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Influence of hydrological regime and climatic factor on waterbird abundance in Dongting Lake Wetland, China: Implications for biological conservation

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ABSTRACT

Understanding how migratory waterbirds respond to hydrology and climate is of great importance for providing valuable insight into conservation in wetland system. Dongting Lake Wetland is an important wintering habitat in the East Asian-Australasian Flyway. However, little is known about the effects of hydrology and climate on wintering waterbirds. Therefore, it is urgent to analyze the relationship between them. To better interpret the ecological significance, we divided the bird species into five functional groups on the basis of their typical feeding habits. Redundancy analysis (RDA) combined with forward selection procedure was applied to select the hydrological and climatic variables with significant influences. Then, response surface methodology (RSM) was carried out to identify the thresholds of the variables. The results showed that inflow and water level were probably the two critical variables accounting for 52.13% and 47.87% of the variation in the bird species, respectively. However, other variables did not reach a significant level in this study. As for the group-level, different functional bird groups had different reflections to inflow and water level. Minimal guaranteed values of the two variables were identified as 3518.82–3736.28 m^3/s and 22.61–23.49 m respectively based on the hydrological requirements and the weights of all groups. The results highlighted that the minimal requirements of inflow and water level should be satisfied to provide appropriate habitats for waterbirds. Besides, the regulatory authorities and environmental protection agencies should develop relevant law or regulation to protect waterbird habitats from human destruction especially the activities which could change the hydrological regime.

1. Introduction

Waterbirds, amongst the most symbolic ecological assets in wetlands, are good indicators of environmental changes and natural resources of great ecological value (Mistry et al., 2008; Reid et al., 2013). Waterbirds are of high mobility and aggregation in response to the fluctuations in resources and the demands of their different life requirements (Cumming et al., 2012). Declining of waterbird abundance has been reported from many major breeding sites (Wen et al., 2011; Reid et al., 2013). Many studies demonstrate that waterbird abundance is positively related with the availability of wetland habitats (Roshier et al., 2002; Meehan et al., 2010; Szostek and Becker, 2015). The changes of habitats quality would affect the distribution, diversity and abundance of waterbird (Şekercioğlu et al., 2004). There is increasing evidence that wetlands are in declining health throughout the whole world due to hydrological changes, intensive agriculture, urbanization, climate change, and so on (Kingsford and Thomas, 2004; McRae et al., 2008; Wang et al., 2013; Zeng et al., 2013a,b; Ward et al., 2015).

In recent years, it is a central issue in ecology to study the effects of hydrological regimes and climatic factor on waterbird abundance, which has attracted increasing global attention in the filed of engineering design, ecological conservation and

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environmental management (Li, 2009; Paton et al., 2009; Wen et al., 2011; Reid et al., 2013). Hydrological regimes, including water level fluctuation, water depth and inflow, have turned out to be important abiotic factors which could affect the waterbird foraging and inhabiting (Timmermans et al., 2008; Bolduc and Afton, 2008; Bellio and Kingsford, 2013). Moreover, climatic factor as one of important inductive factors has been in hot debate for a long time. Previous studies have investigated the links between waterbirds and climate (such as rainfall, temperature and future climate scenarios) and the results show that the impacts of climatic factor on waterbirds are uncertain and complex (Both et al., 2006; Hu et al., 2010; Wen et al., 2011; Barbet-Massin and Jetz, 2015). According to the report of World Wildlife Fund (WWF), wetland birds are at high risk from climate change.

Hydrology is regarded as a fundamental part in the ecology of various wetland dependant organisms (Elderd and Nott, 2008; Royan et al., 2014). Human activities such as agriculture, urbanization and water conservancy project (dam construction, reservoir construction, etc.) would affect the wetland hydrological processes and change hydrological regimes (Whited et al., 2000; Nilsson et al., 2005; Harrison and Whitehouse, 2012). Dam constructions especially the large ones have been pointed out that they would bring some new challenges in hydrological regime of the global river systems (WCD, 2000; Altinbilek, 2002; Xu and Milliman, 2009). Meanwhile, hydrological regime may be altered by precipitation, evaporation, temperature variation (Green et al., 2013). Climate-induced changes, including alteration in the magnitude of water recharge and river flow regimes, may affect the fundamental ecological function and species distribution in wetlands ecosystems (Woodward et al., 2010; Pall et al., 2011). Numerous previous researches indicated that the alteration of hydrological regimes and climate could result in adverse and lasting impacts on the ecosystem function, such as natural habitats loss and fragmentation (Xu and Milliman, 2009; Wang et al., 2013). These studies also provided the theoretic base regarding the relationships between hydrological regimes, climatic factor and waterbirds.

Dongting Lake Wetland (DLW), one of the Ramsar sites, provides an important international habitat for migratory birds in the East Asian-Australasian Flyway (Yuan et al., 2014). Dam construction and weather change are two representative features here. Many scholars indicated that the changes of hydrological regime and the patterns of DLW may result from the comprehensive effects of human activity and climatic factor (Tullos, 2009; Sun et al., 2012; Deng et al., 2013; Gao et al., 2013; Yuan et al., 2015). However, little is known about the effects of hydrological regimes and climatic factor on wintering waterbird abundance and the quantitative relationship between them. Therefore, it is urgent to achieve the deeper understanding of the quantitative relationship between hydrological and climatic variables and waterbirds in DLW.

In this study, redundancy analysis (RDA) and response surface methodology (RSM) were applied to investigate how waterbird abundance was related to hydrological regimes and climatic factor. Specifically, the following questions were addressed:

1. How are wintering waterbird abundance related to hydrological and climatic variables?
2. Are there any differences in hydrological requirements of different functional bird groups?
3. Which variable(s) can be the critical one(s) markedly correlating with the waterbird abundance?
4. Can we identify the thresholds of critical variables?

Understanding how bird species response to the hydrological regimes and climatic factor would provide insights into waterbird conservation and habitat management in DLW. In addition, our study would be of reference significance in protecting waterbirds for other wetlands.

2. Materials and methods

2.1. Study site

This study was conducted in Dongting Lake Nature Reserve, which is situated in the middle reach of Yangtze River region and south of Hunan Province, China (approximately 28°30′ N–30°20′ N, 111°40′ E–113°10′ E) (Li et al., 2013; Liang et al., 2014). Dongting Lake (DTL), the second largest freshwater lake with a catchment area about 2625 km^2 in China, is directly connected with the Yangtze River. The water from Yangtze River flows into the lake mainly via the Songzi estuary, the Taiping estuary and the Ouchi estuary. Moreover, DTL also receives water from the other four major tributaries, namely, Xiangjiang River, Zishui River, Yuanjiang River and Lishui River (Fig. 1). At last, the water drains back into the Yangtze River from the only outlet of DTL (Chenglingji estuary).

DTL lies in the subtropical monsoon climate zone, with a wet season between July and September and a dry season between November and February. The entire nature reserve is almost inundated in wet season (with the water level ranging from 20.13 m to 30.32 m), while vast mud flats and grass lands expose along with the water level falls in dry season (with the water level ranging from 20.13 m to29.77 m). Because of its special geographical position, unique climate conditions and natural dry-wet cycles, DLW provides appropriate and complex eco-environment for a wide variety of flora and fauna, especially providing an important wintering habitat and pathway for East Asian migratory birds. DLW includes three important nature reserves namely East Dongting Lake Wetland (EDLW), West Dongting Lake Wetland (WDLW) and South Dongting Lake Wetland (SDLW). And the three wetlands were listed in the Ramsar Convention respectively in 1992, 2002 and 2002. Tens of thousands of migratory birds come here every winter, among which there are about 46 nationally protected species and 37 internationally protected species. Statistics showed that about 60–70% of Lesser White-fronted Goose (*Anser erythropus*), one of the globally endangered species, were found to overwinter in DLW. Moreover, the total population of Oriental White Stork (*Ciconia boyciana*) is less than 3000 all over the world, but about eight hundred were once recorded in DLW (Yuan et al., 2015).

2.2. Bird survey

Wintering waterbirds fly to DLW around September and fly away around March, and the peak population is present in January. Thirty-five representative sampling sites were investigated in our study and the survey area accounted for almost 100% of the whole DLW (Fig. 1). Surveyors (skilled ornithologists) were divided into nine groups. Simultaneous survey is of great importance to avoid repeat counting. Therefore, bird surveys were carried out based on point counting (Buckland et al., 2001; Wu et al., 2011; Yuan et al., 2014) approximately at the same time, that is, 8–12 January 2006, 8–12 January 2007, 8–12 January 2008, 8–12 January 2009, 8–12 January 2010, 9–13 January 2011, 11–15 January 2012 and 15–18 January 2013 (the number recorded in January 2006 represented the wintering waterbird abundance in 2005, and so on). Birds were observed by monocular (Swarovski ATS80) and binocular (Nikula 10 × 42). The bird surveys were undertaken within a radius of 1 km of each sampling site on fine weather without rain or significant wind (Chapman and Reich, 2007). To exclude year-to-year variation in bird patterns, the same route and the same sampling sites were followed by same method every year.

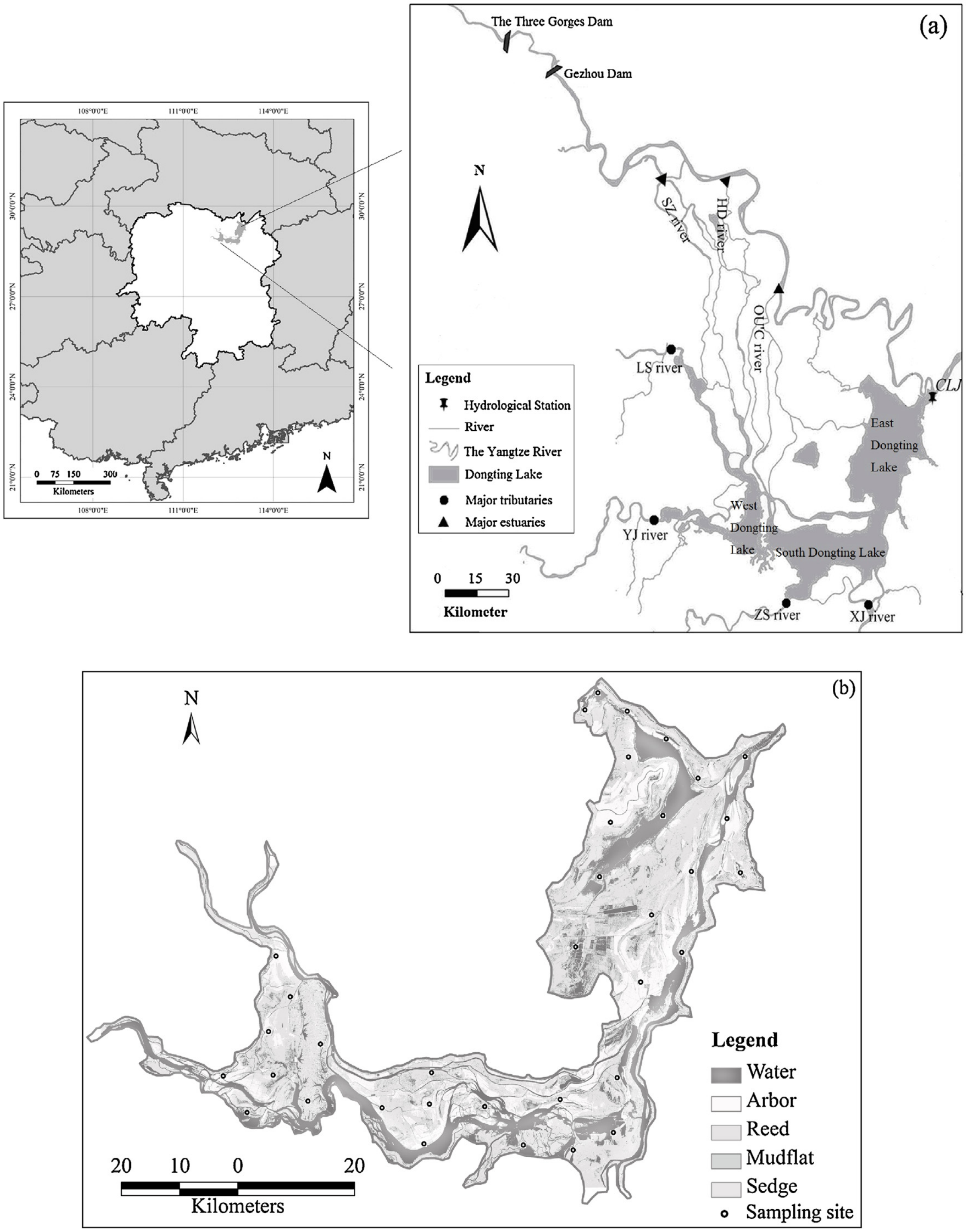

Fig. 1. Map of study area. (a) Study area. (b) Sampling sites. SZ, Songzi; HD, Hudu; OUC, Ouchi; LS, Lishui; YJ, Yuanjiang; ZS, Zishui; XJ, Xiangjiang; CLJ, Chenglingji.

Waterbirds were identified to species level. To better interpret the ecological significance, we divided the wintering waterbird species into five functional groups on the basis of their typical feeding habits by reference to the classification method provided by Cumming et al. (2012) and Wang et al. (2013). Some species have multiple feeding habits. Therefore, in the case of species foraging in different habitat groups, the dominant diet character was chosen for grouping. Five functional groups were identified as tuber eaters, sedge eaters, seed eaters, invertebrate eaters and fish eaters. Feeding functional groups of waterbirds in DLW were shown in Table 1. Moreover, details of the observed wintering waterbirds and their functional groups were presented in Appendix Table A1.

2.3. Explanatory variables

Four hydrological variables (inflow, minimum inflow, water level and minimum water level) and four climatic variables (rainfall, 3-month rainfall before bird survey, temperature and minimum temperature) were assembled as explanatory variables. The summary of the explanatory variables was provided in Table 2. The data of daily water level and inflow from 2005 to 2012

Table 1
Summary of the different feeding functional groups of the waterbirds in Dongting Lake Wetland.

Functional group	Number of species	Annual mean abundance	Typical species
Tuber eaters	8	3382	*Cygnus columbianus*, *Grus leucogeranus*, *Grus grus*
Sedge eaters	6	46,936	*Anser fabalis*, *Anser albifrons*, *Anser erythropus*, *Anser cygnoides*
Seed eaters	17	45,212	*Anas falcata*, *Anas crecca*, *Anas acuta*, *Fulica atra*
Invertebrate eaters	22	23,091	*Platalea leucorodia*, *Recurvirostra avosetta*, *Charadrius alexandrinus*, *Calidris alpina*
Fish eaters	26	11,449	*Tachybptus ruficollis*, *Phalacrocorax carbo*, *Ardea alba*, *Ciconia boyciana*, *Larus ridibundus*

were obtained from the Chenglingji Hydrological Station which is an important hydrological control station located at the outlet of DTL. Daily climatic data in the DTL region during the period of 2005–2012 were acquired from China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do). We selected three representative weather stations, namely Yueyang Weather Station (representing EDLW), Changde Weather Station (representing WDLW) and Nanxian Weather Station (representing SDLW). In order to keep coherent with the time of bird census, explanatory variables in dry season were analyzed in this study.

2.4. Data analysis

In order to investigate the correlation of waterbird abundance with hydrological and climatic variables, Detrended Correspondence Analysis (DCA) was first performed to decide which analysis method to choose, whether linear or unimodal response model. The species population square matrix of the sum standardization-transformed was used as a response variable. As for the explanatory variables, we applied log_{10}-transformation ($log_{10}(x+1)$). The largest gradient length of the first four DCA axes was less than 2. Therefore, RDA was carried out to ordinate the temporal composition of the waterbirds to hydrological regime and climatic factor at the community-level (Wang et al., 2014). Forward selection procedures were then applied to select the variables with significant influences ($P \leq 0.05$) and to exclude the variables that didn't effect significantly ($P > 0.05$). RDA and Monte Carlo permutation test with 999 permutations were performed to evaluate the significance of variables separately. DCA and RDA were carried out in CANOCO version 4.5 (Ter Braak and Šmilauer, 2002; Lepš and Šmilauer, 2003).

To infer the optimal hydrological and climatic conditions that were significantly related with waterbird abundance, RSM based on central composite design (CCD) was used in our study. The analysis was carried out at the group-level, namely identifying the thresholds of critical explanatory variables for each group. Response analysis was performed using Design-Expert version 8.0.6 (Kirmizakis et al., 2014). RSM is an empirical statistical technology with the purpose of revealing the relationship between independent and dependent variables or the interactive effects between multiple single factors to determine the best conditions of parameters. Moreover, this method is usually applied to develop models utilizing data gleaned from experiments or simulations. The appropriate model was selected according to the comparison of all possible models, including mean square and *P*-value. Meanwhile, the appropriate model would be automatically suggested in the results of Fit Summary, one procedure of Design-Expert. And then, the graphical perspective was generated after the fitness of the mathematical model (Montgomery, 2009).

3. Results

3.1. Waterbird population

From 2005 to 2012, a total of 79 species of wintering waterbirds were encountered in DLW, of which there were 8 species of tuber eaters, 6 species of sedge eaters, 17 species of seed eaters, 22 species of invertebrate eaters and 26 species of fish eaters (Table 1; Table A1). During the eight-year bird survey, about 43.04% species were recorded in all years while only 18.99% were recorded in only one year. The total population varied every year with the mean value of 155,035. The population was steady during the period 2005–2007, and significantly increased in 2008. However, it gradually decreased after 2008 (Fig. 2). Sedge eaters and seed eaters were most abundant, accounting for approximately 70.26% of the total bird population. While tuber feeders were least abundant, only accounting for 2.48% of the total bird population. Among the 79 species, Dunlin (*Calidris alpine*), Bean Goose (*Anser fabalis*), Lesser White-fronted Goose (*A. erythropus*), Greater White-fronted Goose (*Anser albifrons*), Falcated Duck (*Anas falcata*), Eurasian Teal (*Anas crecca*) were six dominant species (with an average population over 7000), accounting for about 61.44% of the total bird population.

3.2. Redundancy analysis

RDA was performed to explore to the degree that hydrology and climate affected the wintering waterbird abundance. The results of the RDA ordination were shown in Table 3. The all canonical axes explained approximately 83.1% variance of species data and 99.9% variance of species-environment relation, among which the cumulative explanation of the first two axes reached 77.9% of species data and 94.6% of species-environment relation. Monte Carlo permutation tests for the first and all canonical axes were significant ($P = 0.002$, $P = 0.001$, respectively). Moreover, the eigenvalues of the first two canonical axes were much higher than the other axes, which meant that the two axes were the main explanatory axes. For species-environment relation, approximate 68.5% and 26.1% of the variation were respectively explained by axis 1 and axis 2. On the whole, the first two canonical axes could explain the relationship between species and the environmental variables well. The

Table 2
Summary of explanatory variables and their description.

Variable	Unit	Mean (range)	Description
Rainfall	mm	1275.29 (716.5–1887.4)	Yearly sum of daily rainfall
$Rainfall_3$	mm	207.70 (67.9–336.6)	3-month (October–December) rainfall before bird survey
Temperature	°C	13.34 (−3 to 35.1)	Cumulative mean daily temperature in dry season
T_{min}	°C	7.68 (−2.9 to 20.4)	Minimum temperature in dry season
Inflow	m^3/s	4020.89 (2638–6728.9)	Cumulative mean inflow in dry season
Minimum inflow	m^3/s	1436 (1090–1870)	Minimum inflow in dry season
Water level	m	23.29 (20.13–29.77)	Water level in dry season
Minimum water level	m	20.44 (20.13–21.70)	Minimum monthly mean water level in dry season

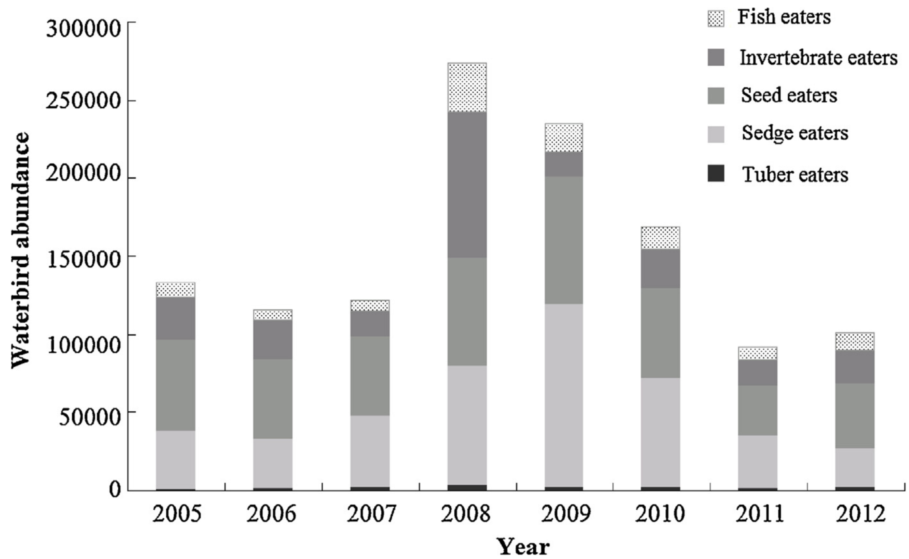

Fig. 2. Waterbird abundance of five groups in Dongting Lake Wetland during the period of 2005–2012.

Table 3
Summary of redundancy analysis ordination.

	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalue	0.685	0.261	0.046	0.007
Species–environment correlations	0.972	0.964	0.948	0.897
Cumulative % variance of species	67.5	77.9	80.5	83.1
Cumulative % variance of species–environment	68.5	94.6	99.2	99.9
Test of significance of first canonical axis	$P = 0.002$			
Test of significance of all canonical axes	$P = 0.001$			

biplot of the overall species distribution and hydrological variables was shown in Fig. 3.

3.3. Forward selection

The explanatory variables of significant influence on the waterbird abundance were identified by forward selection procedure.

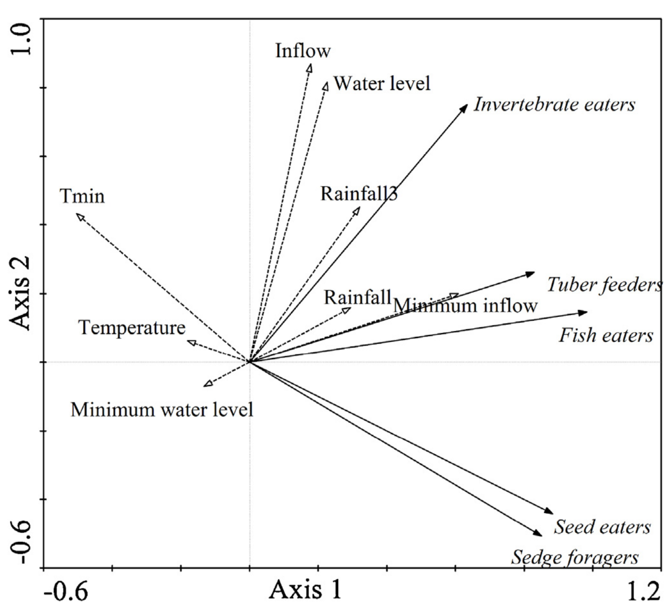

Fig. 3. RDA ordination diagram of species distribution and explanatory variables in Dongting Lake Wetland. Waterbird species were represented by solid lines with filled arrows, whereas explanatory variables were meant by dotted lines with unfilled arrows.

The results suggested that the effects of the explanatory variables differed with each other. Percentages of variation explained by each particular variable without the other shared explanatory variables were shown in Table 4. In forward selection procedure, inflow and water level were checked out to be the major variables markedly correlating with the abundance of waterbird species ($P \leq 0.05$), however other variables did not reach a significant level. More specifically, inflow alone accounted for 52.13% ($P = 0.001$) of the variation in the bird species, while water level solely explained 47.87% ($P = 0.021$) of the variation.

3.4. Response surface methodology

At the community-level, inflow and water level were proven to be the critical variables. As for the group-level, RSM and CCD were combined to estimate the responses of waterbird groups to the critical variables and to identify the thresholds of the variables. Firstly, it is necessary to select an appropriate model for each waterbird group. The summary of final selected-models was shown in Table 5. By comparison, the two factor interaction model (2FI model) was finally applied for tuber eaters, invertebrate eaters and fish eaters,

Table 4
Effects of explanatory variables on species population. Eigenvalues, *P*-value and *F*-ratio were obtained from the partial RDA.

Variable	Eigenvalue	Net effect (%)	*P*-value	*F*-ratio
Rainfall	0.021	2.13	0.949	0.155
$Rainfall_3$	0.266	26.60	0.117	2.191
Temperature	0.096	9.57	0.441	0.626
T_{min}	0.245	24.47	0.190	1.965
Inflow	0.521	52.13	0.001	6.45
Minimum inflow	0.085	8.51	0.675	0.546
Water level	0.479	47.87	0.021	5.500
Minimum water level	0.043	4.26	0.824	0.273

Table 5
Summary of selected models for different waterbird groups.

Group	Selected model	*R*-squared	Model		Inflow		Water level		Inflow-water level			
			F-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value	Coefficient	Std. error	*F*-value	*P*-value
Tuber eaters	2FI	0.862	8.331	0.034	8.412	0.044	9.148	0.039	0.210	0.065	10.561	0.031
Sedge eaters	Quadratic	0.947	7.081	0.128	0.036	0.867	2.792	0.237	–	–	0.264	0.659
Seed eaters	Quadratic	0.995	87.561	0.011	57.056	0.017	19.937	0.047	−28.142	3.029	86.339	0.011
Invertebrate eaters	2FI	0.971	45.018	0.002	18.111	0.013	2.922	0.163	3.642	0.850	18.344	0.013
Fish eaters	2FI	0.892	10.970	0.021	13.377	0.022	6.909	0.058	1.972	0.528	13.941	0.020

while quadratic model was chosen for the other two groups. The coefficients and *P*-values in Table 5 suggested the selected models were appropriate and reasonable except the model for sedge eaters (not reaching a significant level). Especially, the analysis of variance indicated the model for seed eaters proved to be highly significant with highest coefficient of determination value ($R^2 = 0.995$).

The RSM results demonstrated significant effects of the two hydrological variables (inflow and water level). The inferred inflow and water level that would accommodate the minimal hydrological requirements for all the wintering bird groups were illustrated by response surface plots (Fig. 4). The result showed that the minimal guaranteed values of inflow and water level for tuber eaters ranged from 3575.57 m^3/s to 3688.19 m^3/s, 23.35 m to 24.28 m, respectively (Fig. 4a). As for sedge eaters, the minimal combined hydrological requirements were inflow within 3641.53–3766.01 m^3/s and water level within 22.25–23.32 m (Fig. 4b). The guaranteed values of inflow and water level for seed eaters were 3350.33–3688.19 m^3/s, 22.14–22.75 m, respectively (Fig. 4c). In order to protect invertebrate eaters and fish eaters, the minimal combined requirements were inflow within 2824.47–3312.79 m^3/s and water level within 23.43–23.78 m for invertebrate eaters, while inflow within 4101.12–4451.49 m^3/s and water level within 23.51–24.12 m for fish eaters (Fig. 4d and e). In order to identify reasonable minimal guaranteed hydrological variables, we first calculated the weights of all functional groups according to the proportions of their population. The weights of tuber eaters, sedge eaters, seed eaters, invertebrate eaters and fish eaters were 0.01, 0.37, 0.33, 0.2 and 0.09, respectively. At last, we proposed that minimal guaranteed requirements of inflow and water level were 3518.82–3736.28 m^3/s and 22.61–23.49 m in dry season.

4. Discussion

4.1. The variety of bird species and the possible influence factors

Waterbirds are good indicators of environmental change in the wetland ecosystems (Mistry et al., 2008; Reid et al., 2013). Recent studies showed that the bird community responded most strongly to the variations in discharge with a time lag of 2–4 months (Cumming et al., 2012). Moreover, the peak wintering waterbird abundance is present in January. Hence, we mainly focused on the wintering migratory waterbirds surveyed in January in this study. At the level of the whole lake, waterbird abundance fluctuated each year, and the variations in different functional groups were obvious. The total population gradually decreased especially after 2008 (Fig. 2), which might correlate with the changes of hydrological regimes in DLW caused by the operation of the Three Gorges Dam (TGD) and climatic factors. Moreover, the changes appeared gradually rather than immediately. Therefore, the aim of this paper was to explore the relationships between waterbirds and hydrological and climatic variables.

Most waterbirds are of mobility, aggregating and dispersing in response to fluctuations in resources and the requirements for their survival. Numerous researches revealed that the spatial distribution and abundance of waterbirds were related to habitat characteristics, such as water level, water area, water depth, vegetation area, vegetation structure, landscape structure and so on (Chandler and King, 2011; McKinney et al., 2011; Bunce et al., 2013; Pap et al., 2013; Walz and Syrbe, 2013). Recent studies showed that waterbirds were attracted to the suitable foraging habitats when such habitats were present or moved elsewhere when such habitats were absent (Cumming et al., 2012). Waterbirds entered or remained in an area as a response to the suitable foraging conditions. Yuan et al. (2014) have discussed the relationship between environmental variables and Anatidae birds in EDLW, showing that water area, reed area and sedge area were critical variables. Sedge eaters and seed eaters were two dominant functional groups because there may be abundant natural resources, food and living conditions for them. The influence of hydrology on waterbird has caused wide public concern (Wen et al., 2011; Bellio and Kingsford, 2013; Wang et al., 2013). Therefore, we also should take hydrological alteration into consideration especially related to dam construction.

4.2. The influence of hydrological and climatic variables on waterbird

Previous studies showed that the influence of hydrology on bird community were obvious (Timmermans et al., 2008; Bolduc and Afton, 2008; Bellio and Kingsford, 2013). Similar results were obtained in our study. At community level, the wintering waterbird abundance was linked to the hydrological variables. The results of RDA showed that inflow and water level were probably the critical hydrological variables for all groups, accounting for 52.13% and 47.87% of the variation, respectively. The changes of inflow and water level could result in the variation of habitat characteristics definitely, which in turn affected waterbird abundance. Inflow could bring nutrients and other energy sources from the upstream to increase the primary production (Wang et al., 2011). In the dry season, low water level was beneficial to the growth of emergent vegetation, such as sedge and reed, which could attract tuber eaters, sedge eaters and seed eaters. Moreover, waterbirds that forage in deep or open water, such as invertebrate eaters, fish eaters and some seed eaters, responded most obviously to the changes of hydrology while shallow water foragers such as tuber eaters, sedge eaters didn't (Table 5; Fig. 4). In other words, the influence of inflow and water level in dry season on waterbird abundance might be related to the quantity and distribution of the shallow water, mudflats and meadows. Similar results were obtained by Wang et al. (2013) in Poyang Lake. Yuan et al. (2014) also showed patch density, which was associated with inflow and water level, was one of the critical environmental variables markedly correlating with the bird abundance. However, inflow and water level should keep at a proper level, that is, too high or too low might not be the best in our study (Farago and Hangya, 2012). Minimum inflow and minimum water level in dry season were not found to have significant correlations with waterbirds in DTL, which slightly differed from the study in Poyang Lake (Wang et al., 2013).

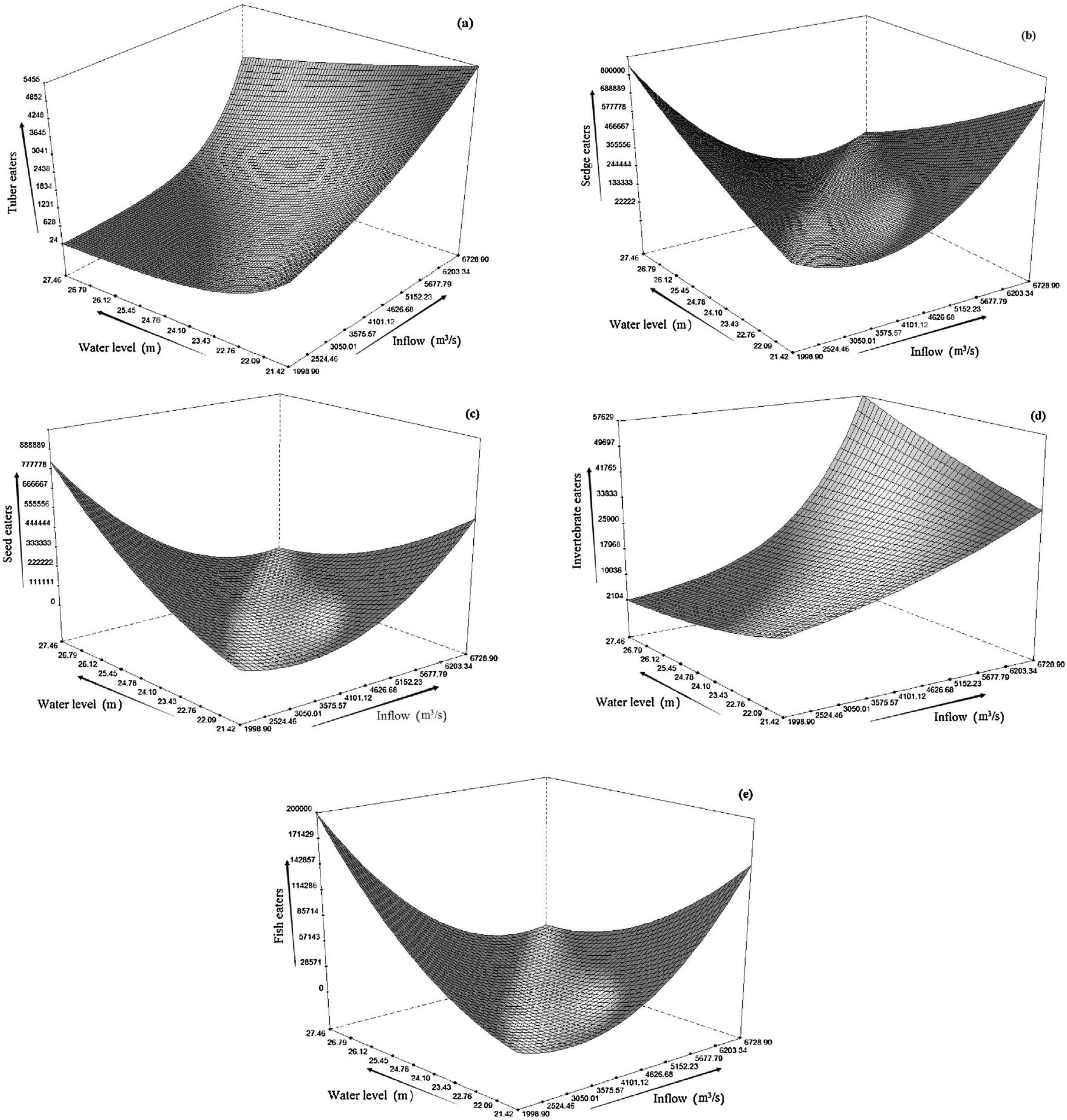

Fig. 4. Response surface plots for the interactive effect of the critical explanatory variables on different waterbird groups. (a) Tuber eaters, (b) sedge eaters, (c) seed eaters, (d) invertebrate eaters and (e) fish eaters.

As for the climatic factors, recent studies showed that rainfall and temperature were two driving forces to cause the change of waterbirds (Chambers and Loyn, 2006; Traill et al., 2009; Wen et al., 2011). Moreover, Wen et al. (2011) showed that annual rainfall and minimum winter temperature were positively related to bird abundance in the lower Murrumbidgee River. Nevertheless, our conclusions were not exactly the same. In our study, all functional groups were positively related to rainfall, but the effect of it did not reach a significant level (Fig. 3). Minimum temperature in dry season turned out to be positively associated to some species, such as invertebrate eaters and fish eaters. However, the correlation did not reach a significant level either. It is possible that a warmer winter would attract more waterbirds, especially dabbling foragers. The differences between our results and previous studies might be due to the rather short time series of bird surveys (eight years). No significant correlation between climatic variables and bird species was found in this study. Nonetheless, it did not imply that those variables were of no importance. Therefore, further work is needed to determine the effects of these variables.

4.3. The thresholds of critical variables for waterbird conservation

For all groups, inflow and water level turned out to be the critical hydrological variables in our study. The thresholds of inflow and water level for all the wintering bird groups were illustrated by response surface plots (Fig. 4). It can be seen from the result that different functional bird groups have different reflections of inflow and water level because of their different hydrological requirements. The complexity of fluctuations in bird species can be interpreted and predicted by their foraging styles. In order to protect the waterbirds in DLW, we should take the requirements of all groups into consideration. In our study, the weights of all functional groups were calculated according to the proportions of their population. We suggested that minimal guaranteed requirements of inflow and water level were 3518.82–3736.28 m^3/s and 22.61–23.49 m in dry season based on the hydrological requirements and the weights of all groups. However, Liang et al. (2014) showed that ecologically acceptable water level range of Chenglingji was 15.59–22.07 m during non-flood season. The difference between the two studies may be resulted from different study time series, that is, Liang et al. analyzed water level data from 1950 to 2005 while we analyzed the data from 2005 to 2012. Moreover, the former paid great attention hydrological alteration and wetland ecosystem health while we mainly focused on the foraging habits and conservation of waterbirds. As for the minimal guaranteed inflow, there were no research papers to proof our results. Nevertheless, the coefficients and *P*-values of the selected models suggested that the models were appropriate in this study (Table 5). Of course, more studies should be carried to testify and improve our results in the further researches.

4.4. Conservation implications

DLW, located in the East Asian-Australasian Flyway, is an important wintering habitat and pathway for migratory birds. It is facing some new challenges of the operation of TGD and climate change. Studies of waterbirds responding to hydrological variation would provide a solid basis to guide conservation and management of waterbirds. Our results indicated that inflow and water level should be taken into consideration when implementing biodiversity conservation and habitat restoration in DLW. We therefore recommend fulfilling the minimal requirements of inflow and water level in order to provide appropriate habitats for waterbirds. According to Yuan et al. (2015), anthropogenic and climatic factors influenced hydrological regimes in DLW, with climatic factors (exactly rainfall) as the main driving factor during the period of 1961–1980 and 1981–2002 while anthropogenic activity (exactly dam construction) as the main driver during the period of 2003–2010. Under the circumstance of uncontrollable climatic factor, we might put forward effective engineering measures to adjust the hydrological process, so as to protect waterbird habitats. The results of the study would offer a reference to the operation regulation of upstream water conservancy projects, such as TGD. Reservoir operation could maintain the ecological integrity by regulating water release and storage capacity. Besides, the regulatory authorities and environmental protection agencies should develop relevant law or regulation to protect waterbird habitats from human activities especially which could change the hydrological regime (land use, etc.). Caisang Lake, an experimental zone in East Dongting Lake Nature Reserve, was once an important habitat for *Grus grus*, *A. erythropus*, and *Recurvirostra avosetta*. Nowadays, Caisang Lake is exploited to plant lotus root. The change of water level, decrease of benthos and lotus leaf-covered water surface destroyed its original ecological function. As a consequence, the habitat decreased gradually. Therefore, it is urgent to prohibit overexploitation and carry out close management in some important habitats. Protected area is also a key part of biological conservation strategies in the background of climate and land use change. Learning from the experience of Murray-Darling Basin, we can produce a comprehensive, representative, and efficient protected area system to recover environmental flow in Dongting Lake. Protected area, especially the key habitats should be priority and be protected formally.

Understanding the regional inter-relationships between waterbirds and the comprehensive hydrological variables remains an important goal for the future research in DLW. Meanwhile, our study would have great reference significance in protecting waterbirds for other wetlands. As long as both species and hydrological data are available, researchers and managers can get quantitative relationship between species and hydrology for habitat restoration and management.

5. Conclusion

This study demonstrates an appropriate approach to quantitatively analyze the effects hydrological regimes and climate change on waterbirds. The aims of this study were: (1) to identify how wintering waterbird populations were related to hydrological and climatic variables, (2) to reveal the critical variable(s), and (3) to identify the thresholds of critical hydrological variables. The results showed that inflow and water level were the two critical variables accounting for 52.13% and 47.87% of the variation in the bird date. Minimal guaranteed requirements of the two variables were identified as 3518.82–3736.28 m^3/s and 22.61–23.49 m respectively. The results highlighted that the minimal requirements of inflow and water level should be satisfied to provide basic habitats for waterbirds. Besides, the regulatory authorities and environmental protection agencies should develop relevant law or regulation to protect waterbird habitats from human destruction especially which could change the hydrological regime. This work would provide potential insights into waterbird conservation and habitat management in Dongting Lake Wetland and other wetlands.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2016.01.076.

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