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Geomorphologic dynamics and maintenance following mudflat, creek and pond formation in an estuarine mangrove wetland

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ABSTRACT

Mudflats, creeks and ponds serve as critical habitat for shorebirds and fish in subtropical estuarine wetlands. A wetland restoration project was launched to remove partial mangrove trees from a predefined area and form a mudflat patch. A creek-pond-combo (CPC) construction project was also conducted in the Shezi wetland area along the Danshuei River. Long-term measurements were performed to test for geomorphologic responses and related habitat changes. The dynamic topography revealed significant patterns of sediment deposition, with the highest deposition rates found in the CPC habitat area. The sediment trap efficiency of the CPC was roughly seven-fold higher than that of the mudflat area. The CPC area gradually evolved into a mudflat habitat area through processes of sediment deposition and was significantly reduced in size and more shallow after typhoon events. The shrinking phenomenon occurred prior to deposition and at a faster rate. CPC construction is recommended every two years, and the related maintenance costs are estimated to be approximately 1,500 US dollars per year. The findings of this study indicate that long-term investments should be made to maintain CPC areas in estuarine mangrove wetlands.

1. Introduction

Migratory shorebirds are attracted to the estuarine wetlands of the Danshuei River in northern Taiwan during their wintering cycle because of the area's diverse habitat features, including mudflats and mangrove forests (Lin, 1994; Pan, 1998). However, mudflat areas have recently decreased because mangrove areas have spread and invaded other habitats (Lee and Shih, 2004; Lee and Yeh, 2009; Shih et al., 2011; Yang et al., 2013). Mudflats, ponds and creeks serve as critical habitat areas for shorebirds and fish in subtropical estuarine wetlands. Construction efforts, such as mangrove deforestation, mudflat maintenance and tidal creek construction, can promote a greater diversity of habitat types and attract shorebirds (Huang et al., 2010). Such an approach was pursued through the maintenance of tidal mudflats by removing mangrove seedlings at the Hong Kong Mai Po Ramsar Site, which resulted in increased biodiversity (WWF Hong Kong, 2006). Several researchers have suggested the inclusion of creeks in construction project maintenance efforts to support species and maximize habitat value (Coats et al., 1995; Morzaria-Luna et al., 2004; Lewis, 2005; Mitsch, 2005; Wallace et al., 2005; Lewis and Gilmore, 2007; Zedler and West, 2008). Although the construction of mudflats, creeks and ponds benefits wetland biodiversity, such development would alter sediment deposition processes in deposited mangrove swamps. Only a limited number of studies have monitored wetland morphology changes following mudflat, creek and pond restoration projects. We initiated a cost-effective restoration project in the Shezi wetland. This study attempts to examine the responses of the wetland's geomorphologic dynamics following the project. One-way analysis of variance (ANOVA) was utilized to assess the significance of the changes with the 60 months monitoring data. The reconstruction works for habitat maintenance strategies were also addressed.

2. Materials and methods

2.1. Study area

The Shezi wetland is located along the Danshuei River in Taipei, Taiwan. The total study area is approximately 53,685 m^2 in size and

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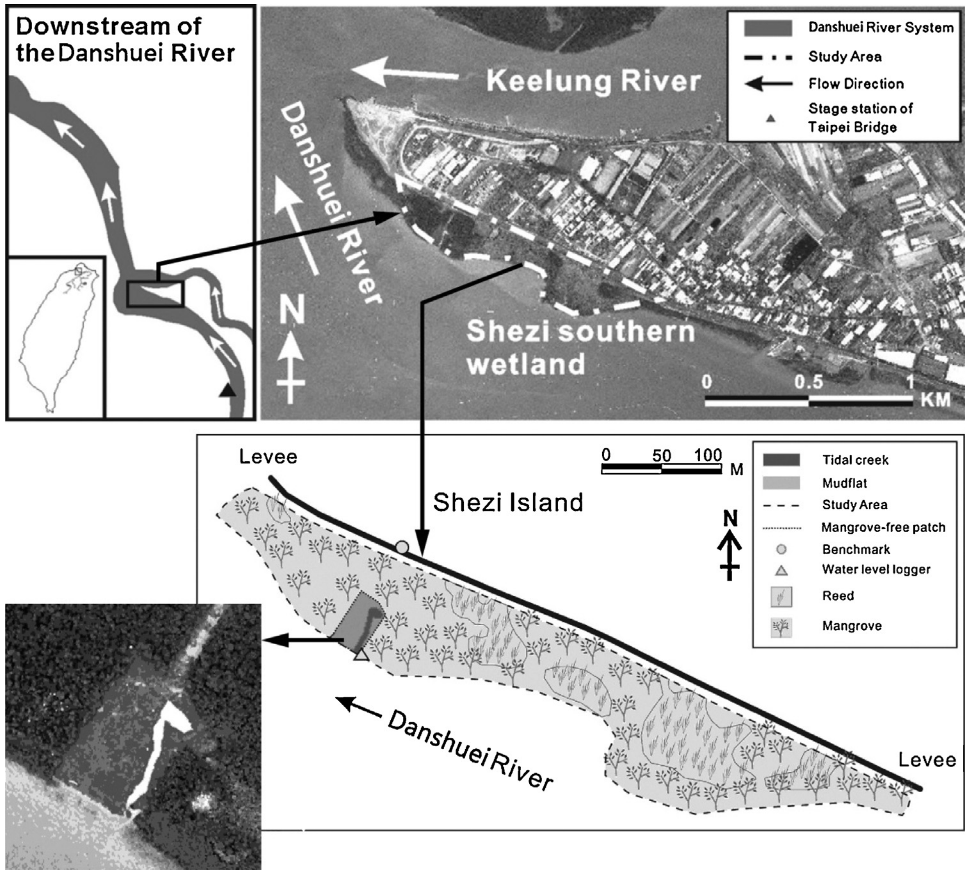

Fig. 1. The location of the study area. The Shezi mangrove wetland is located in Tanshui River, Taipei, Taiwan. The total study area was about 53685 m^2 in area and located approximately 11 km upstream of the river mouth. The map of the revised allocation of the study area, including the mangrove-free patch and the mangrove-retained regions used in the monitoring program.

located approximately 11 km upstream from the mouth of the river (Fig. 1). The Shezi wetland is an estuarine wetland with a high density of mangroves and average water salinity level of 15 ppt. In March 2007, the aboveground portions of *Kandelia obovata* mangrove trees were manually removed from a predefined area to form a 1,756 m^2 mudflat patch. The belowground roots were left in the sediment. A cutting point of several centimeters below the mangrove tree growth zone was applied to prevent re-sprouting. The belowground roots were left in the sediment to minimize substrata disturbance and compression effects. Within the mangrove-free patch, a 190 m^2 creek-pond-combo (CPC) was also constructed over a one-month period. The restoration project was executed following two seminars with experts and one briefing session with local residents. Local resident involvement in the project was encouraged. The cost of the initial restoration project was approximately 3,000 US dollars, and the construction cost was less than two US dollars per square meter.

The average elevation (EL) was 0.9–1.2 m above sea level, and the distance between the mangrove-free patch and river levee was 50 m. The upstream topography of the tidal creek was characterized by an open-water area of approximately 70.0 m^2, averaging 12.5 m in width and 5.6 m in length. The midstream and downstream creek area spanned approximately 120.0 m^2, averaging 3.7 m in width and 32.4 m in length. The average EL of the creek bed was approximately 0.0 m, and the downstream and combined upstream and midstream areas had an EL of −0.15 m and 0.35 m, respectively. However, the outlet of the tidal creek was recorded at an EL of 0.55 m, which produced a pool that was approximately 0.55 m deep along the ebb of the creek. The deepest segment of the upstream area was 0.75 m.

2.2. Topography changes

The topography was studied using a TOPCON Total Station (GTS226), and the adjacent Tenth River Management Office, Water Resources Agency (WRA), Ministry of Economic Affairs (MOEA), Taiwan was used as the benchmark reference. The benchmark EL and water-level records were obtained from the Taiwanese fundamental benchmark of Keelung. This fundamental benchmark was determined by the mean sea level and has been adopted as the zero orthometric height of Taiwan. A five-year-long monitoring project was conducted, and the wetland topography was surveyed during the following six time periods: at initial construction (March 2007) and in the 7th (October 2007), 15th (June 2008), 19th (October 2008), 30th (September 2009), and 60th (March 2012) month after construction. Features before and after construction were monitored and recorded, and the topography records were used to calculate sediment deposition volumes based on Eq. (1).

$$\Delta V_N^{N+1} = \sum_{i-1}^{m} \left(L_i \times B_i \times \Delta h_i \right) \tag{1}$$

where ΔV_N^{N+1} denotes the variant sediment deposition volume between time N and N+1; Li denotes the control length equal to the average distance between the upstream (L_i^{i+1}) and downstream $\left(L_{i-1}^{i}\right)$ areas; Bi denotes the river width at cross-sections; and $\triangle$hi denotes the difference in average EL at the two time points. Please see Fig. 2 for further details.

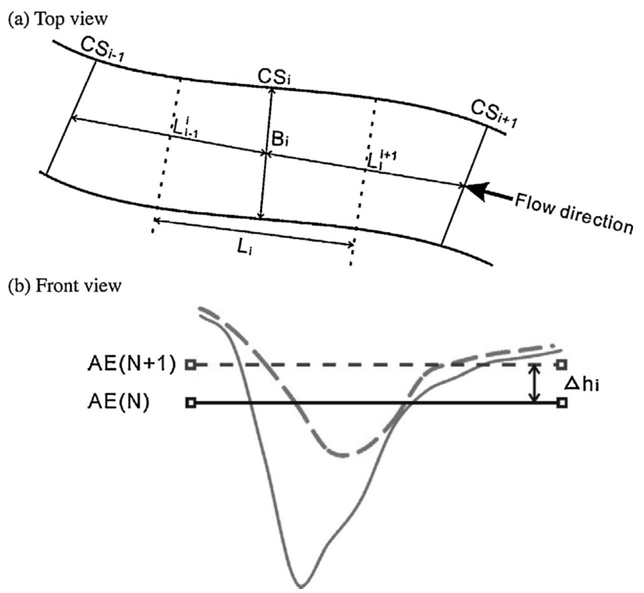

Fig. 2. The schematic plot for the sediment deposition volume calculation (a) Top view of the river channel illustrates the definitions of river width Bi, control length Li, distance to downstream cross-section L_{i-1}^{i} and distance to upstream cross-section L_i^{i+1}; $L_i = \left(L_{i-1}^{i} + L_i^{i+1}\right)/2$. (b) Front view of river cross-section, i.e., horizontal cross-section. The dotted line represents the N + 1th cross-section and its average elevation AE(N + 1), while the bold line describes the previous cross-section and its average elevation AE(N). The symbol △hi indicates the difference between AE(N) and AE(N + 1).

2.3. Inundation and habitat classification

The water stage records for the Taipei Bridge gauge station, which was constructed by the Tenth River Management Office, WRA, MOEA and is located 6.3 km away from the study area, were used in this study. The Taipei Bridge gauge-station water-stage records were validated before use. The tidal regime of the Danshuei River is semidiurnal with mixed tides. The mean high water level tide (MHWL) EL was recorded at 1.40 m above sea level, and the mean low water level (MLWL) EL was recorded at −0.85 m.

A HOBO Water Level Logger (model U20-001-01) was installed in the mangrove-free patch to monitor the water stage, and the Weibull method (Chow, 1988) was employed to analyze the exceeding probability (*EP*) level based on Eq. (2).

$$EP = [m/(N+1)] \times 100\% \tag{2}$$

where *EP* is the probability that a given water stage will be met or exceeded (% time); *m* denotes the water stage record of m in descending order; and *N* denotes the total number of data points. The *EP* was employed to classify the habitat types, and Jenkins and Greenway's (2007) criterion was employed to define the habitat types based on water stages and inundation periods as shown in Table 1. Three habitat types were examined: open water area (OW, pond area), deep mudflat (DM, creek area) and shallow mudflat (SM, bare mudflat with visible water).

Table 1
Habitat classification criterion of the mangrove-free patch for the open water (OW), the deep mudflat (DM) and the shallow mudflat (SM).

Habitat type	Bed elevation (m)	Inundation frequency (%)
OW	<0.55	>38.1
DM	0.55–0.95	24.4–38.1
SM	>0.95	<24.4

2.4. Statistical analyses

The analysis of variance (ANOVA) method employs a collection of statistical models and associated procedures to address different sources of variation (Cohen, 1988), and it serves as a statistical test of equivalence among the means of several groups. A descriptive statistics one-way ANOVA (Spiegel, 1961) was used to identify significant changes in wetland topography. The null hypothesis, Ho, states that each wetland topography population mean will be the same, and the alternative hypothesis, H1, states that at least one wetland topography population mean will differ from the others. A confidence interval of 95% was employed for the one-way ANOVA statistical significance test.

3. Results

3.1. Topographic changes

Topographic changes following the construction project are illustrated in Fig. 3. The sediment deposition volume of the CPC fluctuated from 1.2 to 22.5 m^3/month, and the CPC area gradually diminished from 526.7 to 378.9 m^2. In addition, deposition rates of the upstream, midstream and downstream areas were recorded at 4.5, 1.5 and 1.4 cm/month, respectively, with an average speed of 2.5 cm/month. The area upstream of the CPC is located in the tidal pond, and the area downstream is located in the control point of the tidal creek.

Annual shrinking and deposition rates of the CPC and mudflat are shown in Table 2. The shrinking phenomenon was discovered prior to deposition, and the CPC area shrank at a rate of 6.47 cm/year. The CPC and mudflat areas exhibited deposition rates of 2.46 and 0.36 cm/year, respectively. Fig. 4 illustrates the side slope of the CPC, and they decreased gradually from 0.38 to 0.06 towards

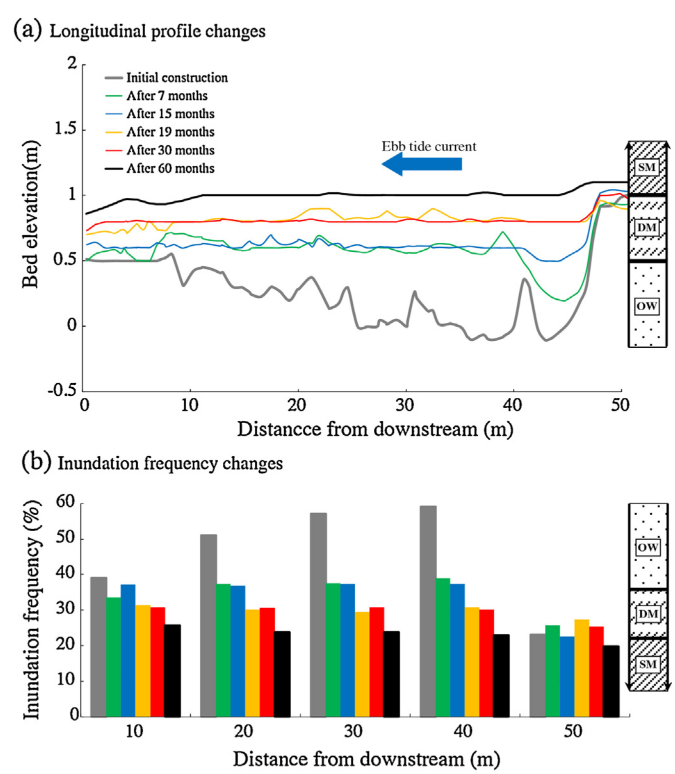

Fig. 3. The changes of longitudinal profile and inundation frequency of the creek-pond-combo (CPC). The results revealed that the open water habitat (OW) evolutes to deep mudflat (DM) and shallow mudflat (SM) habitats due to sediment deposition.

Table 2
The annual shrinking and deposition speeds after the creation of creek-pond-combo (CPC) and mudflat.

Construction works	CPC	Mudflat
Shrinking speed (cm/yr)	6.47	–
Deposition speed (cm/yr)	2.46	0.36

– No data.

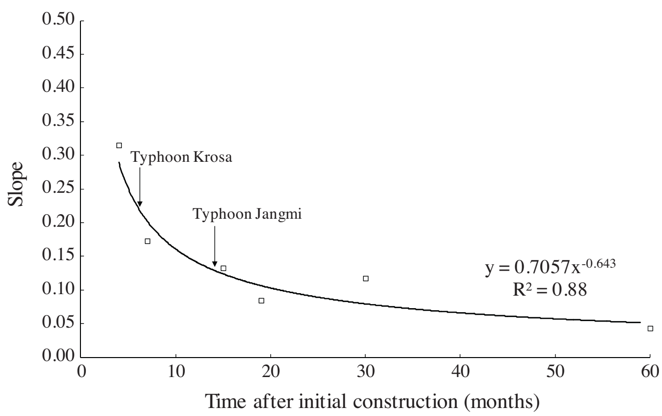

Fig. 4. Changes of the side slope at the upstream, midstream and downstream of the creek-pond-combo (CPC). The side slopes decrease gradually from 0.38 to 0.06 when approaching the deep mudflat. The steep and moderate declines of the side slope occur in the flooding period. The results reveal that typhoons play a major role in sediment deposition.

the mudflat habitat. Furthermore, a reduction in steep and moderate side slopes occurred during flooding periods, indicating that typhoons play a major role in sediment deposition processes. The dynamic topography exhibited a significant deposition trend (ANOVA, $P < 0.05$)

3.2. Inundation and habitat changes

The EP of the OW, DM and SM areas were >38.1%, 24.4–38.1% and <24.4%, respectively. The EL of the OW was lower than 0.55 m because the control point was located at the outlet of the CPC area. The inundation time, or EP, was therefore longer than 38.1% for the OW. In addition, the DM area would likely be inundated 24.4–38.1% of the time. The SM area would be inundated less than 24.4% of the time.

Much of the study area was characterized by monogenetic mangrove forest prior to habitat construction, and reed marsh and mudflat areas were rare. Following the initial CPC construction, the coverage ratios of the OW, DM and SM habitats increased. However, only the SM habitat increased in area from 2.29% to 3.07%, with the OW and DM habitats decreasing from 0.25% and 0.74% to 0.00% and 0.20%, respectively, after six years (Table 3). Because of sediment deposition, the OW area significantly declined and gradually evolved into a mudflat habitat (Fig. 3).

Table 3
The coverage ratio of each habitat before and after construction.

Time	Initial construction	After 7 months	After 15 months	After 19 months	After 30 months	After 60 months
Habitat type	Coverage ratio (%)					
Mangrove	71.76	71.76	71.76	71.76	71.76	71.76
Reed	24.96	24.96	24.96	24.96	24.96	24.96
OW	0.25	0.12	0.07	0.04	0.00	0.00
DM	0.74	1.03	0.84	0.67	0.76	0.20
SM	2.29	2.13	2.36	2.57	2.51	3.07

OW: the pond area; DM: the creek area; SM: the mudflat area.

4. Discussion

4.1. Morphological responses and implications

The Shezi mangrove wetland is located upstream of the confluence of the Keelung River and Danshuei River and forms part of the backwater area. Consequently, these wetlands formed through sediment deposition during flooding periods. Habitat diversity increased following initial habitat construction; however, subsequent sediment deposition decreased the habitat diversity. Topographic calculations showed that the OW area generated by the construction of the CPC was subject to the highest degree of sediment deposition, whereas only limited sediment deposition occurred in the mudflat areas, which may allow for wetland reclamation. The steepest angle of the regression line slope was found in the OW, suggesting that the highest degree of sediment deposition would occur in the pond area. Compared with the OW, only slight sediment deposition occurred in the SM and DM areas. Headcutting phenomena were observed after the CPC excavation period, which suggests channel bottom erosion upstream and supports previous research on construction efforts (Teal and Weinstein, 2002; Larkin et al., 2008). We also found that the CPC became significantly smaller and shallower after typhoon events. This shrinking phenomenon was discovered prior to deposition, and the rate of shrinking was 2.63 times higher on average than the rate of deposition. In addition, using a regression model that has strong correlations with actual data provides practical approaches to future management.

$$Y = 0.7057X^{-0.643}, R^2 = 0.88$$

where Y represents the slope of the CPC and X represents the number of months following construction.

4.2. Potential benefits for fish, shorebirds and benthos

Lewis and Gilmore (2007) suggested that tidal hydrology projects must be designed to incorporate fish habitat, including tidal creeks, to provide access and low-tide refuge for mobile nekton because the mangrove forest is generally flooded by tidal waters. The authors also argued that a fully successful restoration design must mimic tidal stream morphology and hydrology patterns along an estuarine gradient across a heterogeneous mixture of mangrove ecosystem communities. The mudflat area examined in the present study increased following habitat construction, and a 4.1-fold increase was observed in the annual average number of shorebirds (Huang et al., 2012). The peak ratio of the number of shorebirds to the total number of birds also exhibited an increasing trend of 35–80%. The migration routes of these birds are affected by various global-, regional- and local-scale factors. Thus, although the observed increase in the number of shorebirds may not be completely attributable to habitat rehabilitation efforts, our observations are encouraging. Polychaete levels differed considerably among the various habitats and were highest in the creek and lowest in the mudflat (personal observations by HL Hsieh). The most abundant polychaete species was the spionid *Prionospio japonicus* followed by the capitellid *Capitella* sp. I and sabellid *Laonome albicingillum*. Other rare polychaete species included the nereid *Neanthes glandicincta* and spionids *Malacoceros indicus* and *Polydora fusca*. The high abundance of polychaetes in the tidal creek indicates that this area is a suitable habitat for these worms. The bare mudflats appeared to show a greater abundance of polychaetes relative to the adjacent vegetated mangrove areas (Huang et al., 2012). Based on our observations, tidal creek development, even after a short period, allows polychaetes to colonize new habitats. Based on observations of polychaetes, which are consumed by fish in the Danshuei River estuary (Shao, 1999) as well as by shorebirds (Thompson et al., 1992), we believe that CPC construction could benefit local wintering shorebirds and other consumers, including fish.

4.3. Habitat type maintenance

We propose deepening and widening CPC areas in locations where habitat heterogeneity is likely to degrade following construction. CPC maintenance was developed to support topographic surveys and habitat assessments and retain the width and depth at rehabilitated levels. Based on the findings of this study, the following habitat maintenance strategies are suggested: (1) in mudflat areas, mangrove seedling removal should be performed in May of each year by volunteers because *K. obovata* mangrove seedlings mature from November to April of the following year; this maintenance strategy supports the management plan of the Hong Kong Mai Po Ramsar Site; and (2) in CPC areas, mechanical excavation should be performed to deepen and widen creeks and ponds in May for two years. The annual cost of maintenance is estimated at approximately 1,500 US dollars, which is half of the initial construction cost because the flooding period spans from June to December and wintering birds visit from September to April of the following year at this site. Engineering works implemented in the suggested time period would not only prevent disturbances to wintering shorebirds but would also remove sediment deposited during typhoon events. When building a mudflat, a CPC system of tidal creeks and tidal ponds is recommended. Tidal ponds serve as reservoirs that retain a high amount of water during flooding periods and promote sediment flushing during ebb tide periods. Local scour occurs in tidal creeks because of empty flushing effects resulting from water flowing away from the tidal ponds during ebb-tide periods. Thus, the suggested configuration of tidal ponds and tidal creeks is intended to decelerate sediment siltation. However, to avoid sediment deposition acceleration, tidal pools should not be dredged too deeply.

4.4. Sea level rise effects

The results of this study show that the current inundation frequencies are >38.1%, 24.4–38.1% and <24.4% for the OW, DM, and SM areas, respectively. To predict future trends in sea level, the rate of increase of the northern Taiwan sea level (24.2 cm/100 years), which was presented by Tseng (2009), was applied. Current EP curves and a sea-level-rise scenario are illustrated in Fig. 5. Following Yang et al. (2013), the tolerant inundation frequency of *K. obovata* was recorded at between 5.73% and 38.25% for the Shezi wetland. The OW was found to expand, and the mudflat area (SM + DM) shrank because of rises in sea level. The DM completely evolved into an OW habitat, and the majority of the SM area also evolved to a DM. Therefore, the *K. obovata* mangrove growth area would evolve into a higher EL mudflat. The Guandu wetland, which is located close to the Shezi wetland, would shrink by approximately 35% by 2100 because landward migration would be limited by levees (Yang et al., 2013). We predict that the mangrove area will decline because of increases in non-mangrove area, i.e., SM + DM and OW areas, related to the combined effects of sea level rises and artificial levee construction. Mangroves along muddy OW areas effectively trap large amounts of mud from sheltered, coastal waters. The complex flow field around vegetation that generates zones of flow stagnation enhances sediment deposition (Wolanski, 2007). In addition, sediment flushing effects during ebb tides would increase, and sediment deposition patterns would decelerate or prevent future re-dredging efforts.

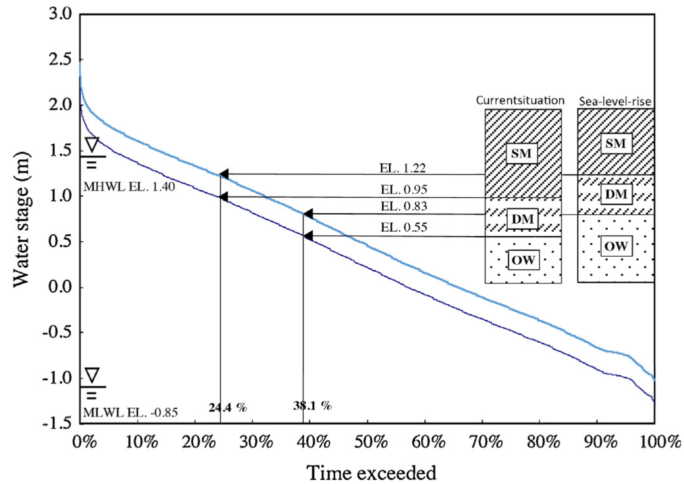

Fig. 5. Current Exceeded probability (EP) curves and a sea-level-rise scenario at Shezi wetland in current situation. The EPs of the open water (OW), the deep mudflat (DM) and the shallow mudflat (SM) were greater than 38.1%, 24.4%–38.1% and lower than 24.4%, respectively. The OW was found to expand, and the SM and the DM shrank because of rises in sea level. The DM completely evolved into an OW habitat, and the majority of the SM area also evolved to a DM.

5. Conclusions

Mangrove trees alone do not create a biologically diverse ecosystem or support sustainable ecosystem functions (Hsieh et al., 2015). In addition to mangrove vegetation, other essential components of mangrove ecosystems include mudflats, tidal waterways, and shallow water areas. Such systems host diverse aquatic and terrestrial fauna and flora (Bosire et al., 2008; Nagelkerken et al., 2008) and circulate water, thus connecting all of these components (Macintosh and Ashton, 2002; Macintosh and Ashton, 2002). Water converts mangrove swamp subsystems into river or coastal ecosystems when mangroves are located in estuaries or coastal regions, respectively (Wolinski, 2007). Mangrove expansion decreases the area of bare mudflats and consequently limits habitat diversity (Shih et al., 2015). This study demonstrates that mangrove-vegetated wetlands of Shezi wetland may be restored through partial mangrove removal and OW and mudflat construction projects. Our results suggest that effective mangrove expansion control and mudflat and CPC maintenance can attract shorebirds. This study presents reconstruction methods that sustain ecological functions according to the sediment deposition behaviors characteristic of the Shezi wetland. As a main principle of ecological engineering, maintenance plans should minimize costs and efforts from outside of the system (Odum and Odum, 2003; Mitsch and Jørgensen, 2003). CPC and mudflat maintenance strategies address different concerns, with CPC strategies designed to maintain CPC width and depth and mudflats strategies designed to resist mangrove seedling invasion and vegetation. Performing reconstruction projects in May is recommended to avoid flooding periods and minimize disturbances to migratory birds. In addition, yearly mudflat and biennial CPC maintenance cycles are recommended. The annual cost of the restoration project is calculated at approximately 1,500 US dollars, and continuous investment in estuarine mangrove wetlands is encouraged. Wolinski (2007) and Craft et al. (2002) called for superior methods of addressing issues related to tidal prism establishment to promote scouring in developed or restored tidal creeks to limit or prevent re-dredging efforts. We also highlight the importance of sediment flushing because erosion will occur in tidal creeks as a result of empty flushing effects during ebb tide periods. Thus, we have suggested a tidal pond and tidal creek configuration that can decelerate sediment siltation through a comprehensive design strategy, which includes suitable longitudinal slopes. This study also indicates that a long-term monitoring program should be established as part of construction efforts to examine impacts to biotic and abiotic factors. Such assessments are critical to the design of future management programs. The findings encourage the promotion of mudflats, creeks and ponds construction projects in estuarine wetlands and recommend necessary investments in habitat maintenance.

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