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Publisher Taylor & Francis

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Journal of Environmental Science and Health, Part A

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title~content=t713597268>

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To cite this Article Liu, Wen-Cheng, Hsu, Ming-Hsi and Kuo, Albert Y. 'Sensitivity analysis of a mathematical model of chlorophyll distribution in the tidal Keelung river', Journal of Environmental Science and Health, Part A, 35: 4, 489 — 514

To link to this Article: DOI: 10.1080/10934520009376983

URL: <http://dx.doi.org/10.1080/10934520009376983>

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SENSITIVITY ANALYSIS OF A MATHEMATICAL MODEL OF CHLOROPHYLL DISTRIBUTION IN THE TIDAL KEELUNG RIVER

Key Words: Chlorophyll distribution, numerical model, Keelung River, water quality, sensitivity analysis, light extinction

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ABSTRACT

Large temporal and spatial variations in chlorophyll concentration found in estuarine and coastal waters have been attributed to a diverse set of physical, chemical and biological factors. The Keelung River has the largest tidal excursion and the most serious pollution problem among the three tributaries of the Tanshui River system in northern Taiwan. It receives extremely high anthropogenic nutrient loadings from municipal and industrial discharges with little or no treatment. The observed data show very high nutrient concentrations in the river, with total nitrogen of order of several milligrams per liter and total phosphorus of 1 mg/l. However, the summer chlorophyll 'a' concentrations are generally less than 10 µg/l. A time-dependent, laterally averaged, two-dimensional hydrodynamic and water quality model (HEM-2DT) was applied to the tidal reach of the Tanshui River estuarine system to simulate the phytoplankton dynamics, nutrient cycling and dissolved oxygen distribution. The numerical model was

calibrated and verified with observed chlorophyll 'a' and nutrient distributions in the Keelung River, and then used to investigate the various factors regulating chlorophyll 'a' distributions in that river. The sensitivity analyses include water-column light extinction, nutrient reduction, freshwater discharge, boundary condition and effect of salinity distribution. The result reveals that light availability is the predominant limiting factor of phytoplankton growth, while nutrient concentrations are not limiting. The reduction of nutrient N and P loadings have no effect on chlorophyll 'a' concentration in the Keelung River.

INTRODUCTION

Pronounced gradient in environmental habitat properties characterizes estuaries and influences the composition and dynamics of estuarine phytoplankton communities (Smayda, 1983). Large temporal and spatial variations in chlorophyll concentration found in estuaries and coastal waters have been attributed to a diverse set of physical, chemical and biological factors. These factors include: (1) physical concentration along fronts (Seliger et al., 1981) or in vertically stratified systems (Colern and Cheng, 1981; Tyler et al., 1982; Cloern et al., 1983); (2) advective input or removal (Malone et al., 1980); (3) incident light (Haertel et al., 1969); (4) water-column light extinction (Cadee, 1978); (5) depth of the mixed-layer (Riley, 1952); (6) temperature (Williams, 1966); (7) nutrient concentration (Williams, 1972; Eppley, 1981; Nixon and Pilson, 1983); (8) grazing (Martin, 1970; Malone et al., 1980).

Despite the variety of factors that may regulate chlorophyll distributions, light availability is often the predominant factor when nutrient concentrations are non-limiting (Bannister, 1979; Laws and Bannister, 1980). Incident light, water-column extinction, and depth of the mixed-layer are the primary regulators of light availability (Wofsy, 1983). For coastal and oceanic systems, incident light and

depth of mixed-layer have been found to regulate spring bloom formation (Parsons et al., 1966; Gieskes and Krasý, 1975). Wofsy (1983) modeled the relationship between chlorophyll concentration and light availability in brackish regions of the Delaware and Potomac Rivers, and found that suspended sediment concentration was a major regulator of phytoplankton biomass under non-stratified conditions.

The dynamics of phytoplankton production in estuaries has received much attention recently because of the occurrence or threat of 'cultural' eutrophication and the importance of estuaries as natural resources. Although extremely high anthropogenic nutrient loadings from municipal and industrial wastewaters in the Keelung River provide non-limiting nutrient concentrations, regulation of phytoplankton growth by light-limitation restricts chlorophyll concentrations below the nuisance levels found in many eutrophic systems.

A time-dependent, laterally averaged, two-dimensional hydrodynamic and water quality model (HEM-2DT) was applied to the tidal reach of the Tanshui River system to simulate the phytoplankton dynamics, nutrient cycling and dissolved oxygen distribution. The numerical model was calibrated and verified with observed chlorophyll 'a' and nutrient distributions. Sensitivity analysis using the model provides further insight to investigate the various factors regulating chlorophyll 'a' distributions in the Keelung River. This paper presents the model application with emphasis on the sensitivity analysis. The sensitivity analyses include water-column light extinction, freshwater discharge, nutrient N and P loadings, absence of salt, i.e., assuming homogeneous river, and chlorophyll inputs from upstream boundary.

STUDY SITE

The Keelung River is one of the three major tributaries of the Tanshui River. The Tanshui River is the third largest river and the largest estuarine system in

Taiwan. The drainage area of the entire Tanshui River basin is about 2726 km², which includes the metropolitan city of Taipei. The downstream portion of the river is severely polluted by municipal and industrial wastewater discharges. During low flow period, anoxia occurred in some portions of the river. According to water quality surveys conducted by the Taiwan Environmental Protection Administration (1992), the lengths of slightly, moderately and seriously polluted reaches are 5.15 km, 18.29 km and 21.66 km, respectively, in the Keelung River. Sanitary sewers and wastewater treatment plants are in the planning stages or under construction in Taipei City while in Taipei County, the construction of a huge regional wastewater treatment plant with an ocean outfall has just been completed to reduce the pollution in the Tanshui River system.

The Keelung River has a drainage area of 501 km² and a total length of 87 km. The annual mean rainfall is 3970 mm, 46% of which is concentrated in the months from September to December. The average limit of salt intrusion is located at Ta-Chih bridge, 12 km from its confluence with the Tanshui River. The lower portion of the river, from Kuan-Du bridge to Chiang-Pei bridge, is influenced by tidal variation. The Keelung River channel regulation project (Figure 1), which includes short-cut for two meanders, began in 1991 and was completed in 1994. The purpose of the project was mainly for flood control. The project resolved the housing problem for 13,000 residents who lived in the original floodplains of 555 hectares in area. The residents were relocated to the reclaimed land and thereby improving their original poor environmental and living conditions.

The study area occupies the lower level part of the basin, where the main residential and industrial areas are located, and spans over two municipalities: Taipei City and Taipei County. River flows during 1996 were obtained from continuous water stage and discharge measurements at Wu-Tu which is the upstream boundary of the model domain. The flow rates (Figure 2) are

FIGURE 1
Tanshui River system and model segmentation.

FIGURE 2

Flow rates at Keelung River used for 1996 calibration and verification runs.

significantly influenced by rainfall. Water quality data were obtained from field sampling programs of Taiwan EPA (1996). The observed data show very high nutrient concentrations in the river, with total nitrogen of order of several milligrams per liter and total phosphorus of 1 mg/l. However, the summer chlorophyll 'a' concentrations are generally less than 10 $\mu\text{g/l}$.

MODEL DESCRIPTION

Two aspects of hydrodynamics dominate transport processes in most estuaries. These are the oscillatory tidal flow and the vertical circulation structure usually governed by the interaction between sea and fresh river waters, and also by wind and thermal gradients. The HEM-2DT model (Hsu et al., 1996; 1997), a laterally integrated, two-dimensional, real-time model, was modified and expanded to cover a wide range of applications, such as the propagation of tidal waves in estuaries and their tributaries, salinity, water quality and cohesive

sediment transport. As the relationship between water quality and flow gets special attention nowadays and this model is suitable for modeling both, it becomes a useful tool in water quality management. The HEM-2DT model, consisting of a hydrodynamic model and a water quality model, is based on the principles of conservation of volume, momentum and mass. The hydrodynamic model generates outputs of flow velocity, surface elevation, and salinity that are used in water quality model to calculate water quality constituent distributions. The hydrodynamic and water quality models were solved using a two time level, finite difference method with a spatially staggered grid.

The water quality part of the HEM-2DT model is based upon the two-dimensional transport equation. The partial differential equation describes the concentration of a constituent in a two-dimensional system as function of time and space. The source/sink term of the equation includes all chemical and biological processes to which a specific constituent is subject to. Eight water quality state variables are modeled : chlorophyll 'a', organic nitrogen, ammonium nitrogen, nitrite-nitrate nitrogen, organic phosphorus, inorganic (ortho) phosphorus, carbonaceous biochemical oxygen demand and dissolved oxygen (DO). The mass-balanced equation can be written as follows:

$$F(t, x, z, C, \beta) = 0 \tag{1}$$

where

$$F = (F_1, F_2, \dots, F_8)^T \tag{2}$$

$$F_i(t, x, z, C, \beta) = \frac{\partial(C_i B)}{\partial t} + \frac{\partial(C_i B u)}{\partial x} + \frac{\partial(C_i B w)}{\partial z} - \frac{\partial}{\partial x} K_x B \frac{\partial C_i}{\partial x} - \frac{\partial}{\partial z} K_z B \frac{\partial C_i}{\partial z} - B \cdot S_i(t, x, z, C, \beta) \tag{3}$$

where t = time; $S_i(t, x, z, C, \beta)$ = functions describing the time rate of internal increase (or decrease) of mass by biochemical reaction and external addition (or withdrawal) of the i state variable; u and w = laterally averaged velocities in the x - and z -directions, respectively; $\beta = (\beta_1, \beta_2, \dots, \beta_m)^T$ = parameters to

be calibrated; m = number of unknown parameters; K_x and K_z = dispersion coefficients in the x - and z -directions, respectively; B = river width; $C = (C_1, C_2, C_3, \dots, C_8)^T = (\text{Chl}, \text{N1}, \text{N2}, \text{N3}, \text{P1}, \text{P2}, \text{CBOD}, \text{DO})^T$ = concentrations of the state variable, where Chl = chlorophyll a ($\mu\text{g/l}$), N1 = organic nitrogen (mg/l), N2 = ammonium nitrogen (mg/l), N3 = nitrite-nitrate nitrogen (mg/l), P1 = organic phosphorus (mg/l), P2 = inorganic phosphorus (mg/l), CBOD = carbonaceous biochemical oxygen demand (mg/l), and DO = dissolved oxygen (mg/l). The model formulation of source and sink function are fully described in Park and Kuo (1993).

MODEL CALIBRATION AND VERIFICATION

The model was applied to the whole Tanshui River system, including the other two tributaries up to limits of tide as well as the Keelung River. However, because of the scarcity of chlorophyll data in the main stem and other tributaries, the water quality portion of the model was calibrated for the Keelung River only. The following discussions are, thus, restricted to the Keelung River.

The upstream boundary for the model is located beyond the limit of tide at Wu-Tu station and downstream boundary is at the Tanshui River mouth. The tidal reach of the Keelung River was divided into 37 segments with $\Delta x = 1.0$ km. Because surface elevation at low tide is 1.5 m below mean sea level at spring tide, the thickness of the top layer is 2.0 m to maintain surface elevation above the bottom of the layer at all times. The thickness of other layers is 1.0 m. The maximum depth was divided into 6 layers in the Keelung River. The measured cross-sectional profiles in each segment were averaged and schematized. The model transects in the tidal Keelung River are shown in Figure 1.

Hydrodynamic model calibration and verification included those for mean tidal range, surface elevation, longitudinal velocity, flow rate, turbulent mixing, and salinity distribution. They had been completed for the whole Tanshui River

system in the first phase of this study (Hsu et, al., 1999). The hydrodynamic model parameters were taken from the result of that study. The water quality model simulation was conducted for the period from January 1 to November 30, 1996. The field data collected by the Taiwan EPA during that period were used for the model calibration and verification. Four sets of field data on February 13, April 16, August 7 and November 2, 1996 in the Keelung River were available for testing the validity and degree of applicability of the water quality model.

Time-varying boundary conditions for the hydrodynamic model were specified. The upstream boundary condition was specified with daily freshwater discharge measured at the Wu-Tu gauging station. Hourly tidal elevation measured at the Tanshui River mouth was used for the downstream boundary condition. The four slackwater surveys were all conducted at the slack before flood. The salinity and water quality conditions measured at the mouth were linearly interpolate in time and used for the daily downstream boundary conditions.

The nonpoint sources of nutrients, DO and CBOD from the watershed above the fall line were evaluated with a regression analysis using freshwater discharge rates and nutrients, DO and CBOD concentrations measured at the fall line. Daily input for the concentrations of Chl was obtained from the linear interpolation of monitoring data. The CBOD and nutrient loadings below the fall line were estimated for the Keelung River by Chung (1995).

Model Calibration

The guideline of model calibration reported by Thomann (1982) suggested that this is the first stage tuning of a model to a set of field data. The calibration or tuning should include a constituent set of theoretically defensible parameters and inputs, i.e., parameters should not vary outside of the range reported in the literature nor should the parameters vary in an “unstable” fashion outside the range of accuracy. The real-time water quality model was calibrated with a

simulation of distributions of the state variables from January 1 to November 30, 1996. The field data of the slackwater survey conducted on February 13 and April 16 was used for the model calibration. The calibrated results and field observations on April 16 are shown in Figure 3. The figures show large variations of concentrations for all state variables over tidal cycle, except nitrite-nitrate nitrogen, which had little longitudinal gradient. The lower portion of the river had low DO concentration due to high point source loads in this stretch of the river. The phytoplankton-related coefficients employed in the model calibration are listed in Table 1. The light extinction coefficient (K_c) is specified from 0.42 cm^{-1} to 0.45 cm^{-1} in the Keelung River.

The figures show that model results and field measurements were in reasonable agreement. Discrepancies were often attributable to observation of the consistency principle between calibration and verification rather than to failure to curve-fit the model results to the field data. Some differences, however, did exist between the model results and the field measurements for some isolated data points. This is expected because the model calculated the lateral average concentrations while the field data were point measurements, and also because of the random variability inherent to natural systems.

Model Verification

The water quality model calibrated with one set of field data does not guarantee that validity of the model can be extended beyond the data set used in the calibration. By verification tests, one may examine the response of the model, with a particular set of parameter values, to a different ambient condition. Simulation by the model with calibrated parameter values was extended through November 2, 1996. The capability of the model was tested through comparisons of the model predictions and the field data collected on August 7 and November 2. Verification results on August 7 are shown in Figure 4. The figures present the daily ranges predicted by the model at the surface and bottom layers, respectively,

FIGURE 3

Model calibration results on April 16, 1996 (a) chlorophyll 'a' (b) DO (c) CBOD (d) ammonium nitrogen (e) nitrite-nitrate nitrogen (f) inorganic phosphorus (g) total phosphorus.

(continued)

FIG. 3. Continued

FIG. 3. Continued

along with field data. There is a distinctive DO concentration sag at 5 to 10 km from the river mouth, which is a result of high point source loads in the lower portion of the river. The model prediction shows that the peak summer chlorophyll 'a' concentration is of order of 10 $\mu\text{g/l}$, which is in good agreement with field observation. Both figures of calibration and verification show that model results and field measurements are in reasonable agreement.

SENSITIVITY ANALYSES

A primary use of the calibrated and verified model is sensitivity analysis to examine the behavior of the prototype in response to any alterations made. Experiments of this nature would be difficult or impossible to conduct on the prototype. Sensitivity analysis is a powerful tool that can be used to improve understanding of the present chlorophyll distribution in the Keelung River and to explore the factors that are primarily responsible. The sensitivity analysis was conducted by running the model with all coefficients as in the calibration run except the one being examined.

TABLE 1
The Values of Phytoplankton-Related Coefficients

Coefficient	Meaning	Value
a_c	ratio of carbon to chlorophyll in phytoplankton	0.05 mg C per μg Chl
a_n	ratio of nitrogen to chlorophyll in phytoplankton	0.007 mg N per μg Chl
a_p	ratio of phosphorus to chlorophyll in phytoplankton	0.001 mg P per μg Chl
a_r	fraction of consumed phytoplankton recycled by zooplankton	1.0
PQ	photosynthesis quotient	1.0 moles O_2 per mole C
RQ	respiration quotient	1.1 moles CO_2 per mole O_2
K_{mn}	half-saturation concentration for uptake of inorganic nitrogen	0.025 mg/l
K_{mp}	half-saturation concentration for uptake of inorganic phosphorus	0.001 mg/l
k_{gr}	optimal growth rate at 20°C	2.0 day^{-1}
θ_1	constant for temperature adjustment of growth rate	1.066
I_s	optimal solar radiation rate	250 langley's day^{-1}
$K_{e,\text{Chl}}$	light extinction due to self-shading of plankton	0.00018 $1/\mu\text{g cm}^{-1}$
K_{Chl}	settling rate of phytoplankton	0.0 cm/day
$R(20)$	respiration rate at 20°C	0.17 day^{-1}
θ_2	constant for temperature adjustment of respiration rate	1.08
$P(20)$	mortality rate at 20°C	0.02 day^{-1}
θ_3	constant for temperature adjustment of mortality rate	1.0

FIGURE 4

Model verification results on August 7, 1996 (a) chlorophyll 'a' (b) DO (c) CBOD (d) ammonium nitrogen (e) nitrite-nitrate nitrogen (f) inorganic phosphorus (g) total phosphorus.

(continued)

FIG. 4. Continued

FIG. 4. Continued

Water Column Light Extinction

Despite the variety of factors that may regulate chlorophyll 'a' distribution, light availability is often the predominant factor under conditions where nutrient concentrations are not limiting (Pennock, 1985). The effect of light intensity was examined by increasing or decreasing the light extinction coefficient (K_e). Result in Figure 5 shows that the chlorophyll concentration increases significantly as K_e decreases. As high anthropogenic nutrient inputs provide non-limiting nutrient concentrations, decrease of K_e stimulates more phytoplankton growth. On the other hand, since chlorophyll was seriously limited by light under verified condition, further increase in K_e only reduced chlorophyll concentration slightly.

Nutrients Reduction

Estuaries have generally been regarded as one of the most productive of aquatic systems, and the nutrient supply from freshwater inputs is clearly important in sustaining the high rates of primary production. Limitation of primary productivity by low nutrient availability has been reported by Cloern (1987) for reaches of some estuaries. However, estuaries often receive high

FIGURE 5

Sensitivity to light extinction coefficient, conditions on August 7, 1996.

nutrient (N and P) loadings with river discharge and urban/industrial inputs, providing a non-limiting nutrient supply for phytoplankton growth (Fisher et al., 1988; Harding et al., 1986). The model was run to assess the change of phytoplankton growth as the result of the on-going clean-up project with sewage interception systems. Nitrogen and phosphorus concentrations in the river will decrease significantly, but chlorophyll concentration is not affected by reduction of the nutrient loadings (shown in Figure 6). Therefore we may conclude that inorganic nutrients play a minor role in the distribution of phytoplankton biomass in the Keelung River under 1996 condition.

Freshwater Discharge

The ability of planktonic population to maintain itself within an estuarine segment is determined mainly by its rate of growth relative to the proportion of

FIGURE 6

Sensitivity to reduction of nutrient loadings, conditions on August 7, 1996 (a) ammonium nitrogen (b) nitrite-nitrate nitrogen (c) inorganic phosphorus (d) chlorophyll 'a'.

(continued)

FIG. 6. Continued

population biomass lost through flushing from the segment during each tidal cycle (Ketchum, 1954). Because of changes in river discharge, the flushing time of a given estuary may fluctuate considerably (Grabemann et al., 1990). The results from model simulation with altered freshwater discharge rates are presented in

FIGURE 7

Sensitivity to freshwater discharge rate, conditions on August 7, 1996.

Figure 7. It shows that the effect of freshwater discharge rate over the range used in the sensitivity runs is significant only in the first 10 km from river mouth. The chlorophyll concentration increases (decreases) as freshwater discharge increases (decreases).

Upstream Boundary Condition

The effect of incoming phytoplankton chlorophyll at upstream boundary was examined with two sensitivity runs: (1) chlorophyll 'a' concentration of 5 $\mu\text{g/l}$ entering the estuary from up-river; and (2) chlorophyll 'a' concentration of 15 $\mu\text{g/l}$. The chlorophyll 'a' distribution in Figure 8 shows that upstream boundary concentration has an important impact on the estuary. It indicates that the chlorophyll concentration increases all over the estuary with the incoming concentration increased at the up-river boundary. The transport through the estuary assumes an important role in the phytoplankton dynamics in the tidal Keelung River.

FIGURE 8

Sensitivity to upstream boundary condition, conditions on August 7, 1996.

FIGURE 9

Sensitivity to the present of salt, conditions on August 7, 1996.

Homogeneous River

Pennock (1985) suggested that the predominant physical factors regulating phytoplankton biomass were suspended sediment concentration, which primarily affected the spatial distribution of chlorophyll, and vertical stratification, which impacted both spatial and temporal variability in the Delaware estuary. In order to investigate the relationship between chlorophyll concentration and salinity distribution, a sensitivity run was conducted with absence of salt, i.e., assuming homogeneous river (note that the gravitational circulation no longer exists). Figure 9 shows that little impacts occur without including salinity distribution. The results suggest that temporal and spatial variations in chlorophyll concentration is not attributed to vertical stratification (salinity gradient) in the Keelung River.

CONCLUSIONS

Phytoplankton productivity in estuaries has been studied extensively because these systems are often very productive at the higher trophic levels that are of commercial importance. However, human populations in the drainage basins of estuaries produce anthropogenic nutrient inputs that enhance primary productivity and potentially impact water quality, threatening the commercial harvests. A time-dependent, laterally averaged, two-dimensional hydrodynamic and water quality model (HEM-2DT) was applied to the tidal reach of the Tanshui River system to simulate the phytoplankton dynamics, nutrient cycling and dissolved oxygen distribution. The water quality model, supplied with the information of physical transport processes from hydrodynamic model, provides real-time predictions of eight water quality state variables. The water quality model has been calibrated and verified using field data collected in the Keelung River at various seasons. Considering the random variability inherent to natural systems and the goal of consistency in calibrated coefficients, the agreement between model predictions and field observations is more than satisfactory.

The model sensitivity analysis provided further insight to the understanding of phytoplankton dynamics. The analysis revealed that chlorophyll distributions in the tidal Keelung River were controlled primarily by light availability. Although observed chlorophyll concentrations were high during the summer, they did not reach the nuisance levels of other eutrophic estuaries. The ability of the tidal Keelung River to receive high nutrient loads without displaying high phytoplankton growth similar to that which has been observed in other eutrophic systems is the water turbidity that limited the availability of light. Incoming phytoplankton from upriver boundary also has significant impact on the transport of chlorophyll throughout all over the tidal river.

ACKNOWLEDGMENTS

The study described in this paper was conducted as a part of the National Science Council, R.O.C., under grant NO. NSC 88-2611-E-002-036 and NSC 89-2213-E-002-075. The authors also thank the Taiwan Environmental Protection Administration for providing the prototype data.

REFERENCES

- Bannister, T. T., *Limnology and Oceanography*, 24, 76-96 (1979).
- Cadee, G. C., *Netherlands Journal of Sea Research*, 12, 368-381 (1978).
- Chung, W. S., "Water Quality Modeling and Risk Analysis of the Keelung River, Taiwan" Master Thesis, Graduate Institute of Civil Engineering, Nation Taiwan University, Taiwan (in Chinese) (1995).
- Cloern, J. E. and Cheng, R. T., *Estuarine, Coastal and Shelf Science*, 12, 83-100 (1981).
- Cloern, J. E., Arther, J. F., Ball, M. D., Cole, B. E., Wong, R. L. and Alpine, A. E., *Estuarine, Coastal and Shelf Science*, 16, 415-429 (1983).
- Cloern, J. E., *Continental Shelf Research*, 7, 1367-1381 (1987).

Eppley, R. W., Ed. T. Platt, In *Physiological Bases of Phytoplankton Ecology*, Canadian Journal of Fisheries and Aquatic Science, 210, 251-263 (1981).

Fisher, T. R., Harding, L. W., Stanley, D. W. and Ward, L. G., *Estuarine, Coastal and Shelf Science*, 27, 61-93 (1988).

Gieskes, W. W. C. and Kraay, G. W., *Netherlands Journal of Sea Research*, 9, 166-196 (1975).

Grabemann, I., Kuhle, H., Kunze, B., Muller, A. and Neumann, L. J. R., "Studies on the Distribution of Oxygen and Nutrients in the Weser Estuary" Ed. W. Michaelis, In *Estuarine Water Quality Management*, Springer-Verlag, Berlin (1990), pp. 341-344.

Haertel, L., Osterberg, C., Curl, H. Jr. and Kilho Park, P., *Ecology*, 50, 962-978 (1969).

Harding, L. W., Meeson, B. W. and Fisher, T. R., *Estuarine, Coastal and Shelf Science*, 23, 773-806 (1986).

Hsu, M. H., Kuo, A. Y., Kuo, J. T. and Liu, W. C., "Study of Tidal Characteristics Estuarine Circulation and Salinity Distribution in the Tanshui River System (1), (2)" Technical Report No. 239 and No. 273, Hydraulic Research Lab., National Taiwan University, Taipei, Taiwan (1996, 1997), 245pp.

Hsu, M. H., Kuo, A. Y., Kuo, J. T. and Liu, W. C., *J. Hydraulic Engrg., ASCE*, 125(2), 166-182 (1999).

Ketchum, B. H., *Ecology*, 35, 191-200 (1954).

Laws, E. A. and Bannister, T. T., *Limnology and Oceanography*, 25, 457-473 (1980).

Malone, T. C., Neale, P. J. and Boardman, D., "Influences of Estuarine Circulation on the Distribution and Biomass of Phytoplankton Size Fractions" Ed. V. S. Kennedy, In *Estuarine Perspectives*, Academic Press, London and Orlando (1980), pp. 249-262.

Martine, J. H., *Limnology and Oceanography*, 15, 413-418 (1970).

Nixon, S. W. and Pilson, M. E. Q., "Nitrogen in Estuarine and Coastal Marine Systems" Eds. E. J. Carpenter and D. G. Capone, In *Nitrogen in the Marine Environment*, Academic Press, London and Orlando (1983), pp. 65-102..

Parsons, T. R. Giovando, L. F. and LeBrasseur, R. J., *Journal of the Fisheries Board of Canada*, 23, 539-546 (1966).

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.

Pennock, J. R., *Estuarine, Coastal and Shelf Science*, 21, 711-725 (1985).

Riley, G. A., *Bulletin of Bingham Oceanographic Collection*, 13, 40-64 (1952).

Seliger, H. H., McKinley, K. R., Biggley, W. H., Rivkin, R. B. and Aspden, K. R. H., *Marine Biology*, 61, 119-131 (1981).

Smayda, T. J., "The Phytoplankton of Estuaries" Ed. B. H. Ketchum, In *Estuaries and Enclosed Seas*, Elsevier Scientific Publication Company (1983), pp. 65-102.

Taiwan, EPA, "Investigation Report of Tanshui River Water Pollution" (1992, 1996).

Thomann, R. V., *Journal of the Environmental Engineering Division, ASCE*, 108 (EE5), 923-940 (1982).

Tyler, M. A., Coates, D. W. and Anderson, D. M., *Marine Ecology Progress Series*, 7, 163-178 (1982).

Williams, R. B., "Annual Phytoplankton Production in a System of Shallow Temperature estuaries" Ed. H. Barnes, In *Some Contemporary Studies in Marine Science*, George Allen and Unwin, London (1966), pp. 699-716.

Williams, R. B., "Nutrient Levels and Phytoplankton Productivity in the Estuary" Ed. R. H. Chabreck, In *Proceedings of the Coastal Marsh and Estuary Management Symposium*, Louisiana State University Press, Louisiana (1972), pp. 59-89.

Wofsy, S. C., *Limnology and Oceanography*, 28, 1144-1155 (1983).

Received: September 16, 1999