Suitable habitat mapping in the Yangtze River Estuary influenced by land reclamations

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Abstract We proposed an approach to calculate estuarine habitat suitability and habitat fragmentation by integrating various environmental factors. Based on fuzzy logic method, water depth, salinity, and fluctuation rate of salinity were integrated into a Habitat Suitability Index (*HSI*) to map suitable habitat pattern of target species in estuaries. Then the *HSI* is used to calculate Habitat Aggregation Index (*HAI*) that represents the degree of habitat fragmentation. The proposed method was applied to the Yangtze River Estuary which has experienced long term land reclamation activities during the past two decades including the transformations of coastal wetlands to urban infrastructures and the deep-water channel construction. We selected Chinese mitten crab (*Eriocheir sinensis*) as a target species in this study, the results indicated that under the impact of land reclamation in the Yangtze River Estuary the isoclines of low salinity moved seaward and the optimum salinity range for Chinese mitten crab has been compressed. The suitable habitat for Chinese mitten crab decreased 325.4 km² and the *HAI* has also decreased 2% during the first stage of land reclamation (scenario 1 to scenario 2) with a transformation of 237.2 km² coastal

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wetlands to concretes. During the second stage of land reclamation (scenario 2 to scenario 3), the combined effects of coastal wetlands disappearance (282.7 km²) and deep-water channel construction (92.2 km) has led to a degeneration of suitable habitat for Chinese mitten crab about 427.4 km² and HAI decreased 6%. Land reclamations in the Yangtze River Estuary not only directly occupied suitable habitat for the Chinese mitten crab, but also altered the habitat patterns and destroyed habitat connectivity, which showed high potential to affect the migration of this species. This proposed approach is flexible for habitat evaluation in estuaries.

Keywords: Habitat fragmentation; Habitat Suitability Index; Land reclamation; Yangtze River Estuary

Regional index terms: China; Shanghai Municipality; Yangtze River Estuary

1. Introduction

Worldwide efforts have been launched to promote sustainable urban development and growth with minimal effects to natural ecosystems, however excessive and disordered reclamation projects often severely damage estuaries (Bulleri and Chapman, 2010). These reclamation activities can weaken estuarine tidal power and change hydrological characteristics (Liu *et al.*, 2005), block ecological and hydrological connectivity in coastal wetlands (Wu, 2002), reduce phytoplankton, zooplankton, aquatic shellfish and fish biodiversity, and cause change in dominant species and community structure (Healym *et al.*, 2002). Land reclamations might directly occupy estuarine habitats (Ma, 2009; Cai, 2012), by transforming coastal wetlands for benthic

organisms into ports and farmland, among other available but often less suitable sites (Sun, 2010). Moreover, land reclamations change habitat distribution patterns under the effects of hydrological processes (Sun *et al.*, 2015; Zhang *et al.*, 2015).

Former studies selected different environmental variables to quantify suitable habitat for target species driven by anthropogenic activities (Yi *et al.*, 2010; Vincenzi *et al.*, 2006; Fukuda, 2009). For example, Van Dolah *et al.* (1999) analyzed dissolved oxygen, sediment chemistry and toxicity averages to assess benthic habitat quality. Amara *et al.* (2007) measured temperature indices of salinity and sediment chemical contaminants to evaluate fish habitat quality. Yi *et al.* (2010) examined water level, velocity, and temperature to understand water inflow effects on carp habitat suitability.

In general, environmental variables chosen for aquatic habitat assessments are taken as an instantaneous measure or an average value representing some specific period of time, which have neglected the spatial variability and fluctuations of critical environmental factors. Montague *et al.* (1993) reported fluctuations in salinity decreased benthos abundance due to physiological stress reducing growth and survival. Feng *et al.* (2008) indicated fluctuations in salinity frequency and amplitude exhibited substantial effects on *Litopenaeus vannamei* (Whiteleg shrimp) juvenile growth rates. Khairnar *et al.* (2015) reported water salinity fluctuation frequency and amplitude and the interaction between the variables affected the growth rate and energy budget of juvenile tongue sole. However, simulations of the effects of fluctuations in environmental factors on organisms under suitable habitat conditions

remain scarce in the literature (Zhang *et al.*, 2015; Li *et al.*, 2015).

Considering different factors to assess the suitable habitat may result in a different pattern of suitable habitat, which may lead to different degrees of habitat fragmentation (Zhang *et al.*, 2015). To date, results of several studies reported habitat fragmentation played an important role in habitat quality (Radinger *et al.*, 2015; Kerezszy *et al.*, 2014; Reino *et al.*, 2013), which might subsequently influence species dispersal patterns (Diebel *et al.*, 2010; Stoll *et al.*, 2013), block biological connectivity, reduce intraspecific gene flow (Dixo, 2009), affect biomass, and even lead to species extinction (Fahrig, 2002; Chelgren *et al.*, 2014).

Instead of assessing suitable habitats with static environmental factors, the objectives of this study were to build an estuarine habitat fragmentation model integrating temporal and spatial variability of estuarine environmental factors. Land reclamation and freshwater inflow alteration effects were analyzed based on spatial pattern variability in suitable habitats after compiling target estuarine species requirements for fluctuation rate, water depth, and salinity.

2. Methods

Aquatic habitat quality under different land reclamation activities was assessed by establishing an estuarine habitat model to calculate habitat suitability and fragmentation based on spatial pattern variation of critical environmental factors. The approach comprised two steps: (a) simulating spatial distributions of critical environmental variables for target species habitat; and (b) mapping suitable habitat patterns and defining the habitat fragmentation index (Fig.1).

<Figure 1>

We selected water depth, water salinity, and fluctuation rate of water salinity as critical environmental factors in this study. The diversity requirements of critical environmental factors for suitable habitat assessment were integrated using the fuzzy logic method, which was employed to calculate the Habitat Suitability Index (HSI) as follows:

$$HSI = fuzzy(H, S, F) \quad (1)$$

where H is water depth, S is salinity, and F is fluctuation rate of salinity. The fuzzy logic method was derived as Figure 2.

Former studies demonstrated fluctuations in water salinity exhibited important influences on aquatic organism growth and some aquatic organisms suffered extensive mortality rates due to instantaneous variation in salinity (Browne and Wanigasekera, 2000; Calliari et al., 2008). Therefore, based on temporal variation in estuarine salinity, we defined a fluctuation rate (F), which represents water fluctuation and selected a standard deviation formula as its expression:

$$F = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(x_i - \frac{1}{N} \sum_{i=1}^N x_i \right)^2} \quad (2)$$

where x_i denotes salinity at moment i , and N represents tide fluctuation time. Standard deviation reflects the data set dispersion measures, therefore within the same time, the larger the fluctuation rate the greater the water salinity fluctuations.

Based on the fuzzy logic method, all variables were translated into different linguistic variables, and the linguistic variables were defined by membership functions shaped by the following four parameters (a_m , b_m , c_m , d_m): i) membership

degree increases linearly from 0 to 1 between a_m and b_m ; ii) membership degree is equal to 1 between b_m and c_m ; and iii) membership degree decreases from 1 to 0 between c_m and d_m (Figure 2). The parameters used to define membership functions for three environmental factors have been shown in Table 1, all these were defined based on requirement of target species to three critical environmental factors (Table 2) and the variation range of these environmental factors in the study area.

<Figure 2>

<Table 1>

<Table 2>

After the linguistic variables and their membership functions are defined, the fuzzy rules connect the input variables to the HSI using the IF–THEN form. For example, “IF salinity (S) IS ‘moderate’ AND depth (H) IS ‘moderate’ AND fluctuation rate (F) IS ‘High’, THEN habitat suitability IS ‘Moderate’”. All the fuzzy rules used in this study have been listed in Table 3, these rules were defined based on the review of the requirement of target species to three critical environmental factors and their membership functions. (Then the minimum–maximum fuzzy inference method was used here to execute the fuzzy rules. From these rules, the habitat suitability output is a fuzzy subset. We calculated the crisp value using the Center of Gravity method. The method is expressed as follows (Klir, et al., 1995):

$$V_{COG} = \int_{Z_{min}}^{Z_{max}} z\mu_c(z) dz / \int_{Z_{min}}^{Z_{max}} \mu_c(z) dz \quad (3)$$

where V_{COG} is the crisp *HSI* value, Z represents the linguistic variable crisp value, Z_{min} and Z_{max} denote minimum and maximum Z , respectively, and $\mu_c(z)$ indicates linguistic variable C membership.

<Table 3>

Based on the HSI value calculated by the above-described method, the estuary habitat is divided into four HSI levels, 0-0.25, 0.25-0.5, 0.5-0.75, and 0.75-1.0 (0-0.25 represents very unsuitable habitats for Chinese mitten crab to spawn, 0.25-0.5 represents unsuitable habitats, 0.5-0.75 represents suitable habitats, 0.75-1 represents very suitable habitats). Different habitat types were distributed in the study area; therefore the habitat aggregation index (*HAI*) was used to represent fragmentation of one habitat type. The formula to represent fragmentation of individual habitat types was expressed as (He, *et al.*, 2000):

$$HAI_i = e_{i,i} / \max_e_{i,i} \quad (4)$$

Where $e_{i,i}$ represents the total edges shared by habitat type i itself, $\max_e_{i,i}$ will take one of the three forms:

$$\max_e_{i,i} = 2n(n - 1), \text{ when } m=0, \text{ or}$$

$$\max_e_{i,i} = 2n(n - 1) + 2m - 1, \text{ when } m < n, \text{ or}$$

$$\max_e_{i,i} = 2n(n - 1) + 2m - 2, \text{ when } m \geq 0.$$

Where n is the side length of largest integral square, $m = A_i - n^2$, and A_i denotes areas of habitat type i (e.g., if type i has 60 cells in raster landscape, the largest integral square will be 7×7 cells, $n = 7$, $m = 11$, and $\max_e_{i,i} = 104$; if type i has 70 cells in raster landscape, the largest integral square will be 8×8 cells, $n = 8$, $m = 6$, and $\max_e_{i,i} = 122$).

A high *HAI* value indicates that the habitat in the study area is composed of a few gathering habitats within a large area, and a low *HAI* value indicates that the habitat is

composed of many fragmentary habitats within a small area.

3. Study Area

The Yangtze River Estuary is China's largest silt delta and also is an integral component of the large marine ecosystem in the East China Sea. The estuarine section from Xuliujing is divided into north and south branches, and the south branch is divided into a south and north passage at Jiuduansha (Fig. 3).

<Figure 3>

In order to develop the economy and meet the need for land along the Yangtze River Estuary; consequently excessive and disordered reclamation occurred, including sea aquiculture, farmland, port, and deep-water constructions(Wu *et al.*, 2002; Li *et al.*, 2011; Song *et al.*, 2013). Changes in shoreline and subaqueous elevation over the last two decades were divided into three scenarios (Fig. 4). Scenario 1 (S1) was used to characterize the initial coastline and terrain conditions before land reclamation, during this period (1998) land reclamation activities have not occurred in the Yangtze River Estuary, so we select it as the initial scenario.c In the scenario 2 (S2), land reclamations occurred largely in Nanhui, Chongming Island, and Hengsha, the estuary channel has been seriously compressed, 237.2 km² coastal wetlands were transformed to concretes used for urban infrastructures. Compared to S2, the estuary channel was further compressed and additional 282.7 km² coastal wetlands disappeared in scenario 3 (S3), besides, a deep-water channel was constructed in the south of Hengsha. Reclamation areas and deep-water channel length are shown in Table 4.

<Figure 4>

The Yangtze River Estuary plays an important role in the regional economy, but is also an ecologically sensitive area, serving as the spawning grounds for the Chinese mitten crab (*Eriocheir sinensis*) (Jiang *et al.*, 2014). Ni *et al.* (2006) conducted field surveys in the Yangtze River Estuary from 1980 to 2000 and reported that the annual yield of Chinese mitten crab decreased from 46.3 to 2.0 tons. Since 2004, government organizations have cultivated the Chinese mitten crab and released the species to the Yangtze River Estuary to ensure successful reproduction and restore declining populations.

From March to May, Chinese mitten crabs primarily spawn in estuaries, where water depth is less than 10 m and salinity ranges from 3 to 18 ppt (Jiang *et al.*, 2012). In addition, seawater fluctuations in the study area, which effect fluctuations in water salinity at spawning sites, exhibit a substantial influence on the larvae survival of Chinese mitten crabs (Cheng *et al.*, 1997). Hence water depth, water salinity, and fluctuation rate of water salinity were selected as critical environmental factors in this study, the optimal requirements for these factors were consistent with the spawning season of Chinese mitten crab from March to May. We defined these optimal requirement ranges based on literature reviews (Rudnick *et al.*, 2005; Barnes *et al.*, 2006; Inglis *et al.*, 2006; Blumenshine *et al.*, 2012; Sun *et al.*, 2012; Jiang *et al.*, 2014; Zhang *et al.*, 2015; Sun *et al.*, 2015). The requirements of Chinese mitten crab to these factors have been shown in Table 2.

4. Results

The Environmental Fluid Dynamics Code (EFDC) was applied to simulate water depth and salinity distribution in study area, as used by (Peng *et al.*, 2011; Seo and Ahn, 2012). The hydraulic and water quality model in this study integrated Cartesian orthogonal horizontal coordinates, which consisted of 60000 horizontal cells, with each cell dimension equal to 80×120 meters. The coastline boundary and underwater topography data used in this model was extracted in GIS based on sea chart. The calculated tidal heights, water velocity, and salinity were compared with data measured at LXG, HS, V1, V2, Y1, and Y2 stations respectively in Figure 5, and all validation data were obtained in the Yangtze River Estuary from 11 to 12 February, 1998 (Luo *et al.*, 2003). The model performance confirmed the simulation results were congruent with observed data.

<Figure 5>

The freshwater inflow during Chinese mitten crab spawning season (February and March) fluctuated around $7000 \text{ m}^3/\text{s}$ in the Yangtze River Estuary; therefore we chose $7000 \text{ m}^3/\text{s}$ as the freshwater inflow boundary condition for the model. Comparisons of changes in average water depths, velocities, salinities, and fluctuation rates over nine sites (T1-T9) under the three scenarios (S1-S3) are shown in Figure 6 (scenarios shown in Fig. 4).

< Figure 6>

For the most part, S2 exhibited overall greater contributions to land reclamation causing compression of the estuary channel compared with S1. Water depths at sites

T2, T4, T5, and T9 near land reclamation projects decreased at least 1.0 m; flow velocities at most sites showed an ~0.2 m/s rise, particularly at T5, T6, T8 and T9; Salinity at sites T3, T4, and T5 decreased to 0 ppt, while at sites T6 and T7, salinities decreased at least 5; Fluctuation rate values at sites T3, T4, and T5 reduced to 0 and values for other sites also decreased. S2 to S3, deep-water channel construction increased water depths at site T3 and T7 at least 3.0 m, resulted in an increase of velocity at site T7 about ~0.5m/s, the salinities at two notable sites T6 and T7, which located near the deep-water channel, , increased 7 and 20, respectively. Therefore, results indicated that land reclamations changed environmental variables notably.

Salinity distributions under different scenarios are depicted in Figure 7. The isoclines of low salinity moved toward seaward and low salinity area between the 2 and 20 was compressed nearly 595 km² from S1 to S2. The deep-water channel construction in S3 resulted in average salinity inside the channel was 10 ppt greater than the average salinity outside the channel. Overall, land reclamations altered the previous balance of environmental components and compressed the low salinity area that are suitable for Chinese mitten crab to spawn.

<Figure 7>

Based on the fuzzy logic method described in Section 2, we calculated the Habitat Suitability Index (*HSI*) and divided the habitat into four types according to four *HSI* levels: 0–0.25, 0.25–0.5, 0.5–0.75, and 0.75–1.0 (0–0.25 represents very unsuitable habitats for Chinese mitten crab to spawn, 0.25–0.5 represents unsuitable habitats, 0.5–0.75 represents suitable habitats, 0.75–1 represents very suitable

habitats). We defined the habitat with $HSI > 0.5$ as suitable habitat for Chinese mitten crab (when $HSI > 0.5$, Chinese mitten crab have a relatively proper condition to spawn in the Yangtze River Estuary). In addition, we applied the Habitat Fragmentation Index (HAI) to assess suitable habitat fragmentation. Different habitat type distributions with different HSI level under $7000\text{m}^3/\text{s}$ freshwater flow are shown in Figure 8. A water depth, salinity, and fluctuation rate variation gradient showed suitable habitats ($HSI > 0.5$) were primarily concentrated in Dongtan, Jiuduansha, and Hengsha (sites T6, T7, and T8). From S1 to S2, a marked drop of suitable habitat was observed, however suitable habitats still exhibited connectivity. From S2 to S3, suitable habitat area was reduced, in addition, the suitable habitats were separated into six fragments or distinct patches..

<Figure 8>

Meanwhile, we also compared the difference in distribution of habitats with and without fluctuation rate as input variable. The distribution of habitats without fluctuation rate as an input variable is depicted in Figure 9. A qualitative visual comparison between Figure 9 and Figure 8 reveals intuitive differences, where habitat areas ($HSI > 0.5$) become larger. In addition, the distribution of suitable habitats (comparison of Figs. 8 and 9) showed fewer fragments and an increase in suitable habitat and connectivity in the absence of fluctuation rate (Fig. 9).

< Figure 9>

Changes of suitable habitat area and HAI are depicted in Figure 10. From S1 to S2, suitable habitat decreased from 1438.9 to 1113.6 km^2 . Meanwhile, HAI exhibited

a 0.03 decrease (0.93 to 0.9), indicating a small change in suitable habitat fragmentation. From S2 to S3, suitable habitat decreased to 686.3 km² and *HAI* exhibited a decrease of 0.06 (0.90 to 0.84) (Fig. 11). The deep-water channel construction resulted in salinity inside at least 10 ppt higher than the salinity outside the channel; and water depth inside were nearly 5 m greater than it outside the channel. Consequently, suitable habitat was distributed near the deep-water channel in S2, and contiguous habitat degraded was absent in S3. The suitable habitat was fragmented into six patches under S3.

<Figure 10>

5. Discussion

Worldwide efforts have been launched to promote sustainable urban development and growth with minimal effects to natural ecosystems, however excessive and disordered reclamation projects often severely destroy the estuary and offshore habitat environment (Bulleri and Chapman, 2010; Ma, 2009; Cai, 2012). This study shows that transformations of coastal wetlands to cement ground reduced water depth, decreased water salinity and fluctuation, while deep-water channel construction increased velocity and water salinity inside the channel (Fig. 6 and Fig. 7). In addition, compared to coastal wetlands transformation, deep-water channel construction would be severely damaging habitat connectivity. Therefore, land reclamations altered the previous balance in environmental components and changed the distribution of suitable habitats. In addition, input variable selections to calculate habitat suitability are critical, as variables must model results congruent with natural

conditions. Here, we chose water salinity and depth to reflect current Yangtze River Estuary conditions and water fluctuation rate to represent fluctuation influence on water salinity and consequently the effects on Chinese mitten crabs. When fluctuation rate was removed as a variable, the suitable habitat area ($HSI > 0.5$) become larger. Moreover, the distribution of suitable habitats showed fewer fragments and the suitable habitats has more connectivity. Overall, land reclamations and input variable selections showed decisive role to simulate suitable habitat distribution for Chinese mitten crab.

We compared the simulated potential suitable habitat distribution of Chinese mitten crab in our study with the field surveyed major spawning sites of Chinese mitten crab reported by Jiang *et al.* (2014) in Figure 11. It indicated that spawning positions were consistent with our simulated results, it also confirm that fluctuation rate was an important input variable.

However, Chinese mitten crabs did not occupy some suitable habitat located at the north end branch of the Yangtze River. Alternatively, Chinese mitten crabs preferred selecting suitable habitat in the south end branch as spawning sites. The reason for this behavior might be attributed to the species dispersal ability. From March to May, the Chinese mitten crab relies on water currents and swims via currents to the Yangtze River Estuary to spawn. However, due to land reclamation and sedimentation, freshwater inflow to the north is limited relative to the south branch. Caldwell *et al.* (2013) indicated water currents have an influence on dispersal capacity, and Radinger *et al.* (2015) demonstrated species with high compared with low mobility make better

use of potential suitable habitat. Therefore, rather than navigating unsuitable and less suitable habitat to reach suitable north branch areas, Chinese mitten crabs selected suitable habitat at the end of the south branch as spawning sites. Another reason could be that Crab habitat in north branch is fragmented by unsuitable habitat that is too large for the crabs to cross (Zollner and Lima, 2005; Turgeon *et al.*, 2010).

< Figure 11>

Variations of freshwater inflows can also influence suitable habitat distribution in estuaries (Zhang *et al.*, 2015; Sun *et al.*, 2015). In the present study, freshwater inflows were altered from 7000 m³/s to 40000 m³/s. Therefore, we calculated suitable habitat of Chinese mitten crab under changed freshwater inflows (Fig. 12). Changing freshwater inflow from 7000 to 40000m³/s resulted in a decrease of suitable habitat area from 1438.9 to 217.2 km² under S1. Similarly, suitable habitat areas decreased from 1113.6 to 175.9 km² under S2 and it decreased from 686.3 to 46.5 km² under S3. Increased inflow resulted in an increase of fragment patches number, which was accompanied by a reduction of patch area and an increase of distance between patches. Li *et al.* (2015) derived an ecologically-based flow regime taking into account the effects of flow regime to habitat fragmentation. Sun *et al.* (2015) determined recommending environmental flows in the estuary considering the adaptation of potential suitable habitats with variations in the flow regime. In our study, increased freshwater inflows resulted in a reduction of *HAI* in S1 from 0.93 to 0.61, and a decrease from 0.90 to 0.1 in S2. However, *HAI* in S3 decreased from 0.84 to a minimum of 0.49, then subsequently increased to 0.90. Therefore, the ideal

freshwater inflow for Chinese mitten crabs to spawn was 7000 m³/s.

<Figure 12>

On the whole, the numerical model in this study was used to simulate the habitat distribution of Chinese mitten crab under the anthropogenic impacts of reclamation in the Yangtze River Estuary. We achieved a more accurate description of potential suitable habitat utilization of Chinese mitten crabs and a more robust basis to manage and protect Chinese mitten crab habitat.

6. Conclusion

In this study, we selected water depth, water salinity and fluctuation rate of salinity as input environmental variables to map the habitat distribution of Chinese mitten crab with different Habitat Suitability Index (HSI) based on fuzzy logic methods, Habitat Fragmentation Index (*HAI*) was used to represent estuarine habitat fragmentation. Field survey result about Chinese mitten crab distribution published in other study was compared with our simulated result, it indicated that we could determine suitable habitat locations of the Chinese mitten crab based on a set of environmental factors specific to the Yangtze River Estuary, and provide a basis to calculate habitat fragmentation.

Land reclamations directly occupied suitable habitats in coastal wetlands, altered aquatic habitat distribution patterns and destroyed habitat connectivity in estuaries. The Yangtze River Estuary is trumpet-shaped, land reclamations compressed the estuary channel and increased flow velocity and salinity, reduced suitable habitat areas of Chinese mitten crab. In addition, deep-water channel construction reduced

habitat via fragmentation to a greater extent than land reclamation.

Acknowledgments

This work was supported by National Basic Research Program of China (973) (2013CB430402), the National Science Foundation for Innovative Research Group (No. 51121003), the National Natural Science Foundation of China (No. 51279007), and the Fundamental Research Funds for the Central Universities.

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524 Table 1 Linguistic values assigned to input and output variables in habitat suitability models (HSI).

Linguistic Terms	Input environmental variables			Output variables
	Salinity range	Depth range	Fluctuation range rate	HSI range
VL (Very low)	[0 0 2 4]	[0 0 1 3]	[0 0 4 6]	[0 0 0.2 0.3]
L (Low)	[2 4 7 9]	[1 3 6 8]	[4 6 10 12]	[0.2 0.3 0.45 0.55]
M (Moderate)	[7 9 13 15]	[6 8 9 11]		
H (High)	[13 15 17 19]	[9 11 18 20]	[10 12 15 17]	[0.45 0.55 0.7 0.8]
VH (Very high)	[17 19 31 31]	[18 20 37 37]	[15 17 24 24]	[0.7 0.8 1 1]

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528 Table 2 Requirement of Chinese mitten crab to critical environmental factors.

Model variable	Minimum	Maximum	Source
Salinity (ppt)	3	18	Rudnick <i>et al.</i> 2005)
Depth (m)	2	10	Inglis <i>et al.</i> (2006)
			Sun <i>et al.</i> (2012)
			Wang <i>et al.</i> (2012)
Fluctuation rate	0	16	Zhang <i>et al.</i> (2015)
			Sun <i>et al.</i> (2015)

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530

531 Table 3 Fuzzy rules defined for habitat suitability of Chinese mitten crab.

NO.	S	H	F	HSI	NO.	S	H	F	HSI
1	VL	VL	VL	L	43	M	M	M	L
2	VL	VL	L	M	44	M	M	H	L
3	VL	VL	M	L	45	M	H	VL	L
4	VL	L	VL	L	46	M	H	L	M
5	VL	L	L	M	47	M	H	M	L
6	VL	L	M	L	48	M	H	H	L
7	VL	M	VL	VL	49	M	VH	VL	L
8	VL	M	L	L	50	M	VH	L	L
9	VL	M	M	VL	51	M	VH	M	L
10	VL	H	VL	VL	52	M	VH	H	L
11	VL	H	L	L	53	H	VL	VL	L
12	VL	H	M	VL	54	H	VL	L	M
13	L	VL	VL	L	55	H	VL	M	L
14	L	VL	L	M	56	H	VL	H	L
15	L	VL	M	L	57	H	L	VL	L
16	L	VL	H	L	58	H	L	L	M
17	L	L	VL	L	59	H	L	M	L
18	L	L	L	M	60	H	L	H	L
19	L	L	M	L	61	H	M	VL	VL
20	L	L	H	L	62	H	M	L	L
21	L	M	VL	VL	63	H	M	M	L
22	L	M	L	L	64	H	M	H	VL
23	L	M	M	L	65	H	H	VL	L
24	L	M	H	VL	66	H	H	L	L
25	L	H	VL	L	67	H	H	M	L
26	L	H	L	L	68	H	H	H	VL
27	L	H	M	L	69	H	VH	VL	VL
28	L	H	H	VL	70	H	VH	L	L
29	L	VH	VL	VL	71	H	VH	M	L
30	L	VH	L	L	72	H	VH	H	VL
31	L	VH	M	L	73	VH	L	L	M
32	L	VH	H	VL	74	VH	L	M	L
33	M	VL	VL	M	75	VH	L	H	VL
34	M	VL	L	H	76	VH	M	L	L
35	M	VL	M	M	77	VH	M	M	VL
36	M	VL	H	L	78	VH	M	H	VL
37	M	L	VL	M	79	VH	H	L	L
38	M	L	L	H	80	VH	H	M	VL
39	M	L	M	M	81	VH	H	H	VL
40	M	L	H	M	82	VH	VH	L	L
41	M	M	VL	L	83	VH	VH	M	VL
42	M	M	L	M	84	VH	VH	H	VL

533 Table 4 Type changes and land reclamation area for three scenarios.

Types	Scenario 1 – Scenario 2	Scenario 2 – Scenario 3	Source
Wetland transformations	237.2 km ²	282.7 km ²	Wu <i>et al.</i> , 2002 Li <i>et al.</i> , 2011
Deep-water channel	0	92.2 km	Song <i>et al.</i> , 2013

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Figure captions

Fig. 1. Approach to assess habitat suitability and fragmentation. Step 1: Temporal and spatial variability of environmental factors; Step 2: Suitable habitat assessment.

Fig. 2. Fuzzy logic method.

Fig. 3. Yangtze River Estuary measurement station locations.

Fig. 4. Yangtze River Estuary reclamations.

Fig. 5. Measurement and calculation data for different variables and stations. (LXG: Lian Xinggang; HS: Hengsha; Y1: The first salinity verification point; Y2: The second salinity verification point; V1: The first velocity verification point; V2: The second velocity verification point)

Fig. 6. Changes in water depth, salinity, and fluctuation rates for different time points (T1-T9) and scenarios (S1-S3).

Fig. 7. Salinity distribution under different scenarios.

Fig. 8. Different habitat type distributions, measured by HSI values, under different scenarios with freshwater flow at 7000m³/s.

Fig. 9. Different habitat type distribution, measured by HSI values, in the absence of fluctuation rate as an input environmental variable for the three different scenarios (S1, S2, and S3).

Fig. 10. Area and fragmentation changes (HAI-index) throughout suitable habitat.

Fig. 11. Simulated suitable habitat distribution for scenario 3 (S3) compared with primary Chinese mitten crab spawning sites ('spawning sites' Jiang *et al.*, 2014; 'suitable habitat' our simulated results).

557 **Fig. 12.** Areas and fragmentation changes (HAI-index) by different freshwater inflows
558 for three scenarios (S1, S2, and S3) throughout suitable habitat.
559

Figure 1.

Figure 2.

Figure 3.

569

570 Figure 4.

LYG

HS

V1 Velocity

V1 Direction

V2 Velocity

V2 Direction

S1

S2

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11.

Figure 12.