Thammasat Int. J. Sc. Tech., Vol. 10, No. 1, January-March 2005

Hydrodynamic Modeling of Songkhla Lagoon, Thailand

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Abstract

Songkhla lagoon is a combined freshwater and estuarine complex of high productivity. At present, parts of the lagoon are undergoing rapid development which can have far reaching impact upon the ecology of the area. The effect of such changes should be recognized to protect the valuable environmental resources of the lagoon and its lagoonal basin. A mathematical model has been developed and successfully applied to the lagoon in order to describe the performance of water level and current. For the shallow water lagoon, the depth-averaged two-dimensional hydrodynamic model is applied. The alternating direction implicit (ADI) method is used to solve the partial differential equations. The model has been applied to study the flow characteristics - variation of water level, velocity, and current pattern for the whole of Songkhla lagoon.

Keywords: hydrodynamic modeling, Songkhla lagoon, alternating direction implicit (ADI), boundary types, Computational Grid Pattern.

1. Introduction

Songkhla lagoon is the largest lagoonal water resource in Thailand and Southeast Asia. It is located in the southern part of the country and surrounded by three provinces which are Songkhla, Phatthalung and Nakorn Si Thammarat. The total drainage basin area is 8,233 km^2, of which 1,042 km^2 is lagoon surface. The average depth of the lagoon is 1.2 to 1.8 m. It is a shallow coastal lagoon formed by interaction of land and ocean processes over geological time. The lagoon system consists of Thale Sap Songkhla, Thale Sap, Thale Luang and Thale Noi as shown in Fig. 1. The lower eastern side of Thale Sap Songkhla opens into the Gulf of Thailand allowing tides to propagate into the lagoon.

Due to population growth and rapid development, the natural resources of the lagoon have been overexploited. The effect of changes upon the ecology of the area concerned should be recognized to protect the valuable environmental resources of the lagoon and its lagoonal basin. A clear understanding of the process governing the hydrodynamics of the lagoon will help to carry out activities for sustainable development in the lagoon.

The objective of this study is to develop a mathematical model to describe the flow field in the lagoon. A depth-averaged two-dimensional hydrodynamic model is developed to determine the performance of water level and current patterns in the lagoon.

2. Materials and Methods

Governing Equations

The basic equations included in the hydrodynamic models are the conservation of fluid mass equation and momentum equations. The equations are first developed in three-dimension. By depth averaged integration, the equations are reduced into two-dimensional equations which are suitable for the shallow depth estuaries or lagoon when compares with long length of tide. The procedure of formulation is similar to Leendertse's procedure (1967). The alternating direction implicit (ADI) method is used to solve the partial differential

equations. The governing equations are shown as follows:
Continuity equation:

$$\frac{\partial(\eta)}{\partial t}+\frac{\partial\left[(h+\eta)U\right]}{\partial x}+\frac{\partial\left[(h+\eta)V\right]}{\partial y}=R_I \qquad (1)$$

Momentum equations in x and y directions:

$$\frac{\partial U}{\partial t}+\left(U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}\right)-fV+\left(g\frac{\partial \eta}{\partial x}\right)+A_h\nabla^2U+g\frac{U\sqrt{U^2+V^2}}{(h+\eta)C_z^2}-\frac{\rho' C_d W W_x}{(h+\eta)}=0 \qquad (2)$$

$$\frac{\partial V}{\partial t}+\left(U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}\right)+fU+\left(g\frac{\partial \eta}{\partial y}\right)+A_h\nabla^2V+g\frac{V\sqrt{U^2+V^2}}{(h+\eta)C_z^2}-\frac{\rho' C_d W W_y}{(h+\eta)}=0 \qquad (3)$$

$$U=\frac{1}{(h+\eta)}\int_{-h}^{\eta}u\,dz \qquad (4)$$

$$V=\frac{1}{(h+\eta)}\int_{-h}^{\eta}v\,dz \qquad (5)$$

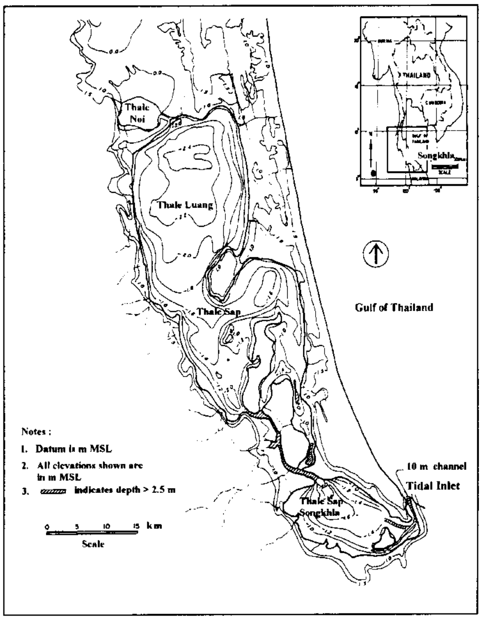

Fig. 1 Songkhla Lagoon System

where

U and V= depth-averaged velocity in x and y directions
h = mean water depth (see Fig. 2)
η = water surface elevation above or below mean depth
f = Coriolis parameter
= $2\Omega\sin\phi$
Ω = angular rotational velocity of earth
ϕ = latitude of interested position
p = average pressure
g = gravitational acceleration
A_h = horizontal eddy viscosity
= $-\alpha\frac{(\Delta x)^2}{2\Delta t}$
α = averaging factor
Δx = spatial increment in x direction
Δt = temporal increment
∇^2 = Laplacian operator = $\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$
C_z = Chezy coefficient
= $\frac{h^{1/6}}{n}$
n = Manning's roughness coefficient
ρ' = ratio of air to water density
C_d = wind resistant coefficient
= $(1.1 + 0.0536W)\times10^{-3}$
W, W_x, W_y = absolute wind velocity in m/s and corresponding components in x and y directions
R_I = rainfall intensity

Model Setup

The Songkhla lagoon has a surface area of approximately 1,042 km^2 and depth of about 1.2-1.8 m. There are 8 major canals draining water into the lagoon, namely Khlong Pa Phayom, Khlong Tha Nae, Khlong Na Thom, Khlong Tha Madua, Khlong Pa Bon, Khlong Phru Pho, Khlong Rattaphum and Khlong U-taphao. In addition, there is a swamp in the northern part, Khru Khruan Kreang. Fig. 3 shows the delineation of sub-catchments in the study area.

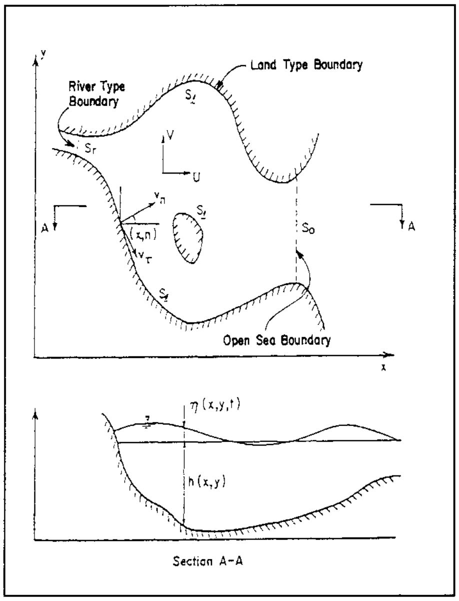

Fig. 2 Boundary Types in Hydrodynamic Model

The area covered for modeling is the entire lagoon; 55 x 76 km with 55 x 76 grids. Since the accuracy of computed results depends on the computing grid, the grid should be fine enough to represent variation of shoreline configuration and yield accurate result. However, small grid sizes will need more computational time. Considering the layout constraints and computational time, the grid size is fixed at $\Delta x = \Delta y = 1000$ m. The time increment is determined to satisfy Courant stability criterion. Fig. 4 shows the computational grid pattern for the lagoon. The depth averaged two-dimensional hydrodynamic model is developed to describe the current and flow pattern in the lagoon.

Daily flows of each sub-catchment, obtained from the NAM model, are used as input data at the river boundary in the model. Hourly tide at the tidal inlet, recorded by the Hydrographic Department, is used as the open sea boundary condition. Hourly water levels at gauging stations located throughout the lagoon are used to compare with the simulated results. Hourly flow current and tide at the tidal inlet and the middle point of the lagoon, which were measured in 1976 and 1977, are used to compare with the simulated results in Thale Sap Songkhla.

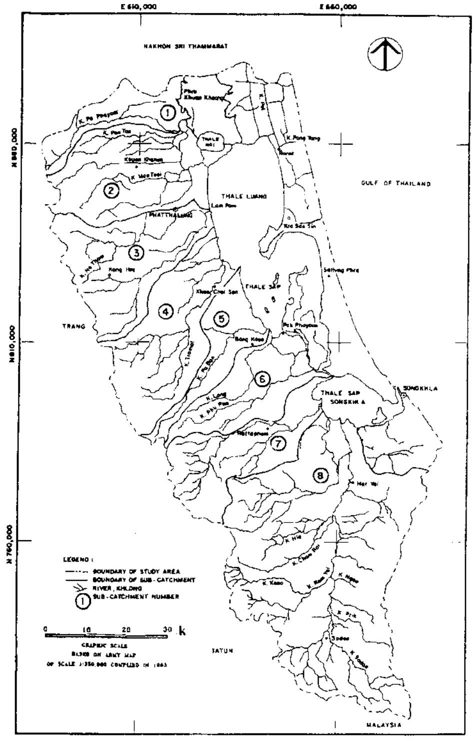

Fig. 3 Schematisation of Catchment System in the Study Area

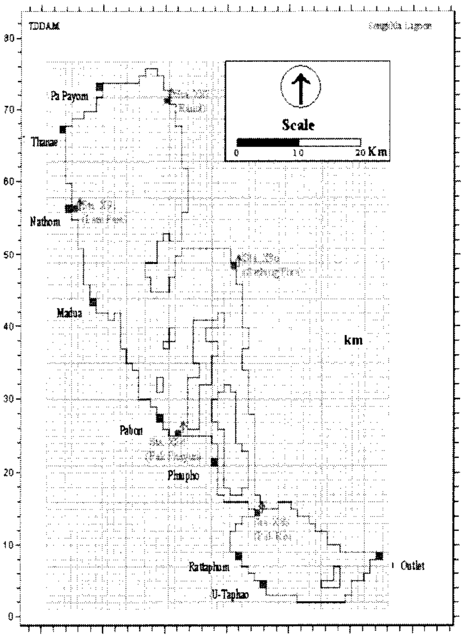

Fig. 4 Computational Grid Pattern

3. Model Calibration and Verification

Calibration

In the calibration of the developed hydrodynamic model, values of hourly water level at open sea and river boundaries are used as input. In the study, comparisons of model calibration results were done in 1977 for current. There are also measurements of currents in Thale Sap Songkhla and for water level in the recent year 1991. The model was first calibrated using 1991 data for the upper part of the lagoon. There are five gauging stations in the upper part of the lagoon which measure water level, namely X.84, X.86, X.87 X.88 and X.91, as shown in Fig. 4. The model was then calibrated for the water level and velocity in the lower part of the lagoon. There are twelve gauging stations in the lower part of the lagoon, as shown in Fig. 5, out of which seven stations, Station B (Pak Ro), Ban Cha Ting Mo, Station A (Tidal Inlet), Sta. 12, Sta. 10, Sta. 9, and Sta. 8, have been selected for model calibration.

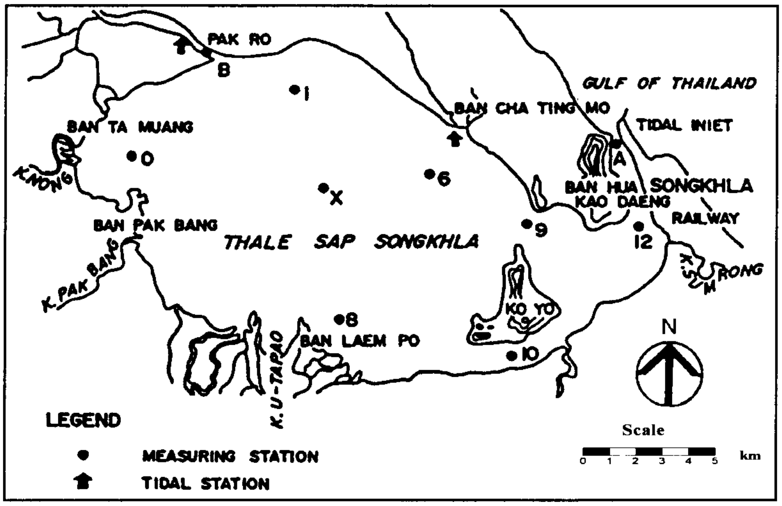

Fig. 5 Location of Gauging Stations in the Lower Songkhla Lagoon

For the upper part of the lagoon, Manning's roughness coefficients in the range of 0.013 to 0.035 were inputs to the model. The simulated water level were compared with the obtained water level in 1991 at gauging stations in the upper part of the lagoon, as shown in Fig. 6. Suitable values for Manning's roughness coefficient for different reaches of the lagoon have been arrived at by considering the comparison of water level at relevant stations. Table 1 presents the Manning's roughness coefficients at different sub-systems of the lagoon.

Accuracy of model simulation is given by the measure of simulation error, that is, the difference between the simulated value and the value that actually occurs. In the study, root mean square error (RMSE), correlation coefficient (r) and efficiency index (EI) are used to measure simulation error. RMSE tends to be zero for perfect agreement. The measure of the strength of linear relationship between two

Table. 1 Manning's Roughness Coefficients in the Upper Part of the Lagoon

Sub-system	Manning's roughness	Relevant Station
Thale Luang	0.020	Sta. X.91 (Lam Pam)
Middle Thale Sap	0.020	Sta. X.84 (Pak Phayun)
Ao Thong Ban	0.035	Sta. X.86 (Sating Phra)
Khlong Luang	0.020	Sta. X.88 (Pak Ro)

variables is given by the correlation coefficient, r, when r >0, there is a positive correlation; when r < 0, there is a negative correlation; and when r = 0 there is no linear correlation. EI is commonly used for measurement of the degree of association between simulated and observed values. The value of this coefficient approaches 1 for perfect agreement. If EI is greater than 0.7, the model is acceptable. The statistical evaluations of water level at different stations are presented in Table 2.

Table. 2 Statistical Evaluations of Model Calibration in the Upper Part of the Lagoon

Item	Water Level				
	Sta.X87	Sta.X91	Sta.X86	Sta.X84	Sta.X88
RMSE (m)	0.04	0.05	0.09	0.07	0.06
r	0.97	0.97	0.95	0.93	0.93
EI	0.97	0.97	0.86	0.91	0.93

It can be seen in Table 2 that the values of RMSE of water levels vary from 0.04 to 0.09 m. Values of correlation coefficient, r, and efficiency index, EI, vary from 0.93 to 0.97 and 0.86 to 0.97 respectively. The statistical evaluations of model calibration in the upper part of the lagoon is acceptable.

Manning's roughness coefficients in the range of 0.013 to 0.030 were selected to calibrate the model for the lower part of the lagoon. The simulated water level and velocity results were compared with the observed values in April 1977. Best agreement was obtained when a Manning's roughness coefficient value of 0.013 was used, as shown in Fig. 7. The statistical evaluations of calibration for the lower part of the lagoon are presented in Table 3.

Table. 3 Statistical Evaluations of Model Calibration in the Lower Part of the Lagoon

Item	Water Level	
	Sta. B (Pak Ro)	Ban Cha Ting Mo
RMSE (m)	0.02	0.03
r	0.80	0.86
EI	0.85	0.71
Item	Velocity	
	Sta. B (Pak Ro)	Sta.A (Tidal Inlet)
RMSE (m/s)	0.18	0.21
r	0.88	0.96
EI	0.71	0.85

Values in Table 3 show a low range of RMSE (0.02-0.21), high correlation coefficient (0.80-0.96), and efficiency index (0.71-0.85), all in the acceptable range. The calibrated Manning's roughness coefficients are used to represent the roughness of Songkhla lagoon as shown in Fig. 8.

Verification

Manning's roughness coefficients obtained from model calibration were used to validate the model. The model verification was conducted for the wet year 1994 after the calibration for the upper part of the lagoon. Comparisons of simulated and observed water levels in 1994 are plotted in Fig.9. Table 4 shows statistical evaluations of model verification of water level.

Table. 4 Statistical Evaluations of Model Verification in the Upper Part of the Lagoon

Item	Water Level				
	Sta.X87	Sta.X91	Sta.X86	Sta.X84	Sta.X88
RMSE (m)	0.09	0.06	0.07	0.11	0.08
r	0.98	0.97	0.96	0.95	0.74
EI	0.93	0.97	0.96	0.92	0.70

For the lower part of the lagoon, the model verification for current is conducted for the year 1976. Comparisons of simulated and observed velocity are shown in Fig. 10. The statistical evaluations of model verification for lower Songkhla lagoon are presented in Table 5.

Table. 5 Statistical Evaluation of Model Verification in the Lower Part of the Lagoon

Item	Water Level	
	Sta. B (Pak Ro)	Ban Cha Ting Mo
RMSE (m)	0.07	0.07
r	0.95	0.89
EI	0.68	0.74
Item	Velocity	
	Sta. B (Pak Ro)	Sta. A (Tidal Inlet)
RMSE (m/s)	0.28	0.42
r	0.97	0.88
EI	0.61	0.45

As can be seen from the values in Tables 4 and 5 the results of model verification provide similarly good performance as those of model calibration. Therefore, the calibrated Manning's roughness coefficients can represent the flow characteristic of the Songkhla lagoon.

4. Illustrative Application

The model is applied to study the flow characteristics of the study area such as water level, velocity and current pattern. Daily flow of each sub-catchment which is obtained from NAM model is input data of the model. Hourly tide at the tidal inlet is used as the open sea boundary condition. The simulation period of the model is one month, in April 2001, representing the dry season and one month, in December 2001, for the wet season scenario. The simulation results of the model are the water level, velocity and current pattern in the study area as shown in Figs. 11 to 14. It is found that the velocity is very small (< 0.01 m/s) in the upper part of the lagoon, Thale Luang. While the velocity in the lower part, Thale Sap Songkhla, is in the range of 0.01 to 0.10 m/s. The high velocity occurring at the tidal inlet is in the range of 0.40 to 0.60 m/s. At the tidal inlet, there is outflow in the low tide period and inflow in the high tide period in both dry and wet seasons. While at the connecting canal between Thale Sap and Thale Sap Songkhla, Ban Pak Ro, the inflow occurs through Thale Sap Songkhla corresponding to the upstream discharge of the lagoon. However, a reversed flow sometime occurs due to the high tide effect. The velocity at Ban Pak Ro is in the range of 0.1 to 0.2 m/s in the dry season and 0.2 to 0.4 m/s in the wet season.

Hydrodynamic models usually function as platforms for a large number of applications. The values of water level and velocity from the developed hydrodynamic model can be input for saline intrusion models, sediment transport models or flood control models for further study.

5. Conclusions

A depth-averaged two-dimensional hydrodynamic model was developed to describe the flow field in Songkhla lagoon, a shallow coastal lagoon, in order to study the characteristics of the lagoon such as water level, velocity and current patterns. Calibrated Manning's roughness coefficients are in the range of 0.013 to 0.035. The model was verified and showed satisfactory results. The results show that the model can represent the flow characteristic of the whole Songkhla lagoon. The current in Thale Luang is very small. At Ban Pak Ro, inflow occurs through Thale Sap Songkhla. While at the tidal inlet there is inflow and outflow due to tidal effect. Also, the model can be further applied to various studies such as saline intrusion, sediment transport or flood control structures for determining the effects on the flow characteristics of Songkhla lagoon.

6. References

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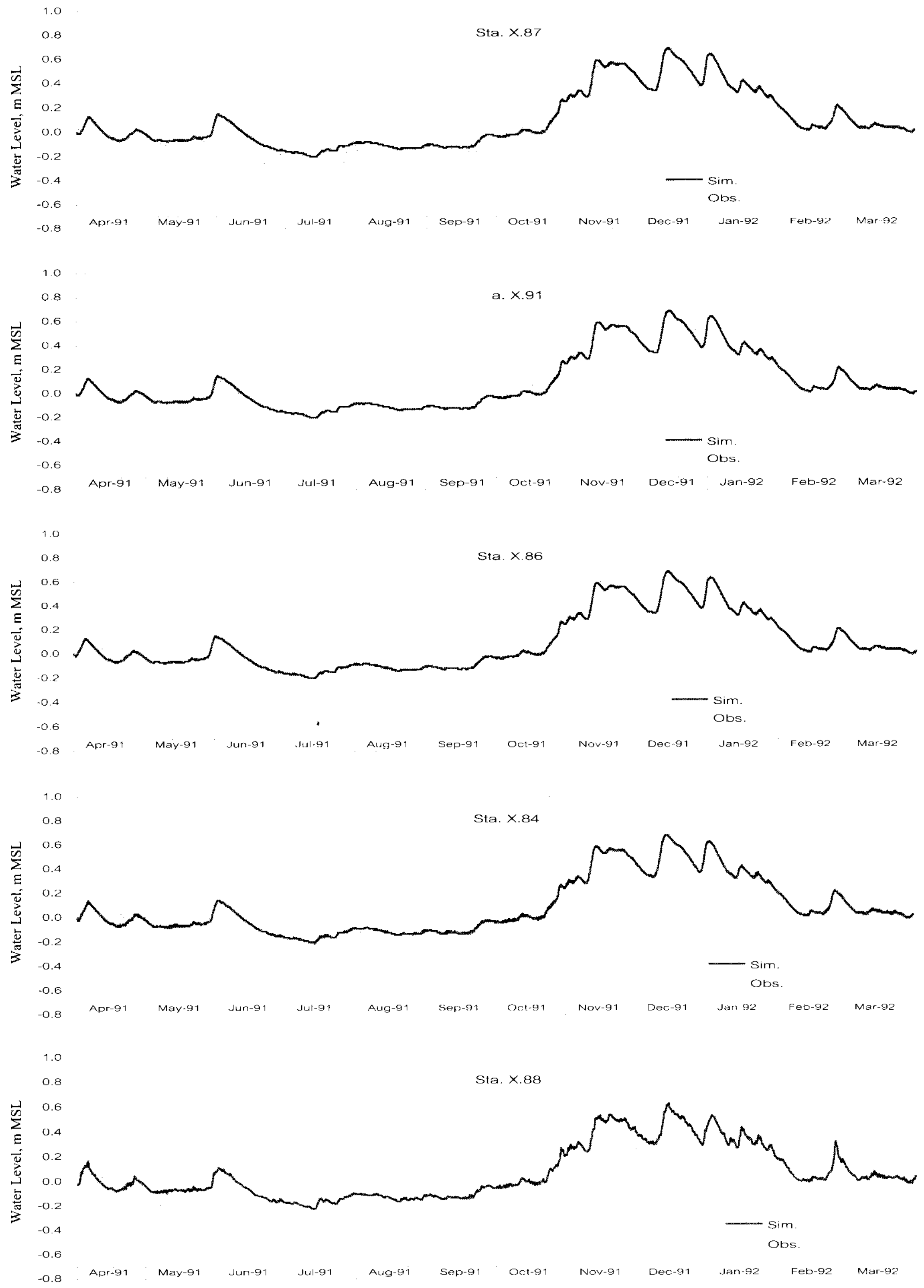

Fig. 6 Comparison between Simulated and Observed Water Level for Model Calibration in 1991

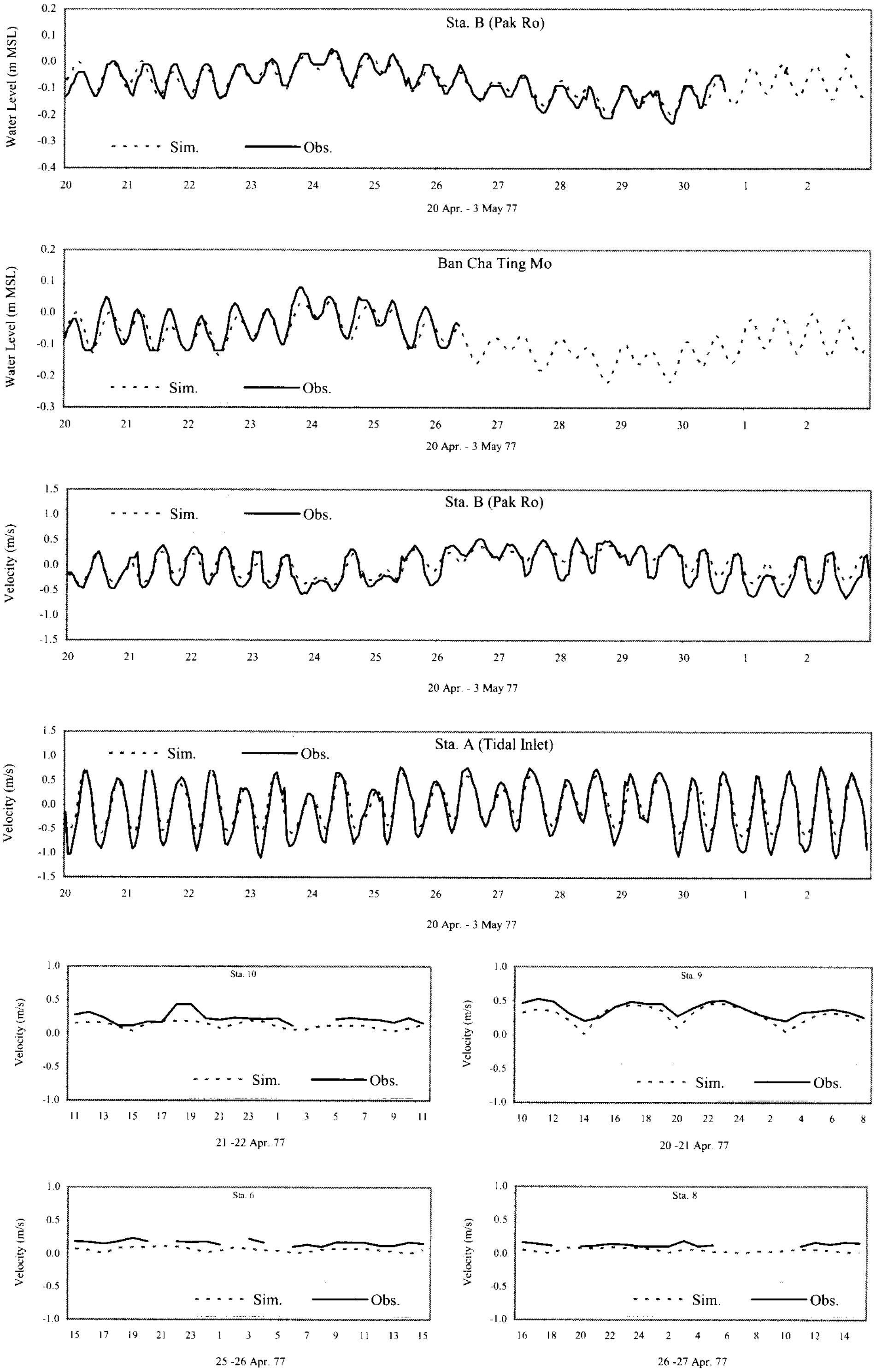

Fig. 7 Comparison between Simulated and Observed Water Level and Velocity for Model Calibration in 1977

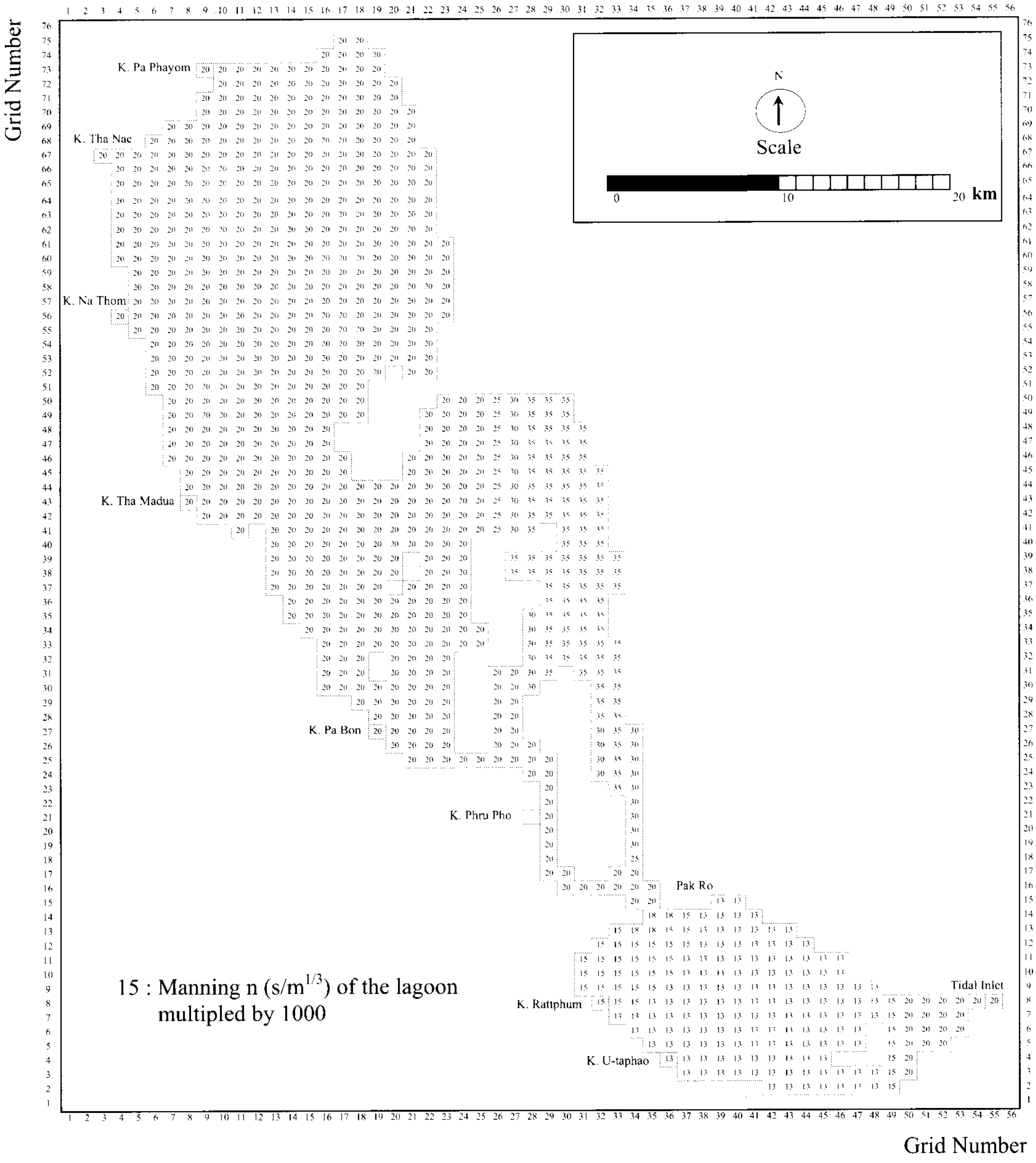

Fig. 8 Calibrated Manning's Roughness Coefficient

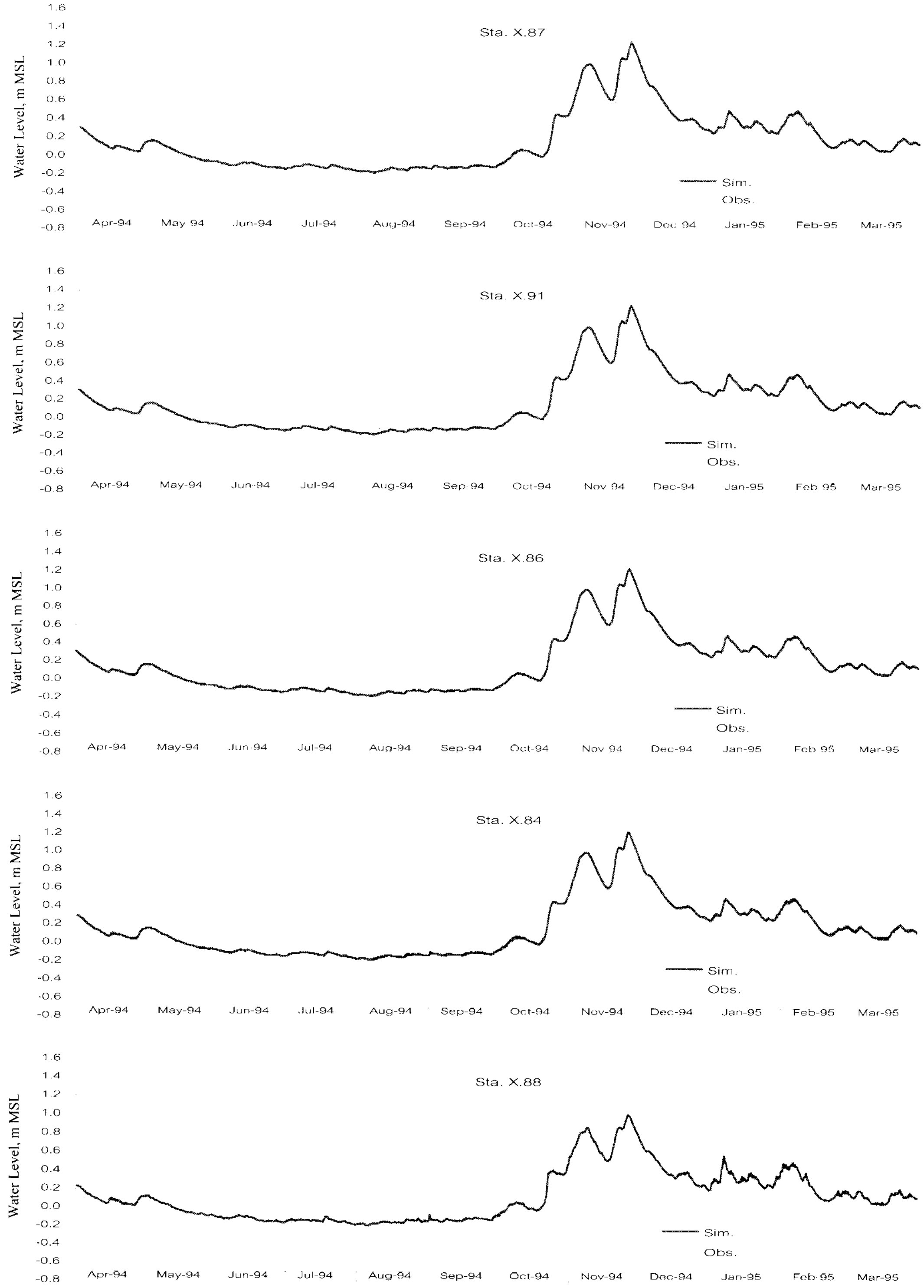

Fig. 9 Comparison between Simulated and Observed Water Level for Model Verification in 1994

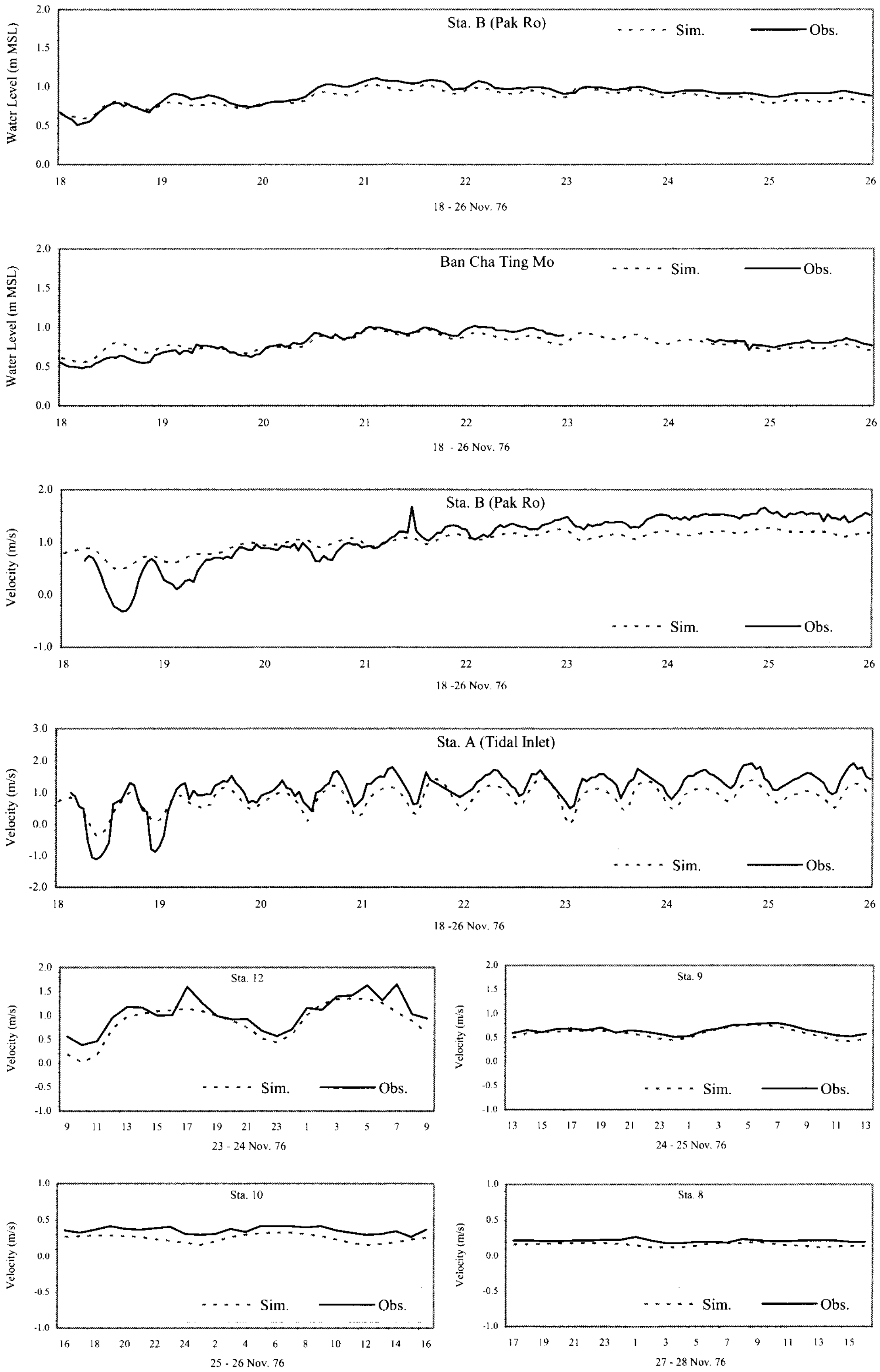

Fig. 10 Comparison between Simulated and Observed Water Level and Velocity for Model Verification in 1976

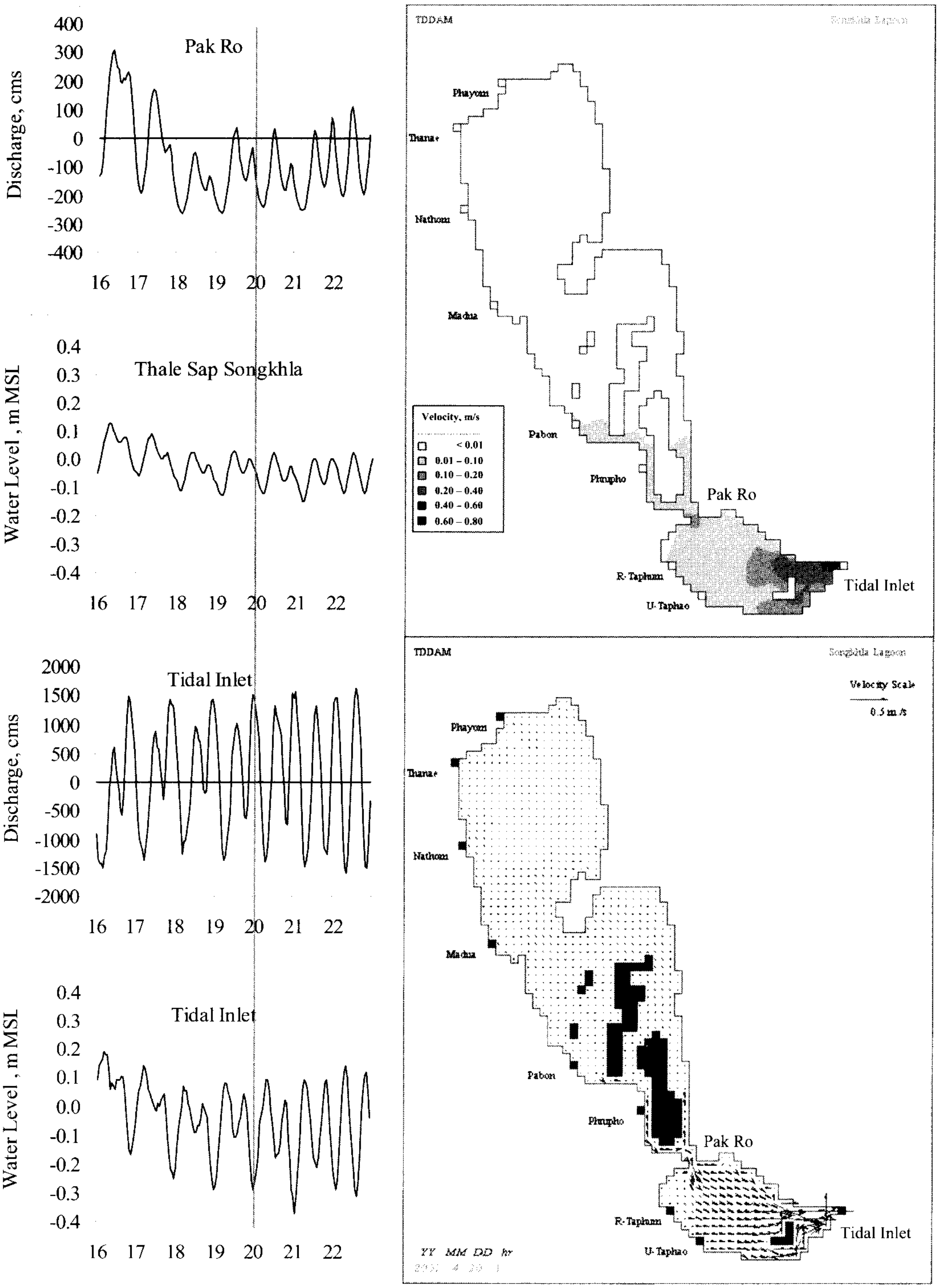

Fig. 11 Simulated Results of Velocity Pattern in Dry Season at Low Tide

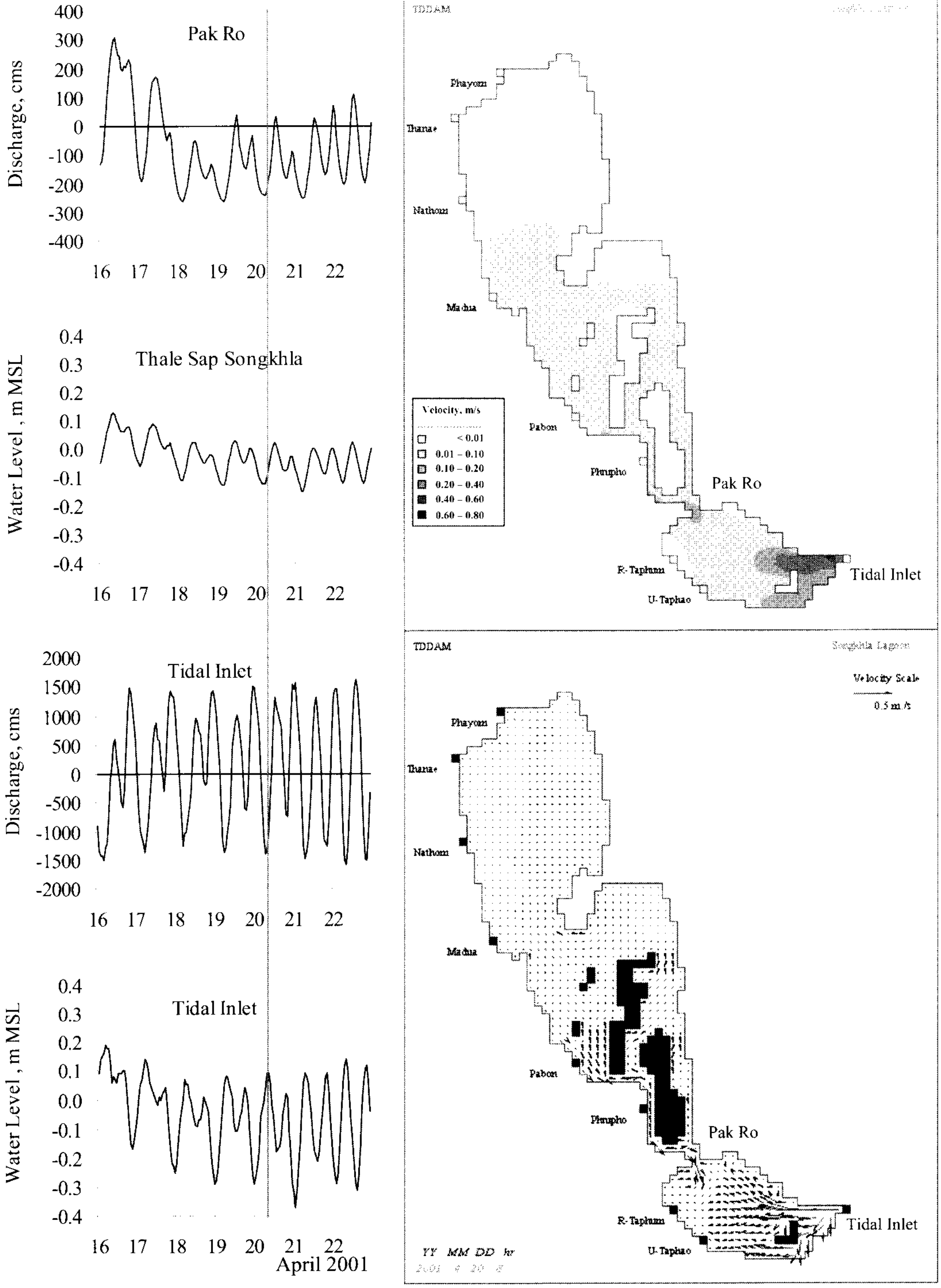

Fig. 12 Simulated Results of Velocity Pattern in Dry Season at High Tide

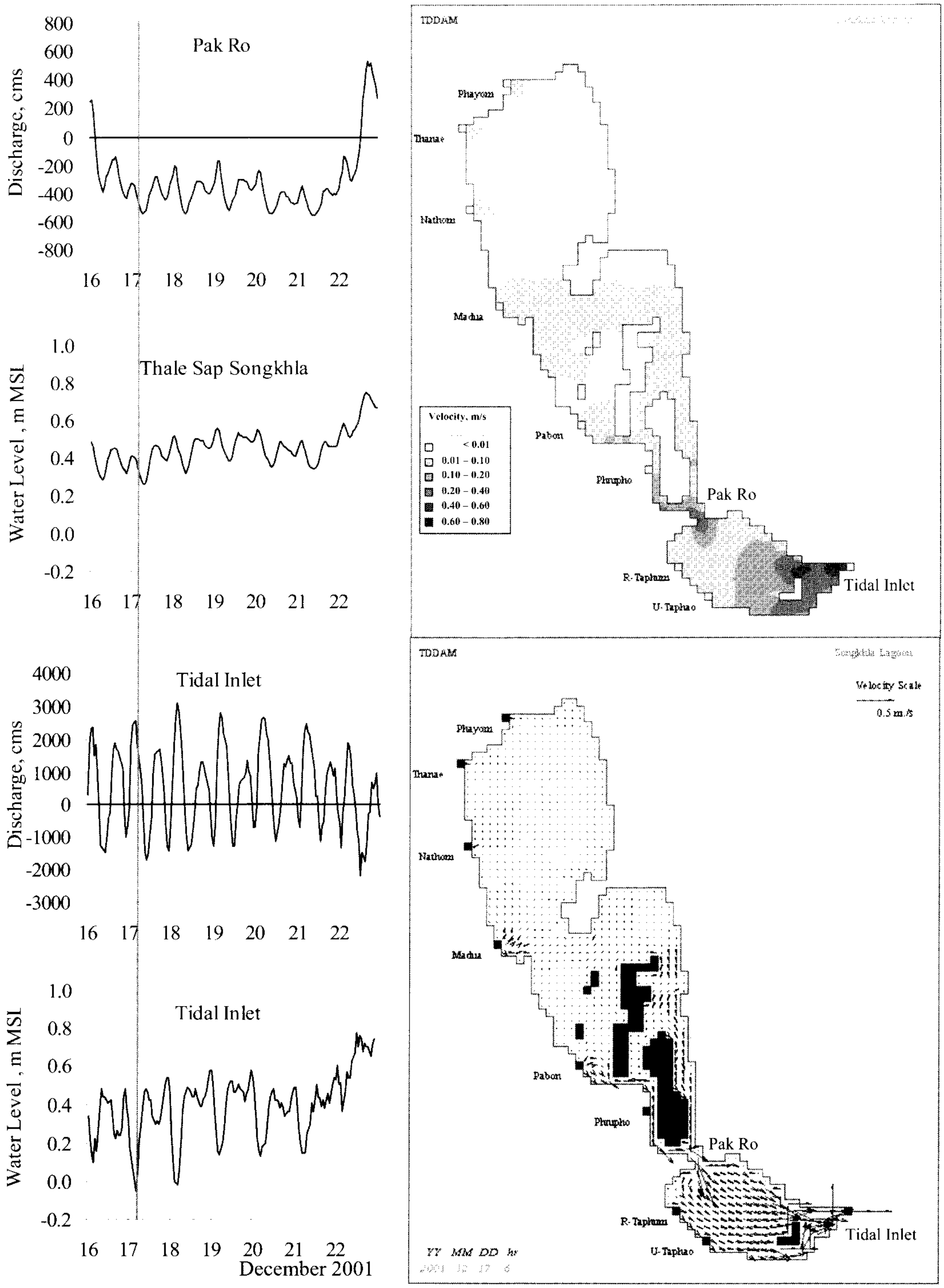

Fig. 13 Simulated Results of Velocity Pattern in Wet Season at Low Tide

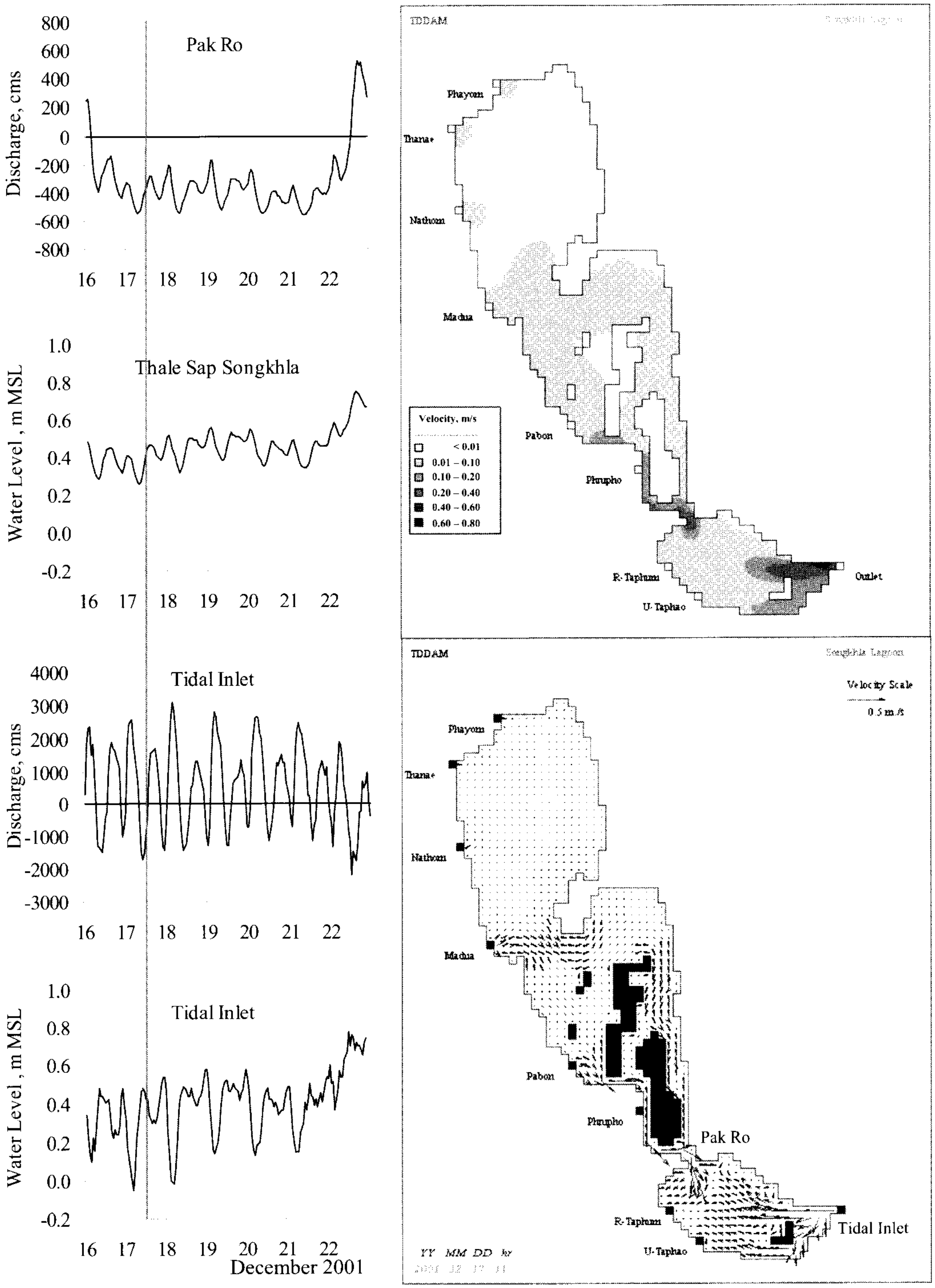

Fig. 14 Simulated Results of Velocity Pattern in Wet Season at High Tide