CALCULATION OF WETLANDS ECOLOGICAL WATER REQUIREMENT IN CHINA'S WESTERN JILIN PROVINCE BASED ON REGIONALIZATION AND GRADATION TECHNIQUES

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Abstract. In this study a method for measuring the regional hydrological connectivity and water supply requirement of wetlands in Western Jilin Province (WJL) is defined and verified. The ecological water requirements of 216 wetlands, under various guarantee frequencies, were calculated and analyzed. In addition, twelve indicators were used to establish an evaluation index system, to characterize their ecological water requirements. The results showed that 12 hydrologically connected regions were delineated in WJL, and the 216 wetlands can be classified to six grades by AHP (Analytic Hierarchy Process) method. The annual minimum, suitable, and maximum ecological water requirements of these wetlands were found to be 7.72×10^8 m^3, 13.76×10^8 m^3, 26.15×10^8 m^3 respectively, with 50% guarantee frequency. The primary water supply to the lakes and marshes was found to be from regional sources that provided a scientific basis for the allocation of water resources from the interconnected river-lake system network (IRLSN) in WJL.
Keywords: *Western Jilin Province, hydrological connectivity regionalization, AHP, ecological water demand.*

Introduction

Western Jilin Province (WJL) is located in the hinterland of Songnen Plain, an ecological fragile region in the transitional zone from semi-humid to semi-arid climate. The region has the largest, and one of the most important, wetland ecosystems in Songhua River Basin (Pan et al., 2006; Ren et al., 2007). At present, maintaining the ecological health of these wetlands is hampered by insufficient knowledge of their water supply requirements.

Geographically, the WJL region is flat and situated mainly on an alluvial plain, making the discharge of surface waters into the region difficult. In recent decades, the influence of climate change (rising temperatures and declining rainfall) and human activities

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(engineered hydraulic structures, such as reservoir) have weakened and damaged existing river-lake connection networks, causing a sharp decline of streamflows into two major rivers in the region, Huolin River and Tao'er River. As a result, the wetlands are showing clear signs of deteriorating ecological functions and acreage losses (Yue et al., 2008).

The amount of river water flowing across WJL (in particular, Nenjiang River, Songhua River) is still abundant for sustaining agricultural activities and wetland ecosystem, if the water resource is appropriately connected and allocated. A large-scale water management scheme, namely "Interconnected River-Lake System Network" (IRLSN), is being planned in WJL. It aims to coordinate the use of various water resources, to replenish lakes of significant ecological or economic values, provide water storage, and restore some ecologically important natural wetlands, such as Xianghia, Momoge, Chagan Lake Nature Reserve Wetlands (Dong et al., 2014). The IRLSN must be guided by a scientific approach of analyzing water supply-demand relation in hydrologically connected or separated regions, as it would be reckless to link waterways and storages without careful research and design.

Hydrology regime is the driving force behind the formation of wetlands (Zhang et al., 2014). Hydrological connectivity is the basis of water supply and allocation; it should be the first to be analyzed in quantitative studies of how waterways in neighboring regions can be connected in water management. Bracken et al. (2013) classified the research around hydrological connectivity into five broad themes based on: i) soil moisture; ii) flow processes; iii) terrain; iv) models; and v) indices. This classification yielded a definition of hydrological connectivity, and laid a foundation of conceptualization and methodology of different research approaches. Many researchers studied regional water resources based on hydrology, bio-ecology, nutrient migration and material deposited (Freeman et al., 2007; Lexartza-Artza and Wainwright, 2009; Lesschen et al., 2009; Luo et al., 2011; Shore et al., 2013). The boundary of their studies were individual catchments, as it is relatively easier to carry out research on a single catchment compared with studies on a vast region with numerous rivers, scattered lakes and marsh wetlands. In China, studies on hydrological connections need to be based on functional structures of regional water network, with evaluation standards and methods that suit the regional conditions (Zang et al., 2014; Li et al., 2014); such approach is used in this study.

After studying hydrological connectivity, the evaluation of water requirement of wetlands needs to be carried out, for protecting and restoring different wetlands and meeting their ecological water requirement according, especially when managed flood is the main source of water connection. While the method of calculating wetland ecological water requirement is well known (Li et al., 2009), only limited studies have been carried out on the wetland water requirement for sustaining ecological functions. Zhang et al. (2013) used the Analytic Hierarchy Process (AHP) approach to determine weighted indices of different factors that affect wetland ecosystem values, incorporating environmental constraints and socio-economic value in each index (Wang et al., 2003; Herath, 2004). Jiang and Lee (2013) proposed a method to simplify the selection of

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wetlands for priority management. Four types of evaluation categories were proposed: areas with a high value for the conservation of the ecosystem; areas with a high potential impact on biodiversity; wetland size; and eco-networks. Then, the overall wetland water requirement was classified via an overlay analysis performed using the analytical results for each evaluation indicator. These previously studies divided the wetlands in WJL to Class 1 and 2 wetlands.

The objectives of this study are to: (1) determine the water supply domain of wetlands in WJL through hydrological connection analyses, (2) establish a more refined grading system of wetland water requirements, using AHP method, and (3) calculate the ecological water requirements of wetlands under different guarantee frequencies. In addition, this study aims to contribute to formulating water resource management strategies for wetland eco-system protection and flood management in the IRLSN scheme.

Materials and Methods

Study Area

Located between 43°22′N–46°18′N and 121°36′E–126°12′E, Western Jilin has an area of 55,340 km^2 that consists of 11 counties (cities): Baicheng, Zhenlai, Taonan, Tongyu, Daan, Songyuan, Qianguo, Qian'an, Changling, Fuyu, Nong'an (*Figure 1*). It is the transitional zone between arid climate in inner-Mongolia and semi-humid in Eastern Jilin. Based on data collected from 20 meteorological stations in WJL, the mean annual rainfall during 1975-2010 was 350-500 mm, while the temperature ranged -30 to -2 °C in January and 12 to 33 °C in July (Li et al., 2015).

Major rivers merging in WJL include Tao'er River, Huolin River. Major rivers crossing WJL include Nenjiang River and the Second Songhua River. As illustrated in *Figure 1*, Nenjiang River is located in northern border of WJL, the Second Songhua River is located in the northeast border, Tao'er River in western WJL, and Huolin River (in central WJL) are tributaries of Nenjiang River.

According to survey data, the total area of natural wetlands in WJL decreased 1100 km^2 from 1980 to 2002. The current area of wetlands is only 22% of the original size (Li, 2011). Three major objectives of IRLSN scheme include: (a) effectively utilizing the flood waters of Songhua River, Nenjiang River, Tao'er River and Huolin River to connect the main wetlands, lakes, ponds and reservoirs in the region, (b) building four core ecological plates on Xianghai, Momoge, Chagan and Boluo Lake, and (c) through effective management of flood water, improving the existing, or creating new, ecological communities in Xianghai, Momoge, Chagan and Boluo Lake areas (Jilin Daily, 2015). As such, the existing 216 wetlands were selected as the main research objects in this study.

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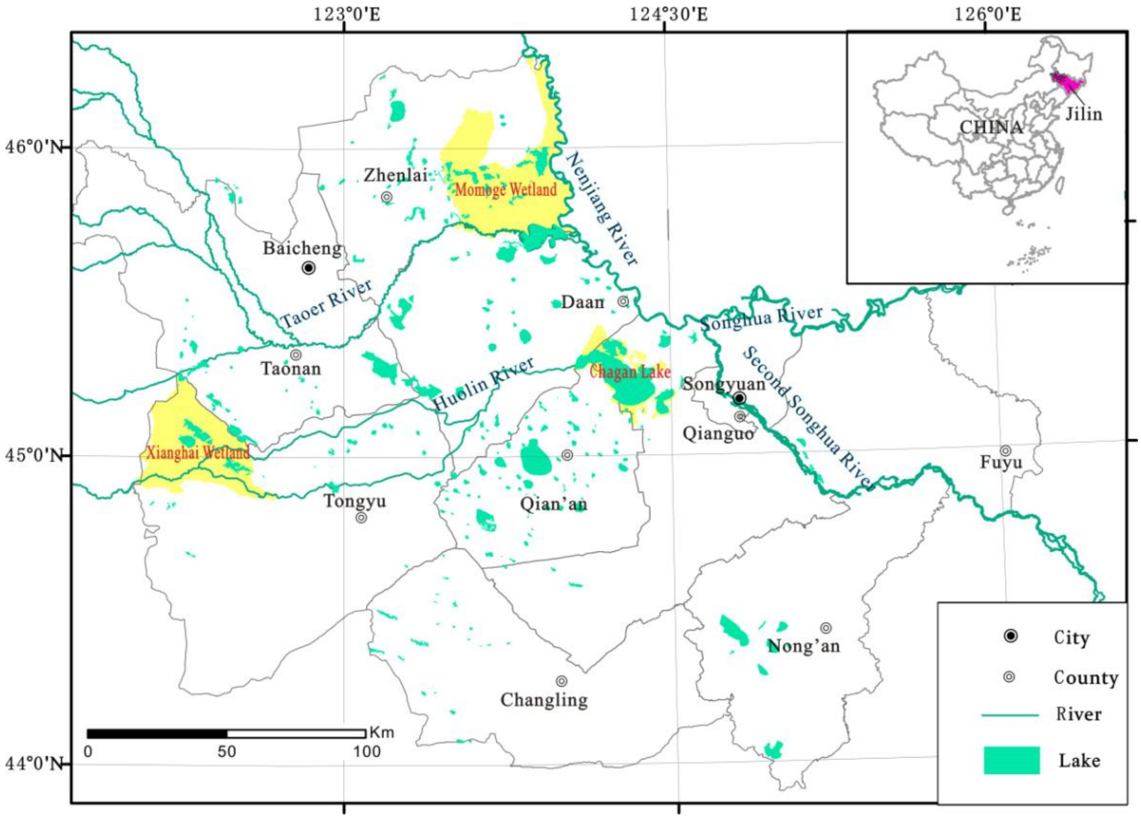

Figure 1. *Distribution of wetlands in Western Jilin province*

Hydrological connectivity analysis

Flood inundation method for analyzing the hydrological connectivity of lakes in WJL

Some flood waters are considered water resources in the IRLSN scheme. A source-flood method (Wang et al., 2010) can be used for flood inundation analysis. In this study, when flood level (H) is given, the flood inundation area has been calculated by seed filling algorithm used in a previous study (Wang et al., 2010), as follows:

a) With known starting grid unit (grid unit with dike break position) and flood level (H), initial a queue structure, add starting grid unit to the queue;

b) Pop first element (grid unit) of the queue, check "up, down, left, right" four nearby grid units in DEM, if grid unit elevation is lower than flood level(H), then add this grid unit to the queue;

c) If the queue is not null, go to step 2, else go to step 4;

d) Output queue, all grid units in queue compose the submerged area.

Watershed delineation method

Watershed delineation is one of the most commonly performed activities in hydrological analyses. Digital elevation models (DEMs) provide good terrain representation, from which watersheds can be derived automatically using GIS

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technology. In this study 1:50000 scale DEM was used for watershed delineation, followed by merging sub-watersheds in WJL according to different water supply resources; allowing different regional hydrological connectivity to be determined.

Grading of wetland water supply requirements by AHP method

The Analytic Hierarchy Process (AHP) (Saaty, 1980) was used to establish the indexed grading system for wetlands. The procedure of using the AHP method, as described by Wang et al. (2003) , included: (a) establishing the index system; (b) constructing the judgment matrix and single permutation of layer; (c) sequencing the ~~al~~ layers; and (d) drading of single element and comprehensive evaluation. Then the natural breaks classification method in the Arcgis technique was used to assign the grades of water supply requirements of the wetlands.

In WJL, the calculation range of wetland ecological water requirement was the wetland in different hydrological connectivity and grading regions. The sum of ecological water requirement of lake, reservoir, and other open water and water requirement of marsh wetland is shown below:

$$D=\sum A_i(ET_i-P)\times 10^{-3} \qquad \text{(Eq.1)}$$

Where: D represents ecological water requirement (m^3); A_i is the area of each part (m^2); ET_i represents the evapotranspiration of each part (mm); and P represents the precipitation of each part (mm).

Results and Discussion

The hydrological connectivity regionalization

Considering different sources of water supply, and combining flood inundation analysis with subwatershed delineation results, the regions that are hydrologically connected have been identified, as shown in *Figure 2*. Flood waters that generated flow into the 216 wetlands in WJL has also been identified (*Table 1*).

The flood water from Nenjiang River artesian flow connected region, Tao’er River artesian flow connected region, Huolin River artesian flow connected region and Second Songhua River artesian flow connected region were found to be Nenjiang River, Tao’er River, Huolin River and Second Songhua River, respectively. Additionally, the water levels corresponding to each of these water supply sources were 131 m, 141.2 to 221.6 m, 152 m, and 175 m, respectively. In addition to flood waters, water sources to the wetland included water diversion from Nenjiang River to Baicheng, and water diversion from Tao’er River to Xianghai and Hadashan hydro junction. The water diversion project from Nenjiang River to Baicheng was dependant on water lifting, and

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the water level of the main channel needed to reach 133m, which could artesianly flow into the channel artesian flow connected region. The function of Yangshapao reservoir was to store the water in the project, and the normal impounded water level was 135.2 m. So, 135.2 m was considered as a threshold of artesian flow, and through the flood inundation analysis, the water level for water lifting was 141 m. For water diversion project from Tao’er River to Xianghai, when the water level reached 175.4 m, the water artesianly supplied the channel artesian connected region. Chuangye resorvoir, used to store water, is located at high geographical position; its water level of 163m artesianly supplied the lakes in its waterhsed. At Hadashan hydro junction, water was diverted from Tao’er River to Huaaopao Lake, and the normal diversion water level was 141 m. The normal water level of Huaaopao was 139 m, which was also considered as a threshold of artesian flow. When the water lifting level reached 154 m, the water supplied Huaaopao Lake lifting the connected region.

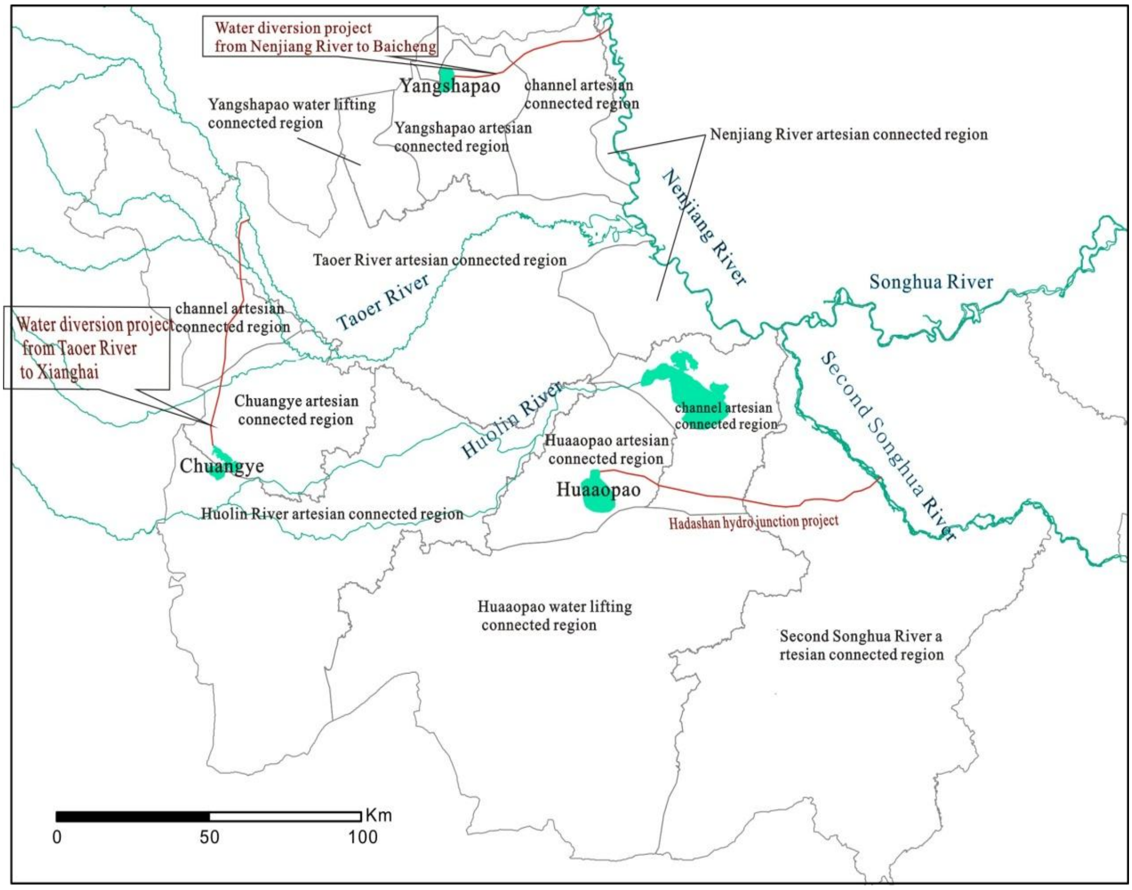

__Figure 2.__ Hydrological connected regions in WJL

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Table1. *Water level of different water supply sources for hydrological connected regions*

Name of hydrological connected regions		**Water level elevation as source of supply (m)**
Nenjiang River artesian connected region		131
Tao’er River artesian connected region		downstream,141.2; upsream, 221.6
Huolin River artesian connected region		152
Second Songhua River artesian connected region		175
Water diversion project from Nenjiang River to Baicheng (NB) connected region	NB channel artesian connected region	133
	Yangshapao Reservoir artesian connected region	135.2
	Yangshapao Reservoir water lifting connected region	141
Water diversion project from Tao’er River to Xianghai (TX) connected region	TX channel artesian connected region	175.4
	Chuangye Reservoir artesian connected region	163
Hadashan hydro junction (HD) connected region	HD channel artesian flow connected region	129
	Huaaopao Lake artesian connected region	139
	Huaaopao Lake lifting connected region	154

Grading of water supply requirements by wetlands

Indices for evaluating

The establishment of the evaluation index system was the key of AHP. Combining the hydro-geomorphology, ecological characteristics and function, and influence of human activities, a grading system was derived to signify water supply requirements by the wetlands in WJL (*Table 2*).

Table 2. *Indexes for evaluating water supply grading for wetlands*

Target hierarchy	Criteria hierarchy	Indices hierarchy
Grading of water supply requirements by wetlands in WJL (A)	Hydro-geomorphology (C1)	The type of water source (P1)
		Distance to water source (P2)
		Geomorphic conditions (P3)
		Relative altitude to water source (P4)
	Wetlands’ characteristics (C2)	Normal storage capacity (P5)

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	Normal storage level (P6)
	water surface area (P7)
Wetlands' function (C3)	regulation capacity of flood (P8)
	Water supply capacity (P9)
	Matter production capacity (P10)
Influence of human activities (C4)	Distance to residential area (P11)
	Distance to farmland (P12)

Scheme of AHP weighting for the indices

After establishing the evaluation index system, the relations among various layers and factors were placed in comparing matrixes that had the ratios of comparative importance of paired factors. Then, the values of the relative weight were calculated. Finally, Matlab was used to calculate the weight of each index according to AHP; resuls shown in *Table 3*.

Table 3. *Weights Scheme for each index*

Weight of Ci	Weight of Pi
(C1) 0.564	(P1) 0.3265
	(P2) 0.0897
	(P3) 0.1162
	(P4) 0.0316
(C2) 0.263	(P5) 0.1086
	(P6) 0.0684
	(P7) 0.0860
(C3) 0.118	(P8) 0.0648
	(P9) 0.0284
	(P10) 0.0248
(C4) 0.055	(P11) 0.0275
	(P12) 0.0275

Grading of water supply requirements of wetlands

Using the comprehensive evaluation method, the composite index of each wetland was calculated. The natural breaks classification method in the Arcgis technique was used to finally determine the water supply grading for wetlands; results shown in *Figure 3*.

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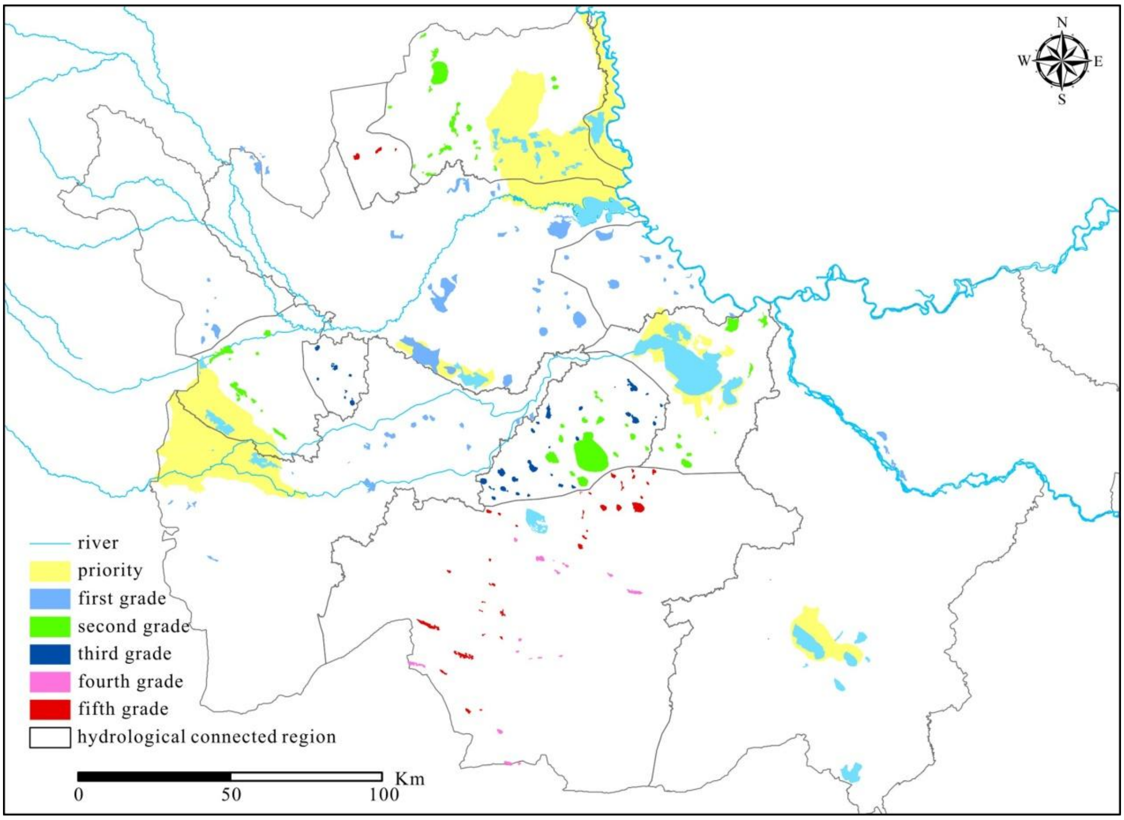

Figure 3. *Water supply grading for wetlands in WJL*

According to the grading results in *Figure 3*, the national or provincial wetland nature reserve (Chagan Wetland, Momoge Wetland, Xianghai Wetland, Niuxintaobao Wetland, Dabusu Wetland and Boluo Wetland) should be prioirities for water supply in the IRLSN scheme. The first grade lakes were mainly near the river. The second and third grade lakes were mostly located near the Water diversion projects. The fourth and fifth grade lakes were at the south of WJL, where the water source was primarily rainfall and surface runoff.

Regionalization and Grade Calculation of Wetlands Ecological Water requirement in WJL

According to the regionalization and grading result, the corresponding ecological water requirement of wetlands was calculated. The ecological water requirements of Chagan Wetland, Momoge Wetland, Xianghai Wetland(national natural wetlands), and Niuxintaobao Wetland, Dabusu Wetland and Boluo Wetland (provincial nature reserves), were found to have the minimum ecological water requirements in WJL. The ecological water requirements of rest open water of lakes, ponds, reservoirs and adjacent marsh wetlands extracted from 2012 landuse map (*Figure 4*) were considered as suitable ecological water requirement in WJL. The maximum ecological water requirements were

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the sum of suitable ecological water requirements and the ecological water requirements of adjacent marsh wetlands extracted from 1950s landuse map (*Figure 4*), and the adjacent mash wetlands were only the the area of marsh wetlands (in 1950s' landuse map) that were converted to saline-alkali soil lands in 2012 landuse map (*Figure 4*).

Through the statictical analysis of monthly precipitation and evaporation from 1960 to 2014 in 10 counties (cities), the monthly precipitation and evaporation under 25%, 50%, 75%, and 90% guarantee rate in each counties (cities) were determined. Sheng et al. (2007) found that the conversion coefficient between evaporation measured by a small evaporation pan and water surface evaporation was 0.5-0.6. In this study, the conversion coefficient was found to be 0.6. In marsh wetlands, the main vegetation was found to be *Phragmites* that typically grow between April and September in WJL. Thus, the ecological water requirement of marsh wetlands were only calculated between April and September. The evaporation was calculated by the 2.5 times of water surface evaporation from June to August, and 1.3 times in April, May and September (Tang et al., 2005). The ecological water requirement of lakes and marshes in each region and grading calculated in this study are shown in *Tables 4*, *5* and *6*.

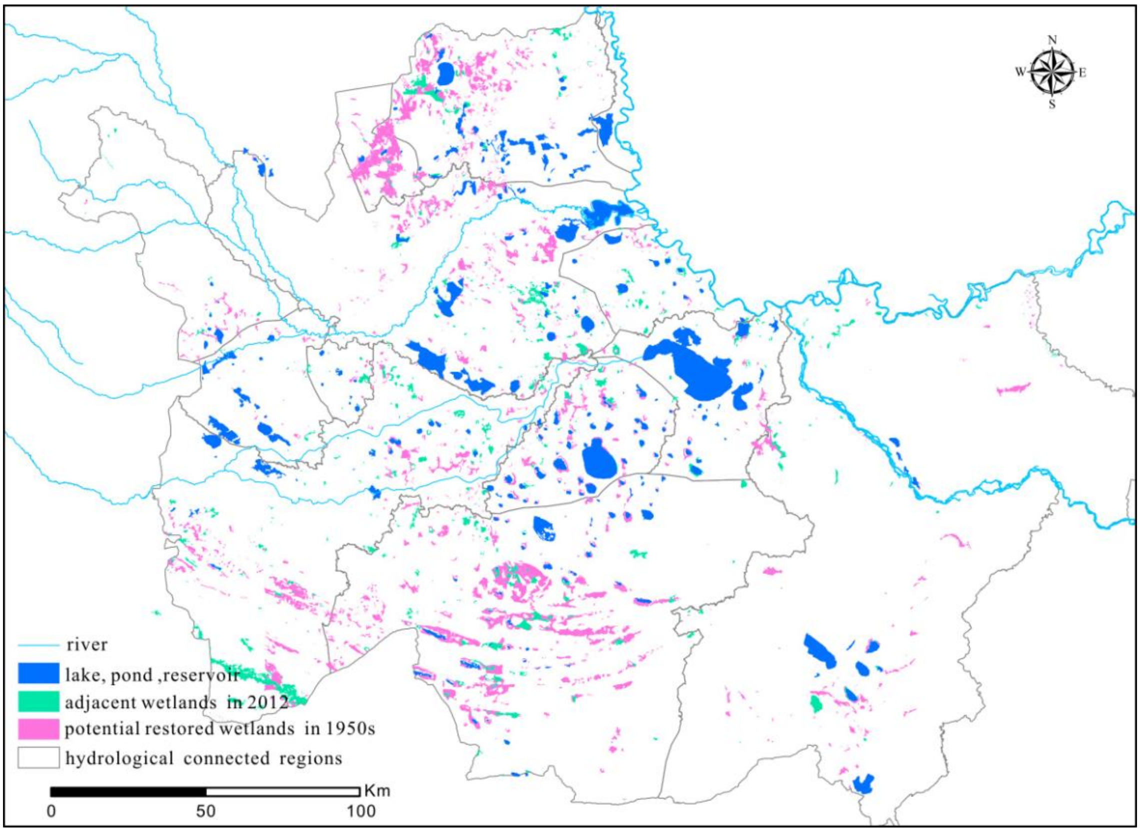

Figure 4. *Distribution of existing and potential restoring wetlands of WJL*

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Table 4. *Minimum ecological water requirements in WJL*

Water supply grade	**name**	**Hydrological connected region**	**Ecological water requirement of open water (10^6m^3)**				**Ecological water requirement of marsh wetland（10^6m^3）**			
			25%	**50%**	**75%**	**90%**	**25%**	**50%**	**75%**	**90%**
priority	Chagan wetland	HD channel artesian flow connected region	-34.16	55.28	115.57	168.10	11.57	22.03	29.45	36.08
	Momoge wetland	NB channel artesian connected region	-0.52	74.66	136.72	178.30	156.96	263.77	357.31	424.62
	Xianghai wetland	TX channel artesian connected region	0.42	26.54	40.36	52.11	41.58	71.98	90.42	106.69
	Niuxintaobao wetland	Tao’er River artesian connected region	0.33	10.64	18.37	24.95	9.23	14.31	18.55	22.22
	Boluohu wetland	Second Songhua River artesian connected region	-24.47	82.66	178.80	241.82	-24.49	82.66	178.80	241.82
	Dabusu wetland	Huaaopao Lake lifting connected region	0.72	8.60	13.46	18.23	36.96	58.62	72.78	87.10
subtotal			-57.70	258.38	503.28	683.51	231.83	513.36	747.31	918.54
total			174.13	771.74	1250.60	1602.06				

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Table 5. *Suitable ecological water requirement in WJL*

Water supply grade	**Hydrological connected region**	**Ecological water requirement of open water ($10^6 m^3$)**				**Ecological water requirement of marsh wetland ($10^6 m^3$)**			
		25%	**50%**	**75%**	**90%**	**25%**	**50%**	**75%**	**90%**
first	Nenjiang River artesian connected region	0.26	1.19	20.73	28.20	11.43	19.20	26.01	30.92
	Second Songhua River artesian connected region	-6.13	2.46	10.95	16.49	17.70	34.66	47.54	60.03
	Tao'er River artesian connected region	10.73	64.74	104.42	137.49	41.13	66.38	86.36	102.41
	Huolin River artesian connected region	0.20	12.19	18.71	24.25	73.00	126.38	158.74	187.32
second	Yangshapao Reservoir artesian connected region	-0.15	21.79	39. 90	52.03	23.45	39.41	53.39	63.45
	Chuangye Reservoir artesian connected region	2.85	9.41	13.88	17.84	2.56	4.43	5.56	6.56
	Huaaopao Lake artesian connected region	-1.43	19.59	31.07	41.98	14.16	22.46	27.89	33.37
	HD channel artesian flow connected region	-0.89	9.77	16.58	22.97	9.61	18.28	24.44	29.95
third	Huaaopao Lake artesian connected region	-0.95	13.06	20.71	27.99	9.44	14.98	18.59	22.25
	Chuangye Reservoir artesian connected region	1.48	4.76	7.01	9.01	3.92	6.78	8.52	10.08
fourth	Huaaopao Lake lifting connected region	-2.17	16.08	29.49	40.21	24.63	41.16	57.02	68.22
fifth	Huaaopao Lake lifting connected region	-1.17	8.66	15.88	21.65	13.26	22.16	30.70	36.74
	Yangshapao Reservoir water lifting connected region	-0.01	1.85	3.39	4.42	1.23	2.08	2.81	3.34
subtotal		2.62	185.57	332.74	444.53	245.53	418.38	547.60	654.63
total		248.16	603.95	880.34	1099.16				
Minimum ecological water requirement		174.13	771.74	1250.60	1602.06				
Suitable ecological water requirement		422.29	1375.69	2130.94	2701.22				

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Table 6. *Maximum ecological water requirement in WJL*

Water supply grade	**Hydrological connected region**	**Ecological water requirement of marsh wetland（10^6m^3）**			
		25%	**50%**	**75%**	**90%**
priority	Chagan wetland	0	0	0	0
	Momoge wetland	47.45	82.08	103.10	121.67
	Xianghai wetland	253.60	0.42	26.54	40.36
	Niuxintaobao wetland	15.59	24.16	31.32	37.52
	Boluohu wetland	2.62	5.88	9.75	12.23
	Dabusu wetland	0	0	0	0
first	Nenjiang River artesian connected region	7.45	12.52	16.96	20.15
	Second Songhua River artesian connected region	32.58	63.82	87.52	110.52
	Tao’er River artesian connected region	97.70	157.65	205.11	243.22
	Huolin River artesian connected region	96.70	167.39	210.26	248.12
second	Yangshapao Reservoir artesian connected region	125.05	210.14	284.67	338.30
	Chuangye Reservoir artesian connected region	7.13	12.35	15.51	18.31
	Huaaopao Lake artesian connected region	34.53	54.75	67.98	81.35
	HD channel artesian flow connected region	6.67	12.70	16.98	20.80
third	Huaaopao Lake artesian connected region	23.02	36.50	45.32	54.23
	Chuangye Reservoir artesian connected region	2.02	3.49	4.39	5.18
fourth	Huaaopao Lake lifting connected region	116.72	195.10	270.26	323.34
fifth	Huaaopao Lake lifting connected region	95.17	159.08	220.37	263.65
	Yangshapao Reservoir water lifting connected region	24.37	40.95	55.47	65.93
total		988.34	1239.00	1671.52	2004.89
Suitable ecological water requirement		422.29	1375.69	2130.94	2701.22
Maximum ecological water requirement		1410.63	2614.69	3802.46	4706.11

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Overall, results from this study demonstrate that the minimum ecological water requirement in WJL was 174.13, 771.74, 1250.60, 1602.06 million m^3 under the precipitation guarantee rate of 25%, 50%, 75%, 90%, respectively. The suitable ecological water requirement in WJL was 422.29, 1375.69, 2130.94, 2701.22 million m^3 under the precipitation guarantee rate of 25%, 50%, 75%, 90%, respectively. The maximum ecological water requirement in WJL was 1410.63, 2614.69, 3802.46, 4706.11 million m^3 under the precipitation guarantee rate of 25%, 50%, 75%, 90%, respectively. Among the wetlands being studied, 54% were identified as priorities for water supply , first grade was about 24%. Among the first grade of suitable ecological water requirements, the Tao’er River artesian connected region accounted for about 39%, and Huolin River artesian connected region accounted for about 41%. The critical sources of water supply to most lakes and marsh wetlands were Tao’er River and Huolin River. Currently, water supplies from these two rivers are rapidly decreasing; this poses a significant risk to the ecological function of the wetlands in WJL.

Conclusion

This study proposed and tested a method for determining the hydrological connectivity and grades of water supply requirements by wetlands in WJL. The ecological water requirement of wetlands in WJL can be classified into three categories: minimum, suitable, maximum. In a hydrological connectivity analysis, WJL was found to consist of 12 hydrological connected regions. Twelve indicators were selected to establish the evaluation index system of wetlands water supply grading in WJL, and 6 grades were determined. The minimum ecological water requirement in WJL was 1.74×10^8, 7.72×10^8, 12.51×10^8, 16.02×10^8 m^3 with precipitation guarantee rate of 25%, 50%, 75%, 90%, respectively. The suitable ecological water requirement in WJL was 4.22×10^8, 13.76×10^8, 21.31×10^8, 27.01×10^8 m^3 with precipitation guarantee rate of 25%, 50%, 75%, 90%, respectively. The maximum ecological water requirement in WJL was 14.11×10^8, 26.15×10^8, 38.02×10^8, 47.06×10^8 m^3. Effective utilization of flood water, as a resource, was found to be essential for supplying water to sustain the lakes and marsh wetlands in WJL.

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