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Simulation of water quality and plankton dynamics in the Danshuei River estuary, Taiwan

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An ecosystem model was developed to simulate the water quality and plankton dynamics in the Danshuei River estuary, Taiwan. The model simulates the hydrodynamics with a laterally integrated 2-dimensional intratidal numerical model, which supplies the physical transport processes for simulation of water quality and plankton state variables. The application of the model to the Danshuei River estuary indicates that the point source loadings are mainly responsible for the degraded water quality and very high nutrient concentrations in the estuary. The impacts of wastewater discharges are tightly controlled by the transport processes. Frequent occurrence of high river flow and flood events rapidly cleanses the estuary by flushing out both pollutants and plankton populations. The plankton is allowed to grow to significant populations if low river flow lasts for a period much longer than the biological time scale.

Keywords: Numerical model, estuary, water quality, plankton dynamics, wastewater discharges, impacts by transport processes.

Introduction

Estuaries are the major pathways where the exchange of substances between land and ocean take place. With extensive volume and abundant nutrients, they are naturally rich in biological resources. However degraded water quality and damaged aquatic ecosystem have become a common problem in many estuaries around the world. Adverse impacts on the estuarine ecosystem by human activities have been widely reported; studies and management of the estuarine environments have gained more and more attention in recent decades.

Transported by water flow, the distributions of water quality constituents are greatly influenced by the advection and diffusion processes of water movement. A comprehensive modeling study of the water quality conditions and ecological system in an estuary cannot ignore the physical transport processes, for example, Malone et al.,^[1,2] Cloern^[3] and Aksnes and Lie.^[4] However most of their simulations of physical processes were highly simplified and lacked predic-

tive capability. The estuarine environment is in many ways more complex than that of the river, lake, or ocean. Both river flow and tidal motions influence the flow of water in estuaries. The river flow varies over a seasonal cycle, whereas the tide fluctuates over a time scale of hours. Wind and barometric pressure also exert their influence on the water level as well as currents. The mixing of fresh water from the river with saline seawater further complicates the hydrodynamics of an estuary. A numerical model solving the equations of motion and mass conservation is generally required for a comprehensive simulation of water movement in an estuary.

Affected by each other, the inter-relationships among hydrodynamics, water quality, and biology are complex and may manifest great variability between any two specific aquatic environments. The best way to get a comprehensive insight into the system is through a theoretically constructed numerical model incorporating all significant physical and biogeochemical processes. An accurate prognostic numerical model can be very helpful in advancing the understanding of the system, aiding experimental design, and linking cause and effect through model experiments. Water quality and biological dynamics have been increasingly brought into numerical hydrodynamic models with predictive capability in recent decades. Take the Chesapeake Bay

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Fig. 1. Schematic map of the Danshuei River estuary and the model segments.

Estuary Model (CBEM) as an example; it is a series of coupled models comprising a hydrodynamic model, called CH3D (Curvilinear Hydrodynamics in 3 Dimension), a water quality model (CE-QUAL-ICM) and a sediment diagenesis model.^[5] In addition to nutrient and dissolved oxygen dynamics, CE-QUAL-ICM also simulates the biomass of three groups of phytoplankton, two groups of zooplankton, benthos, and submerged aquatic vegetation.^[6,7]

As the largest tidal river in Taiwan, the Danshuei River estuarine system (Fig. 1) has been the subject of many observations and researches. It has three major tributaries, the Tahan Stream, Hsintien Stream and Keelung River, of which the lower reaches are influenced by tide as well as the main stem of the Danshuei River. Seawater intrusion reaches into all three tributaries, except during periods of very high river inflow. The hydrodynamic characteristics are mainly controlled by tide, river inflow, and the density gradient induced by the mixing of saline and freshwater.^[8] Because of the relatively large tidal range compared to the depth of the system, the residence time of the main stem estuary was found to be 2.2 days or less.^[9]

The estuarine portion of the river system runs through the capital City of Taipei, with a population of 6 million in its metropolitan area. Huge amounts of domestic wastewater, mostly untreated raw sewage, are discharged into the estuary daily. The water quality has been severely degraded for decades. Hypoxic/anoxic conditions commonly occur in the upper and middle reaches of the estuary during summer months.^[10] Viable biological activities are observed only in the lowest reach of the estuary where the pollutant concentrations are reduced as a result of dilution by seawater.^[15] A three-year observational study of the system from 1998 to 2001 conducted by Taiwan's Academia Sinica reported that the chlorophyll *a* concentration hardly exceeded 5 mg/m³. The primary production rate was on the order of 0.2 g C/m³/day. Zooplankton biomass was observed to range from 1 to 14 mg C/m³. If the amount of carbon fixed by the phytoplankton species is not transferred to the higher trophic level it is termed as nuisance species. Zooplankton play a pivotal role in the transfer of carbon from primary producer, such as phytoplankton, to higher consumers, such as fishes. However few studies have been conducted

on the zooplankton assemblages in this estuary and its surrounding waters.^[12–14]

Various numerical hydrodynamic models have been applied to the system since 1980. These models are either one-dimensional or horizontal two-dimensional models, incapable of simulating the phenomena of salinity stratification and estuarine circulation. Some of them may include simple water quality simulation, but no attempt was made to simulate the plankton dynamics and their interaction with water quality. A vertical two-dimensional model, HEM-2D (2-dimensional Hydrodynamic Eutrophication Model),^[15] has been applied to the Danshuei River estuarine system for the past 10 years. The performance of the model has been proved practicable and reliable.^[8,16–20]

An ecosystem model is developed based on HEM-2D to simulate the plankton dynamics and their interaction with water quality in the Danshuei River estuary. A series of field observations were conducted to support the development of the ecosystem model described herein, including slackwater surveys and intensive surveys. Data collections and the overall observation results are briefly described in the first part of Materials and Methods, followed by the model description that demonstrates the refinement and expansion of the water quality portion of the HEM-2D into an ecosystem model. The refinement includes more detailed simulations of nutrient dynamics and addition of silicon cycle. The expansion includes the simulation of plankton dynamics in accordance with the field observations. Following the model description, the calibration and verification of the ecosystem model are described. The model results are presented and discussions and conclusions are made.

Materials and methods

Data collections

Two slackwater surveys and four intensive surveys were conducted between 2001 and 2004 to collect field data. The slackwater surveys were conducted on October 15, 2001 and April 18, 2002. Both high and low water slack surveys were conducted on each day at five pre-determined sampling stations in the lower estuary (Fig. 1). The measured physical parameters included light penetration, salinity, water temperature, and total suspended solid concentration. The light penetration into the water column was measured by two methods: the Secchi-disc measurement and the measurements of PAR (Photosynthetically Active Radiation) at various depths. Salinity and water temperature were measured using a CTD (Conductivity-Temperature-Depth) sensor. Water samples from various water depths were collected and the concentrations of total suspended solids were measured in the laboratory. Water samples were also collected for the analysis of nutrients, chlorophyll, carbon, and dissolved oxygen concentrations. Water samples were filtered through a cellulose nitrate membrane (pore size 0.45 μm)

for phytoplankton collection, and then brought back to the laboratory for the analysis of structure and biomass. Zooplankton samples were collected near water surface by towing a conical net with 200 μm mesh size. Collected zooplankton were frozen immediately with liquid nitrogen and kept frozen at -20°C until analysis. In the laboratory, the composition and biomass of zooplankton were identified and measured. An attempt to use a net of 120 μm mesh size to collect zooplankton sample proved impractical. The net became too heavy and broken because of the large amount of debris in the water column.

Intensive surveys were conducted at station 2 and station 3 in October 2002 and 2003, and in May 2003 and 2004. In each survey, the measurements and samplings were conducted at both stations at 1.5 hourly intervals through one complete tidal cycle during daylight hours. The parameters measured and samples collected were the same as those in the slackwater surveys. The two stations were selected based on the results of the slackwater surveys and past studies. No significant plankton biomass was observed at stations upriver of station 3. Station 2 is the first station inside the estuary. The observed salinity indicated that seawater intruded to this location with little dilution near the end of flood tide (Fig. 2a). The water quality and plankton conditions at high water slack were similar to the coastal water conditions. At the end of ebb tide, the water column is highly stratified representing the imperfect mixture of seawater and freshwater from upstream drainage (Fig. 2b).

The observed salinity distributions indicate that the lower estuary is a partially mixed estuary. The salinity varies as much as 10 psu in intra-tidal time scale. The vertical distribution also varies greatly from homogeneous to highly stratified. These are the results of high longitudinal gradient and strong tidal current. The nutrient concentrations are very high. The total inorganic nitrogen and biogenic silicon concentrations are both on the order of several g/m^3 . The total phosphorus concentration is on the order of a tenth of g/m^3 . Chlorophyll *a* concentration shows seasonal variation, high in late spring and low in the autumn. It ranges from several mg/m^3 to tens of mg/m^3 . Dissolved oxygen concentration is severely depressed during low tide. It increases during flood tide as a result of dilution by cleaner seawater. The spatial gradients and intra-tidal variations of nutrient concentrations all point out the fact that the nutrients and pollutants are originated from the upper estuary or beyond. The estuary is heavily polluted; the water quality conditions only improve near the river mouth as the result of seawater dilution.

The analysis of observed phytoplankton assemblages confirms that diatoms and green algae are the two dominant groups of phytoplankton in the lower estuary. The spatial gradients and intra-tidal variations suggest that diatoms intrude from the sea on flood tide, whereas the green algae grow autochthonously in the estuary. The predominant group of zooplankton is copepod which intrudes into the estuary from the sea. The copepod biomass (in

Fig. 2. Spatial distribution of salinity (psu) of the slackwater survey on April 18, 2002, (a) slack before ebb; (b) slack before flood.

terms of carbon) often exceeds 50 to 60% of total zooplankton biomass, except during the spawning season of barnacle.

Model description

The model consists of two parts, the hydrodynamic and ecosystem sub-models, which are linked internally. The hydrodynamic sub-model computes the temporal water surface elevation and flow velocity in intra-tidal time scale, providing the information for the physical transport processes of the ecosystem sub-model. The hydrodynamic sub-model was originally developed by Park and Kuo.^[15] It was subsequently expanded for application to estuaries with major tributaries and has been calibrated and verified for application to this estuarine system.^[8] The model treats the Danshuei River and Tahan Stream as a continuous main stem, and the Hsintien Stream and Keelung River as the tributaries. The river system is segmented into 81 segments of equal length, 1 km (Fig. 1).

The ecosystem sub-model is developed on the basis of the water quality component of the HEM-2D model used by Liu et al.^[16] The water quality portion of the original model is greatly expanded from 8 to 21 state variables. They are Refractory Particulate Organic Carbon (denoted by RPOC), Labile Particulate Organic Carbon (LPOC), Dissolved Organic Carbon (DOC), Refractory

Particulate Organic Nitrogen (RPON), Labile Particulate Organic Nitrogen (LPON), Dissolved Organic Nitrogen (DON), Ammonium Nitrogen (NH_4), Nitrite-Nitrate Nitrogen (NO_3), Refractory Particulate Organic Phosphorus (RPOP), Labile Particulate Organic Phosphorus (LPOP), Dissolved Organic Phosphorus (DOP), total Phosphate (PO_4t), Biogenic Particulate Silicon (SU), total Available Silicon (SA_t), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), Diatoms (PB_1), Green Algae (PB_2), Other Phytoplankton (PB_3), Copepod (ZB_1), and Other Macro-Zooplankton (ZB_2). The interactions among the state variables are presented schematically in Figure 3.

The model state variables are enclosed in the solid rectangular boxes. The variables in the boxes enclosed with dashed lines are not modeled explicitly; however they are recognized as having some roles in the modeled system. For example, bacteria feed on DOC and are consumed by zooplankton. Since bacterium is not a model state variable, the two-step process is simulated with a direct uptake of DOC by zooplankton. Micro-zooplankton is not modeled because of the lack of data. The use of towing net with mesh size finer than 200 μm in this estuary is impossible because of the clogging problem.

The grazing of phytoplankton by micro-zooplankton is implicitly included in the grazing by macro-zooplankton. The arrow between two state variables represents a

Fig. 3. Schematic diagram of the biogeochemical interactions among the model state variables.

biogeochemical process transforming one variable to the other. The arrows with one end unattached to any state variable represent external sources or sinks to the modeled system. Each of the arrows in the schematic diagram is simulated with an algebraic equation, which may be found in Wang.^[21] Most of the equations are similar to those used in the eutrophication modeling of the Chesapeake Bay,^[6] except for the formulation of the grazing process.

The simulation of macro-zooplankton is represented by ZB_1 and ZB_2 in this model. Sources and sinks included in the model are growth, basal metabolism, and mortality. The equation describing the kinetic processes of zooplankton biomass is expressed as:

$$\frac{\partial ZB_i}{\partial t} = (GZ_i - BMZ_i - PRZ_i) \cdot ZB_i \quad (1)$$

in which ZB_i is the biomass of zooplankton i ($g\ C/m^3$), $i = 1$ is copepod, $i = 2$ is others; t is time (day); GZ_i is growth rate of zooplankton i (day^{-1}); BMZ_i is basal metabolic rate of zooplankton i (day^{-1}); and PRZ_i is mortality rate of zooplankton i (day^{-1}).

The growth rate of zooplankton depends on food availability, assimilation efficiency, salinity, and temperature. It is supposed that zooplankton graze on phytoplankton, organic carbon, and possibly other species of zooplankton, particularly the micro-zooplankton. Therefore in the ecosystem model, the eight groups of state variables, ZB_1 , ZB_2 , PB_1 , PB_2 , PB_3 , $RPOC$, $LPOC$, and DOC , constitute a multiple prey-predator system. Legović^[22] derived an expression for the predation rate in food webs for both selective and nonselective predation. The specific predation rate on prey j by predator i is expressed as:

$$S_{ji} = \frac{u_{ji} \cdot \frac{\omega_{ji}}{Kh_{ji}} \cdot F_j}{1 + \sum_{k=1}^{n_i} \left(\frac{\omega_{ki}}{Kh_{ki}} \cdot F_k \right)}$$

in which u_{ji} is the predation rate on prey j by predator i in a one prey-one predator system (day^{-1}); ω_{ji} is the preference of predator i to graze on prey j , $\omega_{ji} = 0$ if predator i does not graze on prey j , $\omega_{ji} = 1$ for $j = 1$ to n_i if predator i is a non-selective feeder, $\omega_{ji} < 1$ if predator i is a selective feeder; Kh_{ji}

is the half-saturation concentration of prey j for predator i to graze (g C/m^3); F_j is concentration of prey j (g C/m^3); and n_i is total number of available prey types for predator i . Following this concept and incorporating the assimilation efficiency, respiration cost, and the effects of salinity and temperature, the growth rate of zooplankton is described as:

$$GZ_i = \sum_{\substack{j=1 \\ j \neq i}}^{n_i} S_{ji} \cdot E \cdot (1 - RF) \cdot f_{1i}(S) \cdot f_{2i}(T) \quad (2)$$

in which E is assimilation efficiency; RF is respiration cost of grazing; $f_{1i}(S)$ is the effect of salinity ($0 \leq f_{1i} \leq 1$) on growth of zooplankton i ; and $f_{2i}(T)$ is the effect of temperature ($0 \leq f_{2i} \leq 1$) on growth of zooplankton i and is expressed as:

$$f_{2i}(T) = \exp[-KTGZ_{1i} \cdot (T - TGZ_i)^2] \quad \text{if } T \geq TGZ_i \\ = \exp[-KTGZ_{2i} \cdot (TGZ_i - T)^2] \quad \text{if } T < TGZ_i$$

in which T is temperature ($^{\circ}\text{C}$); TGZ_i is optimal temperature for growth of zooplankton i ($^{\circ}\text{C}$); and $KTGZ_{1i}$ and $KTGZ_{2i}$ are the effects of temperature above and below TGZ_i , respectively, on growth of zooplankton i ($^{\circ}\text{C}^{-2}$).

The basal metabolism rate of zooplankton is considered to be an exponentially increasing function of temperature. That is,

$$BMZ_i = BMZR_i \cdot \exp[KT BZ_i \cdot (T - TBZ_i)] \quad (3)$$

in which $BMZR_i$ is the basal metabolism rate of zooplankton i at temperature TBZ_i (day^{-1}); TBZ_i is the reference temperature for basal metabolism of zooplankton i ($^{\circ}\text{C}$); and $KT BZ_i$ is the effect of temperature on metabolism of zooplankton i ($^{\circ}\text{C}^{-1}$).

Zooplankton mortality includes predation and death. The predation is caused by other species of zooplankton and higher trophic levels. The former is described by Legović^[22] as the predation rate in the above section. The growth rate of the predator is on the contrary the mortality rate of the prey. Higher trophic levels that feed on zooplankton are not explicitly included. In order not to draw additional state variables into this model and to simulate the zooplankton biomass more realistically, the predation rate by higher trophic levels is assumed to be proportional to the total biomass of all available food. Considering the predation caused by other species of zooplankton and higher trophic levels and the natural death, the loss of zooplankton biomass due to mortality is expressed as:

$$PRZ_i \cdot ZB_i \\ = \left[\frac{u_{ij} \cdot \frac{\omega_{ji}}{Kh_{ij}} \cdot ZB_i}{1 + \sum_{k=1}^{n_j} \left(\frac{\omega_{kj}}{Kh_{kj}} \cdot F_k \right)} \right] \cdot ZB_j \cdot f_{1j}(S) \cdot f_{2j}(T) \\ + \left[RZ_i \cdot \left(\sum_{k=1}^2 ZB_k + \sum_{k=1}^3 PB_k \right) + DRZ_i \right] \cdot ZB_i \quad (4)$$

where $j \neq i$

in which RZ_i is the proportional constant (per g C/m^3 per day) and DRZ_i is the natural death rate of zooplankton i (day^{-1}).

The simulation of phytoplankton is represented by three state variables: PB_1 , PB_2 and PB_3 . Sources and sinks for each of the three state variables include growth, basal metabolism, mortality, and settling. Equations describing these processes are largely the same for the three algal groups with differences in the values of parameters in the equations. The kinetic equation describing these processes is:

$$\frac{\partial PB_j}{\partial t} = (GP_j - BMP_j - PRP_j) \cdot PB_j + \frac{\partial}{\partial z}(WS_j \cdot PB_j) \quad (5)$$

in which PB_j is the biomass of phytoplankton j (g C/m^3), $j = 1$ is diatoms, $j = 2$ is green algae, $j = 3$ is other phytoplankton; GP_j is growth rate of phytoplankton j (day^{-1}); BMP_j is basal metabolism rate of phytoplankton j (day^{-1}); PRP_j is predation rate of phytoplankton j (day^{-1}); and WS_j is settling velocity of phytoplankton j (m/day).

The growth of phytoplankton depends on nutrient availability, ambient light, salinity, and temperature and is expressed as:

$$GP_j = GPM_j \cdot g_{1j}(N) \cdot g_{2j}(I) \cdot g_{3j}(S) \cdot g_{4j}(T) \quad (6)$$

in which GPM_j is the maximum growth rate of phytoplankton j under optimal conditions (day^{-1}); $g_{1j}(N)$ is the effect of suboptimal nutrient concentration ($0 \leq g_{1j} \leq 1$) on growth of phytoplankton j ; $g_{2j}(I)$ is the effect of suboptimal light intensity ($0 \leq g_{2j} \leq 1$) on growth of phytoplankton j ; $g_{3j}(S)$ is the effect of suboptimal salinity ($0 \leq g_{3j} \leq 1$) on growth of phytoplankton j ; and $g_{4j}(T)$ is the effect of suboptimal temperature ($0 \leq g_{4j} \leq 1$) on growth of phytoplankton j .

Using Liebig's law of the minimum that growth is determined by the nutrient in least supply, the nutrient limitation for growth of PB_2 and PB_3 is expressed as:

$$g_{1j}(N) = \text{minimum} \left(\frac{NH_4 + NO_3}{KhN_j + NH_4 + NO_3}, \frac{PO_4d}{KhP_j + PO_4d} \right) \quad \text{for } j = 2, 3$$

in which NH_4 is concentration of ammonium nitrogen (g N/m^3); NO_3 is concentration of nitrate-nitrite nitrogen (g N/m^3); KhN_j is the half-saturation constant of nitrogen uptake for phytoplankton j (g N/m^3); PO_4d is concentration of dissolved phosphate (g P/m^3); and KhP_j is the half-saturation constant of phosphorus uptake for phytoplankton j (g P/m^3). Since diatoms require silicon as well as nitrogen and phosphorus for growth, the nutrient

limitation for PB_1 is expressed as:

$$g1_1(N) = \text{minimum} \times \left(\frac{NH4 + NO3}{KhN_1 + NH4 + NO3}, \frac{PO4d}{KhP_1 + PO4d}, \frac{SAd}{KhS + SAd} \right)$$

in which SAd is concentration of dissolved available silicon ($g\ Si/m^3$) and KhS is the half-saturation constant of silicon uptake for diatoms ($g\ Si/m^3$).

The Steele's equation is applied to describe the effect of light intensity on phytoplankton growth in this model. Assuming light intensity declines exponentially with depth from water surface, the integrated and averaged form of Steele's equation over a vertical layer of thickness Δz is:

$$g2_j(I) = \frac{2.718}{Ke \cdot \Delta z} \left[\exp\left(-\frac{I_t}{(I_s)_j} \cdot \exp[-Ke \cdot (H_s + \Delta z)]\right) - \exp\left(-\frac{I_t}{(I_s)_j} \cdot \exp(-Ke \cdot H_s)\right) \right]$$

in which Ke is total light extinction coefficient (m^{-1}); Δz is layer thickness (m); I_t is light intensity at water surface (langleys/day); $(I_s)_j$ is optimal light intensity for phytoplankton j (langleys/day); and H_s is the depth from the free surface to the top of the layer (m).

The total light extinction coefficient is contributed by a background value, the extinction due to total suspended solids, and light absorption by chlorophyll in the water column:

$$Ke = Ke_b + Ke_{TSS} \cdot TSS + Ke_{Chl} \cdot \sum_{j=1}^3 \left(\frac{PB_j}{CChl_j} \right) \quad (7)$$

in which Ke_b is background light extinction coefficient (m^{-1}); Ke_{TSS} is specific light extinction due to total suspended solid (m^{-1} per g/m^3); TSS is concentration of total suspended solid (g/m^3); Ke_{Chl} is specific light extinction due to chlorophyll a (m^{-1} per $mg\ Chl/m^3$); and $CChl_j$ is carbon to chlorophyll ratio of phytoplankton j ($g\ C$ per $mg\ Chl$).

Green algae is a freshwater species, therefore salinity is toxic to green algae and limits its growth. The effect of salinity on phytoplankton growth is described as:

$$g3_j(S) = \frac{ST^2}{ST^2 + S^2} \quad \text{for } j = 2 \\ = 1 \quad \text{for } j = 1 \text{ and } j = 3$$

in which ST is a constant (psu) and S is salinity (psu).

The equations describing the effect of temperature on phytoplankton growth and the algal basal metabolism rate are similar to those for zooplankton. They are expressed as:

$$g4_j(T) = \exp[-KTGP1_j \cdot (T - TGP_j)^2] \quad \text{if } T \geq TGP_j \\ = \exp[-KTGP2_j \cdot (TGP_j - T)^2] \quad \text{if } T < TGP_j \\ BMP_j = BMPR_j \cdot \exp[KTBP_j \cdot (T - TBP_j)] \quad (8)$$

in which TGP_j is optimal temperature for growth of phytoplankton j ($^{\circ}C$); $KTGP1_j$ and $KTGP2_j$ are the effect of temperature above and below TGP_j , respectively, on growth of phytoplankton j ($^{\circ}C^{-2}$); $BMPR_j$ is basal metabolism rate of phytoplankton j at TBP_j (day^{-1}); TBP_j is reference temperature for basal metabolism of phytoplankton j ($^{\circ}C$); and $KTBP_j$ is effect of temperature on metabolism of phytoplankton j ($^{\circ}C^{-1}$).

The grazing is caused by zooplankton and other trophic levels that feed on phytoplankton. Similar to the mortality of zooplankton, the grazing rate by higher trophic levels is assumed to be proportional to the total biomass of all available food. Loss of algal carbon from phytoplankton j by zooplankton grazing and higher trophic levels is expressed as:

$$PRP_j \cdot PB_j = \sum_{i=1}^2 [S_{ji} \cdot ZB_i \cdot f1_i(S) \cdot f2_i(T)] + Pf \cdot \left(\sum_{k=1}^2 ZB_k + \sum_{k=1}^3 PB_k \right) \cdot PB_j \quad (9)$$

in which Pf is the grazing rate of higher trophic levels (per $g\ C/m^3$ per day).

The first term on the right hand side of Eqs. (4) and (9) accounts for the total loss of zooplankton and algal carbon, respectively, by zooplankton grazing. Portion of these carbon is the respiration cost of zooplankton grazing, that is,

$$\sum_{i=1}^2 \left[\sum_{\substack{j=1 \\ j \neq i}}^5 (S_{ji}) \cdot ZB_i \cdot f1_i(S) \cdot f2_i(T) \right] \cdot RF$$

The rest goes to two routes. The first route becomes zooplankton carbon, which is accounted for in zooplankton growth.

$$\sum_{i=1}^2 \left[\sum_{\substack{j=1 \\ j \neq i}}^5 (S_{ji}) \cdot ZB_i \cdot f1_i(S) \cdot f2_i(T) \right] \cdot (1 - RF) \cdot E$$

The second route is recycled to organic carbon, which will be accounted for in the carbon cycling.

$$\sum_{i=1}^2 \left[\sum_{\substack{j=1 \\ j \neq i}}^5 (S_{ji}) \cdot ZB_i \cdot f1_i(S) \cdot f2_i(T) \right] \cdot (1 - RF) \cdot (1 - E)$$

As for the total loss of zooplankton and algal nutrients by zooplankton grazing, the portion of these nutrients, which does not become zooplankton biomass, has to recycle back to organic and inorganic nutrients after being multiplied by the corresponding nutrient to carbon

Table 1. Exponential relationship between water quality concentrations and river discharges of non-point source loadings at specific monitoring stations

Station	Water Quality	Ammonium Nitrogen	Total Nitrogen	Total Phosphorus	BOD ₅	Dissolved Oxygen
Hou-Cun Weir* (Tahan Stream)	Data period	1996–2000	2002	2002	1996–2000	1996–2000
	Regression result	$0.73 \times Q^{-0.21}$ ($R^2 = 0.18$)	$3.72 \times Q^{-0.11}$ ($R^2 = 0.85$)	$0.075 \times Q^{-0.073}$ ($R^2 = 0.05$)	$3.86 \times Q^{-0.14}$ ($R^2 = 0.23$)	$6.18 \times Q^{0.028}$ ($R^2 = 0.04$)
Hsiu-Lang Bridge** (Hsintien Stream)	Data period	1999–2000	1999–2000	1997–2000	2000	2000
	Regression result	$3.03 \times Q^{-0.27}$ ($R^2 = 0.21$)	$7.51 \times Q^{-0.30}$ ($R^2 = 0.45$)	$1.28 \times Q^{-0.52}$ ($R^2 = 0.62$)	$13.2 \times Q^{-0.45}$ ($R^2 = 0.50$)	$3.42 \times Q^{0.15}$ ($R^2 = 0.29$)
Shih-Jian Bridge** (Keelung River)	Data period	2000	1999–2000	1997–2000	2000	2000
	Regression result	$5.16 \times Q^{-0.53}$ ($R^2 = 0.65$)	$3.35 \times Q^{-0.10}$ ($R^2 = 0.14$)	$0.63 \times Q^{-0.38}$ ($R^2 = 0.28$)	$5.47 \times Q^{-0.31}$ ($R^2 = 0.42$)	$4.31 \times Q^{0.12}$ ($R^2 = 0.71$)

*Results of this study. Water quality concentration in the unit of g/m³ and river discharge, Q, in m³/s.

**Results from Liu et al.^[20]

ratios.

$$\sum_{i=1}^2 \left[\sum_{\substack{j=1 \\ j \neq i}}^5 (S_{ji}) \cdot ZB_i \cdot fl_i(S) \cdot f2_i(T) \right] \cdot [1 - E \cdot (1 - RF)]$$

Model calibration/verification

The hydrodynamic portion of the model has been calibrated and verified for application to this estuarine system.^[8] The calibration and verification of the ecosystem model are carried out by simulating the long-term water quality condition, and the plankton and water quality conditions from 2000 to 2002.

Long-term median flow simulation

An examination of Taiwan EPA's long-term monitoring data has concluded that the water quality conditions in the estuarine proper of the Danshuei River system display a conspicuous spatial trend, however with neither seasonal nor long-term temporal trends.^[10] The preliminary model calibration should be with respect to the observed spatial trend. The median values of observed water quality data at each monitoring station were computed and presented as a function of distance upriver from river mouth to construct the typical spatial distributions. These spatial distributions indicate clearly that most of the nutrients and organic carbon come from the upriver reaches of the estuary. The organic carbon and nutrient loadings from both the point and non-point sources become the dominant factors affecting the water quality distributions in the system.

Liu et al.^[20] estimated the loadings of point and non-point sources in the Danshuei River system and investigated

Table 2. Values of plankton related parameters used in kinetic equations

Symbol	Value	Unit
E	0.3	$0 \leq E \leq 1$
RF	0.07	$0 \leq RF \leq 1$
u_{ji}	1.53	day ⁻¹
ω_{ji}	0 ($i = 1, 2; j = 1, 2$), 1 (otherwise)	$0 \leq \omega_{ji} \leq 1$
Kh_{ki}	0.175	g C/m ³
$fl_i(S)$	1	$0 \leq fl_i \leq 1$
TGZ _i	20	°C
KTGZ1 _i	0.004	°C ⁻²
KTGZ2 _i	0.005	°C ⁻²
BMZR _i	0.17	day ⁻¹
TBZ _i	20	°C
KTBZ _i	0.069	°C ⁻¹
RZ _i	0.01	per g C/m ³ per day
DRZ _i	0.02	day ⁻¹
GPM _j	2.0 ($j = 1$ and $j = 3$), 5.5 ($j = 2$)	day ⁻¹
KhN _j	0.025	g N/m ³
KhP _j	0.001	g P/m ³
KhS	0.05	g Si/m ³
(Is) _j	250	langley/day
ST	1000	psu
TGP _j	20	°C
KTGP1 _j	0.004	°C ⁻²
KTGP2 _j	0.005	°C ⁻²
BMPR _j	0.01	day ⁻¹
TBP _j	20	°C
KTBP _j	0.069	°C ⁻¹
Pf	0.01	per g C/m ³ per day

Note 1: In cases where values of indices are not specified, they apply to all possible values.

Note 2: Values not generated in this study are adopted from Cerco and Meyers^[7] and Cerco and Cole.^[23]

Fig. 4. Water quality distribution along the Danshuei River-Tahan Stream under median flow condition, (a) dissolved oxygen; (b) total organic carbon; (c) ammonium nitrogen; (d) total phosphorus.

the water quality for fish survival in Hsintien Stream. The estimated point and non-point source loadings were derived to meet the need of water quality simulation using the HEM-2D model, which has 8 water quality state variables: carbonaceous biochemical oxygen demand (denoted by CBOD), organic nitrogen, ammonium nitrogen, nitrate-nitrite nitrogen, organic phosphorus, phosphate, dissolved oxygen and chlorophyll. These loading data need to be refined for the inputs to the ecosystem model with 21 state variables.

First, the CBOD point source loadings are converted into total organic carbon using the oxygen to carbon ratio, 2.67. Next, the organic carbon, nitrogen, and phosphorus need to be split into dissolved, labile particulate, and refractory particulate fractions. There are no data sets available in this estuarine system for deriving the fraction coefficients for partitioning. The values used in the Chesapeake Bay model are adopted.^[23]

The non-point source loadings from the upstream boundaries were estimated according to the assumption that the field water quality concentrations and river

discharges follow the exponential relationship:^[24]

$$C = aQ^b \quad (10)$$

in which C is the water quality concentration, Q is the river discharge, and a and b are coefficients to be determined. The nearest monitoring stations upriver from the upstream boundaries are Hou-Cun Weir, Hsiu-Lang Bridge and Shih-Jian Bridge in the Tahan Stream, Hsintien Stream and Keelung River, respectively. The regression results of the observed data, including concentrations of ammonium nitrogen, total nitrogen, total phosphorus, BOD₅ (5-day biochemical oxygen demand) and dissolved oxygen, against the corresponding river discharge at the three monitoring stations are listed in Table 1.

It is believed that the BOD₅ test typically measures only CBOD₅ (5-day carbonaceous biochemical oxygen demand) because nitrifying populations are usually too small to exert any appreciable oxygen demand in the first 5 days.^[25] In this manner, the BOD₅ is regarded as CBOD₅. The ultimate CBOD concentration is then estimated as 1.2 times the CBOD₅ based on average values in the municipal

Fig. 5. Water quality distribution in the Hsintien Stream under median flow condition, (a) dissolved oxygen; (b) total organic carbon; (c) ammonium nitrogen; (d) total phosphorus.

wastewater before treatment.^[26] The BOD₅ concentrations in the non-point sources are first derived from the exponential relationship with river discharges and then converted into CBOD. After that, concentrations of organic carbon are obtained using the same estimation method as that used in the CBOD point source loadings. The difference between total nitrogen and ammonium nitrogen in the non-point sources represents the summation of organic and nitrate-nitrite nitrogen. The fraction coefficients for organic and nitrate-nitrite nitrogen used by Liu et al.^[20] are retained, and so is the ratio of organic phosphorus to phosphate.

The median river discharges from 1987 to 2000 are applied at the upstream boundaries, which are 12.8, 23.7, and 9.8 m³/s, respectively, in the Tahan Stream, Hsintien Stream, and Keelung River. A nine-constituent tide and high tide salinity of 30 psu are applied at the river mouth. Long-term median water quality concentrations at the monitoring station near river mouth are applied as the downstream boundary conditions. The estimated point and non-point source loadings do not include the silicon data because silicon is not one of the routine monitoring items in this estuary. The purpose of this median

flow simulation is to see if the estimated loads are close to real conditions in situ. The lack of silicon loadings does not alter the water quality condition since the phytoplankton is not simulated in this model application. A series of sensitivity tests on point source loadings was conducted successively for the purpose of matching the model predictions with the levels of observed peak pollutant concentrations.

Years 2000–2001 simulation

The Taiwan's National Center for Ocean Research (NCOR) conducted 7 sets of field surveys from September 2000 to August 2001 in the lower estuary. The water quality variables measured included salinity, chlorophyll *a*, dissolved oxygen, dissolved organic carbon, ammonium nitrogen, nitrate plus nitrite nitrogen, phosphate, and dissolved silicon. These data were used to further calibrate the model. The model was run to simulate a period starting January 1, 2000 to August 31, 2001. The observed hourly tidal height and the daily freshwater discharges were used, respectively, as the downstream and upstream boundary conditions. The point source loadings of the sensitivity run described in the

Fig. 6. Water quality distribution in the Keelung River under median flow condition, (a) dissolved oxygen; (b) total organic carbon; (c) ammonium nitrogen; (d) total phosphorus.

results of long-term median flow simulation were assumed good estimates of the prototype condition and adopted for this model run. The regression formulas for the non-point source loadings were also adopted. The model could not be run past September 2001 when a disastrous flood hit the area. The hydrodynamic portion of the model broke down when very high flows were specified for the upstream boundary conditions.

The in-situ light attenuation through the water column of the lower estuary was reported to have a relatively low correlation with the concentration of total suspended solids. However the regression with salinity yielded a good estimate for light attenuation coefficient.^[27] Accordingly, instead of Eq. (7), the regression formula

$$K_e = 5.82 \cdot \exp(-0.062 \cdot S) \quad (11)$$

was incorporated in this simulation. The parameter values for the nutrient dynamics were kept the same as those used in the long-term median flow simulation. The values of phytoplankton related parameters were initially set at the

mid-range of values reported in the literature. They were subsequently adjusted within the range to achieve reasonable agreement between the model predictions and field observations.

Years 2001–2002 simulation

The model was restarted on September 19, 2001 after the severe flood, and run until September 2002. There was no discharge record at the main branch of one of the three tributaries during this period. To generate the river flow input for model simulation, the missing record of daily discharge was estimated by regression relation with other gauge records. After September 2002, the discharge records from two of the three tributaries became unavailable and the remaining one had a number of days with missing records. The model simulation was stopped then. At the start of the model run, it was assumed that the big flood flows essentially flushed out all nutrients and plankton from the estuary. The model simulation started with a “clean” estuary. The recruitments of zooplankton, diatoms, and

Fig. 7. Water quality distribution along the Danshuei River-Tahan Stream under median flow condition with increased point source loading, (a) dissolved oxygen; (b) total organic carbon; (c) ammonium nitrogen; (d) total phosphorus.

other algae were facilitated by imposing the boundary conditions at the river mouth. Field observations suggested that green algae originated from within the estuary. A seed population of 0.005 g C/m^3 was assumed after the severe flood.

This study conducted six field surveys from October 2001 to May 2004. This set of data is the only one including plankton biomass in terms of carbon contents per unit volume of water body. Emphasis was placed on the phyto- and zooplankton growth in this series of model simulations. The values of zooplankton related model parameters were adopted from those used by the Chesapeake Bay model,^[7] except for the optimum growth rate. Shieh^[28] computed the filtration rate of copepod captured in this estuary from their gut contents. He arrived at an average value of 0.19 ml/hr per individual.

With the assimilation efficiency of 0.3 and respiration cost of 0.07,^[7] the average optimum growth rate of copepod in this estuary was estimated to be 1.53/day. This value was used in the model simulation. This left the phytoplankton growth rate as the most important parameter to be adjusted to achieve proper agreement of plankton biomass between

the model predictions and field observations. A mid-value literature reported growth rate of 2.0/day was used for the diatoms and other algae in the model. The optimum growth rate of green algae determined in the years 2000–2001 simulation was re-adjusted to achieve the agreement of total phytoplankton biomass between model predictions and field observations. A value of 5.5/day was finally adopted for both the years 2000–2001 and the 2001–2002 simulations. The values finally adopted for plankton related model parameters are listed in Table 2.

Results and discussions

Long-term median flow simulation

The longitudinal water quality distributions predicted by the ecosystem model under median flow condition are presented in Figures 4 to 6. The median values of water quality observations at specific monitoring stations from 1987 to 2000 are also shown in the figures. In Figure 4, both the model predicted and the observed median values of dissolved oxygen concentrations along the Tahan Stream

Fig. 8. Water quality distribution in the Hsintien Stream under median flow condition with increased point source loading, (a) dissolved oxygen; (b) total organic carbon; (c) ammonium nitrogen; (d) total phosphorus.

show a decreasing trend from San-Ying Bridge to Hsin-Hai Bridge, a significant decrease from 8 g/m^3 to $1\text{--}2 \text{ g/m}^3$ over a 15 km reach of the river. In the lower reach of the Danshuei River, the median dissolved oxygen concentrations increase toward the river mouth as a result of seawater dilution. The lowest dissolved oxygen concentrations occur in the river reach from Hsin-Hai Bridge to Kuan-Du Bridge.

Total organic carbon, ammonium nitrogen, and total phosphorous all exhibit the same spatial trends along the Danshuei River-Tahan Stream. The concentrations increase in the downstream direction from San-Ying Bridge, reaching a maximum at the Hsin-Hai Bridge, and then gradually decrease toward the river mouth. Maximum concentrations of pollutants all occur at Hsin-Hai Bridge, and the dissolved oxygen level is severely depressed in the river reach downstream. These evidences indicate that there are certainly some significant amounts of effluents discharged into the river reach around the Hsin-Hai Bridge.

The figures show that the model results generally capture the spatial trends of the observed longitudinal distributions but under-predict the maximum concentrations of organic carbon, ammonium nitrogen, and total phosphorus, and

the severity of the DO depression. This is clear evidence that the point source loadings in the river reach around Hsin-Hai Bridge may have been under estimated.

Figure 5 presents the longitudinal distributions of water quality variables along the Hsintien Stream. Both the model predictions and observed data indicate that the water quality conditions degrade approaching the river mouth where it joins the main stem Danshuei River. The dissolved oxygen concentration decreases, and the organic carbon, ammonium nitrogen, and total phosphorus concentrations increase monotonically toward the river mouth. The under prediction of pollutant concentrations and over prediction of dissolved oxygen level are similar to that in the main stem Danshuei River. The longitudinal distributions of water quality variables along the Keelung River (Fig. 6) indicate that there are significant point source loadings discharged into the river reach at the Bai-Ling Bridge. Both the model predictions and observed data have the maximum pollutant and minimum dissolved oxygen concentrations in this reach of the river. The figure also indicates that the point source loadings are under estimated there.

Fig. 9. Water quality distribution in the Keelung River under median flow condition with increased point source loading, (a) dissolved oxygen; (b) total organic carbon; (c) ammonium nitrogen; (d) total phosphorus.

The point source loadings were estimated based on the population living in the drainage area draining into each model segment. They do not include pollutant loads other than the domestic wastewater. There was a huge pile of solid wastes deposited on the floodplain of the Tahan Stream between Hsin-Hai and Fu-Chou Bridges. The local government has been trying to remove it, but the job is yet to be completed. It is reasonable to assume that this pile of solid wastes is contributing significant amounts of pollutants to the river. A series of model sensitivity runs was conducted by increasing the point source loadings in the three model segments around Hsin-Hai Bridge to match the model prediction of the maximum organic carbon concentration with that of the observed maximum. The total organic carbon loading in the Keelung River was also increased since the model prediction in that river was also low compared to the observed values.

Figures 7 to 9 compare the model results of one of the sensitivity runs with observed values in the three branches of the river system, respectively. In this model run, all forms of

point source loadings in the three segments near the Hsin-Hai Bridge were increased to four times the original estimates and the organic carbon loading was doubled in all segments of the Keelung River. The figures indicate that the model gives a reasonably good quantitative prediction of the dissolved oxygen, organic carbon, and ammonium nitrogen concentrations in all three branches of the river system by simply matching the maximum organic carbon concentration with the observed value. The model still under predicts the total phosphorus concentration. No attempt was made to further adjust the phosphorus loadings since it would not affect the dissolved oxygen concentration in this model application in which the phytoplankton was not simulated.

Years 2000–2001 simulation

The NCOR's field observations were used for model calibration. However they were not designed to collect data for model application. The sampling locations were restricted

Fig. 10. Water quality distribution along the Danshuei River-Tahan Stream on March 16, 2001, (a) salinity; (b) chlorophyll *a*; (c) dissolved oxygen; (d) dissolved organic carbon; (e) ammonium nitrogen; (f) nitrate-nitrite nitrogen; (g) phosphate; (h) available silicon.

Fig. 11. Temporal water quality distribution at Kuan-Du Bridge in years 2000–2001, (a) salinity; (b) chlorophyll *a*; (c) dissolved oxygen; (d) ammonium nitrogen.

to the lowest reach of the estuary and the timing of sampling did not take the phase of tide into account. All observations were made near the water surface. Therefore the model results are presented with the average, maximum, and minimum of the day. Figure 10 presents an example comparison of the model results with the observed data on March 16, 2001.

The figure shows that the model accurately reproduces the observed salinity and chlorophyll. However it under predicts the carbon, nitrogen and phosphorus concentrations while over predicting the dissolved oxygen. Since there was more than one month of low river flow prior to March 16, the non-point source contributions should be minimal. The discrepancy may be attributed to the under estimation of point source loadings. The accurate simulation of the intra-tidal variations of the water quality variables can also be seen in Figure 10. There were two cruises conducted on the same day; the salinity data indicate that cruise #1 was conducted near high tide while cruise #2 was near low tide. The model adequately predicts the observation that higher concentrations of dissolved organic carbon, ammonium nitrogen, nitrate plus nitrite nitrogen, phosphate, and silicon occurred at low tide, and lower concentrations at high tide.

A time series comparison of the model results and observed data at Kuan-Du Bridge is presented in Figure 11.

The predicted salinity is presented with hourly values to show the intratidal variation while the others are presented with daily average values. The figure shows that the river discharge is the dominant factor controlling the water quality conditions in the estuary. The sporadic occurrence of the freshwater pulses flushes out the point source pollutants and plankton from the system. The phytoplankton has a chance to grow only when there is an extended period of low river flow. This occurred in March and August of 2001. The August low flow lasted for two and a half months from mid-June. It further coupled with high temperature and strong solar radiation to cause exponential growth of phytoplankton during the later part of this dry period. The growth was accompanied with increasing dissolved oxygen (Fig. 11c) and decreasing nutrients (Fig. 11d) in the water column. The phytoplankton was finally depressed by the light limitation on the last day of the model simulation and completely flushed out of the system the day after by the disastrous flood resulting from a strong typhoon.

Years 2001–2002 simulation

Figures 12 and 13 show the comparisons of model predicted plankton biomass with those of observed values on October 15, 2001 and April 18, 2002, respectively. It

Fig. 12. Plankton distribution along the Danshuei River-Tahan Stream on October 15, 2001, (a) copepod; (b) total zooplankton; (c) diatoms; (d) green algae; (e) other phytoplankton; (f) total phytoplankton.

is seen that the biomass in October was low because it was not long after the flood event. There has been significant growth by April 2002. By simulating the phytoplankton in three groups, the model generally well reproduced the spatial distribution of algal biomass on that day.

Taiwan's NCOR also collected several sets of data in late 2001 to 2002, including chlorophyll *a*. These data sets re-

veal some temporal variation of phytoplankton biomass in the system. Assuming fixed carbon to chlorophyll ratio, Figure 14 presents a time series plot of model predicted and observed chlorophyll concentrations at Kuan-Du station. The figure shows that the algal biomass decreases in quick response to high freshwater input. It is only during a prolonged low flow period then the phytoplankton gets a chance to grow to significant level.

Fig. 13. Plankton distribution along the Danshuei River-Tahan Stream on April 18, 2002, (a) copepod; (b) total zooplankton; (c) diatoms; (d) green algae; (e) other phytoplankton; (f) total phytoplankton.

A complete calibration and verification of an estuarine ecosystem model would require an enormous amount of field data. In most instances, the investigators have to live with whatever is already available or the resources available for additional data collection. This investigation is no exception. First, we have made use of Taiwan EPA's long-term monitoring data of nutrients and dissolved oxygen to calibrate the parameters relevant to nutrient cycling and DO budgeting. The mid-range values of the

model parameters reported in the literature were initially adopted for model simulation. They were then adjusted repeatedly to achieve reasonable agreement between model results and field data. The NCOR's observation data were used for the calibration of parameters relating to phytoplankton growth. A few reports of primary productivity are available and they were used as a guide to adjust the growth, metabolism, grazing, and settling rates of phytoplankton from their initial set values. This

Fig. 14. Temporal water quality distribution at Kuan-Du Bridge in years 2001–2002, (a) salinity; (b) chlorophyll *a*; (c) dissolved oxygen; (d) ammonium nitrogen.

investigation made special efforts to collect phytoplankton and zooplankton biomass (carbon contents), differentiate species and estimate zooplankton growth rate. The experimentally determined growth rate of 1.53/day used in the model is comparable to the value for mesozooplankton growth rate of 1.75/day used in the Chesapeake Bay model.^[7]

The model simulations of long-term median conditions demonstrate that the point source loadings of pollutants are responsible for the bulk of pollutants in the estuary. The loadings are mainly from the waste discharge of the large population in the city of Taipei. The non-point sources of pollutants from the fluvial sections of the river are relatively small, since the median river flows are relatively low. During the low flow period, the cleansing capacity of the river flow is minimal. The waste discharge is large enough to degrade severely the water quality, particularly in the inner reach of the estuary where the tidal flushing is weak. Hypoxia/anoxia, both in the surface and bottom waters, is a common occurrence throughout the estuary. Ammonium nitrogen concentration is normally as high as several g/m^3 . The water quality improves only toward the river mouth as a result of seawater dilution and tidal flushing. The cyclic intra-tidal variation of water quality is evident by higher nutrient concentrations, lower salinity and dissolved oxygen concentration at low tide, and lower nutrient concentra-

tions, higher salinity and dissolved oxygen concentration at high tide.

Both the model simulation and field data indicate that there is no seasonal trend in the temporal variation of water quality in this estuary. The results of model simulations demonstrate that the water quality and plankton population are mainly controlled by the magnitude of river inflows. The high river flows occur as distinct events in rapid response to sporadic rainfall. They occur as pulses with periods of low flows in-between (Fig. 11 and Fig. 14). The high river flow pulses cleanse the estuary by flushing out the pollutants and plankton populations. Plankton biomass becomes very low right after each high river flow event. The green algae start to build up in the estuary, and the diatoms and copepod return from out of the river mouth. It takes a prolonged period of low river flow for the plankton to build up to a level of viable biomass (Fig. 14). It happens quite often that the low river flow period between successive high flow events is too short to allow for plankton population to build up to significant levels. The estuary depends heavily on the intrusion of planktonic organisms from the surrounding coastal waters.

In addition to being sensitive to the magnitude of river inflow, it was noted through model calibration that the model is very sensitive to the values of the phytoplankton growth rate. The calibrated value of 5.5/day optimum growth rate

for green algae is higher than most of the reported values of 1.0 to 4.0/day, even though a value as high as 8.0/day has been cited. During the low flow periods, a 10% decrease from the calibrated value would result in a situation of no net growth in the estuary at all. On the other hand, a 10% increase in growth rate would result in an algal population well exceeding the observed values. This may imply that the system is in a delicate balance between the biological growth and physical flushing, both of which have very short time scales for this estuary. Wang et al.^[9] estimated that the longest residence time of the estuary is 2.2 days when there is zero river inflow. The residence time decreases sharply to 1.5 days under median flow, and 1.1 days under the mean river flow conditions. That is, the green algae will need a net growth rate of 0.45/day at the minimum to accumulate in the estuary at all. An optimum growth rate much larger than that is required to compensate for the basal metabolism, grazing, settling, light limitation, and to overcome the additional river flow flushing. The nutrient concentrations in the estuary are very high that they do not limit the algal growth.

A model sensitivity run was also conducted with the light extinction coefficient reduced uniformly by 30%. The model would produce comparable results with an optimum algal growth rate of 4.0/day. The light extinction coefficient was determined using a regression equation with salinity as the sole independent variable (Eq. 11). There is a high degree of data scattering in the original data for the low salinity region.^[27] The accuracy of the coefficient may also contribute to the high optimum growth rate necessary for the model calibration. More studies to quantify the light extinction through the water column are warranted.

Conclusions

An ecosystem model was developed to simulate the water quality and plankton dynamics in the Danshuei River estuary, Taiwan. The model simulates the hydrodynamics with a laterally-integrated 2-dimensional intra-tidal numerical model, which supplies the information on physical transport processes for simulation of water quality and plankton state variables. A total of 21 state variables are simulated, including various species of nitrogen, phosphorus and silicon, dissolved oxygen, organic carbon, phytoplankton and zooplankton. The application of the model to the Danshuei River estuary indicates that the point source loadings are mainly responsible for the degraded water quality and very high nutrient concentrations in the estuary. The impacts of wastewater discharges are tightly controlled by the transport processes in the estuary. During low river flow periods, the dominant waste assimilation capacity is the seawater dilution and tidal flushing. The water quality conditions are severely degraded in the inner and middle reaches of the estuary where the tidal flow is weak. The conditions improve only toward the river mouth as a result of seawater dilution.

The plankton is allowed to grow to significant populations if low river flow lasts for a period much longer than

the biological time scale. However the frequent occurrence of high river flow and flood events shortens the estuarine residence time and rapidly cleanses the estuary. Both the pollutant concentrations and plankton population start to build up after each of the high flow events. The climate pattern of the drainage basin makes this most likely to occur in early spring and early summer. The winter rains, late spring Meiyu fronts, and sporadic typhoons in late summer to early fall exclude these periods from sustained phytoplankton growth.

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