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MODELING ESTUARINE HYDRODYNAMICS AND SALINITY FOR WETLAND RESTORATION

Key Words: Wetland, numerical modeling, hydrodynamics, salinity, side storage area

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ABSTRACT

A vertical two-dimensional estuarine hydrodynamic and salinity model is developed to simulate the hydrodynamic characteristics and salinity distribution of the tide-influenced wetland. The Kuan-Du plain, an alluvial fan with vast wetlands and transition of fresh-salt water, situated at the confluence of the main Tanshui River and Keelung River in northern Taiwan is selected as the study case. For the purpose of land development, 85% of the wetlands in the Kuan-Du plain was carved out by a tidal dike constructed in 1968. The municipal government of Taipei recently decided to downgrade the plain of land development and to restore a portion of the carved-out wetland. Thus, the aim of the study is to provide information to help planning wetland

restoration, and to evaluate hydraulic impact of wetland restoration with removal of the tidal dike. The model is first calibrated and verified by the existing reliable measurement data. Simulations are conducted for various combinations of tidal conditions and upstream freshwater discharges. Salinity conditions in the main channel and wetland as well as wetland submergence for the restoration plan and the existing condition are presented and compared.

INTRODUCTION

Wetlands are among the most productive natural landscapes on the earth, fostering various types of biological activities. They are the habitat for many plant species, nursing ground for juvenile fishes, feeding ground for a variety of aquatic animals as well as water fowls and birds. Socio-economically, wetlands may serve as temporary storage areas of flood water, thus reducing flood damages. They retard surface water runoff, helping groundwater recharge, and protecting the shoreline from erosion. They also help to purify water quality by retaining or transforming wastes and nutrients. Recently, wetland protection has received increasing attention worldwide. Most estuarine wetlands are situated at the intertidal zones and influenced by tide. The water and material exchanges between the main body of estuary and its fringing wetland exert great influence on the ecological landscape of the wetland. Therefore, the hydrodynamic, salinity, and water quality conditions in the adjacent main body of estuary are the major factors to be considered in planning the protection or restoration of estuarine wetland.

There are increasing number of studies on the physical and hydrodynamic aspects of estuarine wetlands. Wolanksi et al. (1980) employed a one-dimensional

and two-dimensional linking model to simulate the movement of water and sediments in Coral Creek, which is a tidal creek surrounded by thickly vegetated mangrove swamps in Missionary Bay at the northern end of Hinchinbrook Island, Northern Queensland. With the model, they were able to quantify the relationship between the vegetation density and sediment yield. Wolanski and Gardiner (1981) conducted a two-week experiment over a spring-neap tide cycle in Coral Creek mouth in dry season. They found both tidal inundation and groundwater can help to flush salt from mangrove swamps. Hammer and Kadlec (1986) used a wetland hydrology model to investigate overland flow through vegetated areas and validated it with data of water surface elevation. Leonard and Luther (1995) acquired in situ flow data which indicate that mean flow speed, turbulent intensity, and the shape of the vertical velocity profile are influenced by variations in plant morphology and stem density. Furukawa et al. (1997) conducted a field study of tidal currents, cohesive sediment dynamics and transport of organic carbon in a highly vegetated mangrove swamp at Middle Creek, Cairn, Australia. A depth-averaged, two-dimensional flow model was verified with tidal currents. The interaction between tidal currents and the vegetation-generated jets, eddies and zones of stagnant waters were numerically modeled. Breen (1990) set up an artificial wetland for wastewater treatment and used a mass balance method to quantify system performance, major nutrient storage components, and nutrient removal mechanisms. Ong et al. (1991) pointed out that the hydrodynamics and hypsometry of a mangrove estuary are highly complex. At low tide the water is confined to main channel, but as the tide rises unvegetated tidal flats are inundated

first, then the estuary overflows its banks and progressively floods the mangrove vegetation. The entire area of mangrove vegetation is flooded only during rare extreme high spring tides. During other tides a various extent of the mangrove vegetation is flooded. The hydrodynamic characteristics of mangrove estuary are extremely different during spring and neap tides. Ridd et al. (1990) developed an analytical model of the longitudinal diffusion in a creek draining mangrove swamps. The model was used to investigate the time evolution of contaminant concentrations introduced into the creek and also the exchange between the swamp and near-shore zone. In addition, a two-dimensional numerical model of circulation in a creek-mangrove swamp system was used to calculate the evolution of salinity distribution in the swamps. They showed that it is important to consider the exchange between the main channel and the swamp.

The municipal government of Taipei recently made a plan to restore and increase areas of the Kuan-Du wetland, thus providing the place for recreation and natural landscape. Therefore, the hydrodynamic characteristics and salinity distribution in the main channel as well as in the wetland must be made available for restoration planning. This paper describes a vertical two-dimensional numerical model and its use in simulation of the hydrodynamic characteristics and salinity distribution in the wetland and the main channel of the Tanshui River system. In the model, the Kuan-Du wetland was treated as a temporary side storage area to keep a proper account of water and salt exchanges between the storage area and the channel during the rise and fall of tide. The simulation was carried out with and without increase in the wetland area . The simulation results

are believed to provide useful information and serve to help planning the wetland restoration.

SITE DESCRIPTION

The Tanshui River is the largest tidal river in Taiwan. The entire river system has a drainage area of 2726 km², and a total channel length of 327.6 km. It consists of three major tributaries: the Tahan Stream, Hsintien Stream and Keelung River (Figure 1). The downstream reaches of all three tributaries are tide effected. The Kuan-Du estuarine wetland (Figure 2) is situated at the confluence of the Keelung River and the Tanshui River, lying on an alluvial fan which accumulates deposition of suspended materials, nutrients, and biological debris flushing from all three tributaries. The 1994 mean tidal ranges at the Tanshui river mouth and at the point near the Kuan-Du wetland are 222 cm and 226 cm, respectively. The mean discharges at the tidal limits of the three major tributaries are 62.1 cms, 72.7 cms and 26.1 cms for the Tanhan Stream, Hsintien Stream and Keelung River, respectively. In the Keelung River, seawater intrudes up to about 9 km upstream from the confluence, although the river is tidal for almost 35 km long.

Because of its vast area and topographic effects, the Kuan-Du wetland forms a complicated environment of estuarine wetland, coastal wetland and inland wetland. It is the most important landscape among the twelve remaining estuarine wetlands in Taiwan. Before 1968, the restoration wetland at Kuan-Du plain had an area of 160 hectares. A dike of 3.5 m in height was constructed in 1968 to carve-

FIGURE 1

Map of the tidal reaches of the Tanshui River system.

out 85% of the area for development. The dike was designed to protect against flood of five-year return period. Several gates were built for drainage of the carved-out area inside the dike. A part of the area remains as wetland and is slightly affected by tide. It becomes dominated by low salinity vegetation, with approximately 175 species of plants. The major species are *Scirpus spp.*, *Typha*

FIGURE 2
The Kuan-Du estuarine wetland.

spp., *Carex spp.*, *Phragmites* and *Communis*. The wetland outside the dike is filled with mangroves that can tolerate higher salinity and form the typical tidal salt marsh ecosystem.

ESTUARINE HYDRODYNAMIC AND SALINITY MODELS

The hydrodynamics and salinity distribution in wetland are affected by the tide and salinity in the adjacent channel. Therefore it is necessary to model the exchange of water and salt between the channel and wetland. The model HEM-V2D (Park and Kuo, 1993,1994) is a vertical two-dimensional finite difference model, consisting of coupled hydrodynamic, salinity, and water quality models. The hydrodynamic and salinity models are based on the principles of conservation of volume, momentum, and salt. This paper emphasizes on the modeling application to Kuan-Du wetland to provide information for planning of increasing wetland area. A full description of the model can be found in Park and Kuo (1993,1994).

Governing Equations

The governing equations, which include terms to account for the exchange between main channel and wetland, are solved for the main channel only. They are :

the laterally integrated continuity equation,

$$\frac{\partial(uB)}{\partial x} + \frac{\partial(wB)}{\partial z} = Q_o \quad (1)$$

the sectionally integrated continuity equation,

$$\frac{\partial}{\partial t}(B_\eta \eta) + \frac{\partial}{\partial x} \int_{-H}^{\eta} (uB) dz = q \quad (2)$$

the laterally integrated momentum balance equation,

$$\frac{\partial(uB)}{\partial t} + \frac{\partial(uBu)}{\partial x} + \frac{\partial(uBw)}{\partial z} = -\frac{B}{\rho} \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} (A_x B \frac{\partial u}{\partial x}) + \frac{\partial}{\partial z} (A_z B \frac{\partial u}{\partial z}) + M_0 \quad (3)$$

the laterally integrated mass balance equation for salt,

$$\frac{\partial(sB)}{\partial t} + \frac{\partial(sBu)}{\partial x} + \frac{\partial(sBw)}{\partial z} = \frac{\partial}{\partial x} (K_x B \frac{\partial s}{\partial x}) + \frac{\partial}{\partial z} (K_z B \frac{\partial s}{\partial z}) + S_0 \quad (4)$$

where x = distance seaward along river axis ; z = distance upward in vertical direction ; t = time ; q = lateral inflow per unit river length ; η = position of the free surface above mean sea level ; s = laterally averaged salinity ; u and w = laterally averaged velocities in the x and z directions, respectively ; B = river width ; B_η = width at the free surface including side storage area ; H = total depth below mean sea level ; p = pressure ; ρ = density ; A_x and A_z = turbulent viscosities in the x and z directions, respectively ; K_x and K_z = turbulent diffusivities in the x and z directions, respectively ; Q_0 , M_0 and S_0 = source or sink of water, momentum and salt, respectively, including exchange with side storage area (wetland). Equations 1 to 4 are integrated over a vertical layer thickness of the main channel and then solved by a two-time level, finite difference scheme with spatially staggered grid. The method of solution is detailed in Park and Kuo (1993, 1994).

Model Refinements

The model HEM-V2D is expanded to treat the interaction between tributaries and mainstream of an estuarine system, for application to the Tanshui

River system. The flow conditions at the tributary junction are solved by expanded continuity and momentum equations. The surface elevation and vertical velocity are calculated with Equations (1) and (2) at the mainstream-tributary confluence, with an added effect of tributary inflow or outflow. Because of the spatially staggered grid used in the model, no representative velocity point is situated at the junction segment of the branching model. The momentum balance at the transects surrounding the junction segment is handled by neglecting

horizontal advection term $\frac{\partial(uBu)}{\partial x}$ and turbulent diffusion term $\frac{\partial}{\partial x}(A_x B \frac{\partial u}{\partial x})$.

The magnitudes of these two terms in momentum equation are assumed to be locally negligible in comparison to other terms. Computational tests suggest that this is a realistic assumption. The mass balance equation is modified to account for the flux from or to tributaries. The flux includes horizontal advective term

$\frac{\partial(sBu)}{\partial x}$ and diffusive term $\frac{\partial}{\partial x}(K_x B \frac{\partial s}{\partial x})$. A detailed description of the branched

model can be found in Hsu et al. (1996, 1997).

A strictly vertical two-dimensional model simulates the momentum and mass transport only along the channel in the vertical and longitudinal directions. It does not compute the hydrodynamic and salinity conditions in the shallow areas fringing the main channel. Kuo and Park (1995) proposed a framework for coupling the shallow areas with main channel in numerical modeling of coastal plain estuaries. They demonstrated that the accounting of the mass and momentum exchanges between the main channel and shallow areas is essential not only for the computation of the conditions in the shallow areas but also for the

proper simulation of tidal propagation along the main channel. If the water and momentum exchanges between the shallow areas and the main channel are not accounted for, a model can not reproduce the along channel variations of both the tidal range and tidal phase with a single set of calibrated friction coefficients.

The coupling framework proposed by Kuo and Park (1995) is refined and adopted to the model for the Tanshui River system. The Kuan-Du wetland is treated as a temporary storage area, functioning as a sink or source of momentum and mass to the main channel as the tide rises or falls, respectively. The water level in the wetland is assumed to rise and fall instantly with the main channel, and the inundated area is assumed to increase linearly with water level as it rises above a certain level. Since the volume exchange between the wetland and the main channel is determined by the temporal variation of water surface level in the wetland, and the water depth in the wetland is small, the momentum and mass exchanges are assumed to occur only at the top layer of the vertical two-dimensional model. At the rising tide, the wetland serves as a sink for both momentum and mass. The salinity in the wetland is calculated assuming complete mixing of the incoming water and the water already there. At the falling tide, the wetland acts as a source of mass, but not momentum. The salinity in the wetland remains unchanged and the water leaving for the main channel is assumed to have no longitudinal velocity.

Model Calibration and Verification

Whether the model is suitable for modeling the estuarine system or not, it must be confirmed with the procedure of calibration and verification. Manning's

friction coefficient and the coefficients for turbulent mixing terms are important calibration parameters affecting the calculation of surface elevation and salinity in the channel and wetland. The preliminary calibration of Manning's friction coefficient uses a single constituent, M_2 , tide to reproduce 1994 mean tidal range. Figure 3 shows the comparison of final results. It shows that the tidal range increases slightly as the tidal wave propagates beyond the confluence of Keelung River, mainly because of the narrowing of the river. The mean tidal range at Kuan-Du wetland is 226 cm. The fine-tuned calibration compares amplitude and phase of the individual constituent of a nine-constituent tide selected as boundary condition at river mouth to force the system. The results also compare times of high tide and low tide between computation and observation. The model was verified with the simulation of prototype conditions during the period March 15 to September 30, 1994. The hourly time series data of surface elevation at the computed water surface elevations and current velocities were compared with time series data at various stations (not shown). The comparisons show that the model can faithfully reproduce tidal propagation, tidal flow, and river flow. The estuarine salinity distribution is affected by turbulent diffusion coefficients. The turbulent diffusivity in vertical direction is an important parameter which determines the stratification in water column. Calibration of turbulent diffusion coefficients accounts for both the baroclinic mode of flow and turbulent diffusive mass transport. The model was driven by three time-varying boundary conditions: daily freshwater inflow through the upstream boundaries, hourly tidal elevation and linearly interpolated salinity from measured data at the mouth. The tidal

FIGURE 3

Preliminary calibration : the comparison of 1994 mean tidal ranges (T : Tanshui River—Tahan Stream, H : Hsintien Stream, K : Keelung River).

average salinity and time series data measured on April 12 and June 24, 1994 were used to calibrate the model (not shown). The model's ability to predict mass transport was verified with a simulation of salinity distribution from March 15 to April 30, 1995. The model predictions are compared with the field measurements on April 14, 1995 shown in Figure 4. The verified result shows that the model can faithfully reproduce the prototype salinity distribution. Some vertical stratification occurs near the Tanshui River mouth.

FIGURE 4

Model verification : the comparison of tidal average salinity distributions on April 14 1995 (• field data, —model result).

MODEL APPLICATION

Approach

To provide information for wetland restoration and enhancement in the area inside the 1968-constructed dike, two scenarios were considered for model runs: one with existing dike and the other with dike removed. These two scenarios bracket all possible conditions a restoration plan may result. In each scenario a series of model simulations were conducted with various assumptions of hydrological conditions. In each case the model was run for one year with nine constituent tide as a forcing function at river mouth. The model results with mean freshwater discharges and Q_{90} low flows at upstream boundaries are presented and discussed in this paper.

At the present condition, there are three small tidal gates on the Kuan-Du Dike to drain the water flow from the restoration wetland inside the dike to the main channel. The model side storage area includes only the mangrove wetland outside the dike for which the salinity condition and submergence statistics were computed. The model scenario run with Kuan-Du Dike completely removed provides the extreme conditions for which a restoration plan may attain. These also serve as the conditions prior to the construction of the dike in 1968. The restoration wetland inside the dike, together with the mangrove wetland outside, becomes a vast side storage area as tide rises. Salt water and materials can freely exchange between it and the main channel. The impacts of dike removal on the main channel as well as the conditions in the side storage area were both investigated.

Impact on Conditions in the Estuary

Tide is the principal dynamics forcing the Tanshui River system. It dominates the hydrodynamics of the river and causes periodic fluctuations in many variables. The upriver discharges vary temporally with seasonal effects, which also affect the velocity and salinity distributions in the estuary. The calibrated and verified model is used to investigate the effects of dike removal on tidal characteristics throughout the river system as well as Kuan-Du wetland. Amplitudes and phases of the nine-constituent tide are specified as the downstream boundary condition to force the system. Figure 5 is the time series surface elevation at the river mouth in September 1994, which shows two spring-neap cycles in one month. Historical long-term mean discharges are used for the upstream boundary conditions in the three tributaries. The mean discharges of the Tahan Stream, Hsintien Stream and Keelung River are 62.1 cms, 72.7 cms, 26.1 cms, respectively. The model simulates one-year (705 tidal cycles) hydrodynamic conditions. Table 1 lists mean high tide, mean low tide and mean tidal range at stations along the estuary, under conditions with dike and without dike at Kuan-Du. If the dike is removed to allow increase in wetland area, mean high tide will decrease from 129.1 cm to 126.7 cm, mean low tide will increase from -85.4 cm to -78.5 cm and mean tidal range will decrease from 214.5 cm to 205.2 cm at location near the Kuan-Du wetland. Without the dike at Kuan-Du, the mean tidal range will decrease throughout the estuarine system as a result of increase in side storage area. It is apparent that the construction of the Kuan-Du dike had a significant impact on the tidal characteristics of the Tanshui River system.

FIGURE 5

Time series surface elevation in Tanshui River mouth in September.

The model also simulates the salinity distribution in the estuary under different hydrological conditions, with and without Kuan-Du Dike. One design freshwater flow condition is Q_{90} , a flow with an exceedance probability of 0.90. The salinity boundary condition at river mouth is obtained or estimated from the available field data (table 2). Table 2 also lists the Q_{90} flows at upriver stations, they are 4.0 cms, 6.9 cms and 1.3 cms in the Tahan Stream, Hsintien Stream and Keelung River, respectively. The model is run for one-year (705 tidal cycles) such that the annual variation of spring-neap tidal cycle is included. Figure 6 presents time series surface elevation and salinity during mean tide period in the Keelung

TABLE 1
Mean High Tide, Mean Low Tide and Mean Tidal Range at Various Stations
Under Mean Flow Condition, with and without Kuan-Du Dike

Station	Mean high tide (cm)		Mean low tide (cm)		Mean tidal range (cm)	
	(1)	(2)	(1)	(2)	(1)	(2)
River Mouth	117.5	117.5	-99.4	-99.4	216.9	216.9
Tu Ti Kung Pi	126.0	121.6	-86.2	-79.8	212.2	201.4
Taipei Bridge	141.0	136.5	-83.2	-76.6	224.2	213.1
Ru Kou Weir	146.6	140.8	-82.5	-75.9	229.1	216.7
Hsinhai Bridge	147.1	141.1	-80.8	-74.6	227.9	215.7
Chung Cheng Bridge	149.4	143.2	-82.1	-75.7	231.5	218.9
Ta Chih Bridge	140.7	139.7	-84.9	-73.4	225.6	213.1
In Keelung River near Kaun-Du plain	129.1	126.7	-85.4	-78.5	214.5	205.2

(1) Condition with Kuan-Du Dike (existing).

(2) Condition without Kuan-Du Dike.

TABLE 2
The Boundary Conditions for the Model Simulation

Station	Downstream boundary condition for surface elevation	Upstream boundary condition for flow		Downstream boundary condition for salinity		Upstream boundary condition for salinity
		mean flow	Q_{90}	mean flow	Q_{90}	
Tanshui River mouth	nine-constituent tide for amplitudes and phases	----	----	25 ppt	32 ppt	----
Tahan Stream	----	62.1 cms	4.0 cms	----	----	0 ppt
Hsintien Stream	----	72.7 cms	6.9 cms	----	----	0 ppt
Keelung River	----	26.1 cms	1.3 cms	----	----	0 ppt

FIGURE 6

The time series surface elevation and salinity in the Keelung River off the existing Kuan-Du Dike during mean tide period (a) mean flow condition (b) Q_{90} flow condition.

River off the existing Kuan-Du Dike. The salinity shows a strong periodic fluctuation in response to tide, with high stratification at low tide and almost well-mixed at high tide. Figure 7(a) and 7(b) present tidal average salinity distributions in the Keelung River with and without dike under Q_{90} flow condition. They show that salinity increases in the channel and the limit of salt intrusion moves upriver if the Kuan-Du Dike is removed.

Salinity in the Wetland and the Adjacent Main Channel Segment

The model also simulates the salinity in wetland, as well as in the main channel under different hydrological and tidal conditions, with and without dike at Kuan-Du. Figure 8 presents the effect of dike removal on salinity in the Keelung River at Kuan-Du during mean tide period. The removal of the dike will increase storage area of the wetland and the total tidal prism, which, in turn, results in more salt water intrusion and higher salinity in estuary. Figure 9 shows the comparison of salinity in wetland between the conditions with and without dike at Kuan-Du. The results are presented for both spring and neap tide periods, and under the mean flow and Q_{90} flow conditions. The salinity in wetland without Kuan-Du Dike is higher than that with Kuan-Du Dike. Figure 10 presents the percent of time the salinity in restoration wetland is lower than certain level if Kuan-Du Dike is removed. The time periods when the wetland is totally out of water are not included, therefore the percent of time salinity is lower than the maximum salinity is less than 100%. The times when salinity is lower than 5 ppt are 24.3%, 25.8%, 35.7% and 31.5% in March, April, August and September, respectively, under the mean flow condition. The times when salinity is lower

FIGURE 7

The tidal average salinity distribution in the Keelung River (a) with Kuan-Du Dike (b) without Kuan-Du Dike.

than 20 ppt are 15.3%, 18.8%, 31.0% and 28.4% in March, April, August and September, respectively, under the Q_{90} flow condition. These results provide useful information for Kuan-Du wetland restoration plan, aquatic ecology study, and the understanding of water and salt exchanges between the channel and the wetland.

Mangroves are facultative halophytes, that is, they do not require salt water for growth but are able to tolerance high salinity and thus outcompete vascular

FIGURE 8

The comparison of salinity in the channel off the Kuan-Du wetland during mean tide period, with and without dike (a) mean flow condition (b) Q_{90} flow condition

FIGURE 9

The comparison of salinity in the wetland during spring and neap tide periods, with and without Kuan-Du Dike (a) mean flow condition (b) Q_{90} flow condition.

FIGURE 10

The percent of time salinity is lower than certain level in the wetland under the condition of no Kuan-Du Dike (a) mean flow condition (b) Q_{90} flow condition.

plants that do not have this salt tolerance (Odum and McIvor, 1990). Mangroves have the ability both to prevent salt from entering the plant at the roots (salt exclusion) and to excrete salt from the leaves (salt secretion). Salt exclusion at the roots is thought to be a result of reverse osmosis that causes the roots to absorb only freshwater from salt water. Therefore, salt water is important to the mangroves in eliminating competition from freshwater species. If the Kuan-Du Dike is completely removed, the salinity in wetland will increase no more than 5 ppt and 3 ppt for mean flow and Q_{90} flow, respectively, and fluctuate with tide (shown in Figure 9). Since mangroves in the existing area are salt-tolerant species, we predict that the mangrove zone will gradually expand to restoration wetland with increasing salinity and thus form the attractive landscape of mangrove ecosystems. The restoration plan can be attained by carefully controlling water and salt exchanges.

Wetland Submergence Statistics

The fraction of time a wetland area is submerged under water plays an important role in the ecological landscape of that area. Wetland submergence statistics provide critical information for planning a restoration project. Figure 11 shows the percent of time the wetland is completely exposed if Kuan-Du Dike is removed. The monthly variation reflects the annual cycle of astronomical tide. Wetland is exposed the least of time in July. The average percent of time the wetland is totally without water are 24% and 26% for mean flow and Q_{90} flow, respectively. Figure 12 and 13 show the probabilities that given area of wetland is submerged under water, with and without Kuan-Du Dike, respectively. Because the side storage area is assumed to increase linearly with water surface elevation

FIGURE 11

The percent of time there is no water in the wetland under the condition of no Kuan-Du Dike.

as the tide rises, the submergence probability has a roughly linear variation with area.

The mangrove swamp can develop only where there is adequate protection from tidal action. The range and duration of the flooding of tides exert a significant influence over the extent and functioning of the mangroves swamp. Like tidal Salt marshes, mangroves swamps are intertidal, although a large tidal range is not necessary. Most mangrove wetlands are found in tidal ranges of from 0.5 m to 3 m and more (Chapman, 1976). Mangrove tree species can also tolerate a wide range of inundation frequencies. The mean tidal range, under the condition without Kuan-Du

FIGURE 12

The submergence probability under the condition with Kuan-Du Dike (a) mean flow condition (b) Q_{90} flow condition.

FIGURE 13

The submergence probability under the condition of no Kuan-Du Dike (a) mean flow condition (b) Q_{90} flow condition.

Dike, is 2.05 m in Keelung River near Kuan-Du plain (see Table 1) and calculates 0.75 m in restoration wetland. According to simulation results of tidal ranges and wetland submergence statistics, mangroves should adapt to circumstances of inundation frequencies if the Kuan-Du Dike is removed.

CONCLUSIONS

A vertical two-dimensional estuarine model for the Tanshui River system is developed and used to simulate the hydrodynamic characteristics and salinity distribution of Kuan-Du wetland. In the model, the Kuan-Du wetland is treated as temporary side storage area, with proper accounting of water and salt exchanges between the wetland and the main channel as the tides rises and falls. The model results are also used to calculate submergence statistics in the wetland assuming the Kuan-Du Dike is removed. The extreme scenario, complete removal of the tidal dike, allowing free exchanges of water and material between the wetland and the main channel, has been investigated in the present study. The model predicts that, under this extreme case, the tidal range of the entire Tanshui River system decreases as salt water intrusion increases due to the increasing tidal prism. The salinity in wetland increases as the tidal dike is removed. The existing cyperaceae and reeds, which are salt-intolerant species in the restoration wetland inside the dike, might be replaced by advantage species of mangroves which can tolerate higher salinity. The exchanges of water and material between the wetland and main channel have to be carefully designed to achieve desired expansion and restoration of Kuan-Du wetland. The computed statistics on salinity level and submerged area based on the present model

provide a basis of engineering design of wetland and analysis of environmental impact.

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REFERENCES

- Breen, P. F., *Water Research*, 24(6), 686-697 (1990).
- Chapman, V. J., "Mangrove Vegetation" J. Cramer, Vaduz, Germany, (1976), 447pp.
- Furukawa, K., Wolanski, E. and Mueller, H., *Estuarine, Coastal and Shelf Science*, 44, 301-310 (1997).
- Hammer, D. E. and Kadlec, R. H., *Water Resource Research*, 22(13), 1951-1958 (1986).
- Hsu, M. H., Kuo, A. Y. Kuo, J. T. and Liu, W. C., "Study of Tidal Characteristics, Estuarine Circulation and Salinity Distribution in Tanshui River System (1), (2)" Technical Report No.239 and No.273, Hydraulic Research Lab. National Taiwan University, Taipei, Taiwan, (1996, 1997), 245pp.
- Kuo, A. Y. and Park, K., *Estuaries*, 18(2), 341-350 (1995).
- Leonard, L. A. and Luther, M. E., *Limnol. Oceanogr.*, 40(8), 1474-1484 (1995).
- Odum, W. E. and McIvor, C. C., "Mangroves, in Ecosystem of Florida" Ed. R. L. Myers and J. J. Ewel, University of Central Florida Press, Orlando, (1990), pp.517-548.
- Ong, J. E., Gong, W. K., Wong, C. H., Din, Din, Z. H. and Kjerfve, B., *Estuaries*, 14(1), 38-48 (1991).

Park, K. and Kuo, A. Y., "A Vertical Two-Dimensional Model of Estuarine Hydrodynamics and Water Quality" Spec. Rep. App. Mar. Sci. and Ocean Eng.321, Virginia Institute of Marine Science, Gloucester Pt., VA. (1993), 47pp.

Park, K. and Kuo, A. Y., "Numerical Modeling of Advection and Diffusion Transport in the Rappahannock Estuary, Virigina" Ed. M.L. Spaulding, K. W. Bedford, A. F. Blumberg, R. T. Cheng and J. C. Swanson, Proceedings of the Third International Conference on Estuarine and Coastal Modeling, ASCE, NY, (1994), pp.461-474.

Ridd, P. V., Wolanski, E. and Mazda, Y., *Estuarine, Coastal and Shelf Science*, 31, 541-554 (1990).

Wolanski, E., Jones, M. and Bunt, J. S., *Australian Journal of Marine and Freshwater Research*, 31, 431-450 (1980).

Wolanski, E. and Gardiner, R., *Australian Journal of Marine and Freshwater Research*, 32, 681-683 (1981).

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