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Evaluation of Sustainable Environmental Flows Based on the Valuation of Ecosystem Services: A Case Study for the Baiyangdian Wetland, China

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ABSTRACT. Using China's Baiyangdian Wetland as a case study, we evaluated the sustainable level of environmental flows for the wetland based on a statistical relationship between the ecosystem service values and hydrological data. We used canonical correlation analysis to reveal the relationships between seven major ecosystem services (gross production of agriculture, fish and reeds; water supply; recreation; culture; habitat protection; climate regulation; and water purification) and a hydrological dataset (annual inflows, annual outflows, mean annual water elevation, 7-day low elevation, duration of the flood pulse, and number of days of extreme drought) from 1980 to 2005. Using this approach, we established a gray relationship matrix to reveal the influence of the hydrological parameters on the ecosystem services value. Using the hydrological parameters shown to significantly influence the ecosystem services values as the set of environmental flows, we evaluated the sustainable environmental flows by mean of cubic spline interpolation between data points to identify the maximum wetland ecosystem services value. The results were justified by referring to the natural hydrological regime in the 1960s and 1970s. Based on the results of this comparison, our approach provides an effective way for managers to regulate the flows of water to satisfy the wetland's environmental flow requirements while also obtaining the maximum socioeconomic benefit.

Keywords: environmental flows, ecosystem services value, canonical correlation, gray relationship matrix, interpolation

1. Introduction

Water is a strategic resource for humans as well as for wetland ecosystems (Naiman and Dudgeon, 2011). The importance of maintaining wetland hydrology for ecosystem services has been widely recognized (Bunn and Arthington, 2002). Environmental flows, which represent the water flows required to sustain freshwater ecosystems and the human livelihoods and well-being that depend on these ecosystems, can be described using parameters such as the quantity, timing, and quality of the flows. These parameters provide important management guidance for the restoration and reconstruction of wetland hydrology (Korsgaard, 2006; Powell et al., 2008; Yang and Mao, 2011).

Some researchers have evaluated environmental flows in terms of their ability to sustain specific values such as fish or vegetation diversity and biomass or to restore ecosystem structure (Young et al., 2000; Mawhinney, 2003; Hou et al., 2007; Sisto, 2009; Wang and Yang, 2010; Yang, 2011a; Bai et al., 2012). However, approaches oriented towards single factors result in only a partial and limited consideration of the full range of consequences for the wetlands and the humans, plants, and animals that depend on them. Other researchers have attempted to restore environmental flows so that they more closely resemble the natural flow regime (Lytle and Poff, 2004; Powell et al., 2008), but this approach is difficult to implement in wetland management due to conflicts with human needs, such as the need to withdraw water for irrigation; moreover, this approach neglects the socioeconomic values provided by wetlands.

During the last two decades, ecosystem services have become a popular scientific topic. Ecosystem services have been defined as "the benefits that people derive from ecosystems" (MEA, 2005). The valuation of ecosystem services assigns a monetary value to the services provided by an ecosystem based on the supply of market and non-market values by identifying the total cost of a service (a readily comparable metric), thereby accounting for both ecological and human welfare (Jenerette et al., 2006; Burkhard et al., 2010). Development and resource-allocation decision processes are increasingly under pressure to account for the values of these services in order to maximize both the economic and the environmental outcomes (Barbier et al., 1991; Grêt-Regamey et al., 2008; Egoh et al., 2011). Since the 1990s, attention has been paid to the relationship between wetland hydrology and one or more specific ecosystem services provided by a wetland (Gren et al., 1995; Turpie and Joubert, 2001). For example, Mawhinney (2003) proposed restoring biodiversity in the Gwydir Wetlands through better management of the environmental flows. Crossman et al. (2010) used ecosystem services valuation tools to reconfigure an irrigated

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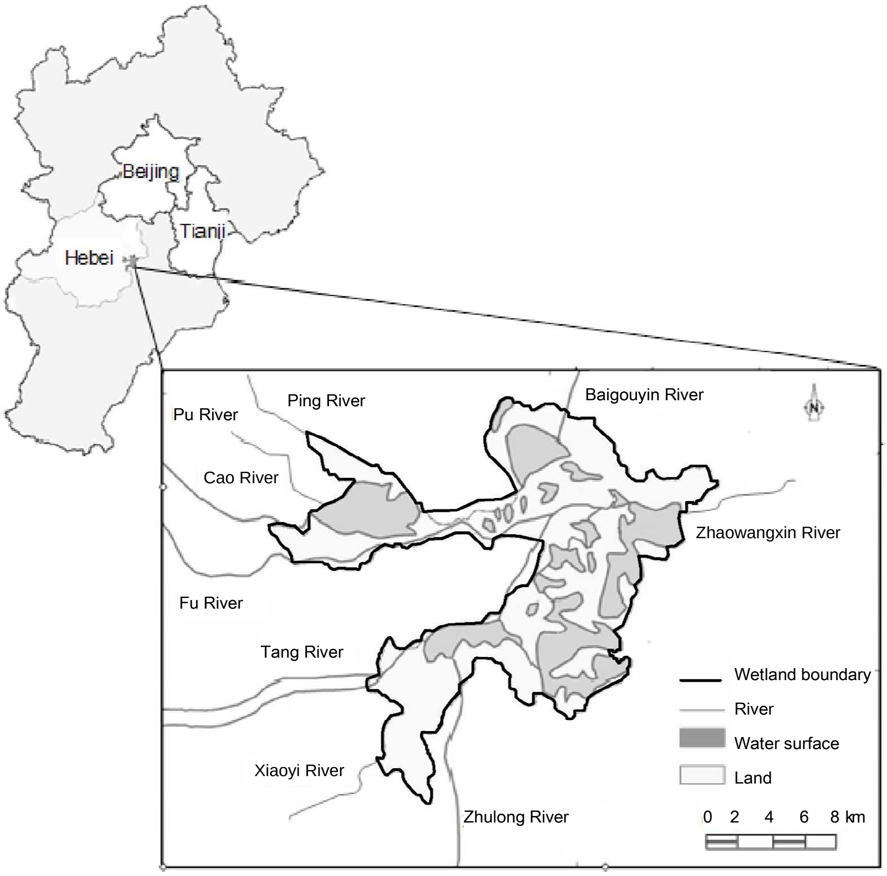

Figure 1. The location of the Baiyangdian Wetland and its associated rivers. Water areas are based on a water level elevation of 7.0 m (relative to the Dagu height datum located at Tianjin). The thick black line represents the maximum extent of the wetland at a water elevation of 10.0 m.

landscape to operate with less water. Smith-Adao et al. (2011) assessed the relationships between a riverine ecosystem and the available water supply to achieve a possible win-win situation for both the environment and human uses of the environment.

Despite a broad range of publications about wetland-specific ecosystem services and the effects of hydrological alterations (Mawhinney, 2003; Hou et al., 2007; Ojeda et al., 2008; Smokorowski et al., 2011; Nedkov and Burkhard, 2012), there have been few assessments of the relationships between a holistic ecosystem services value that accounts for a range of services and the environmental flows associated with that value (Yang, 2011b). Few studies have analyzed the capacity for sustainable environmental flow management to maintain ecosystem functioning and services (Olsen, 2007; Karanja et al., 2008). However, the existing studies have been complex and difficult to implement in practice, and wetlands managers need easily understandable, explicit tools and schemes to support optimal management from a holistic perspective.

In this study, using China's Baiyangdian Wetland as a case study, we developed an analytical framework to evaluate the sustainable environmental flows for a wetland. We used canonical correlation analysis and gray relationship analysis to reveal the relationships between the wetland's ecosystem services value and hydrological data, and used a nonlinear curve-fitting approach to evaluate the sustainable ranges of values for key hydrological parameters, thereby revealing the range of sustainable environmental flows that is possible under the existing constraints. This research provides more useful results than those provided by an approach based on supplying the minimum environmental flows (Zhao et al., 2005; Neubauer et al., 2008; Zhong et al., 2008) because it accounts for ecologically crucial aspects of these flows such as the timing, magnitude, and duration of key hydrological events. Our goal was to develop an analytical framework that can support practical hydrological management of wetlands such as the Baiyangdian Wetland based on seeking a feasible compromise between human and ecological needs.

2. Study Area

The Baiyangdian Wetland (38°43' to 39°02' N, 115°45' to 116°07' E) is the largest shallow freshwater lake wetland in northern China. It is located in Anxin County of Hebei Province (Figure 1). The wetland consists of more than 100 small and

Table 1. Ecosystem Functions, the Associated Economically Valuable Goods and Services, and the Estimation Methods Used to Quantify the Value of these Services

Function	Economically valuable goods and services	Technique used to quantify services
Gross production	Production of valuable food and fiber for harvest	Market prices method
Water supply	Water supply for domestic, industrial, and agricultural uses	Market prices method
Recreation	Sites for sightseeing, recreation, and travel	Travel cost method
Culture	Sites for scientific research	Costanza coefficients*
Habitat protection	Sites for improvement of commercial and recreational fisheries	Costanza coefficients*
Climate regulation	Regulation of the regional macroclimate	Carbon tax
Water purification	Reduced costs of water treatment (i.e., the reduction in the volume of water required for purification)	Replacement cost

* Costanza et al. (1997)

Table 2. The Six Hydrological Parameters in this Study and their Description

Hydrological parameter	Description
Inflows	Inflows include precipitation, several small streams, and intermittent artificial releases of water by the watershed's managers.
Outflows	Outflows refer to the lake's outlet stream, which flows intermittently.
Mean water elevation	The average elevation of the water surface during the calendar year.
7-day low elevation	The lowest elevation for any period of 7 consecutive days during a given calendar year.
Duration of the flood pulse	This parameter represents the number of continuous days with the highest water elevation during a given calendar year.
Days of extreme drought	This parameter represents the number of continuous days with the lowest water elevation during a given calendar year.

shallow sub-areas linked by thousands of natural channels, covering a total surface area of 362.8 km^2. Aquatic vegetation is dominated by reeds. A total of 39 villages are distributed sporadically throughout the wetland area, creating a complex mosaic of terrain and landforms. The precipitation in the Baiyangdian Wetland (a long-term mean of 560 mm per year, with 80% of that precipitation falling between June and September) is characterized by a 16-year periodicity, with alternation between dry and wet periods (Cui et al., 2010). These cycles greatly affect the depth of the lakes, particularly during the summer months. Prior to 1960, the wetland was dominated by natural flows. Since then, dams and reservoirs have been constructed upstream to provide a more reliable supply of water for domestic, industrial, and agricultural uses in the watershed (Li et al., 2004). From 1999 onwards, water flows into the wetland were dominated by withdrawals of this water by the watershed's managers, often leaving insufficient water to sustain the wetland's environmental flows (Yang et al., 2011). As a result of these withdrawals, the lake has become a semi-closed water body with no natural outflows.

The wetland plays several important roles, such as providing habitats for native plants and animals, water purification, protection against floods, and amenities such as esthetics and recreational opportunities (Yang, 2011b). In recent years, water interception by dams upstream of the wetland and excessive water use by the inhabitants of the watershed have resulted in decreasing water depth in the Baiyangdian Wetland, and this has had serious adverse impacts on the dense reed vegetation, which is an important economic resource for local citizens. Between 1960 and 1994, the area of reeds decreased by 44.3%, from a peak of 84.60 km^2 to 47.13 km^2. This is both a statistically significant and an economically significant decrease, since inhabitants of the wetland rely on fishing, agriculture, and harvesting of macrophytes (particularly reeds) for their livelihoods. Agriculture is the most common livelihood within the watershed, with water-intensive rice cultivation the most significant form of agriculture. In previous studies (e.g., Yang, 2011b), no set of sustainable environmental flows could be recommended to the wetlands managers for the restoration and rehabilitation of the ecosystem services.

3. Methods

3.1. Data Collection

3.1.1. Ecosystem Services Valuation

We selected five valuation methods that were best suited to the characteristics of each service: we used the market prices method, the travel-cost method, Costanza coefficients, carbon tax values, and the replacement cost method to evaluate seven kinds of wetland ecosystem services values (Table 1) from 1980 to 2005. For details of the equations and computational processes that we used, see our previous publication (Yang, 2011b).

In the present study, we defined the water supply as the quantity used to directly support humans (i.e., excluding agricultural water use), thereby avoiding the problem of double-counting water that would be consumed in the form of agricultural products. The travel cost method (Woodward and Wui, 2001) was used to evaluate the recreation services provided by the Baiyangdian Wetland. We introduced a dimensionless standardized price index (D) to eliminate the influence of rising prices and inflation. Thus, comparable ecosystem services values could be obtained by calculating the values in each year and

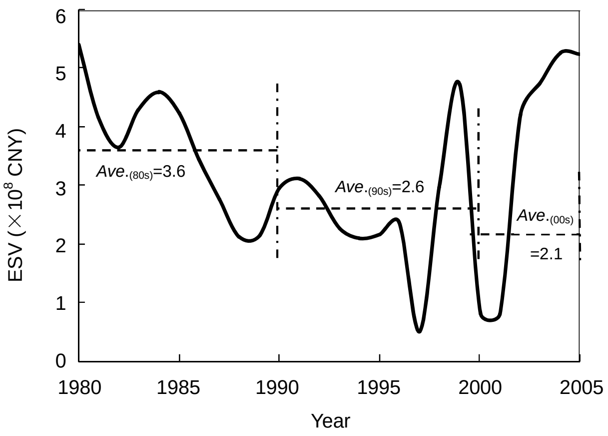

Figure 2. The ecosystem services value (ESV) from 1980 to 2005 for the Baiyangdian Wetland.

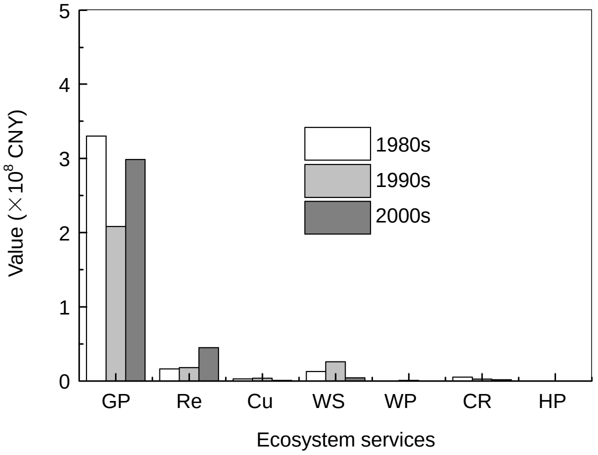

Figure 3. The components of the total ecosystem services value (ESV, standardized using the holistic price index) in the 1980s, 1990s, and 2000s. GP, gross production; Re, recreation; Cu, culture; WS, water supply; WP, water purification, CR, climate regulation; HP, habitat protection. (All services are defined in Table 1.)

dividing them by the dimensionless standardized price index:

$$ESV = ESV' / D \tag{1}$$

in which *ESV* is the standardized (adjusted) total value of ecosystem services, *ESV'* is the calculated total ecosystem services value in a given year, and *D* is a holistic price index (which adjusts costs for the effects of inflation) for China's Hebei Province, which we obtained from Guan and Jiang (2005). *D* ranged from 1.00 to 3.59 during the study period.

3.1.2. Hydrological Data

The data we used to describe the hydrology of the Baiyangdian Wetland during the 26-year period from 1980 to 2005 was provided by the Baoding Hydrographic Bureau, and corresponds to the period for which we calculated the ecosystem services values. Although a wide range of potential hydrological indicators can be used in our study, we selected six critical factors using principal-components analysis (Smith, 2002) from the larger set of indicators proposed by Richter et al. (1996, 1997). The hydrology of the wetland can be described in terms of the components of its water budget, such as inflows and outflows of water, as well as by state parameters such as the water surface area, the elevation of the water surface (i.e., the depth of the water), and the water volume (Table 2). In addition, process parameters such as water-level fluctuations, periodicity, flood pulses, and extreme drought events should be accounted for when describing the wetland's hydrological regime.

3.2. Canonical Correlation Analysis

We used the multivariate statistical technique of canonical correlation analysis to explore the relationships between the ecosystem services values and the corresponding hydrological data. We used Wilk's lambda and chi-square tests of statistical significance to identify the significant parameters in the canonical relationships. To perform this analysis, we used version 18 of SPSS for Windows (SPSS Inc., Chicago, IL).

3.3. Gray Relationship Analysis

Gray relationship analysis, which is also referred to as "gray correlation analysis", aims to determine whether variables are correlated and the degree of their correlation (Liu and Yu, 2007; Xiong et al., 2010). Appendix I provides a detailed description of the calculation method. Briefly, the gray relationship coefficient ε_{ij} represents the degree of influence of a reference series (*j*) on a comparison series (*i*), and takes the form of a relative distance. The smaller the distance, the greater the influence on the comparison series (Liang et al., 2007; Chen and Ou, 2009). As a pre-processing step, each data series was normalized by dividing the respective data from the original series by their average before calculating the gray relational coefficients.

4. Results

4.1. Changes in the Ecosystem Services Value

Figure 2 shows the changes in the values of ecosystem services from 1980 to 2005 for the Baiyangdian Wetland, with the values adjusted (standardized) using a holistic price index to facilitate comparisons. The total ESV exhibited irregular fluctuations, but showed an overall decreasing trend; the ESV decreased from an average of 3.6 × 10^8 CNY during the 1980s to 2.6 × 10^8 CNY during the 1990s and a further decrease to 2.1 × 10^8 CNY in the 2000s. However, these averages conceal key aspects of the inter-annual fluctuations, such as an overall decrease from 1980 until about 1997, followed by two increases (separated by a large decrease) between 1997 and 2005 to around the value at the start of the study period.

Among the components of the total ecosystem services value, the largest was the gross production value (Figure 3), which consists of the production of food, fiber, and fish for harvest, followed by the recreation and water supply values (whi-

Table 3. Autocorrelations in the Hydrological Data Set (all values significant at P < 0.05)

Variables	Inflows	Outflows	Mean water elevation	7-day low elevation	DFD*	Days of extreme drought
Inflows	1.00	0.93	0.52	0.44	0.56	-0.31
Outflows		1.00	0.45	0.41	0.58	-0.21
Mean water elevation			1.00	0.80	0.62	-0.78
7-day low elevation				1.00	0.84	-0.84
Duration of the flood pulse					1.00	-0.55
Days of extreme drought						1.00

* DFD: Duration of the flood pulse.

Table 4. Autocorrelations in the Ecosystem Services Value Data Set (all values significant at P < 0.05)

Variables	Gross production	Recreation	Culture	Water supply	Water purification	Climate regulation	Habitat protection
Gross production	1.00	0.40	0.04	-0.05	-0.02	0.35	0.04
Recreation		1.00	-0.27	-0.20	-0.14	-0.40	-0.27
Culture			1.00	0.97	0.94	0.36	0.98
Water supply				1.00	0.96	0.14	0.97
Water purification					1.00	0.15	0.94
Climate regulation						1.00	0.36
Habitat protection							1.00

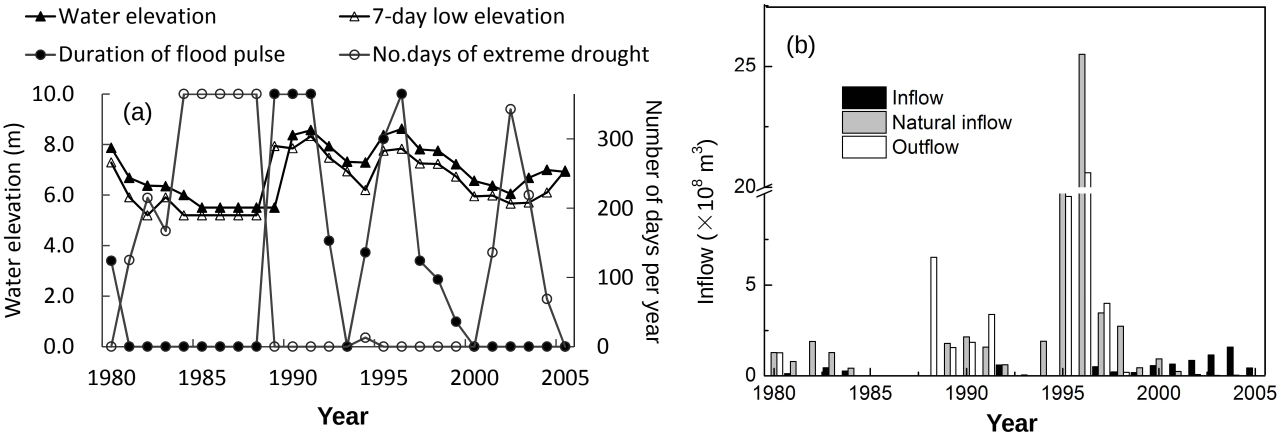

Figure 4. The hydrological changes in the Baiyangdian Wetland from 1980 to 2005. (a) Key hydrological parameters and (b) inflows (artificial inflow plus natural inflow) and outflows. The elevation values represent the mean wetland surface level above the Tianjin height datum (shown in Figure 1).

ch accounted for 3.7 to 8.7% and 1.6 to 2.2% of the total ESV from 1980 to 2005). The components of gross production had the following mean values from 1980 to 2005: crops accounted for 65% of the total, followed by 22% for reeds, 12% for fish, and 1% for other products.

4.2. Hydrological Data Changes

Figure 4a summarizes the changes in four key hydrological parameters (mean water elevation, 7-day low elevation, duration of the flood pulse, and number of days of extreme drought) from 1980 to 2005. Inflows to the lake include precipitation, the contributions from several small streams or rivers, and intermittent artificial releases of water from upstream reservoirs by the watershed's managers. A drought has occurred since 1999, so natural inflows into the wetland were nearly zero (Figure 4b); therefore, maintenance of the wetland's aquatic ecosystem has increasingly depended on artificial water releases. There were 13 emergency releases into the Baiyangdian Wetland between 1981 and 2005, with amounts ranging between 0.12 × 10^8 and 1.50 ×10^8 m^3 (Figure 4b). The water elevation remained relatively constant at a high level (8.20 to 8.30 m) for most of the year from 1988 to 1990 and in 1996; in other years, water levels fluctuated greatly, reaching values lower than 6.0 m in many years. Outflows from the wetland have been close to zero since 1999 (Figure 4b), but before that year, outflows were often significant, with a maximum outflow of 20.6 × 10^8 m^3 in 1996, versus an average of 2.59 × 10^8 m^3 before 1999. However, the lake has become a semi-closed water body with no natural outflows since 1999. The 7-day low elevations followed the same trend as the mean water elevation, which can be attributed to the current management pattern, which was de-

Table 5. Correlations (Rc), Standardized Canonical Coefficients, Canonical Correlations, Percentages of Total Variance Explained, and Redundancies between the Ecosystem Services Value and the Hydrological Data

	First canonical variate		Second canonical variate	
	Canonical loading	Standardized canonical coefficient	Canonical loading	Standardized canonical coefficient
Hydrological data set				
Inflows	-0.48*	0.40	0.14	-1.85
Outflows	-0.48*	-0.34	0.39*	2.13
Mean water elevation	-0.96*	-0.91	-0.15	-0.92
7-day low elevation	-0.87*	-0.39	0.21	-0.82
Duration of the flood pulse	-0.73*	-0.022	0.417*	0.84
Days of extreme drought	0.72*	-0.27	-0.097	-1.18
Percentage of variance explained		53%		7%
Redundancy analysis		26%		0.3%
Ecosystem services value set				
Gross production	0.25	200	-0.50*	-16.95
Recreation	0.10	5.92	-0.40*	-8.00
Culture	-0.74*	0.0027	-0.004	0.00029
Water supply	-0.87*	-0.25	0.025	-0.22
Water purification	-0.84*	-0.99	-0.096	-0.30
Climate regulation	0.29	-1.95	-0.041	-0.52
Habitat protection	-0.74*	-0.0027	-0.004	0.00029
Percentage of variance explained		38.5%		5.9%
Redundancy analysis		14%		0.024%
R_c	0.96		0.84	
R_c^2	0.92		0.71	

* Cutoff for interpretation of significant parameters = 0.30; R_c, canonical correlation.

signed only to satisfy the minimum environmental flows (the minimum water elevation) required by the wetland.

4.3. Relationships between the Hydrological Data and the Ecosystem Services Value

We used canonical correlation to examine the relationships between the hydrological and ecosystem value parameters by examining the number of reliable canonical functions, the magnitudes of the canonical correlations, the significance of the canonical correlations, and the structure of each parameter set that maximized the relationship between the sets (Hair et al., 1998). Tables 3 and 4 show the auto-correlations in each set. For the hydrological data set, the strongest positive correlations (≥ 0.8) were inflows with outflows, mean water elevation with 7-day low elevation, and 7-day low elevation with duration of the flood pulse; the strongest negative correlations (≤ – 0.8) were mean water elevation and 7-day low elevation with the number of days of extreme drought. For the ecosystem services value, the strongest positive correlations (≥ 0.8) were culture with water supply, water purification, and habitat protection; water supply with both water purification and habitat protection; and water purification with habitat protection. There were no strong negative correlations (≤ – 0.8).

We also computed the canonical correlation coefficients between the ecosystem services value as a set of predicted variables and the hydrological data as a set of criterion variables. Table 5 summarizes the standardized canonical coefficients, the percentage of total variance accounted for by each set, and the redundancies. Table 5 shows that the strength of the relationship between the two sets of variables could be assessed by the magnitude of the canonical correlation coefficients. Of the six canonical correlations that we computed, only the first two canonical variates were statistically significant ($p < 0.01$). The canonical correlation (R_c) for the first variate was 0.96, and this variate accounted for approximately 45.8% of the overlapping variance (Wilk's $\lambda = 0.004$, $\chi^2(42) = 100.25$, $p < 0.001$), and the second canonical correlation was 0.84 and accounted for 6.4% of the overlapping variance (Wilk's $\lambda = 0.052$, $\chi^2(30) = 53.302$, $p < 0.005$). These results indicate that the first canonical variate was moderately strongly related to the ecosystem services value, but the second variate was only weakly related. The sum of the first two canonical variates accounted for 60.0% of the variability in the hydrological parameter set and 44.4% of the variability in the ecosystem services value parameter set.

A cutoff score of 0.30 has been suggested as the minimum acceptable canonical loading value when interpreting the component variables of a given canonical variate (Lambert and Durand, 1975; Tabachnick and Fidell, 2007). These values are identified with an asterisk in Table 5. All of the variables in the hydrological data set had a meaningful contribution to the first canonical variate based on this criterion. However, for the ecosystem services value data set, gross production, recreation, and climate regulation did not contribute meaningfully to the first canonical variate. These results suggest that the first canonical variate relates primarily to hydrological parameters.

Only two variables in the hydrological data set had a mea-

Table 6. Identification of the Dominant Hydrological Parameters

	Hydrological parameters					
j	Inflows (j =1)	Outflows (j = 2)	Mean water elevation (j = 3)	7-day low elevation (j = 4)	Duration of the flood pulse (j = 5)	Days of extreme drought (j = 6)
r_j	5.9645	5.9509	6.0438	6.041	5.7877	5.623
Rank	3	4	1	2	5	6

* $r_j = \Sigma a_{ij}$

ningful contribution to the second canonical variate (outflow and the duration of the flood pulse). Only two variables in the ecosystem services value set had a meaningful contribution to the second canonical variate (gross production and recreation). These results suggest that the second canonical variate relates primarily to the direct-use value component of the ecosystem services.

4.4. The Set of Dominant Environmental Flows

We created a relational matrix for the relationships between the hydrological dataset and the ecosystem services value dataset using the gray relationship method. The matrix of $A_{7\times6} = \{a_{ij}\}$ is shown below (for $i = 1$ to 7, representing gross production, recreation, culture, water supply, water purification, climate regulation, and habitat protection, respectively, and $j = 1$ to 6, representing inflows, outflows, mean water elevation, 7-day low elevation, duration of the flood pulse, and days of extreme drought, respectively). Most of the relationships were strong ($r > 0.8$), with the exception of the relationships between habitat protection and the duration of the flood pulse and the number of days of extreme drought, and the relationship between water purification and the number of days of extreme drought:

$$A_{7\times6} = \begin{vmatrix} 0.8836 & 0.8836 & 0.8836 & 0.8836 & 0.8838 & 0.8838 \\ 0.8790 & 0.8789 & 0.8791 & 0.8791 & 0.8810 & 0.9913 \\ 0.8313 & 0.8308 & 0.8344 & 0.8341 & 0.8567 & 0.8422 \\ 0.8274 & 0.8243 & 0.8280 & 0.8280 & 0.8322 & 0.8347 \\ 0.8393 & 0.8362 & 0.8513 & 0.8499 & 0.8201 & 0.7343 \\ 0.8550 & 0.8547 & 0.8568 & 0.8566 & 0.8718 & 0.8751 \\ 0.8489 & 0.8394 & 0.9106 & 0.9097 & 0.6421 & 0.5716 \end{vmatrix}$$

Table 6 summarizes the dominant hydrological data that are potential factors in management of the wetland's environmental flows. From Table 6, $r_3 > r_4 > r_1 > r_2 > r_5 > r_6$. Based on this result, mean water elevation has the highest priority among the six hydrological parameters, followed by the 7-day low elevation, inflows, outflows, duration of the flood pulse, and the number of days of extreme drought.

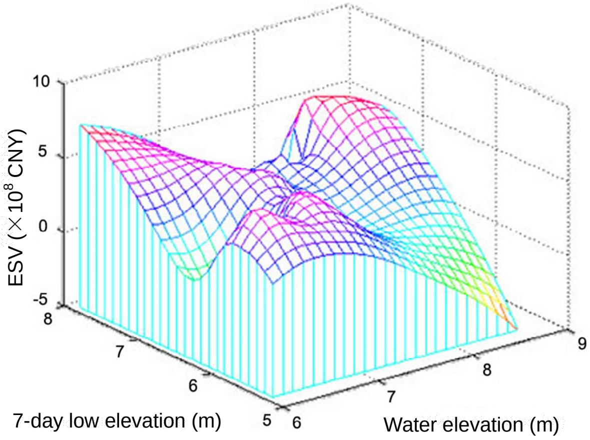

Figure 5. Relationships between the total ecosystem services value (ESV) and two key hydrological parameters (mean annual water elevation and the 7-day low elevation).

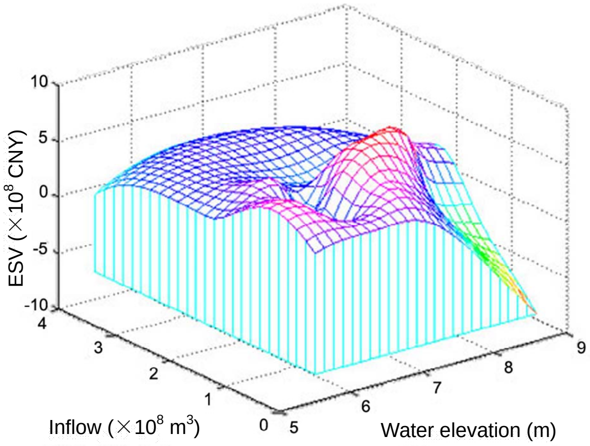

Figure 6. Relationships between the total ecosystem services value (ESV) and two key hydrological parameters (annual inflow and mean annual water elevation).

4.5. Evaluation of Sustainable Environmental Flows

We adopted the cubic spline function (Moon, 2001) to interpolate between data points for various parameters within the watershed, and used the results to fit a curve to describe the relationships between the total ecosystem services value and the dominant environmental flow factors. To identify local and overall maxima and minima, we used values estimated using these curves rather than visual inspection of the resulting graphs.

Figure 5 shows the response surface for the relationship between the total ecosystem services value and two key hydrological parameters (the mean water elevation and the 7-day low elevation) after interpolation. The result is a stable and smooth curve. Once the 7-day low elevation is fixed, a higher water elevation does not increase ESV; in contrast, when the water elevation is fixed, a higher 7-day low elevation increases ESV. There were obvious low values for ESV where the 7-day low elevation was close to a mean water elevation of 8.7 m, whi-

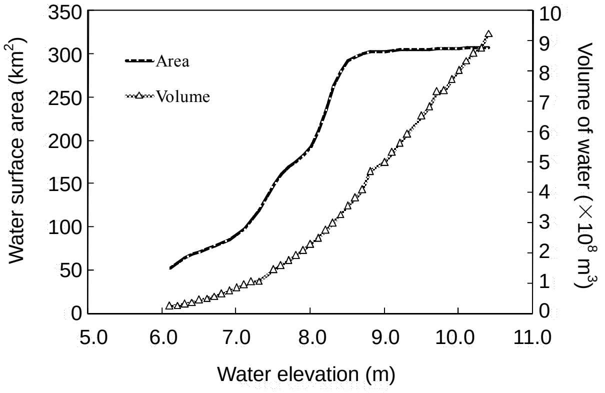

Figure 7. The relationship between water elevation and two water parameters (water volume and surface area) for the Baiyangdian Wetland.

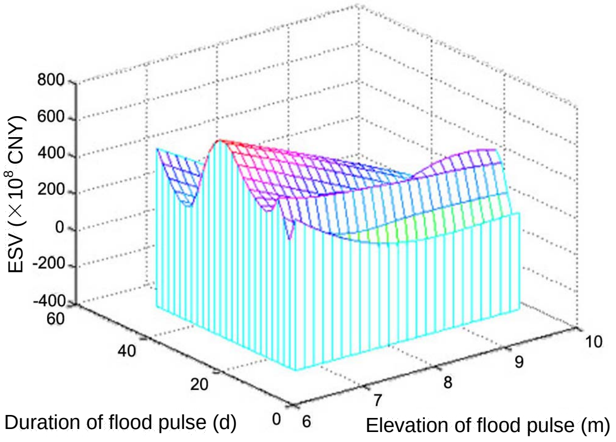

Figure 8. Relationships between the total ecosystem services value (ESV) and two characteristics of the flood pulse (the highest water elevation during a flood pulse and the duration of the flood pulse).

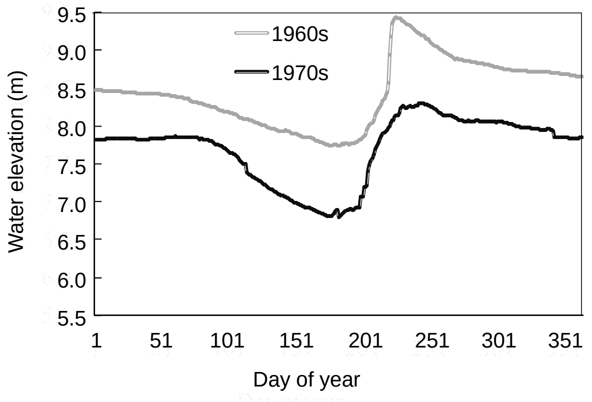

Figure 9. Water elevation fluctuations in the 1960s and 1970s in the Baiyangdian Wetland.

ch demonstrates that if the water elevation rarely fluctuates during a given year, a low ESV is likely. Figure 5 also shows a local optimum for ESV when the annual mean water elevation ranges between 6.9 and 7.1 m and the 7-day low elevation is about 6.0 m; the global optimum for ESV is achieved when the annual mean water elevation ranges between 8.0 and 8.2 m and the 7-day low elevation ranges between 7.0 and 7.5 m.

We also fitted the relationships between the total ecosystem services value and two key hydrological parameters, the annual inflow into the lake and the mean water elevation (Figure 6). The ecosystem services value reached its global optimum when 3.0×10^8 m^3 of water flows into the lake and the mean water elevation ranged between 7.5 and 8.3 m. We also calculated a water storage curve that describes the relationship between water elevation and the water volume and surface area in the Baiyangdian Wetland (Figure 7). Based on this curve, an inflow of 3.0×10^8 m^3 released into the lake could raise the initial water elevation from 6.0 m to a final elevation of 8.2 m. This means that releasing enough water from other rivers or reservoirs into the wetland could guarantee a high ESV.

We therefore analyzed the effect of the flood pulse water elevation and duration on the ecosystem services value (Figure 8). The largest ESV was obtained in two parts of the response surface: first, when the highest water elevation during a flood pulse reached about 9.0 to 9.4 m and the pulse lasted for 20 days, and second, when the highest water elevation ranged between 6.7 and 7.8 m and the pulse lasted for 30 days.

We further examined our results using hydrological data from the 1960s and 1970s as a basis for comparison. Historically, the fluctuations in mean water elevation in the Baiyangdian Wetland during the 1960s and 1970s, before intensive management of the watershed began, depended on the natural precipitation and runoff received as inflows. Based on data from the Baiyangdian meteorological station, mean precipitation during the 1960s was roughly 16% higher than the long-term average (1956 to 2008); in contrast, precipitation during the 1970s was about 10% lower than the long-term average. The fluctuations in mean water elevation in the 1960s and 1970s followed similar patterns during the two periods, although water levels were consistently higher during the 1960s (Figure 9). The lowest elevation occurred at the end of June, whereas a flood pulse increased the water elevation during the first 10 days of August. The magnitude of the peak water elevation ranged from 9.25 to 9.45 m for 20 days in the 1960s, which corresponds roughly to the values in Figure 8 for a wet year. In contrast, the peak water elevation ranged from 8.00 to 8.20 m for 31 days in the 1970s, which is slightly higher than the values in Figure 8 for a normal or drought year.

5. Discussion

In this study, we analyzed the relationships between a set of ecosystem services values and a set of hydrological data from a statistical perspective, and evaluated the effects of the critical factors that affect environmental flows, including the annual mean water elevation, inflows and outflows, the 7-day low elevation, and the elevation and duration of the flood pulses.

The flow regime of a wetland is one of the major drivers of its ecological processes, and flood pulses are essential to a wetland's health (Stewardson and Gippel, 2003; Reich et al., 2009). Based on the results of the present analysis, we can tentatively recommend the following sustainable environmental flows set for Baiyangdian Wetland: an annual mean water elevation of between 7.5 and 8.3 m, a 7-day low elevation of no less than 6.0 m, an annual inflow into the lake of 3.0×10^8 m^3, and flood pulse events with a peak water elevation of 9.0 to 9.4 m for 20 days in wet years and 6.7 to 7.8 m for 30 days in normal or drought years.

In recent years, less natural water has flowed into the wetland due to a combination of regional drought and the excessive irrigation and industrial demands in upstream regions. As a result, restoration of the wetland's water regime mainly depends on artificial regulation by means of inputs from the other rivers or reservoirs. Experience with environmental flow releases during the study period suggests that recharging the Baiyangdian Wetland's water in winter could decrease the water loss along the diversion canals due to decreased evaporation from the water surface as a result of the cooler temperatures. This would also mitigate the problem caused by freezing of the water surface; the ice thickness is sufficiently high that it reduces the space available for the lake's fish, potentially causing serious population decreases in years with low water levels. To accomplish these goals, we recommend two artificial water releases each year: the first one should occur in January to improve the wetland's water storage, and the second one should occur during the first 10 days of August to emulate the historical flood pulse regime. The implementation of these environmental flow releases is not practical given current water availability, but will become feasible when major hydraulic engineering projects are complete, including the South-to-North Water Transfer Project (Zhang, 2009) and the Wangkuai–Xidayang Reservoirs Coordination Project (Yuan et al., 2007). The former is expected to be complete in 2014; and the latter is expected to be completed in 2013. These projects should supply enough water to the Baiyangdian Wetland to meet its environmental flow needs.

Previous research on the environmental flows of wetlands seems to have mostly been designed to help researchers calculate the minimum flow requirements for a given wetland. Moreover, the water allocated to the wetland in these studies was geared solely to provide these minimum flows (Wang et al., 2008; Zhong et al., 2008). Even our previous research (Yang, 2011b) only revealed a significant curvilinear (quadratic) relationship between ESV and water depth, but did not explicitly recommend the magnitude and other characteristics of the environmental flows to the wetland's managers. However, increasing numbers of studies have shown that both flood and drought periods are important features of most ecosystems that are supplied by running water (e.g., Poff et al., 1997; Lytle and Poff, 2004), and the paradigm of restoring a natural flow regime has become a fundamental part of the management of such ecosystems. For this reason, our research considered multiple components of the flows, including their magnitude, duration, and timing. Although we emphasized the importance of flood pulse timing and duration, drought is also important since it defines one of the natural flow regimes that occur when there are long periods of below-average rainfall during certain periods of the year. We captured these phenomena by considering the relationships between the 7-day low elevation and the number of days of extreme drought, as well as between flooding and drought (Table 3).

In the present work, we added to our previous research (Yang, 2011b) by recommending sustainable environmental flows that maximize ESV under the current constraints, thereby supporting decision-making by the wetland's managers, but some aspects of our research require improvement. These include an analysis of combinations or interactions among the components of environmental flows, defining and resolving any intrinsic drawbacks of the ESV calculation, and examining the spatial attributes of the environmental flows (e.g., identifying parts of the wetland that are most vulnerable to inadequate flows). Our analysis identified a set of potentially suitable environmental flows defined by specific values of hydrological parameters, but this set represents a compromise between two management patterns for the environmental flows: supplying the minimum environmental flows and restoring the natural flow regime.

We used a traditional procedure for economic valuation to establish ESV. Such calculations have considerable uncertainty and their value has therefore been criticized in the scientific literature, particularly for cross-sectional estimates based on average values rather than specific values for the system being studied (Pimm, 1997; Masood and Garwin, 1998; Balmford et al., 2001; Jenerette et al., 2006). Despite these criticisms, this approach represents a convenient way to provide first approximations suitable for quantifying the change in ESV provided by an ecosystem over a given period: even though the actual values for a given year may be inaccurate, this error should be consistent through a study period, therefore allowing comparisons of *relative* values among the years within that period. The results can be easily understood by decision-makers and aid decision-making to promote more sustainable human-ecological interactions (Farber et al., 2002).

In future research, the hydrological spatial pattern should be considered in more detail to provide a fuller picture of the environmental flows within the wetland, since this spatial pattern is an important component of ecosystem services and functions such as habitat protection, recreation, culture, and climate regulation. By means of spatially explicit statistical analysis, the heterogeneity of hydrology and vegetation during high-water periods, as well as the hydraulic connectivity of various parts of the wetland and the submergence cycle of the floodplain, could be analyzed to provide managers with more spatially explicit guidance on management of the wetland's environmental flows.

6. Conclusions

In this study, we developed an analytical framework that can be used to evaluate the set of desired sustainable environmental flows, and used the Baiyangdian Wetland as a case study to illustrate the method. The statistical relationships between a set of ecosystem services value parameters and a set of hydrological parameters were analyzed by means of canonical correlation analysis and gray relationship analysis, and this revealed the influence of the key hydrological parameters on the ecosystem services value. Based on this analysis, we were able to recommend potentially optimal sustainable values of the key parameters of the environmental flows, including the mean annual water elevation, 7-day low elevation, and the duration of flood pulses and the water elevation during these events. The approach provides an effective way for managers to understand and regulate the flows of water required to satisfy the wetland's environmental flow needs while also maximizing socioeconomic benefits. It is important to note that our approach accounts for only a subset of all the possible additional parameters that could be included within an analytical framework. Future research should attempt to expand our analysis by adding other important factors, such as biodiversity values or values for specific key plant and animal species identified by stakeholders.

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Supporting Material. The supporting materials containing detailed algorithm and examples are available at http://www.iseis.org/jei/download/Supplement_201400276.pdf.

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