Water Policy 20 (2018) 777–793

# Ecological water requirements of wetlands in the middle and lower reaches of the Naoli River

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**Abstract**

In the last few decades, the wetland area of the Sanjiang Plain in northeast China has shrunk severely. To provide a scientific basis for the protection and restoration of wetlands in the Sanjiang Plain, Landsat TM images of 13 typical years of four well-preserved and contiguous wetlands are interpreted by remote sensing technology in the Sanjiang Plain of the Naoli River Drainage Basin. According to the results of the interpretation, the calculation of the minimum and the optimal ecological water requirements of the four wetlands was carried out by combining ecology with remote sensing technology. At the same time, considering the rainfall and surface runoff at different guarantee rates, the artificial recharge of four wetlands was calculated according to the principle of water balance. The results indicate that the wetland area decreased significantly from 1984 to 2013, and natural inflow of water cannot meet the actual water requirements of wetlands. The calculated artificial recharge of the four reserves provides technical support for replenishment of wetlands in the Sanjiang Plain, and lays a good foundation for the restoration of wetland ecosystems in the Sanjiang Plain. At the same time, it also provides a good habitat for rare waterfowl.

*Keywords:* Ecological water requirement; Middle and lower reaches; Wetland

## Introduction

A wetland is a unique ecological system with a variety of functions and rich biodiversity. Due to the change in natural environments, the excessive exploitation of wetlands and the irrational use of wetland resources, the structure of wetland ecosystems has been destroyed, and the wetland area is shrinking gradually, which leads to the damage or loss of wetland ecological function. According to the results of the second national wetland resources survey in China, wetland area in China decreased by 33,963 km$^2$ (8.82%) from 2003 to 2013. At the same time, in many other countries, many wetlands are also shrinking, for instance, the area of Anzali wetland, an internationally important wetland in Iran, decreased by approximately 65 km$^2$ (approximately 69% of the total area) from 1975 to 2013

doi: 10.2166/wp.2018.099

(Mousazadeh *et al*., 2015). Degradation and loss of wetlands seriously affects the survival and reproduction of rare wild animals and seriously restricts regional economic development, which verifies that the protection and restoration of wetlands is necessary. To provide a scientific basis for protection and restoration, it is necessary to study the ecological water requirement of wetlands.

The study of the ecological water requirements of wetlands is an extension and development of the ecological water requirement. In 1993, Covich stressed that water is required to restore and maintain the healthy development of the ecosystem in water management (Covich, 1993). In the 1990s, Gleick proposed the basic concept of ecological water demand (Gleick, 1998). Once the concept of ecological water demand had been proposed, studies on the ecological water requirements of wetlands gradually developed. Researchers began to study the water demands of vegetation, soils and biological habitats (Brock & Casanova, 1997; Baird & Wilby, 1999; Keddy, 1999; Roberts *et al.*, 2000; Mayer & Thomasson, 2004; Catford, 2006). Although these studies did not consider the wetland ecosystem as a whole, it is helpful to study the ecological water requirements of wetlands. At present, in China and other countries, the main calculation methods for the ecological water requirements of wetlands include hydrology, ecology and ecohydrology methods. By using a long series of hydrological data to build the hydrological model, the hydrology method calculates the water requirements of wetlands based on the hydrological characteristics and functions of the wetland ecosystem (Arthington *et al.,* 1998; Ferrati & Canziani, 2005). The method of ecology is such that, in accordance with the structure and function of the wetland ecosystem, the ecological water requirements of wetlands are divided into water requirements for wetland vegetation, for wetland soils, for biological habitats, for contamination purification, etc. (Cui & Yang, 2003; Zhao *et al*., 2005). For instance, according to the investigation, each square kilometre of marsh area can satisfy the reproduction and survival demands of a single red-crowned crane (Shen *et al*., 2009). The ecohydrology method includes ecological water level methods and ecological water surface methods according to the different hydrological parameters (Zhong *et al*., 2005; Zhou & Xu, 2007). The method of hydrology is easy to collect and low-cost, but it does not consider the ecological value of the wetland from the ecological perspective. The adaptability of the ecological method is better, and the application is more extensive, but there may be a defect of repeated calculation between different parts. The method of ecohydrology combining the methods of hydrology and ecology considers the rule of wetlands' ecological water requirements and combines the advantages of the two methods. It is more suitable for the wetland surface water level or the surface area of lake wetland interannual amplitude and is simple to control for easy classification calculation; at the same time as its hydrological and ecological data, terrain data demand is higher. Due to high data and terrain requirements, the current is not widely used. Rapidly developed 3S technology has been used extensively as a more accurate method that combines remote sensing technology and ecology to calculate the ecological water requirements of wetlands (Li *et al*., 2004, 2010; Tang *et al*., 2005; Wang *et al*., 2006; Dai *et al*., 2007; Rebelo *et al*., 2009; Lu, 2012). The ecological water requirements of wetlands in the Sanjiang Plain are mostly based on the above research. The research results of typical Honghe wetlands in the Sanjiang Plain are extensive (Luan *et al*., 2004; Zhao *et al*., 2004; Yang *et al*., 2008a, 2008b), but there are fewer results for the well-preserved and well-developed typical wetlands of the Naoli River Basin (Liu, 2005; Pan *et al*., 2015).

The Sanjiang Plain in China is an important stopover site and breeding ground for wild birds in eastern Asia, such as the red-crowned crane, the Oriental white stork and the little swan. However, the swamp wetland area decreased from 35,259 $km^2$ in 1954 to 8,099 $km^2$ in 2005, a decrease of 77.03% in 50 years (Wang *et al*., 2009). The rapid reduction of wetland area has led to the destruction of the structure and function of typical wetland ecosystems and the decline of biodiversity. In this study, 13 different years are selected from 1984 to 2013, and based on the current situation of the Sanjiang Plain wetland and the results of regional precipitation and runoff changes and character analysis, the areas of land-use types are calculated in different periods using Landsat TM satellite images of four well-preserved and contiguous nature reserves in the hinterland of the Sanjiang Plain. According to the interpretation results, the ecological water demands of the four wetlands are calculated, and the precipitation and surface runoff at different guarantee rates are considered. Based on the method of water balance, the artificial recharge requirements of four wetlands are determined by a method combining ecology with remote sensing technology.

According to the calculation results, we provide technical support for the artificial recharge of wetlands in the Sanjiang Plain so that the wetlands can replenish water rationally, restore ecosystem diversity and provide good habitats for rare waterfowl.

## Materials and methods

### *Study area*

The Sanjiang Plain, which is located in eastern Heilongjiang Province on the north-eastern border of China, is not only a nationally significant grain production region but also contains the largest national concentration of freshwater marsh wetlands. By 2006, Sanjiang Plain had 24 established inland wetland nature reserves (Wang *et al*., 2009). This study will focus on four of those nature reserves: the Naoli River National Nature Reserve, the Sanhuanpao National Nature Reserve, the Qixing River National Nature Reserve and the Dongsheng Provincial Nature Reserve. The geographical coordinates of the nature reserves are 132°5′–134°10′E,46°30′–47°22′N and the total area is 2,275.26 $km^2$. This region has the obvious characteristics of a continental monsoon climate and the annual average temperature is 2.3–2.7°C. The average annual rainfall is 537.4 mm, and the precipitation is mainly concentrated in the months of June, July and August. Basic information on the nature reserves is listed in Table 1.

The four nature reserves are in the Naoli River Basin, and they are well-preserved typical wetlands of the Sanjiang Plain. Precipitation and surface runoff are the main sources of water recharge in these reserves. The Qixing River is the main source of surface water recharge for both the Qixing River Nature Reserve and the

Table 1. Basic information on the nature reserves.

| Nature reserve | Area ($km^2$) Total area | Core area | Buffer area | Experimental area | Main protection object | Type | Level |
|---|---|---|---|---|---|---|---|
| Naoli River | 1,605.95 | 370.45 | 531.24 | 704.26 | Wetland ecosystem and rare waterfowl | Inland wetland | National level |
| Sanhuanpao | 276.87 | 109.19 | 101.14 | 66.54 | Wetland ecosystem and rare waterfowl | Inland wetland | National level |
| Qixing River | 200.00 | 79.60 | 36.00 | 84.40 | Wetland ecosystem and rare waterfowl | Inland wetland | National level |
| Dongsheng | 192.44 | 69.68 | 65.68 | 57.08 | Wetland ecosystem and rare waterfowl | Inland wetland | Provincial level |
| Total | 2,275.26 | 628.92 | 734.06 | 912.28 | – | – | – |

Sanhuanpao Nature Reserve. The Naoli River is the main source of surface water recharge for the Dongsheng and Naoli River Nature Reserves. In addition, the Hamatong River, the Qiliqin River and the Waiqixing River are the tributaries of the Naoli River, and they comprise the source of water recharge for the Naoli River Nature Reserves. The location map of the regional river system and nature reserves is shown in Figure 1.

Due to the change of natural conditions, such as the reduction of precipitation and the continuous drought, the wetland replenishment cannot be satisfied, resulting in the degradation of the wetland. Besides being influenced by natural factors, the interference of human activities is greater. The surface water interception from upstream water conservancy projects, farmland reclamation, dry field change of paddy fields and many kinds of disturbance cause wetland ecosystem destruction, and then the anti-interference and self-recovery declines and vulnerability increases.

## Methods

*Interpretation of land-use type area by remote sensing*. Based on the feature analysis of hydrological factors (precipitation and runoff) and how they have changed over the years, 13 different years were selected and analysed, including the current year (2013), the low flow years' period (2006–2008),

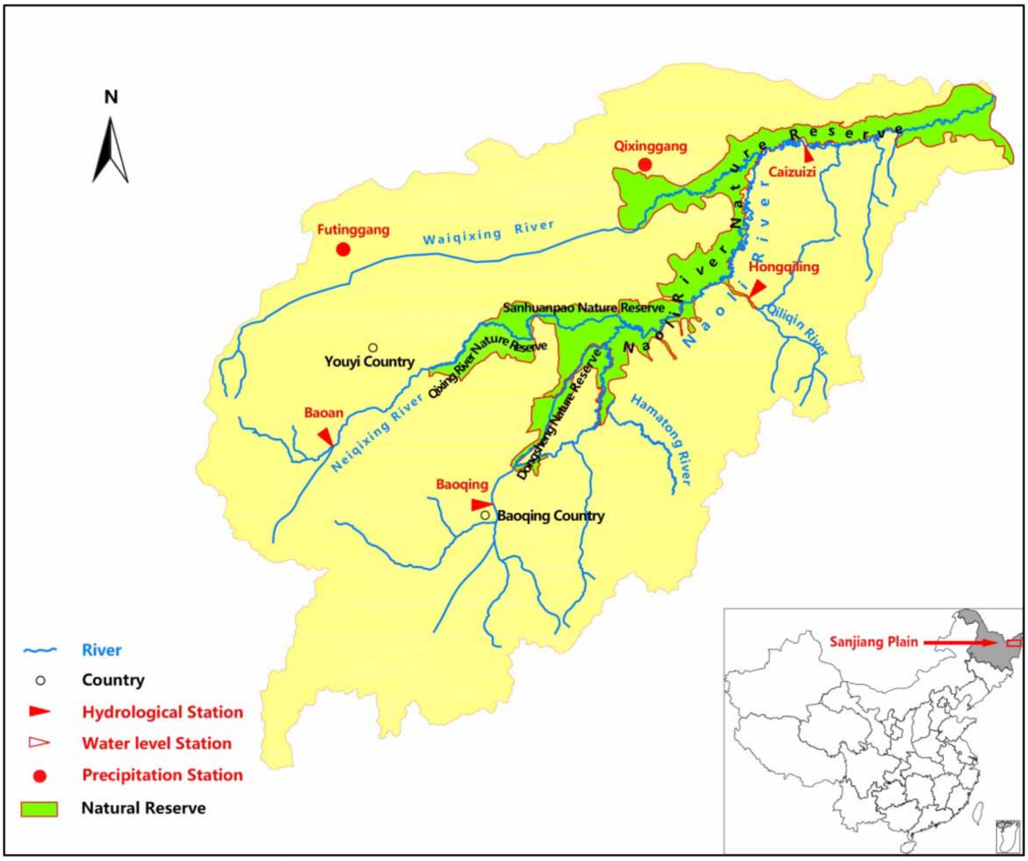


Fig. 1. Location map of the river system and nature reserves in the Naoli River Basin.

the normal years' period (1998–2000), the high flow years' period (1990–1992), and 1984, 1987 and 1994. According to the actual situation and demand, as well as referring to the national standardized 'current land-use classification' in China, using ENVI5.1 to decode satellite images, the area of land-use types in the study area was obtained (Figures 2–5), and the specific steps are as follows:

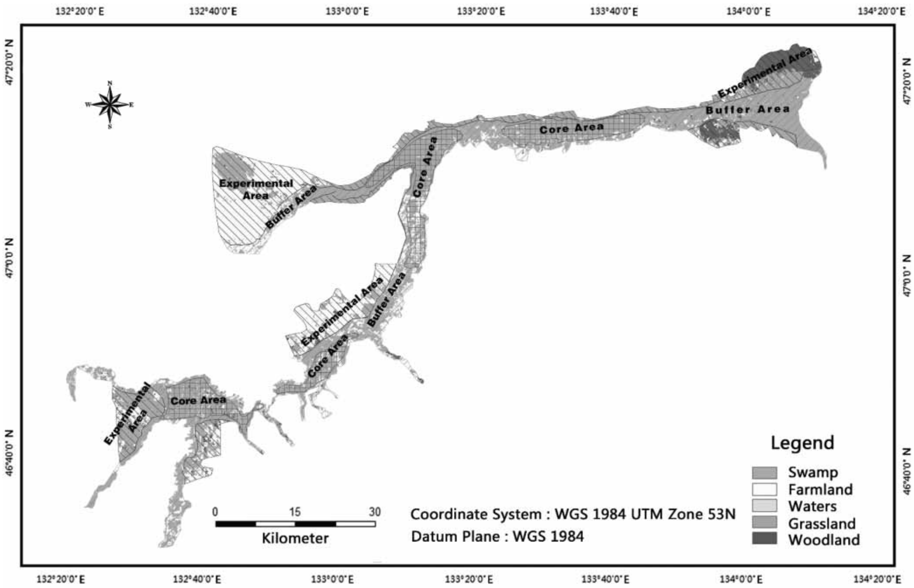


Fig. 2. Land-use map of the Naoli River Nature Reserve in 2013.

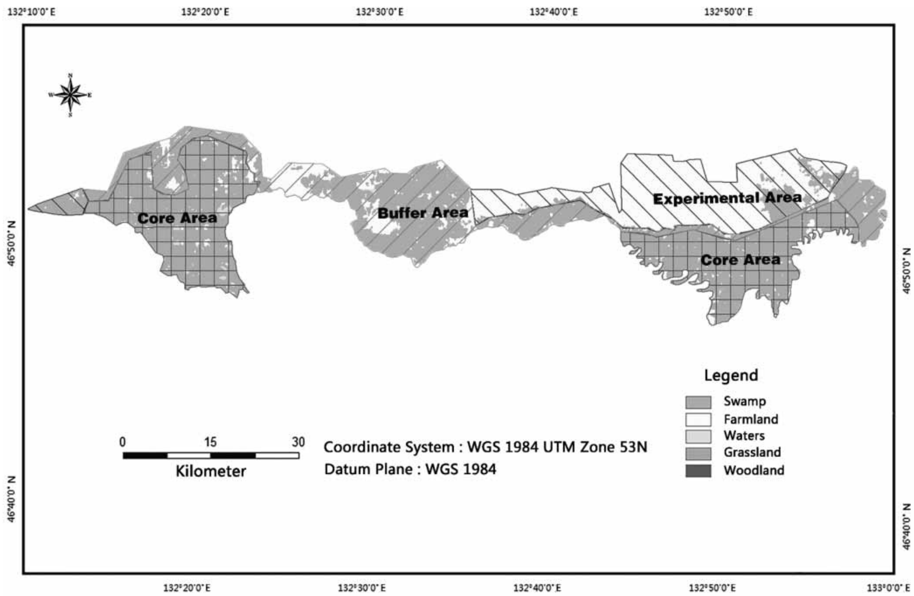


Fig. 3. Land-use map of the Sanhuanpao Nature Reserve in 2013.

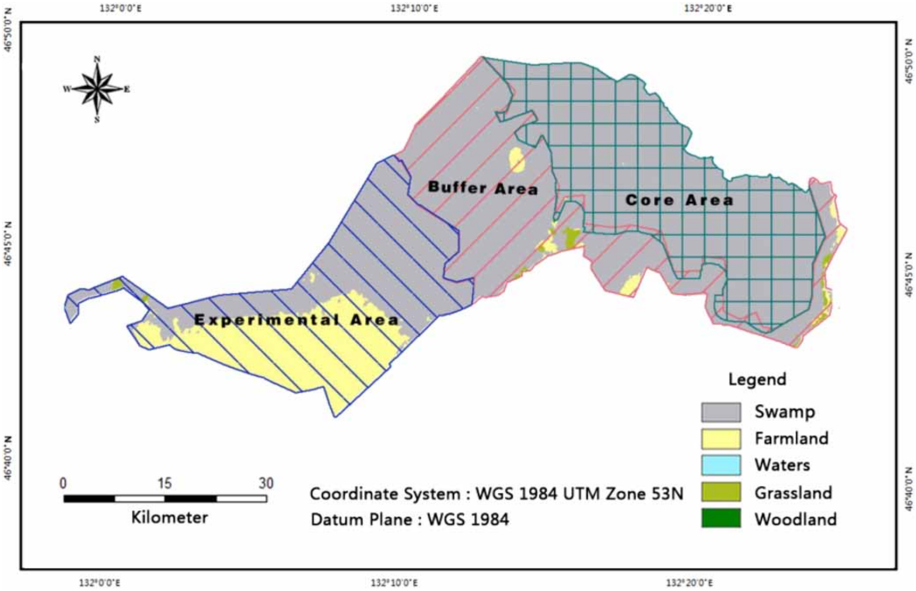


Fig. 4. Land-use map of the Qixing River Nature Reserve in 2013.

(1) Image selection: focusing on the image quality of June to September and the image of the volume cloud as the image to be processed.
(2) Image cropping and splicing: according to the nature reserve boundary and geographic coordinates, the remote sensing image is cropped, and some images need to be spliced before cropping.
(3) Image analysis: analysing and determining vegetation density and water distribution by normalized vegetation index NDVI and normalized water index NDWI.
(4) Image classification: based on the field study sample, the image interpretation analysis is carried out based on the sample oriented classification method.
(5) Analysis: analyse the rationality of interpretation results, repeat the previous operation, and finally get the desired result.

Figures 2–6 show that the land-use types of the nature reserves are rich, including waters, farmland, swamp, woodland and grassland. The waters represent the surface waters, including reservoirs, lakes/ponds and rivers. With the decrease in the water supply, the declining groundwater level and the impact of human activities, the swamp area decreased most seriously, by 42.57% in 30 years, from 1,963.82 $km^2$ in 1984 to 1,127.91 $km^2$ in 2013. Most of the swamp has been converted into arable land and a small part has degenerated into grassland. At the same time, the forest area also showed a clear downward trend, indicating that some of the forest has been cut down or otherwise destroyed. For the core area, the decrease of wetland area is mainly manifested in the decrease of swamp area and the increase of farmland in the late 1990s. At present, the wetland ecological environment is badly in need of protection and restoration.

*Target determination of ecological water requirement*. Determination of the wetland ecological restoration target is a prerequisite for the calculation of wetland ecological water demand and refers to many

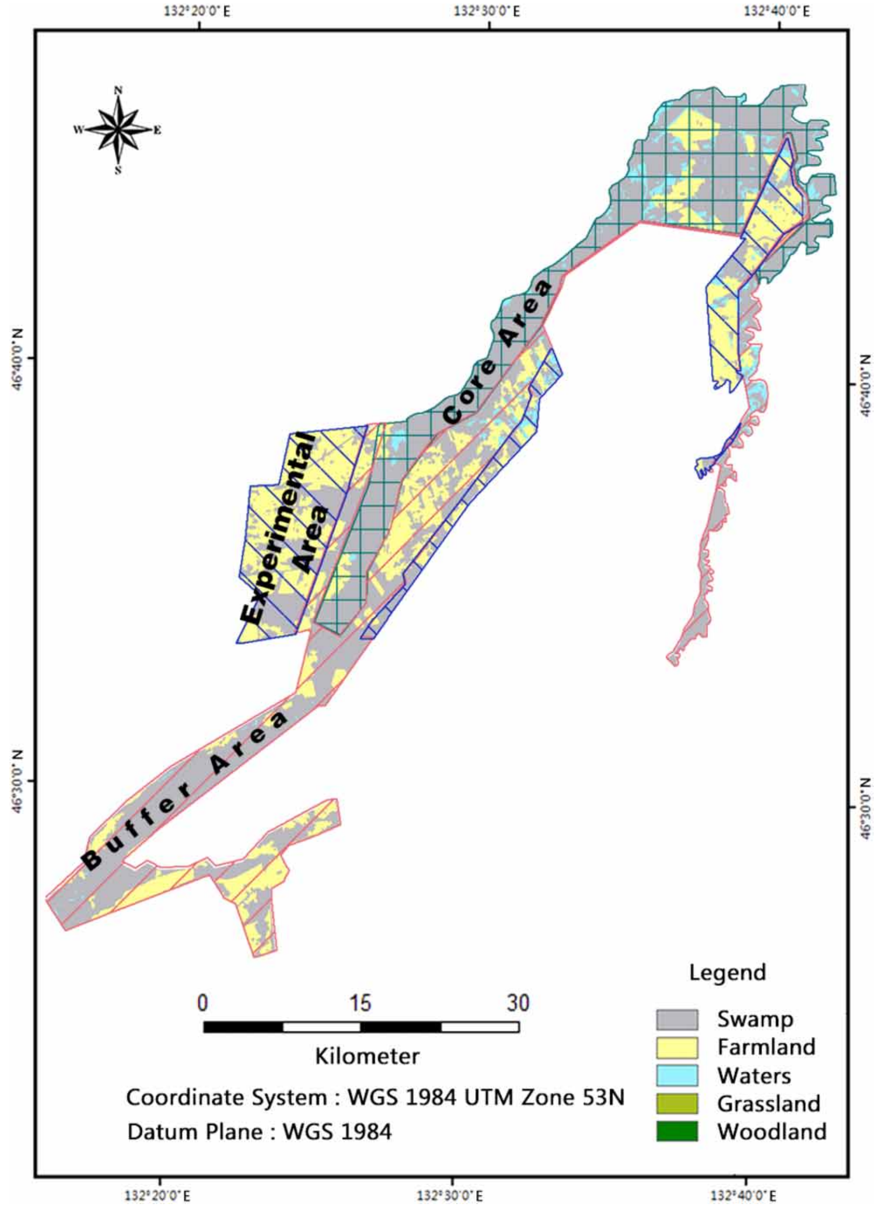


Fig. 5. Land-use map of the Dongsheng Nature Reserve in 2013.

aspects. The main purpose of a nature reserve is to protect wetland ecosystems and rare waterfowl. Therefore, the specific target of wetland ecological restoration is to restore the wetland area and water depth to a certain level for maintaining a good development of biological habitat. On this basis, the evaluations must consider evaporation, transpiration and other parts of the water balance, to maintain the wetland ecosystem water balance.

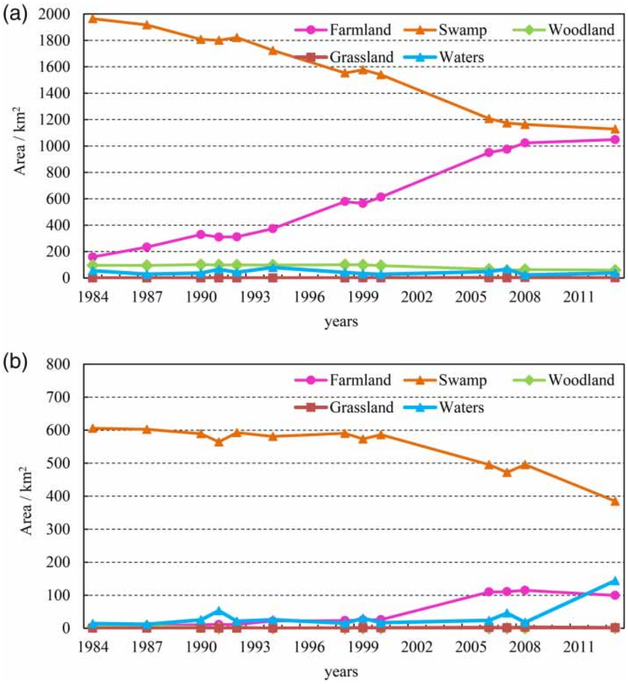


Fig. 6. The area of land-use types in different periods in the nature reserves (a) and the core area of nature reserves (b).

Due to the composition, structure, actual demand of the wetland ecosystem and the limited amount of regional water resources, the maximum ecological water requirement is difficult to achieve in reality. Wetlands cannot be restored to near-original levels even if water is transferred by artificial means, so the maximum level has no practical significance. Therefore, the ecological water requirements of wetlands are divided into two levels: minimum and optimal. The minimum ecological water requirement is the minimum amount of water needed for the system to maintain its own development and prevent it from degenerating. Once below this amount, the ecological system will be degraded or even destroyed. The optimal ecological water requirement is the amount of water that the wetland ecosystem needs to reach an ideal state. It is of great significance to reasonably determine the goal of ecological restoration of wetland at all levels.

(1) Principles

- The First Principles of Wetland Ecosystem Structure and Function Restoration

  Wetland ecosystem structure directly determines the type of vegetation in nature reserves, indirectly affecting rare waterfowl foraging and nesting activities. However, people have blindly plundered wetland resources; thus, the wetland ecosystem structure and function have been destroyed, and the robustness and self-recovery ability weakened. The destruction of habitat has the greatest impact on rare birds, and when the intensity of the disturbance is large, they may become endangered. Therefore, to protect rare and endangered waterfowl and waterfowl habitats, the restoration of damaged wetland ecosystems should be the primary principle to maintain the main ecological functions of wetlands and enable them to operate normally.

- The Auxiliary Principle of the Core Area and Buffer Wetland Restoration
  The core area is the essence of a nature reserve, the core of the wetland ecosystem, and the minimum space where Huan, cranes and other rare birds inhabit and multiply, so it needs to be strictly protected. In addition to the core area, the buffer area is less affected by human activities and maintains a good landscape. It is also the main foraging area and the resting place for waterfowl during the spring and autumn migratory seasons. The buffer area mainly serves to isolate the core area and the experimental area, and it also has a good shielding effect on the core area. In the effort to return farmland to wetland and to restore vegetation, the buffer area can be fully recovered and the ecosystem can be developed better. Therefore, the restoration of wetland ecosystems should consider the core area and buffer wetland restoration as the auxiliary principle.
- The Principle of Equal Emphasis on Food Security and Ecological Benefits
  Wetland ecosystem protection and management is a difficult project that involves the complex relationships between the natural system and human system. Under the goal of protecting and restoring the balance of the wetland ecosystem, the production of a commodity grain base in the Sanjiang Plain should also be guaranteed. Since 1949, with the rapid development of population and state investment, the Sanjiang Plain has experienced four peak periods of land reclamation. In the mid-1980s, large-scale land reclamation basically ended, and the impact of human activities on land-use types gradually decreased. Therefore, the restoration of wetland ecosystems should be based on the principle of equal emphasis on food security and ecological benefits. Under the premise of ensuring grain demand, we should focus on the restoration of the wetland ecosystem and maximize the ecological benefits of wetland.
- The Defined Principles of the Overall Planning of Nature Reserve
  In terms of the current situation of the nature reserves, there are some problems that should be dealt with, such as wetland degradation and declining biodiversity. To effectively protect and restore the wetland resources, the relevant departments will formulate the overall planning of a nature reserve according to the local conditions, such as returning farmland to wetland or forest. The overall planning directly is related to the determination of the target. Therefore, the target of wetland ecological restoration should be determined in consideration of the current status of wetlands based on the defined principles of the overall planning of nature reserves.
- The Principle of Taking the Establishment Time of Nature Reserves as the Boundary
  With the continuous degradation of wetlands and the increasing awareness of the importance of wetlands, a number of nature reserves have gradually been established by the local government in the Sanjiang Plain. With the approval of the establishment of the Nature Reserve and Protection Area Management Bureau, wetland management and protection work have been carried out gradually. Management system construction, improvement of infrastructure, special rectification actions and publicity and educational activities have basically curtailed the disordered development and construction activities that result in the destruction of nature reserves, and the impact of human beings on wetlands has gradually reduced. Therefore, the establishment time of each nature reserve is an important time point with respect to wetland area change. Before and after the establishment of the nature reserve, wetland area change may display two different trends.
- The Reference Principle of Trend Analysis of Wetland Water Supply
  Precipitation and surface runoff are important sources of the wetland water supply, and the amount of water directly determines the wetland area. Meanwhile, precipitation has a direct

impact on the surface runoff process, and directly or indirectly determines the development of wetlands. Wetland surface inflow is affected by climate and human factors. With the increase in population and grain demand, the area of irrigated paddy fields is expanding. Therefore, the amount of water flowing into the wetland is decreasing and the ecological structure and function of wetlands are destroyed. Wetland ecological restoration is based on the restoration of wetland ecosystem structure and function. Therefore, the target of wetland ecological restoration should be determined by the results of an analysis of the amount of water flowing into the wetland.

(2) Target determination

The target of wetland ecological restoration is determined according to the specific target and the principle as follows: the minimum target of wetland ecological restoration should ensure that the wetland ecosystem of the core zone reaches the best condition, and the wetland ecosystem structure and function of the buffer zone will be restored to a better level on this basis. The suitable ecological water requirements refer to the restoration and protection of the core zone and buffer zone.

Through a comprehensive analysis, it was determined that the core area remained intact in the late 1990s, and the buffer zone was slightly affected, but the structure and function of the wetland ecosystem could be at a good level across the different hydrological years. Therefore, it indicates that the wetland ecosystem is in a stable state and that the wetland area can meet the survival needs of rare animals and plants. At the same time, from the perspective of returning farmland to wetlands, wetland area can be restored to the levels of the late 1990s over a certain period of time. Therefore, it is reasonable to set the target of wetland ecological restoration to the levels of the late 1990s. The ecological restoration targets for nature reserves are shown in Table 2.

*Calculation method of ecological water requirement.* According to the specific goal of wetland ecological restoration, the calculation of wetland ecological water requirement is based on the water balance of the wetland ecosystem. According to the actual situation, the wetland ecological water requirement is divided into consumptive water demand and non-consumptive water demand. The consumptive water demand includes the water requirement for water evaporation, for wetland vegetation, and for wetland soil; the non-consumptive water demand includes the water requirement for biological habitat.

Table 2. Ecological restoration targets for the nature reserves.

| | Restoration targets | | |
|---|---|---|---|
| Nature reserve | Recovery level | Suitable wetland area ($km^2$) | Minimum wetland area ($km^2$) |
| Naoli River | The late 1990s | 1,070.70 | 350.16 |
| Sanhuanpao | The late 1990s | 218.10 | 106.69 |
| Qixing River | The late 1990s | 168.88 | 79.48 |
| Dongsheng | The late 1990s | 133.20 | 67.70 |
| Total | – | 1,590.88 | 604.03 |

*Note:* Wetland area refers to the combined area of swamp and water.

The water requirement for water evaporation is mainly consumed in the water area of the nature reserves. It is calculated as follows:

$$W_w = \sum A_w E \cdot 10^{-3} \tag{1}$$

where $W_w$ is the water requirement for water evaporation, $m^3$; $A_w$ is the water area of the wetland, $m^2$; and $E$ is the evaporation, mm.

The water requirement for wetland vegetation is the amount of water needed for the normal growth of vegetation. The water consumption of transpiration and soil evaporation are the main water consumption components, which together account for 99% of the water demand of plants (Liu *et al.*, 2007). Therefore, the plant water demand is approximately understood as the sum of the leaf transpiration of plants and the amount of soil evaporation, known as evapotranspiration. It is calculated as follows:

$$W_p = E_p A_m \cdot 10^{-3} \tag{2}$$

where $W_p$ is the water requirement for wetland vegetation, $m^3$; $E_p$ is the vegetation evapotranspiration, mm; and $A_m$ is the marsh area of the wetland, $m^2$.

The water requirement of wetland soil is closely related to plant growth, soil type, thickness and area, and soil water content is the basis for calculating the water requirement of wetland soil. It is calculated as follows:

$$\mathrm{W_s} = \alpha\gamma H_s A_s \tag{3}$$

where $W_s$ is the water requirement of wetland soil, $m^3$; $\alpha$ is the field holding capacity and saturated water holding volume percentage; $\gamma$ is the soil bulk density; $H_s$ is the soil thickness, m; and $A_s$ is the soil area of the wetland, $m^2$.

The water requirement for biological habitats is the amount of water required to provide the fish, rare waterfowl and other organisms with sufficient space to survive and reproduce. The wetland ecological system composed of water and swamp vegetation is an important habitat for waterfowl and other animals. At the same time, rare waterfowl also have certain requirements on water depth. Therefore, the water depth and the flooded area are selected as the key indicator of the water requirement for biological habitats. It is calculated as follows:

$$W_h = A_h H_h \tag{4}$$

where $W_h$ is the water requirement for biological habitats; $A_h$ is the surface area of the wetland; and $H_h$ is the average depth of the wetland.

## Results and discussion

### *Calculation of water requirement*

*The water requirement for water evaporation.* According to the hydrographic atlas of Heilongjiang Province, the measured evapotranspiration data from regional hydrological stations were converted into water surface evaporation, and the average evaporation of water surface in the reserve was obtained by means of the arithmetic average method. The water requirement for water evaporation can be obtained by putting the water surface evaporation and water surface area into Equation (1). Because the water requirement for wetland vegetation is mainly concentrated in May to October and is the main component of the wetland ecological water demand, the water evaporation in May to October was analysed. The results are shown in Table 3.

*The water requirement for wetland vegetation.* There are many kinds of marsh vegetation, including herbaceous swamps and swamp meadows, but only the most abundant plant species of all of the marsh vegetation are selected. According to the survey, reeds and *Carex lanceolata* are the most abundant species in herbaceous swamps. Since there are no actual reed evapotranspiration values for the nature reserves, the evapotranspiration of the reed is replaced by what has been measured in the Zhalong wetland, which is in close proximity to the nature reserves in latitude and longitude (Wang & Xu, 2005). The evapotranspiration of the *Carex lanceolata* is from experimental observation (Chen & Ku, 1993). Swamp meadow soil is wet throughout the year, so it can be regarded as a moist meadow. The evaporation of grass has a proportional relation to the water evaporation in the near wet condition (Cui, 1994). At the same time, according to the growth characteristics of marsh vegetation in the north, the marsh vegetation begins to grow in May and gradually withers and loses the function of transpiration in October. Hence, the evapotranspiration of marsh vegetation is only calculated from May to October. The results are shown in Table 4.

According to the vegetation evapotranspiration and wetland area, the water requirement for wetland vegetation in the nature reserves can be obtained by Equation (2). The results are shown in Table 5.

*The water requirement of wetland soil.* The types of soil in the nature reserves include albic soil, marsh soil, black soil and meadow soil. The field holding capacity percentage is 0.45, and the soil

Table 3. Water requirement for water evaporation ($10^8$ $m^3$).

| Level | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|
| Min | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.10 |
| Sui | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.17 |

Table 4. Swamp and swamp meadow vegetation evapotranspiration (mm).

| Vegetation types | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|
| Reeds | 159.3 | 174.7 | 170.3 | 155.2 | 121.2 | 89.2 | 870.1 |
| *Carex lanceolata* | 117.7 | 225.6 | 250.2 | 238.2 | 160.2 | 114.6 | 1,106.5 |
| Swamp meadow | 63.4 | 95.8 | 95.0 | 85.5 | 51.2 | 44.1 | 435.0 |

Table 5. Water requirement for wetland vegetation ($10^8$ $m^3$).

| Level | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|
| Min | 0.77 | 1.13 | 1.20 | 1.12 | 0.79 | 0.58 | 5.6 |
| Sui | 2.31 | 2.58 | 2.51 | 2.29 | 1.76 | 1.31 | 12.8 |

thickness is 0.25 m. The calculated area is the swamp area. In addition, the soil freezing period occurs from November to April of the following year. Therefore, the water requirement of wetland soil is not considered during the freezing period. When the parameters and calculated area are brought into Equation (3), the water requirement of wetland soil can be calculated; the results are shown in Table 6.

*The water requirement for biological habitats.* The main objects of protection in the nature reserves are the wetland ecosystem and rare waterfowl. According to field surveys, migratory birds (red-crowned cranes, oriental white storks, etc.) have certain depth requirements for foraging and nesting, but there are no requirements on the meadow. Therefore, the water depth of a herbaceous marsh should be guaranteed to maintain the habitats. The average depth of 0.25 m is the best water depth for migratory birds, as it can provide a good waterfowl habitat and meet the basic growth needs of marsh vegetation. The water requirement for biological habitats can be obtained by Equation (4). The results are shown in Table 7.

*Total amount of wetland ecological water demand for consumption.* Wetland ecological water demand for consumption should be supplied monthly based on the actual water demand. Wetland ecological water demand for non-consumption can be supplied flexibly according to the characteristics of regional water resources. After meeting the supply needs in the first year, no further re-supply is required.

Table 8 shows that the major water demand period is mainly from May to October, which is also the growth period of the plants. In June and July, the plants grow vigorously, and the water demand is more than that of the other months.

### *Calculation of water supply*

Precipitation and surface runoff are the main water supply sources of a wetland and are affected by natural conditions and human activities. In natural conditions, the amount of water supplied to the

Table 6. Water requirement for wetland soil ($10^8$ $m^3$).

| Level | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|
| Min | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.07 |
| Sui | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 | 1.75 |

Table 7. Water requirement for biological habitats.

| Level | Water surface area ($km^2$) | Water depth (m) | Water requirement ($10^8$ $m^3$) |
|---|---|---|---|
| Min | 541.5 | 0.25 | 1.35 |
| Sui | 1,374.8 | 0.25 | 3.44 |

Table 8. Total amount of wetland ecological water demand for consumption ($10^8$ $m^3$).

| Level | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|
| Min | 0.90 | 1.26 | 1.32 | 1.25 | 0.92 | 0.70 | 6.34 |
| Sui | 2.63 | 2.90 | 2.84 | 2.61 | 2.08 | 1.62 | 14.68 |

wetland directly affects the size of the wetland area and determines the direction of wetland evolution. Therefore, for the minimum ecological water demand, precipitation and surface runoff under the 75% and 95% guarantee rates are considered; for the appropriate ecological water demand, precipitation and surface runoff under the 50% guarantee rate are considered.

*Calculation of precipitation recharge*. According to the data from observation stations near the reserves, the mean annual precipitation of the area is 537.4 mm, and the precipitation is mainly concentrated in June to September. The annual precipitation at the different guarantee rates and the monthly values are obtained by frequency analysis and from the typical annual distribution of precipitation (Tables 9 and 10).

*Calculation of surface runoff recharge*. According to the process of natural runoff of the Naoli River and Qixing River and other rivers, the natural runoff process under different guarantee rates is obtained by frequency analysis. Because the wetland type is typical river wetland, the health of the river ecosystem should be guaranteed, except for considering the water demand for consumption. Therefore, ecological base flow should be considered. The water supply of surface runoff to wetlands under different guarantee rates can be obtained after subtracting ecological base flow using the method of Tennant (Table 11).

*Calculation of artificial recharge*. Combined with precipitation recharge and surface runoff recharge under different guarantee rates, the artificial recharge is determined by water balance analysis. The artificial recharge in some months is negative, which indicates that water is in surplus and there is no need

Table 9. Precipitation at the different guarantee rates (mm).

| Frequency | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|
| 50% | 66 | 60 | 158 | 63 | 88 | 38 | 470 |
| 75% | 95 | 46 | 166 | 39 | 25 | 25 | 390 |
| 95% | 56 | 43 | 41 | 122 | 57 | 4 | 320 |

Table 10. Total precipitation at the different guarantee rates ($10^8$ $m^3$).

| Level | Frequency | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|---|
| Min | 75% | 0.6 | 0.3 | 1.0 | 0.2 | 0.2 | 0.2 | 2.4 |
| | 95% | 0.3 | 0.3 | 0.3 | 0.7 | 0.3 | 0.0 | 1.9 |
| Sui | 50% | 1.1 | 1.0 | 2.5 | 1.0 | 1.4 | 0.6 | 7.5 |

Table 11. Surface runoff at the different guarantee rates ($10^8$ m$^3$).

| Frequency | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|
| 50% | 2.2 | 0.7 | 0.8 | 0.1 | 1.5 | 0.5 | 5.8 |
| 75% | 1.7 | 0.6 | 0.6 | 0.0 | 0.2 | 0.0 | 3.1 |
| 95% | 1.7 | 0.3 | 0.2 | 0.0 | 0.5 | 0.1 | 2.8 |

for it to be recharged, and this part of the excess water cannot be used. The artificial recharge at different guarantee rates is shown in Table 12.

From Table 12, the natural inflow of water at different frequencies cannot meet the actual water requirements of wetlands. To make the wetland ecological environment reach a normal level, artificial water transfer should be considered. Water is transferred from the Songhua River to the nature reserves by engineering measures. Under the 75% and 95% guarantee rates, the minimum artificial recharge requirements are $2.6 \times 10^8$ m$^3$ and $2.7 \times 10^8$ m$^3$, respectively, and under the 50% guarantee rate, the optimal artificial recharge of the wetland is $3.38 \times 10^8$ m$^3$.

*Discussion*. The main objects of protection in the nature reserve are wetland ecosystem and rare waterfowl. In the condition of natural replenishment, due to lack of water the wetland ecosystem will degenerate; for example, degradation from marsh to meadow, which reduces the area of habitat of the rare and endangered waterfowl such as the red-crowned crane, the Oriental white stork and little swan. In the condition of artificial recharge, the ecological system structure of the wetland is stable and diversified, which can make the wetland develop in a good direction and fully meet the survival needs of rare and endangered animals and plants.

## Conclusions

(1) According to the results of image interpretation, the types of land use of the nature reserves are rich, but the swamp area of wetlands has declined substantially, from 1,963.82 km$^2$ in 1984 to 844.71 km$^2$ in 2013, which is a reduction of 57.43% over 30 years. Meanwhile, the change of farmland area has the opposite trend; the area of farmland is increasing year by year. These results indicate that the wetland is more affected by human activities.
(2) According to the calculation results of the total amount of wetland ecological water demand for consumption, the natural inflow of water at different frequencies cannot meet the actual ecological water requirements of the wetland. Under the 75% and 95% guarantee rates, the minimum artificial

Table 12. Artificial recharge at different guarantee rates ($10^8$ m$^3$).

| Level | Frequency | May | Jun | Jul | Aug | Sep | Oct | Annual |
|---|---|---|---|---|---|---|---|---|
| Min | 75% | 0.0 | 0.4 | 0.0 | 1.0 | 0.6 | 0.5 | 2.6 |
| | 95% | 0.0 | 0.7 | 0.9 | 0.5 | 0.1 | 0.6 | 2.7 |
| Sui | 50% | 0.0 | 1.3 | 0.0 | 1.5 | 0.0 | 0.6 | 3.4 |

recharge requirements are $2.56 \times 10^8$ m$^3$ and $2.73 \times 10^8$ m$^3$, respectively, and under the 50% guarantee rate, the optimal artificial recharge of the wetland is $3.38 \times 10^8$ m$^3$.

(3) The structure of the wetland ecosystem is stable, and the type is diverse after artificial recharge. According to the wetland characteristics, the wetland can fully meet the needs of nearly 1,400 red-crowned cranes and other types of birds.

(4) After the water requirement for biological habitat is supplied completely in the first year, no further re-supply should be needed. Hence, in the calculation of artificial recharge, it is not considered. According to Table 8, compared to May–July, the required amount of artificial recharge is less in August–October. At the same time, there are a large number of water resources available because it is the end of the Songhua River flood season. It is recommended that the water requirement for biological habitat should be supplied in August to October.

## Acknowledgements

This research was supported by the National Key Research and Development Program of China (2016YFC0400903), the Natural Sciences Foundation of China (51679026, 51209030) and the Fundamental Research Funds for the Central Universities (DUT17JC17). The authors would also like to thank the anonymous reviewers for their reviews and constructive comments related to this manuscript. The authors declare that there is no conflict of interest regarding the publication of this paper.

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Received 7 July 2017; accepted in revised form 9 May 2018. Available online 31 May 2018