

# Estimation of ecological flow requirement in Zoige Alpine Wetland of southwest China

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**Abstract** In many vulnerable wetlands, water is the most crucial factor for sustaining human development, economic growth, as well as existence and evolution of various indigenous ecosystems. This has led to intensive competitions against limited water resources and caused a number of potentially adverse effects on local ecosystems and human society. As water demand by human activities is increasing, balancing water demands between human society and ecosystems is desired to improve economic development without causing too much disturbance on the environment and ecosystems within a wetland. In this study, a computationally efficient quantitative method was developed to calculate the ecological flow requirement (i.e., water demand by ecosystems) in an alpine wetland of western China. The proposed method was also carried out by means of remote sensing images interpretation. Through this method, variations in water demands by human beings and ecosystems could be reflected and analyzed, which would be useful in helping formulate water allocation strategies under multiple objectives such as environmental protection, economic development, and ecological conservation. The method was then applied to assess ecological

flow requirements in Zoige Wetland of western China. The results indicated that to maintain the basic ecological structure and integrity of the wetlands, the minimum reserve of 6.218 billion m<sup>3</sup>/a and a suitable reserve of 6.639 billion m<sup>3</sup>/a of water would be required. Also, the application results indicated that the method is applicable and can be expanded to other similar wetlands for balancing water demands between ecosystems and human beings.

**Keywords** Ecological flow requirement · Quantitative estimation · Zoige Wetland

## Introduction

Due to combined effects of global warming and human disturbance, areas of many wetlands are shrinking greatly across the world (Schneider and Eugster 2007; Rebelo et al. 2009; Rossell et al. 2009). At the same time, in many developing countries like China, desertification is a very serious problem particularly in the vicinity of vulnerable wetlands, worsening the environment in these wetlands and threatening existence and evolution of many indigenous ecosystems. For addressing these problems, water is the most crucial factor that needs to be systematically considered not only within human society but also among local ecosystems. This leads to intensive competition against limited water resources between human beings and ecosystems, calling for quantitative evaluation of water availability to maintain ecological integrity in a wetland with the consideration of human water demand. Therefore, it is necessary to propose effective quantitative methods for estimating and evaluating water resources that are inherently necessary to indigenous ecosystems in a wetland.

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Over the past decades, many studies were conducted for investigating and evaluating water quantity that was necessary to various wetland ecosystems. In these studies, the concept of ecological flow requirement was proposed and defined as a certain amount of water that would be needed to be purposefully reserved in or released into the stream channel for maintaining existence and evolution of aquatic and wetland ecosystems (King et al. 2002; Chen and Zhao 2011). Based on such a concept, there were an increasing number of studies on evaluating ecological flow requirement and incorporating them into the integrated management of water resources (Cui et al. 2009; James et al. 2009; Sisto 2009; Tan et al. 2009, 2010a, b). Considering the diversities in structures, functions and locations of ecosystems, a number of methods were used for estimating ecological flow requirement worldwide such as those based on hydrological (Hughes and Hannart 2003; Li et al. 2009), hydraulic (Wadeson and Rowntree 1998; Liu et al. 2005), and habitat simulation processes (Orth and Leonard 1990), as well as the ones based on hybrid or integration of these methods (Tharme 2003). Among them, a major advantage of hydrological index methods is that the ecological flow requirement can be efficiently calculated without too many requirements on data availability. For example, a typical hydrological method was developed by Hughes and Hannart (2003). They assumed that the ecological flow requirement would decrease along with increasing flow variability, and would increase with an increasing base flow. Their method was widely used to estimate ecological flow requirement when addressing water resource planning problems in South Africa. However, the hydrological methods could not reflect relationships between hydrological indices and ecological processes (Gordon et al. 2004). As an extension of the previous hydrological methods, Cui et al. (2010) proposed an integrated modeling framework to calculate ecological flow requirement through investigating and analyzing variations of ecological habitats under varied water levels. Within such a framework, water level threshold for maintaining ecological integrity could be identified. However, these methods required a diverse range of input data (e.g. biological, geological and socio-economic aspects), which might be difficult to be obtained in real-world cases.

More recently, a few researchers put efforts in the evaluation of ecological flow requirement in many lowland and coastal wetlands (Kashaigili et al. 2007). Comparatively, there have been few reports on the estimation of ecological flow requirement in the alpine wetlands due to the unavailability of data in these wetlands. However, most of these wetlands are of great significance in hydrological cycles and are mainly sources of great rivers. They are playing an important role in maintaining ecological balance not only in the upper plateau but also in the downstream rivers. Therefore, identification and analysis of the most suitable

ecological flow requirement is essential to maintain the existence/evolution of the ecosystems and promote economic development in the basins of these wetlands. This is essentially true in China's Zoige Wetland, the biggest peat highland wetland in the world. As it is located in the source region of the Yangtze River and the Yellow River, Zoige Wetland is called "the kidney of northeastern plateau in China". Also, it poses an important role in maintaining hydrological and ecological balance in the two basins for reducing flooding intensity and improving water holding capacity. Furthermore, it almost has the richest biodiversities in the world. Thus, studies on Zoige Wetland is of great importance because of its ecological and geographical uniqueness, as well as its vulnerability under constant threats of human disturbance (Yan and Wu 2005). Particularly, in recent years, the quantity of water resources in Zoige Wetland is decreasing continuously, further speeding up degeneration and desertification trends of marshes and would finally affect the health of ecosystems in Yellow River and Yangze River Basins. Therefore, it is urgent for achieving sustainable management of water resources with the consideration of necessary ecological flow requirement in the region. Till now, studies on this topic in Zoige Wetland have been scarcely reported. From both theoretical and practical points of view, it is desired to employ an applicable and effective method to evaluate the ecological flow requirement in the region. In detail, the ecological flow requirement could be divided into two interactive components: inner- and off-stream requirement (Qian et al. 2000; Wang 2000; Miao et al. 2003; Liu et al. 2004). The inner-stream requirement contains the minimum stream run-off that is required for preventing water interception of rivers or dry-up of lakes and supplementing water loss due to the evaporation from water surface (Liu et al. 2004). The off-stream requirement is the water amount that could satisfy fundamental water requirement for maintaining the existence and evolution of various ecosystems. Based on theory analysis and real-world verifications, this method possesses the merits of clarity in concept and high-efficiency in computation. However, there were still some disadvantages that were associated with the previous studies, including (a) most of them focused on rough estimation of ecological flow requirement in plain regions with a monotonic ecosystem, (b) most of the previous studies were based on parameters that were identified in site-specific regions or wetlands, and (c) there was a lack of studies that could reflect complex conflicts on water resources in a wetland like Zoige that is not only a source of great rivers, but also critical to many preciously indigenous ecosystems. Thus, quantitative estimation of the ecological flow requirement in Zoige Wetland is desired not only to the ecosystems in local regions, but also for water resources utilization and flooding control in the downstream of Yellow River and Yangze River Basins.

Therefore, the objectives of this study are to: (a) analyze hydrological and meteorological data to quantify the inner-stream ecological flow requirement over a long-term period, (b) combine the effects of land use variations with evapotranspiration of various vegetations to quantify off-stream ecological flow requirement, and (c) calculate the total ecological flow requirement in Zoige Wetland based on the results of inner- and off-stream ecological flow requirement, and then analyze and compare each component of the ecological flow requirement with the consideration of a number of water management policies and strategies.

**Methodology**

Conventionally, the total ecological flow requirement in the wetland can be estimated through a two-step method for consistently calculating two correlated components, i.e., the off- and inner-stream ones. As ecosystems particularly vegetations may consume plenty of soil water in addition to effective precipitation, they need to draw a certain amount of water from the soil. Thus, the off-stream ecological flow requirement mainly refers to the water amount that would be necessary for meeting the fundamental requirement of vegetation’s survival, accounting for a large part of the total available water. Through analyzing land use types and the corresponding variations, the ecological water consumption mechanism of different vegetation types in Zoige Wetland can be comprehensively studied. Meanwhile, the inner-stream ecological flow requirement is the minimum water amount to maintain the ecological balance of lakes and rivers for preventing dry-up and interception. Considering the inherent functions of rivers and other water bodies, the inner-stream ecological flow requirement can be further decomposed into two parts, including (a) the minimum stream flow to prevent river interception and lake dry-up, and (b) the stream flow to supplement evaporation from water surface. Therefore, the total ecological flow requirement could be presented by the following equation:

$$W = W_{\text{off}} + W_{\text{in}} \tag{1}$$

where  $W$  is the total ecological flow requirement ( $\text{m}^3$ ),  $W_{\text{off}}$  is the off-stream ecological flow requirement ( $\text{m}^3$ ), and  $W_{\text{in}}$  is the inner-stream ecological flow requirement ( $\text{m}^3$ ).

**Off-stream ecological flow requirement**

Based on the existing water resource allocation patterns, considering the balance between socio-economic and environmental benefits, the calculation method (Zuo 2002) for estimating off-stream ecological flow requirement can be presented as follows:

$$W_{\text{off}} = \sum w_i = \sum A_i r_i \tag{2}$$

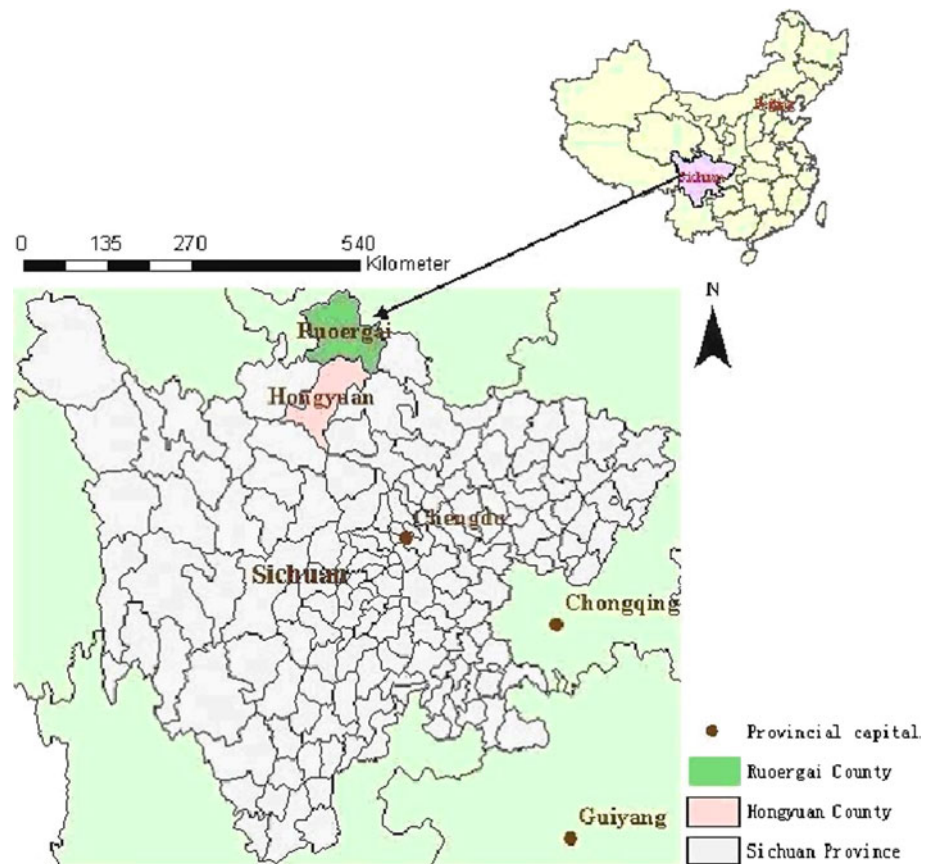
where  $w_i$  is off-stream ecological flow requirement of each type of vegetation ( $\text{m}^3$ ),  $A_i$  is the area of each type of vegetation ( $\text{hm}^2$ ), and  $r_i$  is ecological water demand quota ( $\text{m}^3 \text{hm}^{-2}$ ).

In this study, a series of remote sensing images in 2005 is interpreted based on eCognition software to carry out qualitative analysis of land use variations of Zoige Wetland (Fig. 1). The land use/cover of Zoige Wetland can be quantitatively analyzed (Figs. 2, 3). In the study area, the main vegetation types are grassland and woodland. The grassland can be broadly classified into three types, which are high, medium and low coverage grasslands. The woodland can be further classified into three types, which are forest, shrub and sparse forest land. Different types of vegetation have varying evapotranspiration capacities and water consuming mechanisms. Thus, the ecological flow requirement of vegetations can be calculated with the adoption of ecological water demand quota. The product of the ecological water demand quota and the area is the ecological flow requirement for a specific type of vegetation. In this paper, the evapotranspiration of grassland in each month (Yang and Zhong 1994) is considered as the water demand quota of high coverage grass land (Table 1). According to the previous research studies (Min and Geng 2005), the water demand quota of medium coverage grass land can be set to 70% of that of high coverage grassland while that of low coverage grassland can be set to 70% of that of medium coverage grass land. On the other hand, the main tree species in forest land of Zoige Wetland include fir and spruce, both of which are conifers. Thus, we used the evapotranspiration of coniferous species in each month (Cheng and Chen 2003) as the water demand quota of forest land. The water demand quota of shrub land can be set to 80% of that of forest land. As sparse forest land is the type to be reconstructed, its water demand quota is regarded as the same as that of forest land (He et al. 2004).

**Inner-stream ecological flow requirement**

As for the surface water, the inner-river ecological flow requirement refers to the water demand volume for maintaining ecological function of surface water bodies, which may vary with time and space. Generally, it is considered as the water demands for maintaining basic ecological structure and function of an ecosystem in a river (King et al. 2002). In this paper, the stream run-off to prevent interception and/or dry-up in rivers and lakes and the stream flow to supplement evaporation from water surface are considered as the inner-stream ecological flow requirement, which can be presented as follows:

**Fig. 1** Location of Zoige Wetland



$$W_{in} = W_r + W_e \quad (3)$$

where  $W_r$  is the run-off to prevent water interception of rivers and lakes ( $m^3$ ), and  $W_e$  is ecological flow requirement of evaporation ( $m^3$ ).

#### *Run-off to prevent river interception or lake dry-up*

As a significant factor for maintaining river ecosystem function, the flow of rivers should be kept to a basic threshold, i.e. a certain range of water levels, which can be considered as the run-off to prevent the draught-up of rivers and shrinking of lakes. Some researchers calculated multi-year average run-off as the ecological flow requirement (Tu et al. 2009; Tennant 1976; Wang 2005). According to the previous studies of Tennant (1976), 10% of average run-off could approximately cover 60% of the bottom of a river. Average water level and average velocity should be 0.3 m and 0.23 m/s, respectively. It suggested that such run-off is the threshold to sustain the health of aquatic ecosystems, especially fishes. When the run-off rise from 30 to 100%, coverage of bottom would increase by 40% and the average water level and average velocity would rise to 0.61 m and 0.61 m/s, respectively. This represents the range of the most suitable conditions for supporting living activities of aquatic ecosystems.

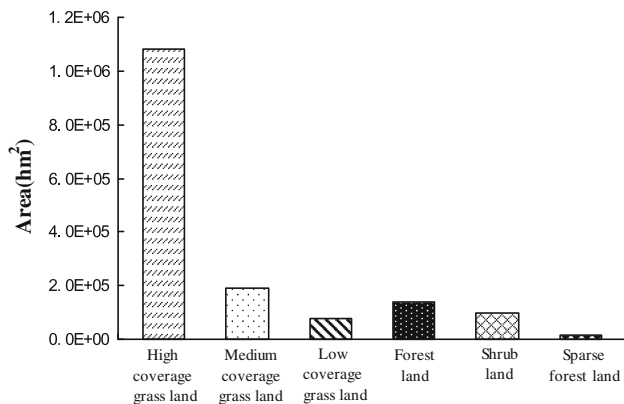
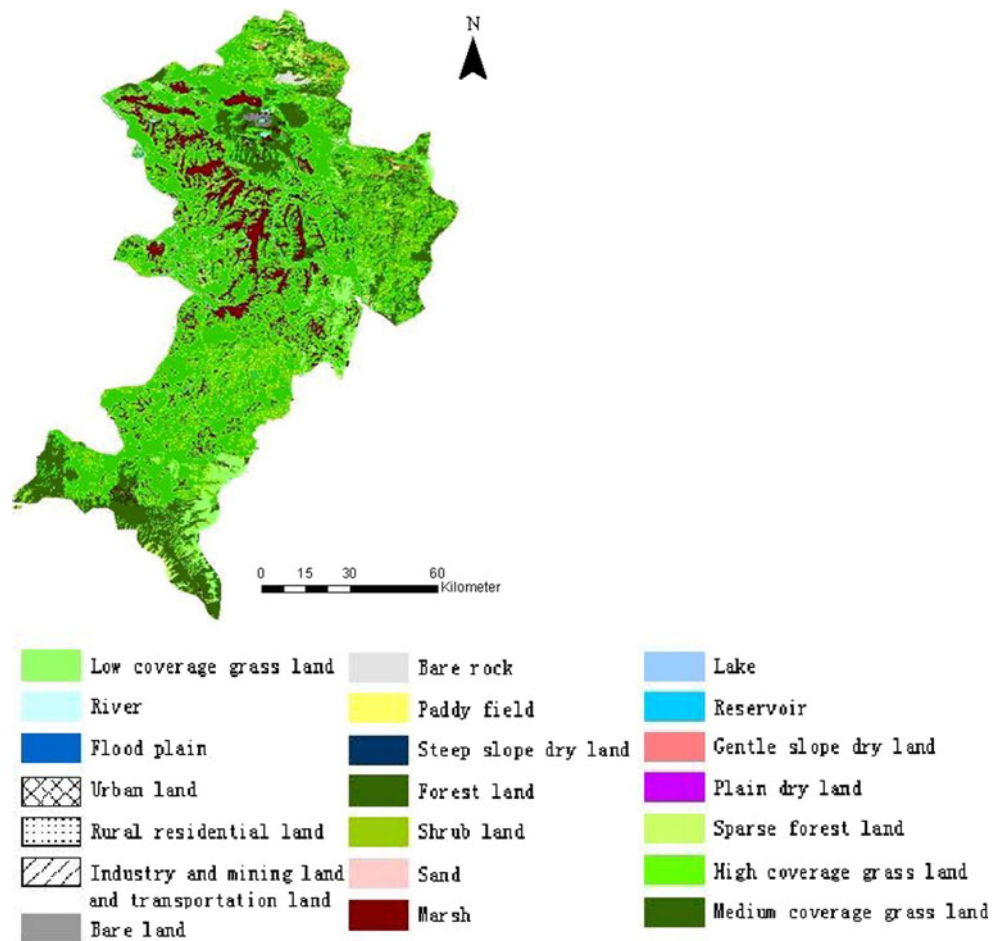
Accordingly, a certain range of multi-year average run-off could be used to determine the ecological flow requirement in a specific river. As Zoige Wetland is located in a cold-temperature highland region, the percentage in this situation should be further customized according to the analysis of local hydrological regimes and the relevant data series. In this paper, 30% of average run-off is considered to be the minimum ecological flow requirement, while 60% of that is considered as the most suitable ones for ecosystems (Wang 2005). Besides, run-off during the icebound season (i.e., from December in the previous year to March of the next year) should be excluded.

As Black River and White River are the main surface water bodies in Zoige Wetland, the multi-year average run-offs in each month of the two rivers are used to compute the ecological flow requirement. The hydrological data was obtained from Dashui and Tangke hydrologic stations (Fig. 4).

#### *Ecological flow requirement to supplement surface evaporation*

When the evaporation from water surface surpasses the precipitation, the wetlands need to supplement the loss from other sources for maintaining ecological health status. The volume to be considered into the wetlands due to

**Fig. 2** Land use/cover of Zoige Wetland (Pang et al. 2010)



**Fig. 3** Areas of landscape types in Zoige Wetland (hm<sup>2</sup>)

evaporation can be referred as part of the evaporation ecological flow requirement. And when the amount of precipitation is more than that of evaporation, the evaporation ecological flow requirement is considered to be equal to zero. Based on the area of wetlands, precipitation and evaporation, the evaporation ecological flow requirement in each month can be estimated as follows (Yang et al. 2005):

$$W_e = \begin{cases} A(E - P) & (E > P) \\ 0 & (E < P) \end{cases} \quad (4)$$

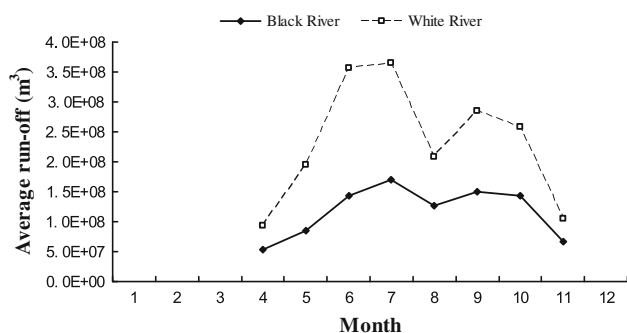
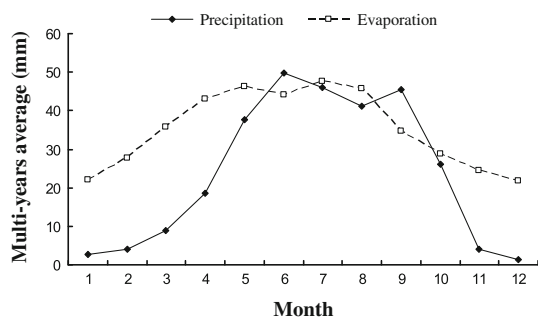
where  $A$  is the water area (km<sup>2</sup>),  $E$  is the average evaporation (mm);  $P$  is average precipitation (mm). From the interpretation results of the remote sensing data (Fig. 2), the total areas of wetlands in the study area is 2,081.72 km<sup>2</sup>. The multi-year average evaporation and precipitation amounts in Zoige Wetland can be acquired in Fig. 5.

### Estimation of ecological flow requirement in Zoige Wetland

Zoige Wetland, which is located between 102°29'E and 102°59'E longitude and 33°25'N and 24°80'N latitude, covers an area of 16,670.6 hectares with the elevation range of 3,450–3,700 m. It is one of the typical plateau wetlands, and plays an indispensable role in the hydrological cycle of western China. In this research, a representative case is screened out, which contains in Ruorgai and Hongyuan Counties of Aba State in Sichuan Province (i.e., Fig. 1). The

**Table 1** Annual ecological water demand by vegetation types

Item	High coverage grass land ( $\text{m}^3 \text{hm}^{-2}$ )	Medium coverage grass land ( $\text{m}^3 \text{hm}^{-2}$ )	Low coverage grass land ( $\text{m}^3 \text{hm}^{-2}$ )	Forest land ( $\text{m}^3 \text{hm}^{-2}$ )	Shrub land ( $\text{m}^3 \text{hm}^{-2}$ )	Sparse forest land ( $\text{m}^3 \text{hm}^{-2}$ )
Jan.	146.17	94.57	58.45	199.17	154.17	199.17
Feb.	211.99	136.69	83.98	320.99	248.99	320.99
Mar.	450.61	288.61	175.21	391.61	295.41	391.61
Apr.	526.53	312.93	163.41	498.53	361.73	498.53
May.	588.39	299.19	96.75	202.39	86.79	202.39
Jun.	412.12	139.42	0.00	0.00	0.00	0.00
Jul.	556.20	251.70	38.55	161.20	37.20	161.20
Aug.	535.13	251.03	52.16	91.13	0.00	91.13
Sep.	114.25	0.00	0.00	164.25	40.65	164.25
Oct.	290.88	125.28	9.36	0.00	0.00	0.00
Nov.	186.31	118.21	70.54	157.31	117.71	157.31
Dec.	144.95	97.25	63.86	119.95	93.15	119.95
Total	4,163.53	2,114.88	812.27	2,306.53	1,435.80	2,306.53

**Fig. 4** Average stream run-off of Black River and White River ( $\text{m}^3$ )**Fig. 5** Average precipitation and evaporation in Zoige Wetland (mm)

main rivers in the study area are Black River and White River. They originate in the mountain areas and flow into the Yellow River, which cover  $6,780 \text{ km}^2$ . Average annual precipitation in the wetland ranges from 560 to 860 mm (Yong et al. 2003; Qiu et al. 2009), which exceeds its average annual evaporation value (i.e., 450 mm).

Approximately 85% of the residents in Zoige Wetland are Tibetan who, as nomads, have lived on grazing over thousands of years. Totally, 73% of Zoige Wetland has

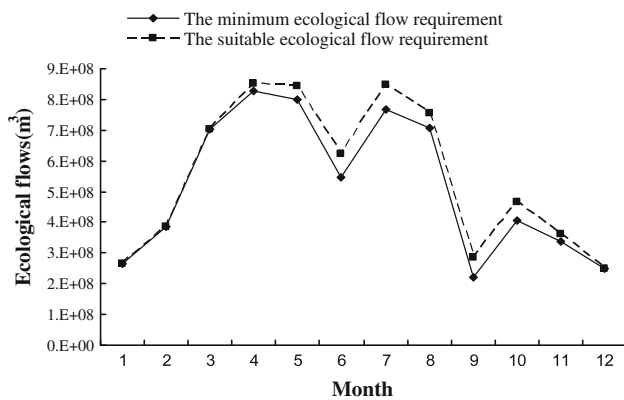
been used for grazing. In the past three decades, the increase of population and development of social economy has been associated with a continuously increasing need for livestock and grassland resources. In the wetland, the overgrazing rate has amounted to 62.52% by the end of 2003, not only resulting in destruction of soil and vegetation, but also leading to serious losses of soil moisture. Since the 1960s, the area of the wetland has been noticed with gradual shrink due to the digging of ditches, which is normally used to drain the wetland for extending the grassland. Severe consequences of the activities have been observed with intensified degeneration of the wetland area and severe losses of soil moisture. Compared with economic boom in other areas of China, the wetland region is still backward in economy, resulting in dual pressures to local government for protecting eco-environment and stimulating economic development. To maximize the utilization of water resources for economic development without causing irreversible effects on local ecosystems due to water shortage, decision makers need to identify and evaluate the compromising decisions with the consideration of economic, environmental and ecological targets. This makes it imperative for helping local government investigate the ecological flow requirement to promote effective water resources management measures.

In detail, in this research, the inner-stream ecological flow requirement is firstly analyzed based on average monthly hydrological data for both Black River and White River in multiple years, as well as meteorological data in Ruorgai and Hongyuan Counties. The former one is obtained from Dashui and Tangke hydrologic stations and the latter one is acquired from the National Meteorological Information Center. Also, to further analyze the land use changes in Zoige Wetland, the German eCognition

object-oriented software is adopted to interpret the Landsat TM images since 2005, through which the off-stream ecological flow requirement can be accurately estimated.

Based on the historical meteorological and hydrological data and the remote sensing interpretation results in 2005, the values of the monthly ecological flow requirement from the computation processes described above can be presented in Fig. 6. It is shown that, due to the special characteristics of groundwater icebound-thawing circulation and vegetation growth laws in plateau wetland, the water demands for various ecosystems of the study area are concentrated from April to October. As precipitation and evaporation are important factors to influence water supply, monthly variations of the ecological flow requirement would have corresponding changes. In Fig. 5, June and September are the only 2 months when the precipitation exceeds evaporation. Correspondingly, the 2 months are the extreme minimum points of water demands. The summary of the monthly outputs is shown in Table 2. The results indicate that to maintain ecosystems in Zoige Wetland in a healthy condition, 6.218 billion m<sup>3</sup>/a would be required as the minimum value of ecological flow requirement for a year. Totally, 6.639 billion m<sup>3</sup>/a would be the suitable value of the ecological flow requirement, of which the off-stream ecological flow requirement would be the primary component within the total one in a year.

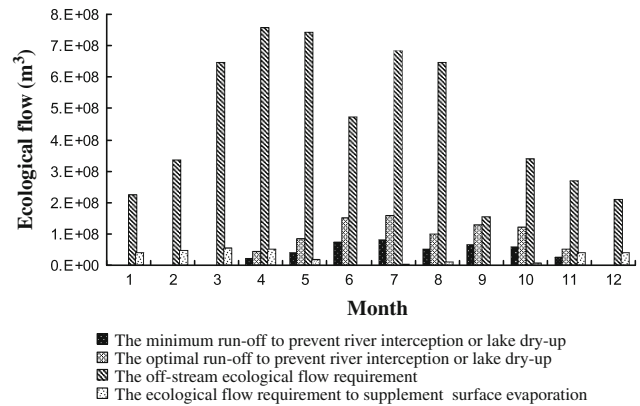
Furthermore, each part of the monthly ecological flow requirements are analyzed and shown in Fig. 7. It can be seen that the off-stream ecological flow requirement almost accounts for a majority of the total in each month, which is far greater than the inner-stream one. Because of the ice-bound season, only the stream run-off to prevent river and



**Fig. 6** The monthly minimum and suitable ecological flow requirement in Zoige Wetland (m<sup>3</sup>)

**Table 2** Components of the ecological flow requirement in Zoige Wetland (10<sup>8</sup> m<sup>3</sup>)

Item	W (minimum)	W (optimal)	W <sub>in</sub> (minimum)	W <sub>in</sub> (optimal)	W <sub>off</sub>
Ecological flow requirement for a year (10 <sup>8</sup> m <sup>3</sup> )	62.18	66.39	7.40	11.61	54.78



**Fig. 7** Components of average monthly ecological flow requirement (m<sup>3</sup>)

lake dry-up from March to November is incorporated into the ecological flow requirement. In summer season, the water requirement is relatively high. While the evaporation loss in this period is lower than that in winter season, this is because annual rainfall concentrates in summer season.

Obviously, the ecological flow requirement in Zoige Wetland can be successfully calculated through the above mentioned two-step method. Remote sensing is the major tool to obtain input data for this method. Considering the study scale of this research (i.e., the entire Zoige Wetland), this is probably one of the most economical and feasible way to acquire input data. Also, at the wetland scale, landscape patterns (e.g., variations of vegetation coverage) are external indicators of the structure and integrity of indigenous ecosystems. They are quite stable and are significantly affected by water availability. This makes it possible to estimate ecological water demand based on variations of landscape patterns which could be obtained through analyzing remote sensing data. However, remote sensing data could be mainly used for large-scale studies. Verification would be necessary under a smaller research scale. On-site monitoring is currently undertaken in a part of this wetland, which could be potentially a solid support for verifying remote sensing data in future studies.

**Conclusions**

In this study, a quantitative method was developed for effectively estimating ecological flow requirements in wetlands. Through this method, variations in land use types and vegetation coverage can be successfully reflected and

analyzed. Also, water resources for supporting ecosystems in the wetlands could be considered and evaluated. The method was then applied to Zoige Wetland in southwestern China, which was the first attempt in similar areas. The results indicated that a minimum reserve of 6.218 billion  $\text{m}^3/\text{a}$  and a suitable reserve of 6.639 billion  $\text{m}^3/\text{a}$  of water should be necessary to maintain basic ecological functions in the wetland. In detail, the suitable reserve for ecosystems comprising the off- and inner-stream ecological flow requirement (5.478 and 1.161 billion  $\text{m}^3/\text{a}$ , respectively). Apparently, the off-stream ecological flow accounted for the majority of this value.

Due to the disturbance of human activities, such as the digging of ditches to drain water from wetland for grazing, Zoige Wetland has been in a water loss condition after the 1970s. Blocking the ditches through the construction of new hydropower projects to prevent the water loss would be the most effective measure for improving available water resources. Moreover, plants that physiologically demand less water resources should be introduced to reduce the total water consumption. Furthermore, adjusting and optimizing the water resource allocation between ecosystems and human beings should be adopted, such as the adjustment of livestock population. The ecological flow requirement in the wetland could be recognized as a critical factor for identify strategies in achieving sustainable water resources management. The results indicated that the method could be applied to other wetlands with similar problems. Further research works will be conducted through coupling hydrological and ecological processes for more accurate quantification of ecological flow requirement in Zoige Wetland in the near future.

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