late 1980's to the early 1990's, influenced by the decrease of inflows and increased temperature. In the 1990's, water depth in the central zone had fluctuant variations in the control of natural precipitation. Since 2001, the water level raised and the fluctuation decreased under the influence of diverted water from the Nenjiang River. The variation in water depth in the central zone corresponded to the actual conditions that were influenced by wetland inflows from natural precipitation, upstream rivers and artificial water-supply. From the late 1980's, increased water use in agriculture and social-economy induced the decrease of inflows from upstream rivers and Nenjiang River, and then altered the hydrological processes in the Zhalong Wetland. The decadal variations of water depth in wetlands were in agreement with the description by Tong et al. (2008).

6 Conclusions

In this study, a wetland module was developed and incorporated with the SWAT model to simulate hydrological processes for the Zhalong Wetland. The module considered the flow exchange between wetland and river channels and aggregated wetlands into groups to represent the hydrological linkage between wetland areas and upland areas within the associated watersheds. The modified SWAT modeling system was calibrated and validated with field measurements including streamflow and water level. The simulation results show that the model with the modified module has a good performance in simulating wetland hydrological processes, which contributes to understanding the variation of hydrological components and functions of the Zhalong Wetland with limited monitoring data. The simulation study reveals considerable variation of wetland hydrological components in the Zhalong Wetland as a whole, which reflects the strong influence of the upstream river basin on the wetland hydrological regime. The variations of water area, water storage and outflow in the study area are largely affected by the wetland hydrological functions of conveyance, storage and retention, while water depth in the central zone is influenced by the inflows. The results gained from this study build a foundation for estimating ecological water requirements for the wetlands, helping develop strategies and plans for water resources management within the river basin, which will promote the sustainable and harmonious development of water resources, social economy and ecological protection, especially in the river basin with important wetland nature reserves.

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HESSD

9, 14035–14063, 2012

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HESSD
9, 14035–14063, 2012

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X. Q. Feng et al.

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X. Q. Feng et al.

Table 1. Major model parameters and their settings.

Parameter	Description	Initial values	Range	Calibrated values
Watershed level				
SMTMP (°C)	Snowmelt base temperature	0.5	[−5.0, 5.0]	0.5
SMFMX (mmH_2O/°C-day)	Maximum snowmelt rate	4.5	[0.0, 10.0]	6.0
TIMP	Snowpack temperature lag factor	1.0	[0.0, 1.0]	1.0
SURLAG (day)	Surface runoff lag coefficient	4.0	[1.0, 24.0]	18.0
Subbasin level				
CH_L1 (km)	Longest tributary channel length in subbasin	16.829~61.452	[0.05, 200]	2.452~30.872
CH_N1	Manning's *n*-value for the tributary channels	0.014	[0.01, 30]	1.014
CH_N2	Manning's *n*-value for the main channel	0.014	[0.01, 0.3]	1.014
HRU level				
SOL_AWC	Available water capacity of the soil layer	0.04~0.18	[0.00, 1.00]	0.04~0.45
ESCO	Soil evaporation compensation factor	0.95	[0.01, 1.0]	0.01
CH_K2 ($mm h^{-1}$)	Effective hydraulic conductivity in main channel allluvium	0.00	[0.01, 500.00]	6.00~18.00

HESSD
9, 14035–14063, 2012

Table 2. Evaluation for simulation results of monthly outflow during calibration and validation periods in the Zhalong Wetland.

Simulation periods	E_{ns}	R^2	PV
Calibration period (1987–1989)	0.86	0.89	0.86
Validation period (2005–2006)	0.66	0.66	0.82

HESSD
9, 14035–14063, 2012

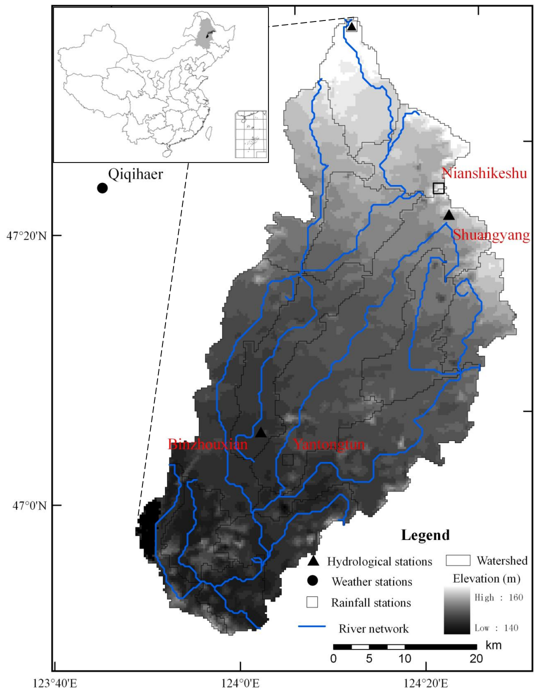

Fig. 1. Location, elevation, hydrological and weather stations, and subbasin division of the Zhalong Wetland.

HESSD
9, 14035–14063, 2012

Simulation of hydrological processes in the Zhalong Wetland

X. Q. Feng et al.

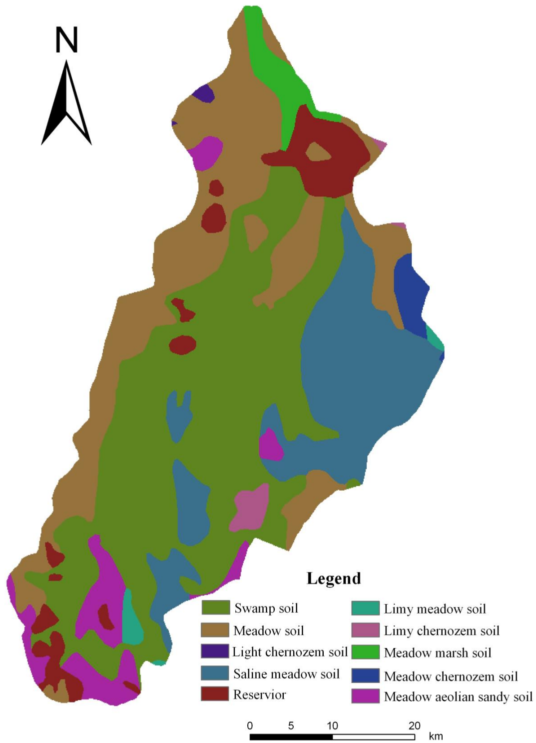

Fig. 2. Spatial distribution of soil types in the Zhalong Wetland.

HESSD
9, 14035–14063, 2012

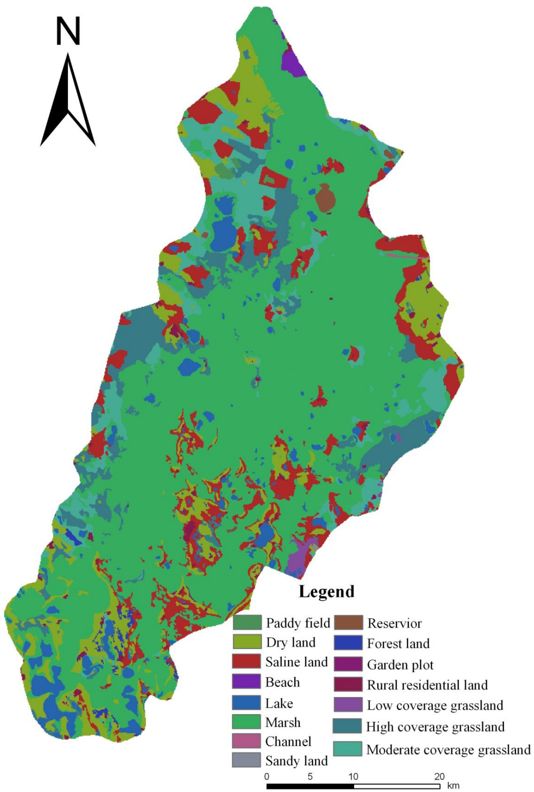

Fig. 3. Spatial distribution of land use types in the Zhalong Wetland in 2006.

HESSD
9, 14035–14063, 2012

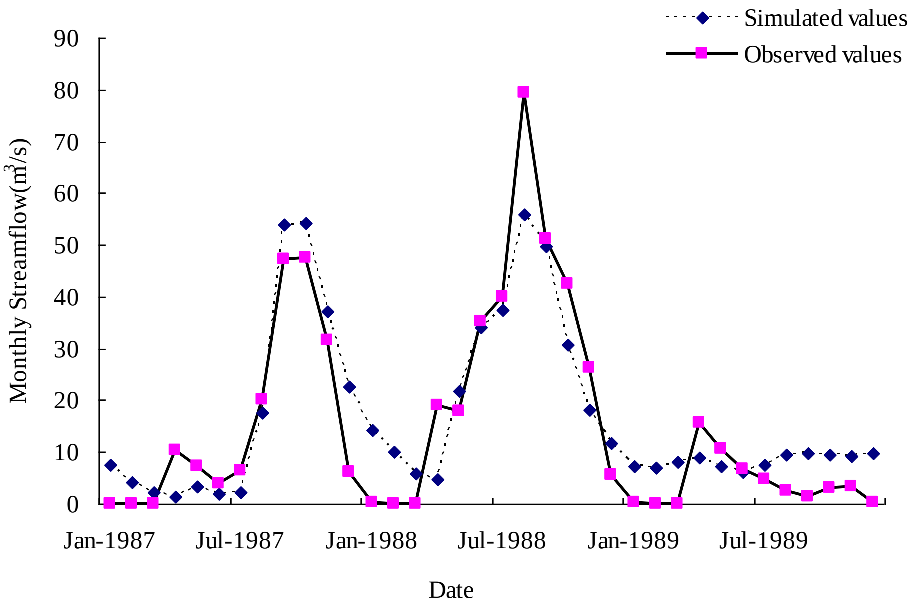

Fig. 4. Comparison between simulated and observed monthly outflow (Binzhouxian station) during calibration period in the Zhalong Wetland.

HESSD
9, 14035–14063, 2012

Simulation of hydrological processes in the Zhalong Wetland

X. Q. Feng et al.

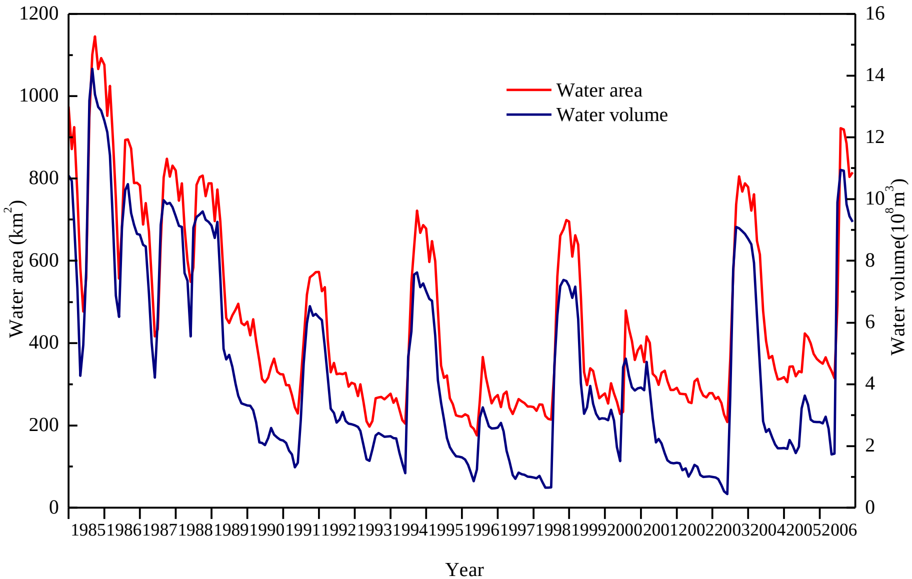

Fig. 5. Simulated monthly water area and water volume in the Zhalong Wetland during 1985–2006.

HESSD
9, 14035–14063, 2012

HESSD
9, 14035–14063, 2012

Simulation of hydrological processes in the Zhalong Wetland

X. Q. Feng et al.

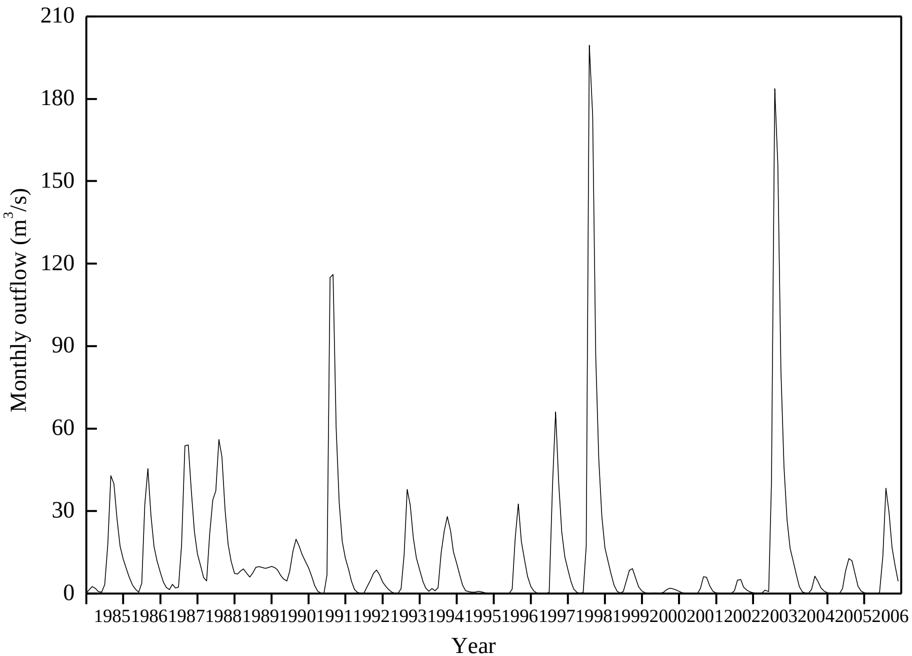

Fig. 6. Simulated monthly outflow in the Zhalong Wetland during 1985–2006.

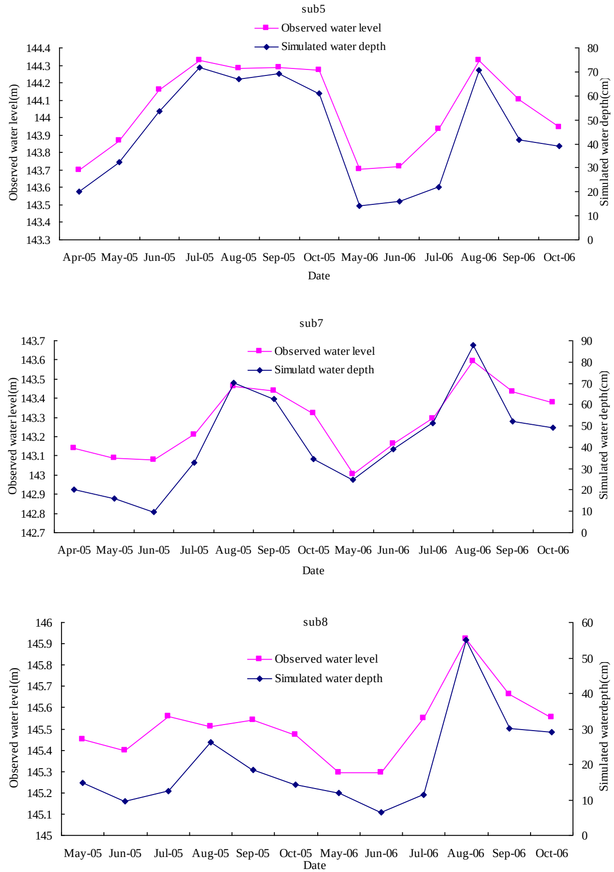

Fig. 7. Comparison between observed water level and simulated water depth in subbasins of the central zone in the Zhalong Wetland for water years 2005 and 2006.

HESSD
9, 14035–14063, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

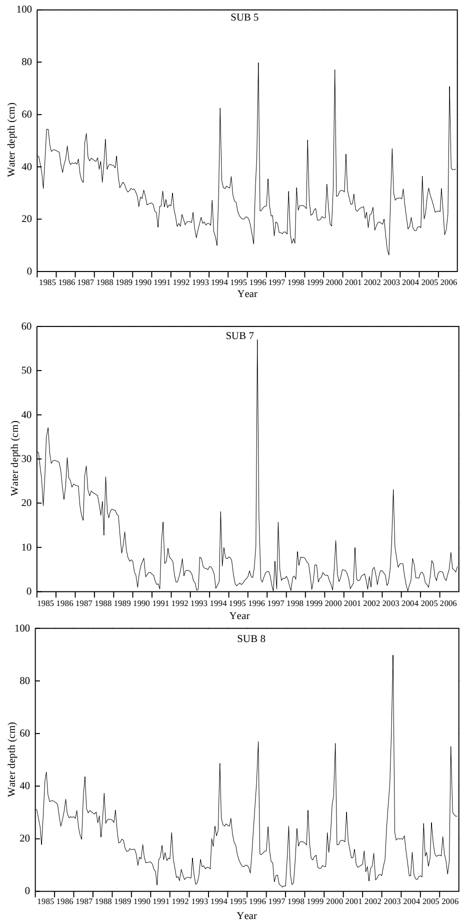

Fig. 8. Simulated surface water depth in different subbasins of central zone in the Zhalong Wetland for water years 1985 and 2006.

HESSD
9, 14035–14063, 2012