



Original Article

Interaction of tide and salinity barrier: Limitation of numerical model

Suphat Vongvisessomjai^{1*}, Phairot Chatanantavet² and Patchanok Srivihok¹

¹ TEAM Consulting Engineering and Management Co., Ltd.,
151 TEAM Building, Nuan Chan Road, Klong Kum, Bueng Kum, Bangkok, 10230 Thailand.

² St Anthony Falls Laboratory, University of Minnesota, Minneapolis, Minnesota, 55414 USA.

Received 27 September 2007; Accepted 31 July 2008

Abstract

Nowadays, the study of interaction of the tide and the salinity barrier in an estuarine area is usually accomplished via numerical modeling, due to the speed and convenience of modern computers. However, numerical models provide little insight with respect to the fundamental physical mechanisms involved. In this study, it is found that all existing numerical models work satisfactorily when the barrier is located at some distance far from upstream and downstream boundary conditions. Results are considerably underestimate reality when the barrier is located near the downstream boundary, usually the river mouth. Meanwhile, this analytical model provides satisfactory output for all scenarios. The main problem of the numerical model is that the effects of barrier construction in creation of reflected tide are neglected when specifying the downstream boundary conditions; the use of the boundary condition before construction of the barrier which are significantly different from those after the barrier construction would result in an error outputs. Future numerical models should attempt to account for this deficiency; otherwise, using this analytical model is another choice.

Keywords: analytical model, numerical model, salinity barrier, tide reflection

1. Introduction

The salinity barrier is a kind of estuarine structure constructed for protecting the salinity intrusion and storing freshwater during low river discharges and also preventing flooding during flood tides and high storm surges from the sea. However, the construction of a barrier at the river mouth or inside the river may result in amplification of the tide due to the creation of a reflected tide at the barrier. This reflected tide and incident tide become a standing tide which creates two major problems; the overspill of saline water during high water, and bank erosion during low water along the tidal reach downstream of the barrier.

Presently, due to the advanced state of computer technology, numerical models play a vital role hydraulic engineering studies. Tidal propagation in estuaries can be

simulated using numerical models or experiment methods. While in some cases, these methods have produced quite accurate predictions, the results provide little insight with respect to the fundamental mechanisms. For instance, in certain estuaries tidal barriers may produce an increase in tidal range but, in another estuary, a decrease may result. In some cases, within the same estuary, a tidal barrier may give an augmentation in the tidal range at the barrier site but a decrease happens further downstream. It was observed that the change in tidal range for a particular barrier location may be significantly affected by the position of the downstream boundary. There is no general theory to explain these diverse results. It is still not clear why tides are considerably amplified in certain estuaries yet quickly dissipated in others (Rahman, 1988). However, it appears that in the vicinity of a barrier site the tidal range is always increased approximately twice as much as before.

In part 3 of this paper, the analytical model for the interaction of the tide and the salinity barrier is developed as

*Corresponding author.
Email address: suphat@team.co.th

we investigate the equations for calculating the water surface fluctuation and tidal discharge as a function of distance and time. With this model, two cases are considered; fully closed gate, and a partially closed gate. In part 4, the limitations of the numerical model are outlined while the strengths of the analytical model are highlighted. Further, in part 4, the analytical model is applied to the case study of a proposed barrier in the Tha Chin River. The previous studies of the interaction between the tide and the salinity barrier in the Bang Pakong River by Vongvisessomjai and Srivihok (2003) and in the Bang Nara River by Vongvisessomjai *et al.* (2003) are also discussed. The objective of this work was to develop an analytical model for purpose of obtaining a better understanding of the underlying physical mechanisms responsible for the tidal barrier phenomenon. Further, by comparing results of the analytical model with previous results obtained by numerical models are highlighted. It is strongly recommended that the analytical model is used in future studies predicting the hydrodynamic characteristics of tidal barriers.

2. Theoretical Considerations

2.1 Governing equations

The unsteady one-dimensional equation of continuity and the equation of motion are used to describe the interaction of tide and river flow; taking into account the convective inertial force and the bottom frictional force. A coordinate system is adopted so that the x -axis is horizontal along the still water level (SWL), the origin represents the river mouth, and the upstream direction is positive. The z -axis is perpendicular to x -axis with its origin at SWL and is positive above the origin. If there is no lateral inflow, the continuity equation can be written in the form as follows:

$$\frac{\partial \eta}{\partial t} + u S_b + u \frac{\partial \eta}{\partial x} + (h + \eta) \frac{\partial u}{\partial x} = 0 \quad (1)$$

in which η is the instantaneous displacement of water surface above the mean water level, u is the instantaneous flow velocity, h is the water depth, and S_b is the bed slope of the reach.

After applying the Newton's law of motion to one-dimensional flow through an element of water, the equation of motion can be written as follows:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial \eta}{\partial x} + g S_f = 0 \quad (2)$$

in which the flow velocity in the river, u , is made up of a steady component, u_0 , created by the discharge of the freshwater and of a time-dependent component, $u(x, t)$, contributed by tide, and g is the gravitational acceleration. The frictional slope, S_f , for unsteady flow, in this case, is assumed to have the same form as the steady flow case and therefore can be evaluated from the Chezy's equation as:

$$S_f = \frac{u|u|}{C_z^2 (h + \eta)} \quad (3)$$

in which C_z is Chezy's coefficient.

2.2 Harmonic analysis of tide

Because the tide is composed of various components which interact simultaneously with the river flow, the resulting records of water levels in the river show rather complicated patterns. The interaction of each individual component of tide in each month is obtained by the harmonic analysis of the hourly water levels. The characteristics of the tide can then be correlated with the river flow. Four predominant constituents of the tide are analyzed for their characteristics as follows:

1. Principal lunar, M_2 , with a period of 12.4206 hours
2. Principal solar, S_2 , with a period of 12.0000 hours
3. Luni-solar declinational, K_1 , with a period of 23.9346 hours
4. Large lunar declinational, O_1 , with a period of 25.8194 hours

The formula of the harmonic analysis of tide is as follows:

$$\eta_r(t) = \Delta h + \sum_{i=1}^N a_i \sin \left[\frac{2\pi t}{T_i} + \delta_i \right] \quad (4)$$

in which $\eta_r(t)$ is the resultant tide recorded as a function of time t at a particular location and it is composed of N constituents. The periods T_i of the i -constituents are known from the astronomical computations. The mean water level Δh , the amplitudes a_i , and phases δ_i are easily calculated from discrete hourly water level measurements, η_r .

2.3 Analytical description of tide with linear frictional force

Ippen and Harleman (1966) investigated analytically the characteristics of damped tides with linear frictional forces. Their useful expressions are summarized as follows:

Water surface fluctuation:

$$\eta(x, t) = a(x) \cos(\sigma t - kx) = a_0 \exp(-\mu x) \cos(\sigma t - kx) \quad (5)$$

Tidal velocity:

$$u(x, t) = \frac{a_0}{h} c_0 \exp(-\mu x) \frac{k_0}{\sqrt{\mu^2 + k^2}} \cos(\sigma t - kx + \alpha) \quad (6)$$

$$c_0 = \sqrt{gh} = L_0/T = \sigma/k_0 \quad (7)$$

and the phase angle:

$$\alpha = \tan^{-1}(\mu/k) \quad (8)$$

in which a_0 is the amplitude of tide at the river mouth, μ is the damping modulus, $\sigma = 2\pi/T$ is the angular velocity, T is the period of tide, $k = 2\pi/L$ is the tide number, L is the length of tide, $k_0 = 2\pi/L_0$ is the tide number at the river mouth, L_0 is the length of tide at the river mouth, and c_0 is the frictionless celerity.

3. Analytical Model

The analytical model in this study has been developed from many sources, including: the theory of harmonic analysis, the analytical description of tide with linear frictional force from Ippen and Harleman (1966), the theoretical investigation of phase angle difference between tides and tidal discharge, and the analytical results from Vongvisessomjai and Rojanakamthorn (1989) and Vongvisessomjai and Chatanantavet (2006), in which the perturbation method was used to determine the interaction of the tide and the river flow, taking into account the nonlinear convective inertia and bottom friction. The model of the interaction of the tide and the salinity barrier can be classified into two cases; a) the fully closed gate case and b) the partially closed gate case. In the case of partially closed operation, some amount of the discharge is allowed to flow through regulating gates.

a) In the case of the fully closed gate;

The resultant water surface fluctuation η_r is defined as below:

$$\eta_r(x, t) = \Delta h_0 + \sum \eta_{incident} + \sum \eta_{reflected} \quad (9)$$

$$\sum \eta_{incident} = \sum_{i=1}^N a_{oi} e^{-\mu_i x} \cos \left[\frac{2\pi t}{T_i} - k_i x + \delta_{oi} - \frac{\pi}{2} \right] \quad (10)$$

$$\sum \eta_{reflected} = \sum_{i=1}^N (a_{oi} e^{-\mu_i (2x_b - x)}) \cos \left[\frac{2\pi t}{T_i} - k_i (2x_b - x) + \delta_{oi} - \frac{\pi}{2} \right] \quad (11)$$

Also, consider the continuity equation (1) in the following simplified form:

$$\frac{\partial \eta}{\partial t} = -h \frac{\partial u}{\partial x} \quad (12)$$

Equations (9) to (11) are used to determine the expression for the tidal velocity or tidal discharge from the above continuity equation. At first, the water level fluctuation equations are differentiated with respect to time, t . After that, integrating the result with respect to distance, x , yields the tidal velocity. After multiply by the effective cross-sectional area A_e , the resultant tidal discharge, Q_r , is found as follows:

$$Q_r(x, t) = \sum Q_{incident} + \sum Q_{reflected} \quad (13)$$

$$\sum Q_{incident} = A_e \sum_{i=1}^N \frac{a_{oi}}{h} c_0 e^{-\mu_i x} \frac{k_{oi}}{\sqrt{\mu_i^2 + k_i^2}} \cos \left(\frac{2\pi t}{T_i} - k_i x + \alpha_{oi} - \frac{\pi}{2} \right) \quad (14)$$

$$\sum Q_{reflected} = -A_e \sum_{i=1}^N \frac{a_{oi}}{h} c_0 e^{-\mu_i (2x_b - x)} \frac{k_{oi}}{\sqrt{\mu_i^2 + k_i^2}} \cos \left(\frac{2\pi t}{T_i} - k_i (2x_b - x) + \alpha_{oi} - \frac{\pi}{2} \right) \quad (15)$$

b) In the case of the partially closed gate;

The resultant water surface fluctuation is defined as below:

$$\eta_r(x, t) = (S_{f0} x + \Delta h_0) + \sum \eta_{incident} + \sum \eta_{reflected} \quad (16)$$

$$\sum \eta_{incident} = \sum_{i=1}^N a_{oi} e^{-\mu_i x} \cos \left[\frac{2\pi t}{T_i} - k_i x + \delta_{oi} - \frac{\pi}{2} \right] \quad (17)$$

$$\sum \eta_{reflected} = \sum_{i=1}^N (a_{oi} e^{-\mu_i x_b} e^{-\mu_i (2x_b - x)}) \cos \left[\frac{2\pi t}{T_i} - k_i x_b - k_i (2x_b - x) + \delta_{oi} - \frac{\pi}{2} \right] \quad (18)$$

The resultant tidal discharge, similar to the case of the fully closed gate, is computed from

$$Q_r(x, t) = Q_f + \sum Q_{incident} + \sum Q_{reflected} \quad (19)$$

$$\sum Q_{incident} = A_e \sum_{i=1}^N \frac{a_{oi}}{h} c_0 e^{-\mu_i x} \frac{k_{oi}}{\sqrt{\mu_i^2 + k_i^2}} \cos \left(\frac{2\pi t}{T_i} - k_i x + \alpha_{oi} - \frac{\pi}{2} \right) \quad (20)$$

$$\sum Q_{reflected} = -A_e \sum_{i=1}^N \frac{a_{oi}}{h} c_0 e^{-\mu_i x_b} e^{-\mu_i (2x_b - x)} \frac{k_{oi}}{\sqrt{\mu_i^2 + k_i^2}} \cos \left(\frac{2\pi t}{T_i} - k_i x_b - k_i (2x_b - x) + \alpha_{oi} - \frac{\pi}{2} \right) \quad (21)$$

in which Δh_0 is the mean water level at the estuary, x_b is the distance from the river mouth to the location of the barrier site, and S_{f0} is the zeroth order form of the frictional slope (Vongvisessomjai and Rojanakamthorn, 1989) defined as below:

$$\eta_0 = -S_{f0} x$$

$$S_{f0} = \frac{-u_0^2}{[C_z^2 (h + \eta_0)]}$$

in which η_0 is the zeroth order solution of the mean water level (Vongvisessomjai and Rojanakamthorn, 1989), $Q_f = A_e u_0$ is the freshwater discharge, δ_{oi} is the phases δ_i at the river mouth obtained from the harmonic analysis of the tide, Eq(4), and α_{oi} is the phase angles α_i of tidal discharge or velocity, Eq(8), at the river mouth. For the case of partially closed operation, the incident tide amplitude and celerity are damped by the released discharge from the salinity barrier including the bottom friction, while, the reflected tide is damped by only the bottom friction during traveling back to the river mouth. The parameters, μ and k , represent the tide amplitude damping modulus and tide number computed from the released freshwater discharge from upstream together with bed resistance, while the parameters, μ_r and k_r , represent the reflected tide amplitude damping modulus and tide number accounting for only effect of bed resistance.

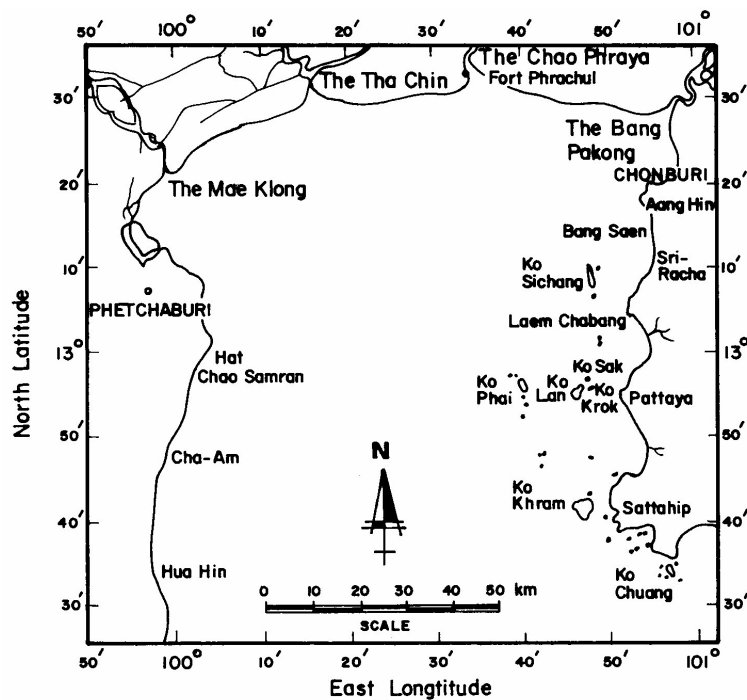


Figure 1. The Upper Gulf of Thailand and four important rivers draining into it.



Figure 2. The Tha Chin River and the proposed barrier site.

4. Numerical Model versus Analytical Model and Discussion

In this part, the analytical model from the previous part 3 is applied to the Tha Chin River, one of four important rivers draining into the Upper Gulf of Thailand, as shown in Figure 1. The results from the analytical model are then

compared with results from the numerical model. Recently, it was proposed to construct the barrier approximately 15 km from the river mouth for the Tha Chin River in order to alleviate the salinity intrusion problem for the provision of freshwater for the irrigation projects. The river and the location of the proposed barrier site are shown in the Figure 2. However, this project was eventually abandoned during the

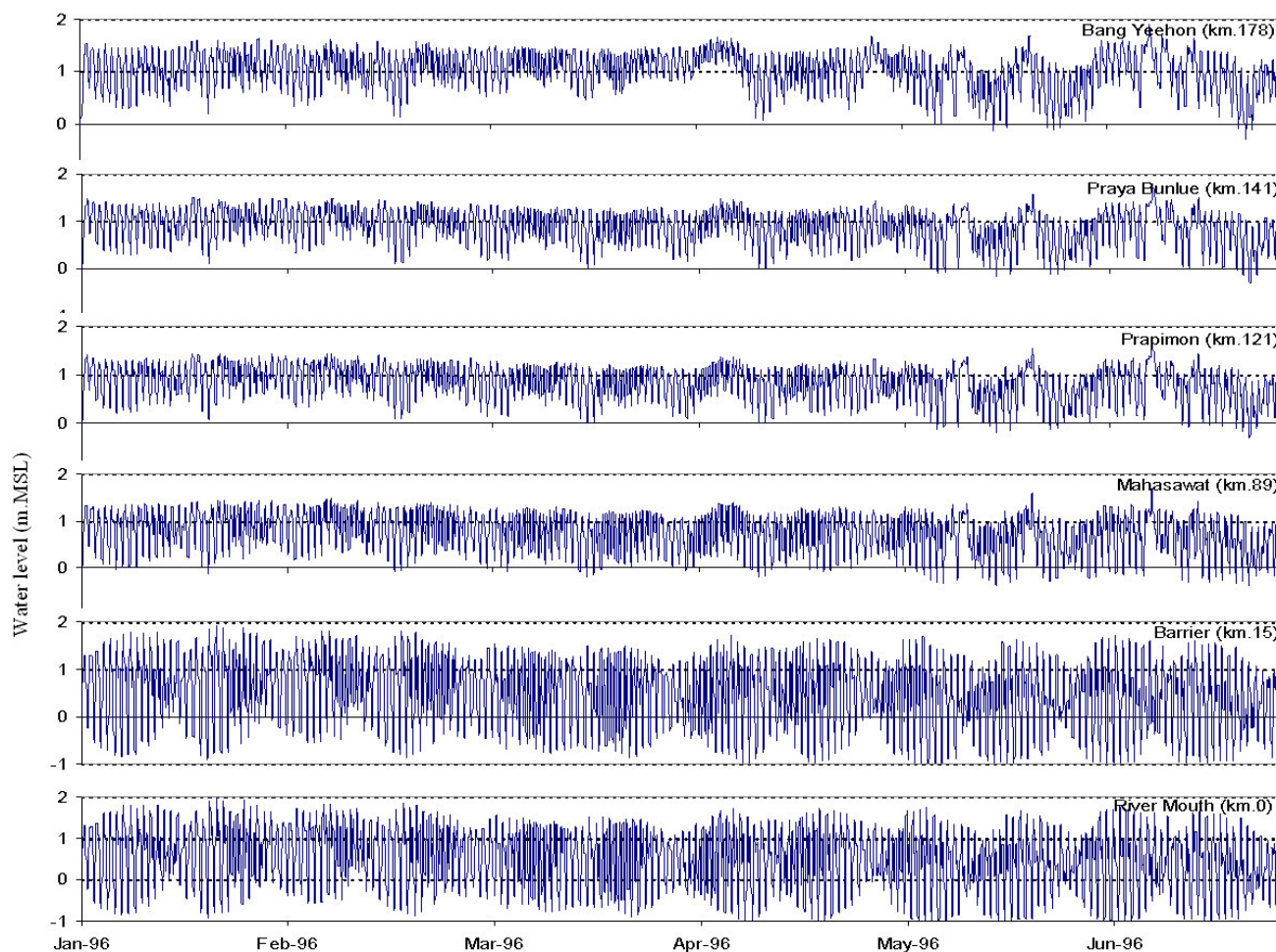


Figure 3. Attenuation of recorded tides in the Tha Chin River in dry season from January to June 1996.

feasibility study because a number of opponents, particularly the local people along the downstream bank. They were primarily worried about the water quality of this river since it is known to be the worst in this aspect among all the rivers in Thailand. The study of water development along downstream region of this river is imperative since there are lots of vital agricultural areas, tourism places, villages, schools, temples, etc. in this area. It can be seen from the Figure 2 that the city of Samut Sakhon is also located near the estuary. Certainly, the local people and economy suffer if the proposed barrier were to cause harm to local environment. Attenuations of recorded tides in the Tha Chin River in dry season from January to June, and for January 1996 are shown in Figures 3 and 4, respectively.

In this application to the Tha Chin River, the results of the analytical computation of the water level at the proposed barrier site during fully closed operation are quite similar to the low flow condition in the dry season, therefore are computed by the use of the average value of damping modulus coefficient and the change of tide number during the dry season, (January to June 1996), as shown in Figures 3 and 4; which show that the river discharge has insignif-

ant effect to damping the tide and has the rather similar condition to the case of fully closed operation of the barrier. A numerical model is utilized to actually predict the water level at the proposed barrier site for the case of natural flow without a barrier. This is due to the lack of experimental data indicating the actual water level at the proposed barrier site. The observed hourly water level data at the Tha Chin River mouth station and at Pho Phraya station (200 km from the river mouth) are used as the downstream and upstream boundary conditions in the model, respectively. The numerical model is also used to predict the water level at the proposed barrier at the site assuming a fully closed barrier. The comparison of water surface fluctuation, in case of fully closed operation at the proposed barrier site, results from the analytical model and from the numerical model, are shown in the Figure 5, together with water level fluctuation data computed from the numerical model for the case of no barrier. It can be seen clearly that the numerical model yields only a slight increment of tidal range at the barrier site, which is impossible, while the analytical model produces a more reasonable result. This is because in running the numerical model, the hydrodynamic downstream boundary

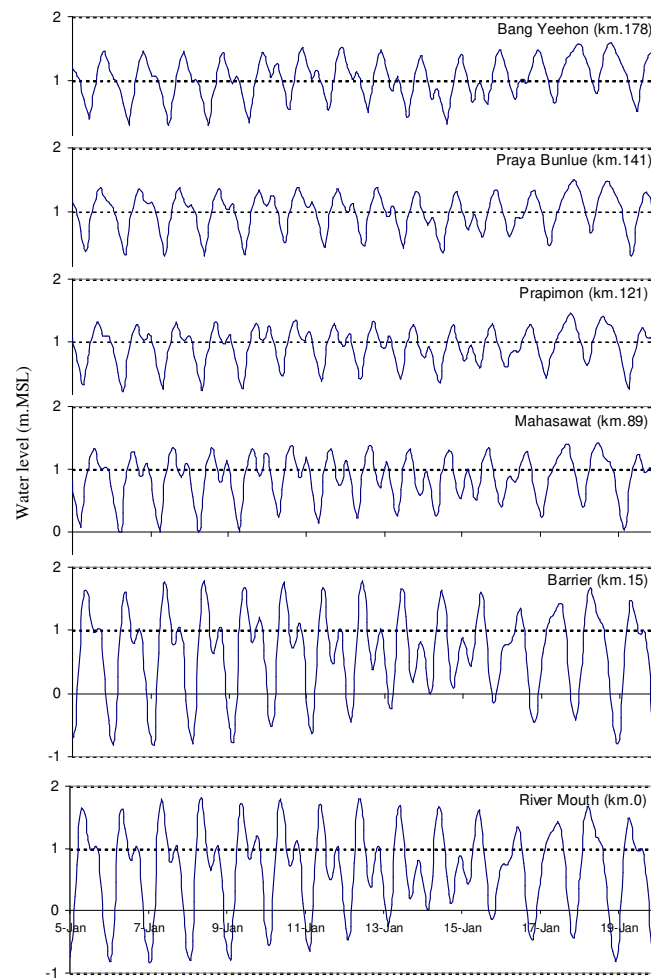


Figure 4. Attenuation of recorded tides in the Tha Chin River in January 1996.

condition, normally hourly water level, is set as input data before construction of the barrier and serves the hydrodynamic characteristics in the vicinity of its site, which actually would be significantly changed due to the barrier construction in creating the reflected tide. Accordingly, when the numerical model is applied into the case where a barrier is located near to boundary condition; the use of the boundary condition before construction of the barrier which are significantly different from those after the barrier construction would result in an error outputs. Future work should address this deficiency in the numerical model.

Considering the water level change due to the salinity barrier in the Bang Nara River, located 6 km upstream of the Bang Nara river mouth (Vongvisessomjai *et al.*, 2003), one can find that after construction of the tidal regulator, the water surface fluctuation at the structure has increased as much as two times, which is shown in Figure 6. However, the tidal range at the structure in the Bang Nara River was increased from only 0.5 m to 1.0 m, which is a small range, due to the natural feature of entering tidal propagation in this estuary. This has not affected the downstream area much; hence, the operation of the tidal regulator in this river not

resulted in adverse conditions. Meanwhile, for the rivers in the vicinity of the Upper Gulf of Thailand, such as the Tha Chin River and the Bang Pakong River, the tidal range at the barrier site would be approximately augmented from 2.5 m up to 6.0 m. Accordingly, it is obvious that the operation of the salinity barrier in the Bang Pakong River, located at 62 km from the river mouth, has faced many problems from this excessive amplification of tidal fluctuation since it causes river bank sliding, over spill of saline water, and flooding problems in the downstream area of the dam. Currently, the barrier is not used. No doubt, if the proposed barrier at 15 km in the Tha Chin River had been operated, there would have been problems similar to the ones in the Bang Pakong River. Obviously, the design and assessment of salinity barrier operation requires keen comprehension of river hydraulic behavior under natural conditions in order to prevent unfavorable effects.

5. Conclusions

It was found from the present study that the analytical model for interaction of the tide and the salinity barrier was

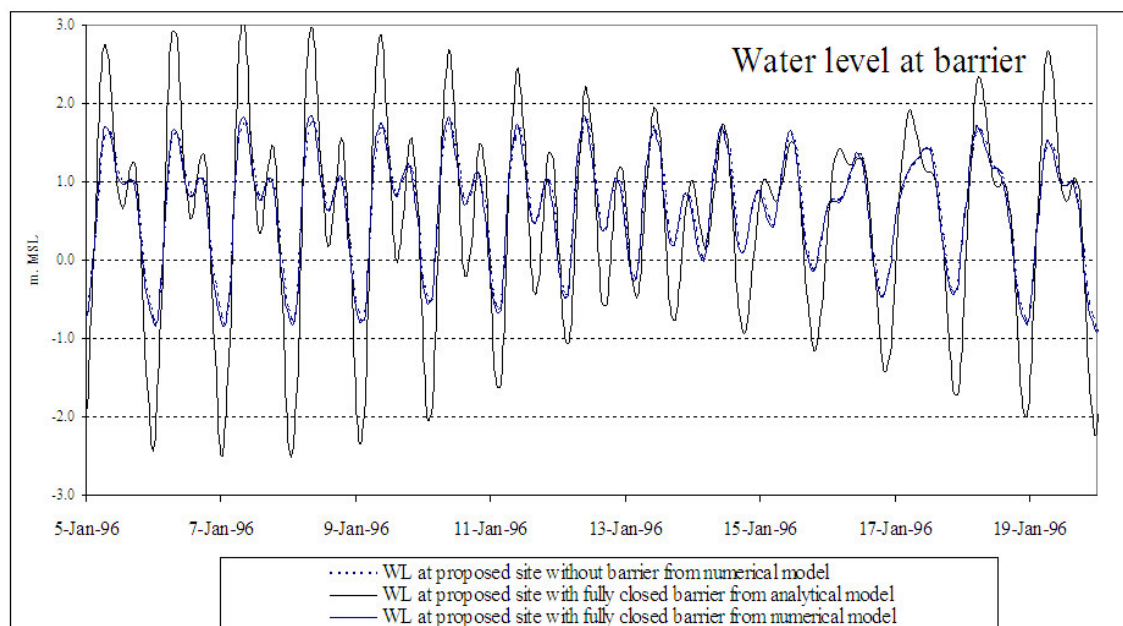


Figure 5. The comparison of water surface fluctuation at the proposed barrier site in the Tha Chin River between the results from the analytical model and from the numerical model for fully closed operation in January 1996.

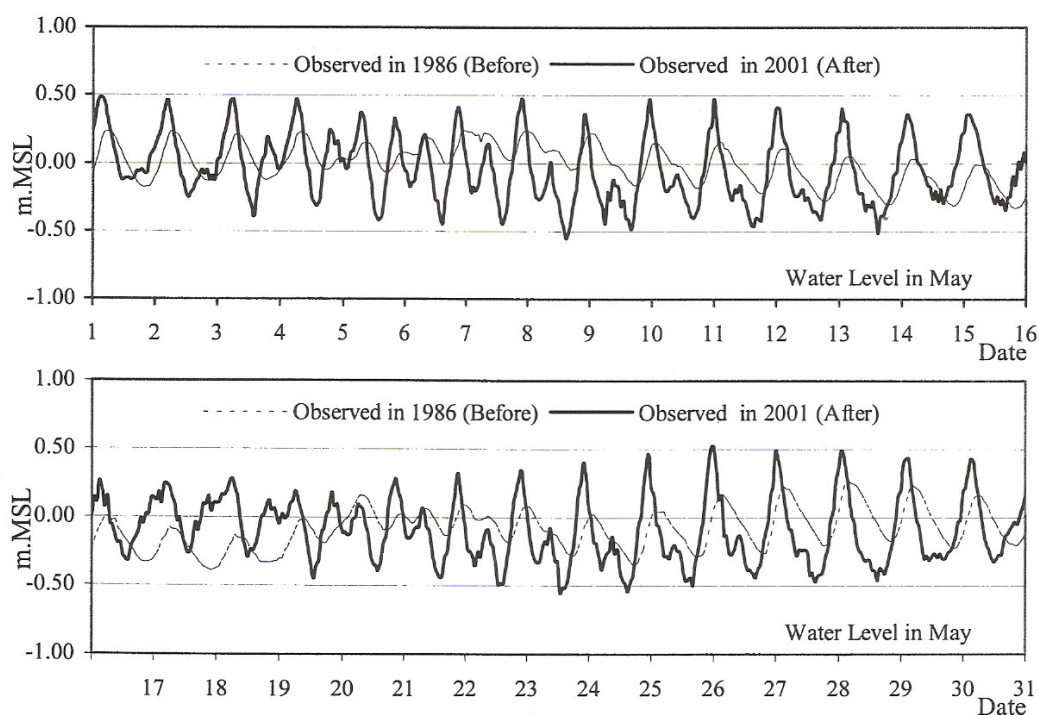


Figure 6. The comparison of observed water level between before and after construction of tidal regulator in Bang Nara River (Vongvisessomjai *et al.*, 2003).

predicted more accurately by the analytical model than the numerical model. However, if the barrier was located far from the upstream and downstream boundary conditions, it was found that the numerical model was sufficient, as in the case of the Bang Pakong river, from Vongvisessomjai and Srivihok (2003). In the Bang Pakong River, the structure was

located at 62 km from the river mouth and it was found that during the operation of closing of the gate, the tidal range at the barrier site would be augmented by approximately twice as much. It was also noted that for the barrier located near the estuary, like the one at the Bang Nara River, which was constructed about 6 km upstream of the Bang Nara river

mouth, the tidal range at the structure site would still increase approximately double due to this obstruction of the tidal propagation. Recently, it was proposed to construct the salinity barrier at approximately 15 km from the estuary for the Tha Chin River. It was found from the numerical model that the damping of water surface fluctuation near the barrier would increase very slightly, which was impossible. This was because in running the numerical model, the hydrodynamic downstream boundary condition, usually hourly water level, was set as input data before construction of salinity barrier and served the hydrodynamic features in the area near its site, which actually would be considerably changed due to the barrier construction in creation the reflected tide. Accordingly, when the numerical model was applied into the case where a barrier was located near to boundary condition; the use of the boundary condition before construction of the barrier which were significantly different from those after the barrier construction would result in an error outputs. Future work should address this deficiency in the numerical model.

References

- Ippen, A.T. and Harleman, D.R.F. 1966. Tidal Dynamics in Estuaries, Chapter 10 of Estuary of Coastline Hydrodynamics, Mc Graw Hill Book Company, Inc.
- Rahman, M., 1988. The Hydrodynamics of Waves and Tides, with Applications, Topics in Engineering Vol. 4, Computational Mechanics Publications, Southampton UK and Boston USA.
- Vongvisessomjai, S. and Rojanakamthorn, S., 1989. Interaction of Tide and River Flow, J. Waterways, Port, Coastal, and Ocean Eng., ASCE, 115(1): 86-104.
- Vongvisessomjai, S. and Srivihok, P., 2003. The interaction between tide and salinity barriers, Songklanakarin J. Sci. Technol., 25(6): 743-756.
- Vongvisessomjai, S., Weesakul, S., and Srivihok, P., 2003. Water level change by tidal regulator in the Bang Nara River, Songklanakarin J. Sci. Technol., 25(6): 757-771.
- Vongvisessomjai, S. and Chatanantavet, P. 2006. Analytical model of interaction of tide and river flow, Songklanakarin J. Sci. Technol., 28(6): 1149-1160.