Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Ecological Engineering 23 (2004) 85–94
ECOLOGICAL ENGINEERING
www.elsevier.com/locate/ecoleng

Impacts of vegetation changes on the hydraulic and sediment transport characteristics in Guandu mangrove wetland

Hong-Yuan Lee[a,*], Shang-Shu Shih[b,1]

[a] *Department of Civil Engineering and Hydrotech Research Laboratory, National Taiwan University, Taipei 106, Taiwan, ROC*
[b] *Department of Civil Engineering, National Taiwan University, Taipei 106, Taiwan, ROC*

Received 3 April 2004; received in revised form 6 July 2004; accepted 9 July 2004

Abstract

Excessive mangrove spreading causes a significant impact upon the ecosystem and flood control operations in the Guandu mangrove wetland (Guandu Natural Reserve), Taiwan. Aerial photos, taken between 1978 and 1994, reveal that marsh habitats, dominated by *Cyperus malaccensis* Lam. and *Phragmites communis* (L.) Trin., have changed into a swamp habitat, dominated by *Kandelia candel* (L.) Druce. The coverage area of *K. candel* has increased from 0.04 ha in 1978 to 20.75 ha in 1994. The *Kandelia* habitat was more salty and located at a higher ground surface elevation than was the *P. communis* habitat. Variations of the water surface elevation and reduction of the channel conveyance due to increase of the coverage area of *K. candel* (L.) Druce were also obtained in this study.

A horizontal two-dimensional model, TABS-2, was applied in this study to simulate the hydraulic and sediment transport characteristics of this estuary wetland. Four cases with different removal ratios show that water surface elevation decreases as the removal ratio increases. When the removal ratio of *Kandelia* reaches 20%, variations of the water surface elevation in the wetland became insignificant. Significant sediment deposition occurs due to the extensive root network of *Kandelia*. The average deposition is about 33 mm during a 200-year return period flood event. Removal of *Kandelia* reduces the sediment deposition rate. When the removal ratio reaches 20%, the reduction in sediment deposition is about 5 mm. Considering the factors of flood protection and sediment deposition, the optimal removal ratio is between 10 and 20%. It also found that mangrove removal improves the ecological restoration of *Uca* (*Thalassuca*) *Formosensis* Rathbun, an endemic species of the fiddler crab in Taiwan.

Keywords: *Kandelia candel* (L.) Druce; Mangrove; Wetland; Removal ratio; Hydraulic simulation; Sediment routing; Ecological restoration

1. Introduction

Coastal wetlands are widely distributed in estuaries throughout the world. Because of the tremendous volumes and varieties of inhabiting plants, they are regarded as being among the most productive ecosystems

* Corresponding author. Tel.: +886 2 23917278; fax: 886 2 23917278.
E-mail addresses: leehy@ntu.edu.tw (H.-Y. Lee), d90521017@ntu.edu.tw (S.-S. Shih).
[1] Tel.: +886 2 23630231 2408x36; fax: +886 2 23631558.

0925-8574/$ – see front matter
doi:10.1016/j.ecoleng.2004.07.003

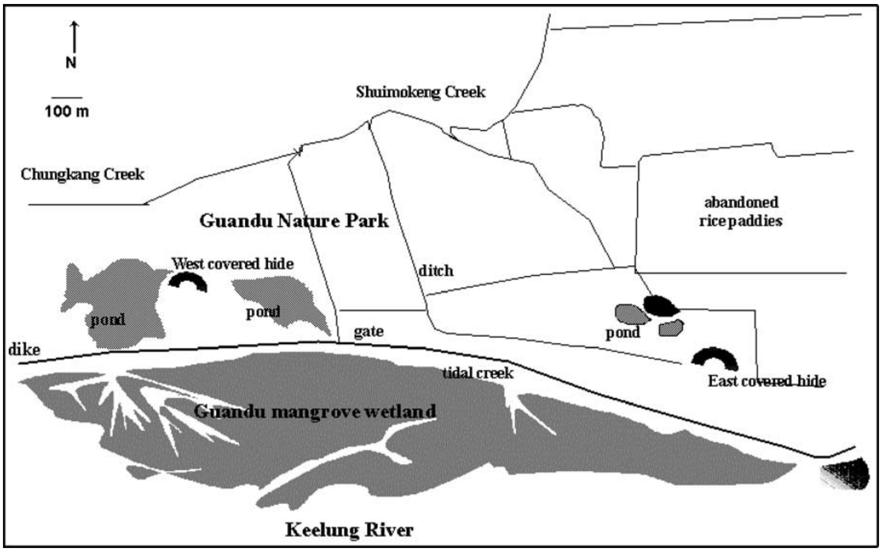

Fig. 1. The location map of the Guandu mangrove wetland. The study site located near the confluence of Keelung River flowed to west direction and Tanshui River flowed to north direction. The northern and southern parts of the tidal creek were the Guandu Nature Park and Guandu mangrove wetland, respectively.

(Teal, 1962; Day et al., 1989). They are known to provide food sources and diverse habitats for large numbers of resident and migratory organisms. Wetlands have also been shown to be very efficient in removal of nutrients from agricultural runoff (Comín et al., 2001). The Guandu Natural Reserve (25°07′N, 121°027′E) lies in the west of the Guandu floodplain, which is located in the confluence of the Keelung and Tanshui Rivers, approximately 10 km from the river mouth, near Taipei, Taiwan. The Guandu wetland near the Keelung River is a semi-diurnal tidal regime with tidal amplitude of approximately 1–2 m. Water temperatures at Guandu range from 18 °C in February to 28 °C in July. The Guandu mangrove wetland is a typical coastal wetland, with *Kandelia candel* (L.) Druce mangrove developing as a result of the tidal action (see also Fig. 1). The vegetation in the reserve comprises *K. candel*, *Phragmites communis* (L.) Trin. and *Cyperus malaccensis* Lam. Recently, due to dike construction and other environmental impacts associated with human activity, *K. candel* spreads progressively and becomes the main specie in this wetland, forming the mangrove swamps (Lin et al., 2003). The increase of *K. candel* cover has some adverse effects on the river hydraulic characteristics, including velocity retardation, increase of water surface elevation and sediment deposition.

The Water Resources Agency in Taiwan widened the river cross-section right downstream of the wetland in 1964 and constructed the Guandu dike in 1968. This dike blocks the tidal influx of salt water and therefore soil salinity in the northern part of the Guandu wetland decreased, where ecological development has diverged from the surrounding catchments and affected only by fresh water. In 1986, the Council of Agriculture (COA) in Taiwan declared the Guandu mangrove wetland, an area of around 55 ha to the south of the Guandu dike, to be a nature conservation area. However, the aforementioned spreading of mangrove has some negative impacts: (1) increased mangrove cover limiting waterfowl usage of this habitat. The study of Froneman et al. (2001) points out that vegetation diversity in and around ponds is important in determining their usage by waterbirds. (2) Increased roughness coefficient of the river leading to a higher mean water surface elevation (Chow, 1973; Lee and Shih, 2003). (3) Reduction of the flow velocity in the wetland causing aggradations in the mangrove wetland (Li and Shen, 1973). The higher water elevations pose a threat to the residents and property along the river.

The original types of plant in this area are shrubs and trees adapted to the harsh seashore environment, having large and smooth leaves. Moreover, the thick in-

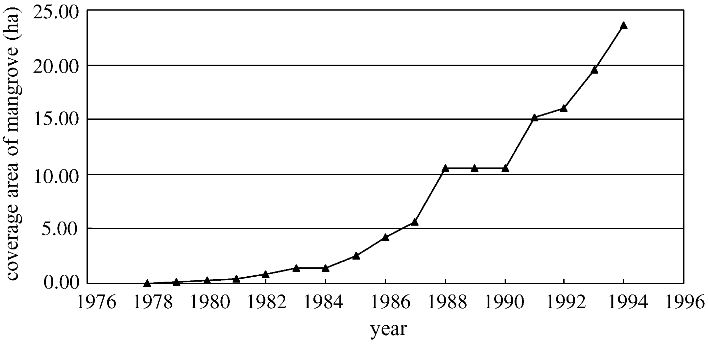

Fig. 2. The variations of mangrove coverage area in Guandu mangrove wetland.

ner tissues and well-developed cuticles of these plants allow them to reduce water evaporation. These plants also have special protective features against the salty environment. Some of these plants are oceanic drift plants, whose lightweight and fibrous fruits ride ocean currents and take root in faraway places. Analysis of aerial photographs taken from 1978 to 1994 revealed that the marsh habitat has changed into a forested wetland habitat. The area covered by *K. candel* has increased from 0.04 ha in 1978 to 20.75 ha in 1994 (see also Fig. 2).

2. Numerical simulation

A horizontal two-dimensional numerical model, TABS-2, is used to simulate the hydraulic and sediment transport characteristics in this study.

2.1. Horizontal two-dimensional model, TABS-2

The TABS-2 model is a two-dimensional, depth-averaged, finite element hydrodynamic numerical model developed by the Waterways Experiment Station of U.S. Army Corps of Engineers. It computes water surface elevation and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields. TABS-2 also computes a finite element solution of the Reynolds form of the Navier–Stokes equations for turbulent flows. Friction is calculated according to the Manning or the Chézy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state problems can be analyzed.

2.1.1. Equations of hydraulic routing

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} - \frac{1}{\rho}\left(\varepsilon_{yx}\frac{\partial^2 v}{\partial x^2} + \varepsilon_{yy}\frac{\partial^2 v}{\partial y^2} + \right) + g\frac{\partial a}{\partial y} + g\frac{\partial h}{\partial y} + \tau_y = 0 \tag{2}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - \frac{1}{\rho}\left(\varepsilon_{xx}\frac{\partial^2 u}{\partial x^2} + \varepsilon_{xy}\frac{\partial^2 u}{\partial y^2}\right) + g\frac{\partial a}{\partial x} + g\frac{\partial h}{\partial x} + \tau_x = 0 \tag{3}$$

where u and v are the horizontal and vertical velocities, respectively, ρ is the density of the fluid, a is the bed elevation, h is the water depth and τ_x and τ_y are shear stresses in the x and y directions, respectively.

2.1.2. Equations of sediment routing

Ariathurai et al. (1977) developed the basic convection-diffusion equation:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) + \alpha_1 C + \alpha_2 \tag{4}$$

where C is the concentration, D_x and D_y are effective diffusion coefficients in the x and y directions, respectively, α_1 is the coefficient of the source term and α_2 is the equilibrium concentration portion of the source term $=-\alpha_1 C_{\mathrm{eq}}$.

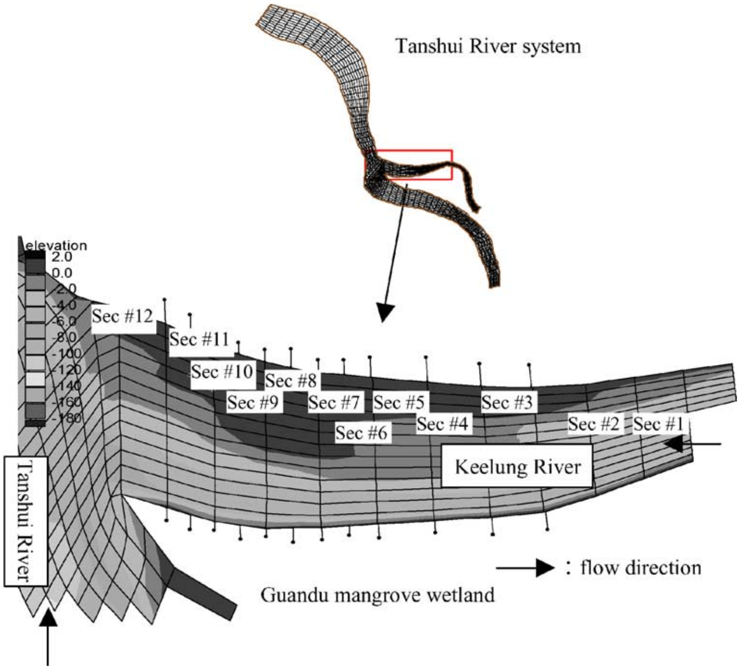

Fig. 3. TABS-2 mesh grid of the study site. The TABS-2's mesh grid of study site. The above and below plots are the Tanshui River System and Guandu mangrove wetland, respectively. The 12 cross-sections site of Guandu mangrove wetland which were used to calculate the bed elevation changes. The numbers of 12 cross-sections were assigned orderly sequentially from upstream to downstream of Keelung River.

Please refer to SMS 7.0 User's Manual (2000) for more details. Fig. 3 illustrates the generated grid.

2.2. Determinations of TABS-2's parameters

2.2.1. River bed roughness coefficient

The *Manning*'s coefficient, *n*, is the most important parameter in open-channel flow computations. This coefficient was originally developed in 1889 by an Irish engineer, Robert Manning, and was later modified to its present, well-known, form:

$$V = \frac{k}{n} R^{2/3} S_f^{1/2} \tag{5}$$

where V is the mean velocity, R is the hydraulic radius, S_f is the slope of the energy grade line and k = 1 in Metric Units or =1.486 in English Units.

The *Manning*'s *n* represents degree of the energy loss caused by the riverbed and riverbank roughness. Many studies investigated this roughness coefficient (Chow, 1973; Fukuoka and Fujita, 1991). In this study, some findings of Wang's (2001) study were used to estimate the values of *n* and then the numerical model parameters were calibrated and verified using the experimental data conduced by the Water Resources Agency in Taiwan (1996).

The *Manning*'s *n* increase with increasing return period flood and reaches a maximum value of 0.283 when the return period flood equals 20 years. The details are provided in Table 1.

2.2.2. Diffusion coefficient and eddy viscosity coefficient

According to the data provided by the User's Manual of TABS-2, the eddy viscosity coefficient in the mangrove wetland and rest of the study sites have been

Table 1
Lists the *Manning*'s *n* in four different return period of flood

Return period (year)	*Manning*'s *n*
20	0.283
10	0.281
5	0.233
2	0.241

Table 2
The representative ranges *of* turbulent exchange coefficients in TABS-2 model

Condition	ε (N s/m^2)
Homogenous horizontal flow around an island	500–5000
Homogenous horizontal flow at a confluence	1200–5000
Steady-state flow for thermal discharge to a slow moving rive	1000–50000
Tidal flow in a marshy estuary	2500–10000
Slow flow through a shallow pond	10–50

selected as 5000 and 2000 N s/m^2, respectively. Details of the table are provided in Table 2.

Elder's (1959) formula is applied to estimate the longitudinal and transverse diffusion coefficients, D_x and D_y,

$$D_x = 5.93\,Du^* \quad (6)$$

$$D_y = 0.23\,Du^* \quad (7)$$

where h is the water depth, and u^* is the shear velocity.

2.2.3. Fall-velocity of sediment

Rubey's (1933) formula is applied to calculate the fall velocity of sphere particles:

$$w = F\left[dg\left(\frac{\gamma_s - \gamma}{\gamma}\right)\right]^{1/2} \quad (8)$$

where F = 0.79 for particles greater than 1 mm, g is the acceleration due to gravity, d is the particle size, r is the specific gravity of water and r_s is the specific gravity of sediment particles. For smaller grain sizes

$$F = \left[\frac{2}{3} + \frac{36\nu^2}{gd^3(\gamma_s/\gamma - 1)}\right]^{1/2} - \left[\frac{36\nu^2}{gd^3(\gamma_s/\gamma - 1)}\right]^{1/2} \quad (9)$$

where $\nu = 1.79^2 \times 10^{-6}/(1.0 + 0.0337T + 0.000221T^2)$ and T is the water temperature in °C.

2.3. Mesh generation and input of boundary conditions

2.3.1. Mesh generation

The finite element mesh generated from the digital maps defines only the x and y coordinates for the numerical node. The bathymetric information thus can be surveyed using field data and interpolated onto the finite element mesh.

The x, y, and z coordinates of this study site were provided based on the field data surveyed by the Water Resources Agency in 2003 and adjusted using the Taipei Government 1:5000 DTM data.

2.3.2. Boundary conditions of steady-state hydraulic simulations

Under the steady-state hydraulic simulation case, the upstream and downstream boundary conditions, including 2, 5, 10, and 20 years return period floods and the river mouth water surface elevation, were cited from the investigations conducted by the Water Resources Agency, Taiwan (1996), as listed in Table 3.

2.3.3. Boundary conditions of sediment transport simulations

The upstream and downstream boundary conditions used in TABS-2's sediment transport simulations are provided in Figs. 4–6, respectively. The 200 years return period flood hydrograph which has 46 duration hours was set as the upstream boundary condition, as shown in Fig. 4 (Water Resources Agency, Taiwan, 1996). Furthermore, the corresponding river mouth water surface elevation is 2.3 m, during a designed 200 years return period flood event. The 200

Table 3
The boundary conditions of upstream and downstream in hydraulic simulations

Return period (year)	Tanshui River (m^3/s)	Keelung River (m^3/s)	Hsin-Dan Creek (m^3/s)	Da-Han Creek (m^3/s)	Water surface elevation of river mouth (m)
2	6200	1200	2800	2200	1.21
5	10400	1780	4800	3820	1.23
10	13400	2120	6300	4980	1.27
20	16000	2400	7500	6100	1.29

Source: Water Resources Agency, Taiwan, 1996.

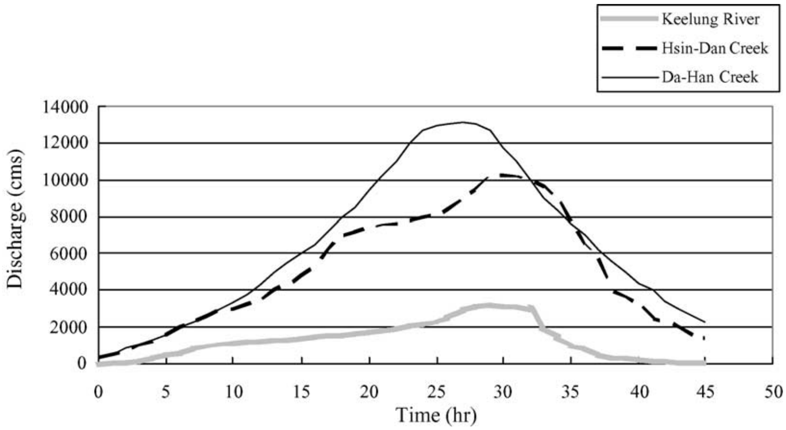

Fig. 4. The 200-year flood hydrograph of Tanshui River System (Water Resources Agency, Taiwan, 1996).

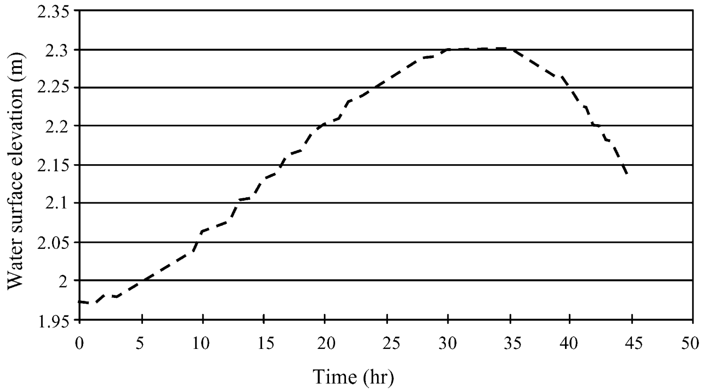

Fig. 5. Temporal variations of the water surface elevations at the river mouth during a 200 years flood event (Water Resources Agency, Taiwan, 1996).

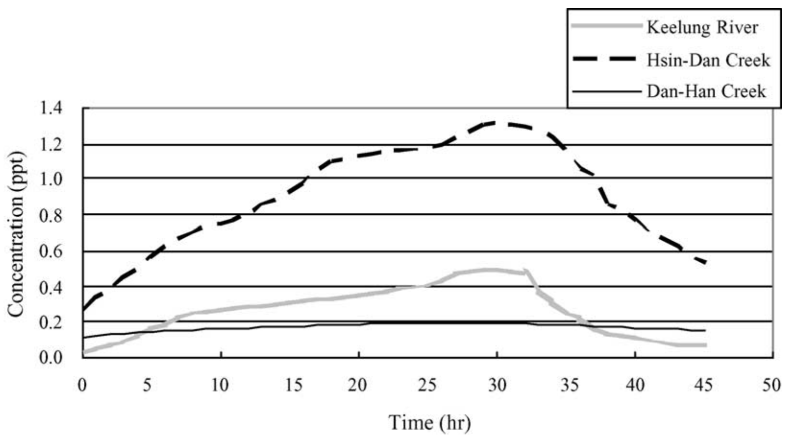

Fig. 6. The upstream sediment supplies of the Tanhsui River System, which includes: Keelung River, Hsin-Dan Creek, and Dan-Han Creek, respectively.

Table 4
Location of four removal areas

Case no.	Removal ratio (%)	Removal area (ha)	Removal location
1	0	0	No removal
2	20	4.52 (6 elements)	Western part
3	30	6.77 (9 elements)	Western and southern part
4	50	11.29 (15 elements)	Western, southern and eastern part

The removal ratio is studied from 0 to 50%.

years return period flood hydrograph is provided in Fig. 5.

The upstream sediment supply rating curves, shown in Fig. 6, developed by Lee et al. (1996) were adopted, and shown as:

$$Q_s = 4.5235Q^{1.1392} \quad : \text{Da-Han Creek} \tag{10}$$

$$Q_s = 1.7472Q^{1.4515} \quad : \text{Hsin-Dan Creek} \tag{11}$$

$$Q_s = 0.3836Q^{1.5841} \quad : \text{Keelung River} \tag{12}$$

where Q_s is the sediment supply rate and Q is the discharge.

2.4. Mangrove removal cases

Four different removal ratios, namely 0, 20, 30, and 50%, were simulated to investigate the impacts of the mangrove removal ratio on the hydraulic and sediment transport characteristics. The locations of the suggested removal area and 12 cross-sections which were used to calculate the bed elevation changes were shown in Figs. 3 and 7. The spatial variations of the water surface elevations under four different return period floods were provided in Figs. 8–11. No significant variations were observed when the removal ratio exceeded 20%.

The western part of the mangrove swamp is older than the others, hence the mangroves in this area are taller than those in the rest of the area. Taller trees tend to induce a higher water surface elevation and raise the risk of flooding. Therefore, the mangroves at the western and southern part of the swamp are suggested to be removed first. The suggested removal areas are shown in Table 4.

3. Results and discussion

3.1. Hydraulic simulation results

According to TABS-2 simulation results, under a 20% removal ratio and 2 years flood condition, water surface elevation will drop ranging from 4 to 76 mm. However, when the removal ratio increases to 30% or 50%, the drop of the water surface elevation remains between 6 and 75 mm. No significant difference was observed. Similar results were also observed in case of 5, 10 and 20 years return period flood simulations. Therefore, the optimal removal ratio recommended is 20%.

3.2. Sediment transport simulation results

Spatial variations of the riverbed elevations are provided in Fig. 12. The sediment transport simulations revealed that sediment deposition occurred in most of the 12 cross-sections, and thus the riverbed elevation increased after 46 h of simulation. The sediment deposition depth ranged between 10.45 to 122.65 mm. We can conclude that mangroves will cause significant sediment deposition.

Furthermore, sediment transport simulations under four different mangrove removal ratios were also investigated. Riverbed deposition ranged between 10.5 and 122.7 mm, with the average value equals to 33.0 mm. The reduction in sediment deposition is about 5 mm when the removal ratio reaches 20%. Long-term sediment transport simulation is still under investigation.

3.3. Summaries

In summary, the optimum removal ratio is 10–20% according to the variations of the hydraulic and sediment transport simulation. The study of Lee et al. (2003) indicated that the spread of *K. candel* will not only imperil the marsh species, i.e. *C. malaccensis* Lam. and *P. communis* but also decrease the mud plate area where is the water birds habitat area. Froneman et al. (2001) points out that vegetation diversity in and around ponds is important in determining their usage by waterbirds. Meanwhile, the endemic specie of fiddler crabs in Taiwan, *Uca* (*Thalassuca*) *Formosensis* Rathbun (Shih, 1994), has vanished from Guandu mangrove wetland (Chen et al., 2003). Removal of *K. candel* will

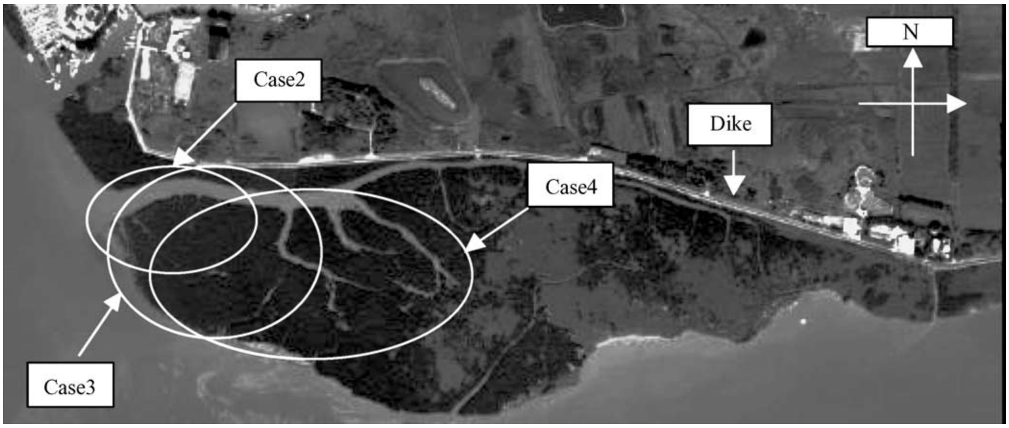

Fig. 7. The location of mangrove removal area (aerial photograph of Guandu in 2002).

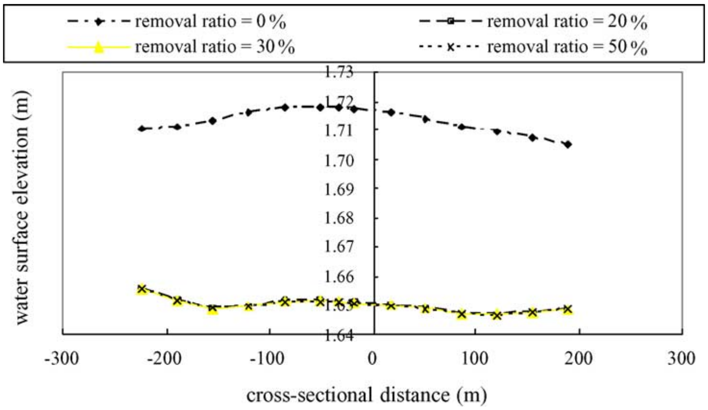

Fig. 8. Spatial variations of water surface elevation with four removal ratios under a 2-year flood event.

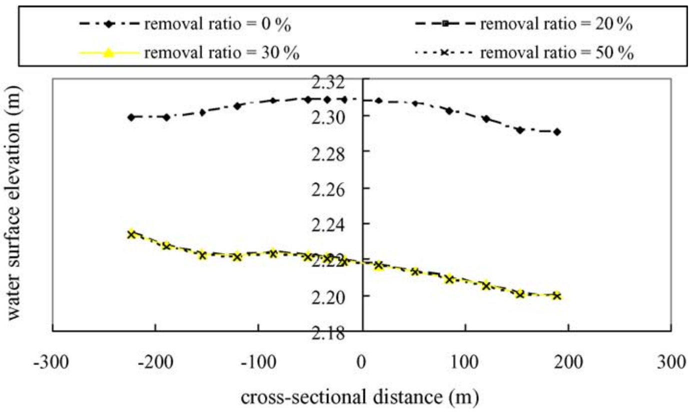

Fig. 9. Spatial variations of water surface elevation with four removal ratios under a 5-year flood event.

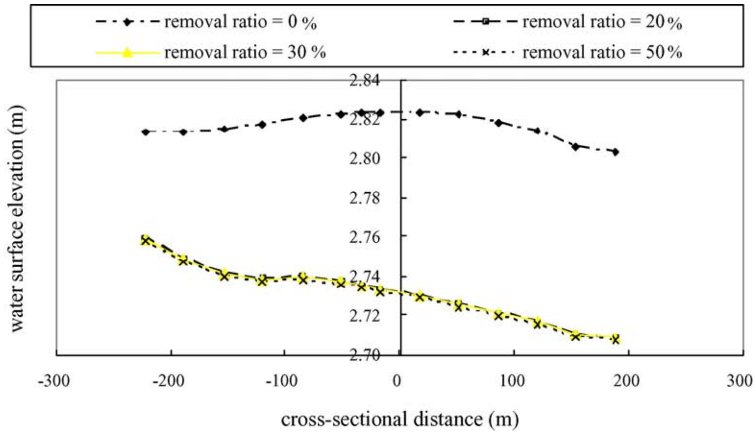

Fig. 10. Spatial variations of water surface elevation with four removal ratios under a 10-year flood event.

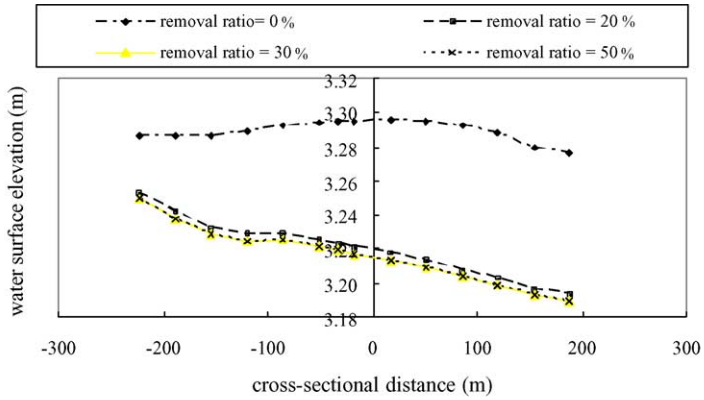

Fig. 11. Spatial variations of water surface elevation with four removal ratios under a 20-year flood event.

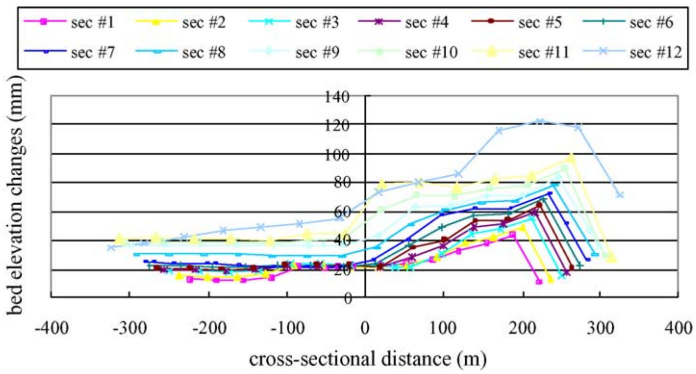

Fig. 12. Spatial variations of the riverbed elevation under a 200-year flood in the Guandu mangrove wetland.

reduce the possibility of flood threat and restore some original species in the Guandu mangrove wetland.

4. Conclusions

1. Aerial photos from 1978 to 1994 were used to analyze the temporal variations of the vegetation cover of Guandu Nature Reserve. The area of *K. candel* increased from 0.04 ha in 1978 to 20.75 ha in 1994.
2. The mangroves in the western part are older and taller and, therefore, this part of mangrove swamp is suggested for removal first. The optimal removal ratio is between 10 and 20%.
3. Sediment transport simulations showed that sediment deposition occurred in most of the 12 cross-sections. After 50 h of simulation, the sediment deposition depth ranged between 10 to 123 mm.
4. Sediment transport simulations with four removal ratios were also investigated. The results show that riverbed deposition ranged between 10.5 and 122.7 mm, with the average of 33.0 mm.
5. Some mangrove removal is helpful in reducing flood threats and improving other habitat restoration.

Acknowledgement

The author would like to thank Chi-Seng Water Management Research for financial support. The authors of this work benefited greatly from discussions with Mr. A.M. Borghuis.

References

Chen, C.P., Hsieh, H.L., Lin, P.F., 2003. Studies of ecological conservation strategy and investigation on mangroves in Hsin Chu City coastal wildlife protected area in 2002. Institute of Zoology, Academia Sinca, Taiwan.

Comín, F.A., Romero, J.A., Hernández, O., Menéndez, M., 2001. Restoration of wetlands from abandoned rice fields for nutrient removal, and biological community and landscape diversity. Restoration Ecol. 9 (2), 201–208.

Chow, V.T., 1973. Open-Channel Hydraulics, MacGraw_Hill International Editions.

Day, J.W., Hall, C.A.S., Kemp, W.M., Yanez-Arancibia, A., 1989. Estuarine Ecology. John Wiley, New York.

Froneman, A., Mangnall, M.J., Little, R.M., Crowe, T.M., 2001. Waterbird assemblages and associated habitat characteristics of farm ponds in the Western Cape, South Africa. Biodiversity Conserv. 10, 251–270.

Lee, H.Y., Shih, S.S., 2003. The environment characteristic investigations and the researches of operating tactics in Guandu Natural Reserve (II). No. 486 Report of Hydrotech Research Institute, National Taiwan University, Chi-Seng Water Management Research and Development Foundation, Taiwan.

Li, R.M., Shen, H.W., 1973. Effect of Tall Vegetations on flow and sediment. J. Hydraulic Division, ASCE, 99, 793–814.

Lin, H.J., Shao, K.T., Chow, W.L., MAA, C.J.W., Hsieh, H.L., Wu, W.L., Severinghaus, L.L., Wang, W.T., 2003. Biotic communities of freshwater marshes and mangroves in relation to saltwater incursions: implications for wetland regulation. Biodiversity Conserv. 12, 647–665.

Shih, S.D., 1994. Fiddler Crabs. National Museum of Marine Biology/Aquarium, Taipei, Taiwan, ROC.

Fukuoka, S., Fujita, K., 1991. Flow resistence due to the momentum transport caused by submerged vegetation in the river course, IAHR, pp. 9–13.

SMS 7.0 User's Manual, 2000. Open-channel flow and sedimentation. Environmental Modeling Research Laboratory, Brigham Young University.

Taipei City Government, 2000. The management research report of Guandu Natural Park and Guandu Natural Reserve (II), Taiwan, ROC.

Teal, J.M., 1962. Energy flow in the salt marsh ecosystem of Georgia. Ecology 43, 614–624.

Wang, C.F., 2001. The study of flow resistance in Keelung River mouth. Master thesis, Department of Agricultural Engineering, National Taiwan University, Taiwan, ROC.

Water Resources Agency, Taiwan, 1996. The hydraulic model study of Tanshui River System and Taipei flood protection project, Taiwan, ROC.