Development of Modeling System to Simulate Hydrodynamic and Environmental Quantities in the Hai Phong Estuary, Vietnam

Nguyen Kim Cuong[1,2], Dinh Van Uu[2], Umeyama Motohiko [1]

[1]Department of Civil and Environmental Engineering
Tokyo Metropolitan University
1-1 Minami-ohsawa, Hachioji, Tokyo 192-0397
JAPAN
[2]College of Science
Vietnam National University, Hanoi
334 Nguyen Trai – Thanh Xuan – Hanoi
VIETNAM
Email: cuongkim@gmail.com

Abstract: *In this study, a hydrodynamic model was developed to simulate tidal currents in the Hai Phong estuary, Vietnam. Three-dimensional thermo-dynamic primitive equations were used to investigate current velocity, water level, and the sediment transport. A special computing procedure was applied to the river boundaries because the tidal range in the area is approximately 4 m. We tested the effects of each quantity against the observed data during the dry season. The deposited and resuspended rates were confirmed by analytical shear stress solution in the wave-current coexisting field. This study was extended to study turbidity in the Do Son beach area.*

Keywords: *HUS-VNU, Modelling system, Hai Phong.*

1. INTRODUCTION

In a shallow estuary, estimation of near-shore currents is usually difficult because of its complex topography, fluctuating sea level and river discharge, and variable wind or wave speed and direction. To elucidate the nature of physical process in an estuary, scientists and engineers have developed many numerical models involving advection, diffusion, and mixing within the water column and have also studied the dynamic behavior near bottom boundary layer (BBL). In this paper, we present some results of a real-time three-dimensional numerical simulation of the Hai Phong estuary conducted for a period of high river discharge during monsoon. The Hai Phong estuary is a mixed estuary on the northeastern coast of Vietnam and is connected to the South China Sea by the Gulf of Tonkin. A major source of fresh water discharge is the Thai Binh river, with monthly average discharges ranging from 200 m^3/s in the dry season to 1,000 m^3/s in the wet season. Sea-level elevation having a typical tidal range of approximately 4 m is observed on the offshore open boundaries. Other important factors that govern circulation in the estuary are surface wind and waves. Our model considers these quantities as surface boundary conditions.

Knowledge of circulation patterns is important for solving suspended sediment transport and water quality problems. In addition, knowledge of bottom stress is significant to determine bed load transport during the process of beach erosion or deposition. Therefore, to include these processes in the circulation model of water column, an adequate expression of BBL is required. The interaction between wave and current near the bed plays an important role and affects sediment transport and bed formation. By using an eco-hydrodynamic model, which links coastal circulation, surface forcing, bottom boundary layer, and environmental or suspended sediment transport models, we computed the transport of sediment materials in response to wind, including storms, and tides over a medium time scale.

The purpose of the study is (i) to simulate the circulation in the Hai Phong estuary, and to understand the effects of transient winds, fluctuating tidal ranges, and river discharges on flow fields; (ii) to calculate sediment transport relative to substantial forces; and (iii) to determine variation mechanism of sediment concentration during a tidal cycle and study the effects of external forces on erosion or depression in the estuary and turbidity in the Do Son beach area.

2. COASTAL SEA MODELLING SYSTEM

The Hanoi University of Science-Vietnam National University (HUS-VNU) modeling system, a three-dimensional (3D) hydrodynamic ocean system (Dinh *et al*., 2006, 2007), was applied to study the Gulf of Tonkin. This model solves for free surface, three components of velocity, temperature, salinity, and turbulent kinetic energy, which are factors used to compute the vertical diffusion coefficient through the classical k-l model. The HUS-VNU standard model, developed by GeoHydrodynamics and Environmental Research (GHER) or University of Liege, is a 3D hydrostatic primitive equation (PE) model that uses an Arakawa C-grid in the horizontal axis and sigma-coordinate in the vertical axis. Further details of the GHER model can be found in studies conducted by Beckers (1991) and Barth *et al*. (2007). The HUS-VNU system consists of four individual models: (i) classical 3D PE model, (ii) surface forcing model, (iii) BBL model, and (iv) sediment transport model. The boundary conditions can be easily described using river discharge, tidal fluctuations, wind stress, and wave force. In addition, the Smagorinsky scheme was used to parameterize horizontal subgrid processes.

In the 3D PE model, the horizontal viscosity was computed using the following equation that considers a Prandtl frequency *M* as

$$\nu_L = l_L M = l_L \left\{ \sum_{\alpha} \sum_{\beta} \frac{\partial u_\alpha}{\partial x_\beta} \frac{\partial u_\beta}{\partial x_\alpha} \right\} \qquad with \quad \alpha, \beta = 1,2,3\,, \tag{1}$$

where l_L = length scale parameter; L = 1 for x-axis and 2 for y-axis. For the surface forcing model, we formularized the wind–wave interaction to obtain surface wave parameters and wind surface stress under variable wind speed and direction. The wind surface stress can be written as

$$\tau = C_D \rho_a u_{10}^2 = \rho_a u_*^2\,, \tag{2}$$

where τ = wind surface stress, C_D = drag coefficient, ρ_a = density of air, u_{10} = horizontal wind speed at 10 m from the mean sea level, and u_* = shear velocity. The drag coefficient C_D can be expressed as

$$C_D = 10^{-3}(a + cu_{10})\,, \tag{3}$$

where $0.70 < a < 1.10$, and $0.01 < c < 0.12$ (Dinh, 1981). By parameterizing the effect of waves on the airflow, Janssen (1991) found that the airflow stress over surface gravity waves is given by

$$u_z = \frac{u_*}{\kappa} ln\left(\frac{z + z_e - z_0}{z_e} \right), \tag{4}$$

where u_z = horizontal wind speed at z, κ = von Karman coefficient, z_e = surface elevation, and z_0 = roughness length. In the BBL model, we calculated the bottom shear stress analytically using current velocity at the point near the bottom layer. The total skin friction velocity in the current and wave coexisting field is given by

$$u_{*cw} = [u_{*c}^2 + u_{*w}^2]^{1/2}\,, \tag{5}$$

where u_{*c} = current friction velocity and u_{*w} = wave friction velocity. These friction velocities are defined as $u_{*c} = (\tau_c / \rho)^{1/2}$ and $u_{*w} = (\tau_w / \rho)^{1/2}$, where τ_c and τ_w are current and wave surface stress, respectively. According to Grant and Madsen (1979) and WAMDI group (1988), these stresses are expressed as

$$\tau_c = \rho C_c u_c^2 \text{ and } \tau_w = \frac{1}{2} f_w \rho u_w^2 \text{ in which } C_c = \frac{\kappa^2}{[ln(30z / k_{bc})]^2} = \frac{\kappa^2}{[ln(z / z_0)]}\,, \tag{6}$$

where k_{bc} = apparent bottom roughness caused by turbulence in the wave boundary layer. At each river mouth, instead of water discharge, the total water level was added as

$$\varsigma = \varsigma_t + \delta_\varsigma \qquad \delta_\xi \approx \frac{v^2}{2g}, \tag{7}$$

where ς = total water level at a river mouth, ς_t = tidal level, δ_ς = water level due to river discharge, and v = average velocity at the river mouth. The 3D sediment transport model, the model for suspended transport of sediments, is expressed using Fick's diffusion equation as

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial x}(cu) + \frac{\partial}{\partial y}(cv) + \frac{\partial}{\partial z}(cw) + \frac{\partial}{\partial z}(cw_s) = \lambda_x \frac{\partial^2 c}{\partial x^2} + \lambda_y \frac{\partial^2 c}{\partial y^2} + \lambda_z \frac{\partial^2 c}{\partial z^2}, \tag{8}$$

where c = sediment concentration, w_s = fall velocity, and λ_x , λ_y , and λ_z = diffusion coefficients. Various formulae have been developed in a two-dimensional steady-state condition on the basis of this equation. When deposition and resuspension processes are considered at the bottom layer, the boundary condition becomes

$$\left[cw_s - \lambda_z \frac{\partial c}{\partial z}\right]_{bottom} = Q = E + D, \tag{9}$$

where Q = source term describing the quantity of sediment per unit area, E = resuspension source, and D = deposition source at the bottom. These source terms depend on the total skin friction shear velocity u_{*cw}, sinking velocity w_s, critical shear stress of resuspension u_{*ce}, and critical shear stress of deposition u_{*cd}. In the formula, the material concentration at a reference height z_a was assumed by a power–law profile as

$$C_z = C_a \left(\frac{z}{z_a}\right)^{-w_s/\kappa u_*}, \tag{10}$$

where C_z = material concentration, and c_a = reference concentration.

The bed load transport rate q_b depends on the critical velocity characterized by the sediment type and the total skin friction velocity determined by the flow feature. In this model, the method of Van Rijn (1984) was used to compute the bed load transport.

3. APPLICATION OF THE NUMERICAL SYSTEM

The HUS-VNU modeling system has been used to simulate offshore water circulations in the South China Sea and the Gulf of Tonkin. In this study, we applied the system to the near-shore flow in the Hai Phong estuary, where the water creates a shallow and topographically complex strong tidal system. Hai Phong is an active economic area in north Vietnam and is a principle port of the country, contributing to its high commercial growth. The French colony built the Bach Dang estuary into a trade base from 1876 to 1890, and since then, the Hai Phong port has handled the country's highest cargo volume. The complex geography was formed by sand from tributaries of the Thai Binh river. The bay consists of numerous small rocky islands. The Bach Dang and Cam rivers flow from the mouth of the Nam Trieu river into the sea, while the Lach Tray river flows from its own mouth. The water of Chanh river flows into the sea through the Lach Huyen channel. Seawater flows directly into the Hai Phong port during flood tide, and the mixed water returns to the bay during an ebb tide. After closure of the Cam river mouth in 1981 by the Dinh Vu dyke, the Lach Huyen and Nam Trieu channels have become major routes to access Hai Phong port. The tidal range in the Gulf of Tonkin is approximately 4 m, which greatly affects salt water intrusion. The management of the Hai Phong port is vital to the economic success of Vietnam. But the erosion and deposition from sediment transport have remarkably increased in recent years, creating shallower channels; the maximum depth was 11–4 m from 1934 to 1938, 10–13 m from 1960 to 1964, and 6–12 m in 1996. These channels are dredged annually to provide safe navigation in the waterway (Nguyen, 1999). The wind erosion in Cat Hai Island and northern Do Son beach area is a serious issue during the southwest monsoon season from May to August, as is turbid water in the Do Son beach area (Dinh *et al*. 2008). The quality of water is also of urgent concern because the beach is a natural heritage of the French colonial era. Understanding the hydrodynamic aspects in the area is crucial to discovering a solution to the deteriorating environment.

Figure 1 The research area near the Hai Phong estuary in Vietnam.

We have performed the following numerical experiments to investigate sediment problems in the Hai Phong estuary. The near-shore circulation was simulated under wind, tide, and water discharge variables. The sediment transport rate was then calculated relative to the substantial forces, and the time of sediment concentration was recorded over a tidal cycle. Finally, we attempted to understand the erosion and depression mechanism on the sea bottom and to interpret turbidity in the Do Son beach area. The HUS-VNU modeling system provided five layers in the sigma coordinates with a special resolution of 200 m. The model was run for 15 days to cover the dry season in which wind speed is negligible. Figure 2 shows two instances of near-surface velocity vector plots at flood and ebb tides. The most notable example is found in the comparison of two different tidal phases in the western and eastern areas of the bay. During flood and ebb tides, the surface water creates shoreward and seaward flows, respectively, in the western area but the flow is reversed in the eastern part of the bay.

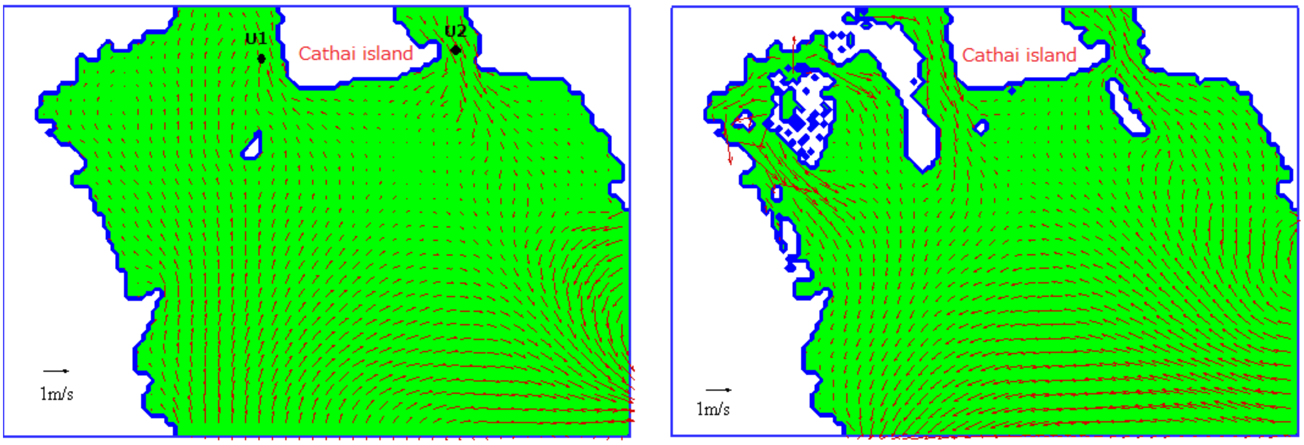

Figure 2 Typical water circulation fields in the high tide (left) and low tide (right).

Figure 3 shows the distributions of surface velocity over a tidal cycle at Nam Trieu (U1) and Lach Huyen (U2). The current turns from a northward flowing direction at flood tide to a southward flowing direction at ebb tide in Nam Trieu, whereas the flow pattern at Lach Huyen is opposite to that of Nam Trieu. Figure 4 shows the variations of current direction observed at Lach Huyen and Nam Trieu on February 18 and 19, 2006. We can observe the phase difference of the current throughout the tidal cycle from 12:00 to 19:00. The phase of the current vector in Figure 3 agrees with that of the observed data at Lach Huyen and Nam Trieu, although they were not obtained by an entirely satisfactory measurement process.

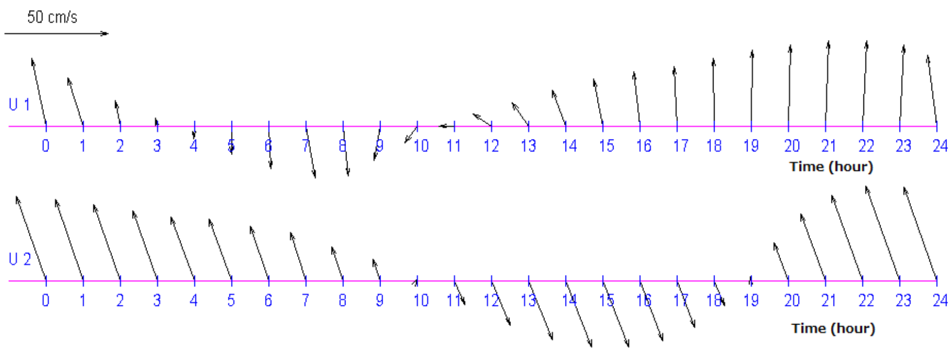

Figure 3 The variation of velocity vectors at the Namtrieu (U1) and Lachhuyen (U2) river mouths.

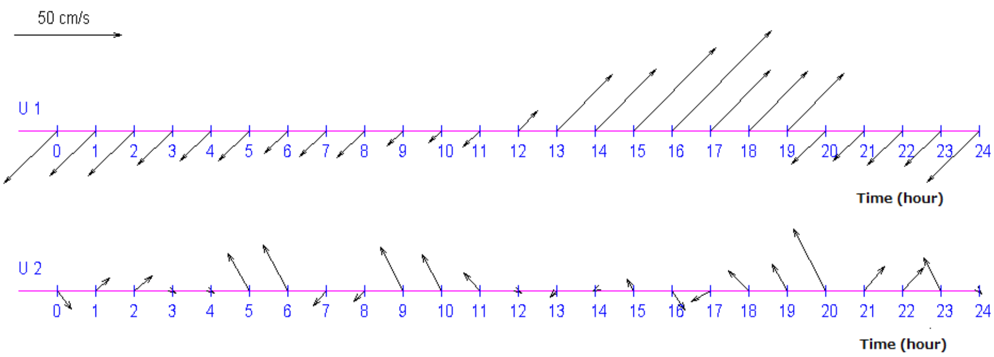

Figure 4 The variation of measured velocity vectors at the Namtrieu and Lachhuyen river mouths in the period of February 18-19, 2006.

The seasonal effects may cause more significant damage to coasts than daily effects such as tidal currents because the storm surge inundates low lands, erodes beaches, and increases the salinity of rivers and estuaries in the storm or typhoon season. The extent and severity of storm impact has recently increased as a result of regional climate change. Because a high sea level causes by a storm of a given severity increase the flood level, the vulnerability of sea front to flooding is intensified This study investigates a hindcasting of water level during a storm surge in the Gulf of Tonkin. The Do Son beach area is of special interest because the coast suffered great losses from several typhoons in the past three decades. Nevertheless, the area will remain the most important zone for resort and tourism in north Vietnam. Figure 5 shows the water level variation for three different wind conditions: (i) U = 0 m/s, (ii) U = 5 m/s from SE, and (iii) U = 15 m/s from SE. For all cases, the water level appears nearly sinusoidal during flood tide and has a constant value (above water) between 15:00 and 24:00 on the first day and 40:00 and 47:00 on the second day. The southeastern wind results in wind and wave set-up and consequently decreases the water depth during ebb tide. The difference in water level is significant when comparing two different wind directions having same wind speed. This investigation confirms that during storm surge, the water level rises by approximately 30 cm at Do Son beach and 20–30 cm at the Cat Hai coast.

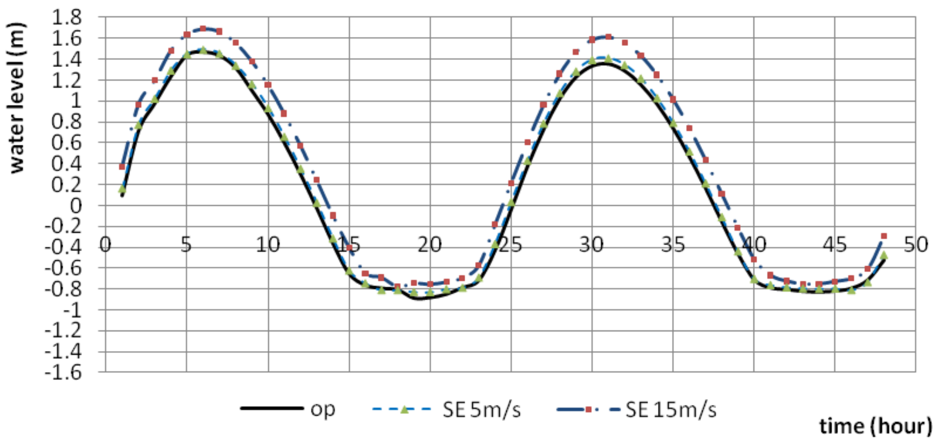

Figure 5 Water surface variations at W (indicated in figure 1) due to some wind conditions: tide alone (op), SE wind speed of 5 m/s, SE wind speed of 15 m/s.

The current velocity of the tide causes the onshore–offshore sediment transport, whereas waves have an important influence on the longshore sediment transport. We determined the volumetric sediment rate using a unit width of the vertical plane extending from the sand bottom to the water surface. We assumed a sand bottom and several river mouths at Hai Phong Bay. We first estimated the temporal distribution of sediment concentration at both shallow and deepwater sites near Cat Hai Island using the sediment transport model. The concentration variation in time is illustrated in Figure 6 in which two different plots of volumetric concentration are calculated for the tide alone and tide–wave combined cases. The sediment concentration varies strongly as a function of time at a shallower depth because of the tidal effect.

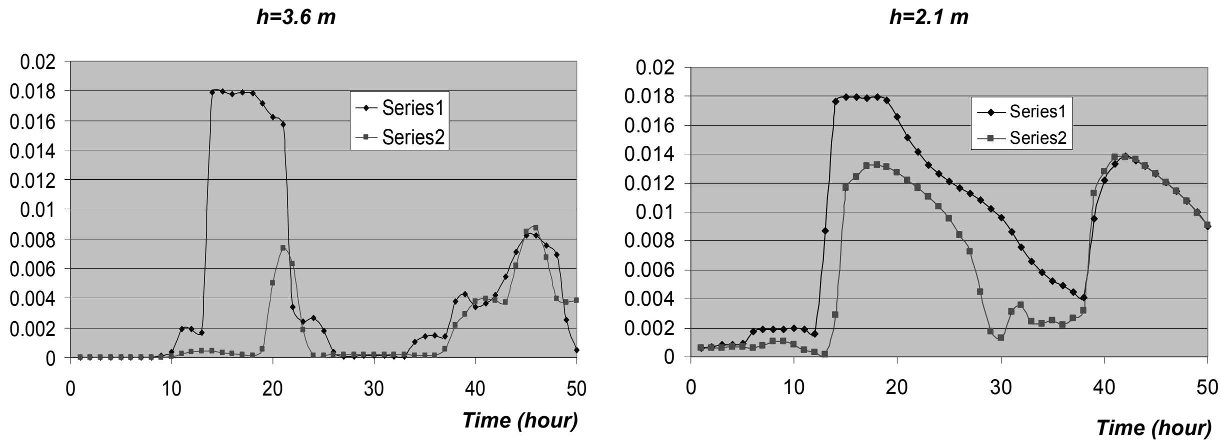

Figure 6 Variation of the volumetric concentration [m^3/m^3] in offshore of the Cathai island (water depth = 3.6 m) and near the Cathai island (water depth = 2.1 m) for storm wind speed of 18 m/s (serie 1) and for tide alone (serie 2).

However, the wind waves play an important role in concentration variation at the deepwater depth. Figure 7 shows two examples of substantial wind response of sediment accumulation or erosion after the 15-day run. Two extreme discharges are 100 m^3/s in the dry season and 1,000 m^3/s in the wet season. The sediment concentrates off the mouth of Lach Huyen river represent the smallest discharge case, but a stretch of suspended sediment is wider in the largest discharge case. Although the amount of river discharge influences sediment transport, the ratio of the discharges at all river mouths is the most important parameter. Note that the suspended sediment reaches Do Son in both cases and results in high turbidity of water in the beach area. The present calculations suggest that the high-sediment water is transported to the southeastern and eastern parts of Cat Ba Natural Reserve Island recently polluted by high-turbidity water.

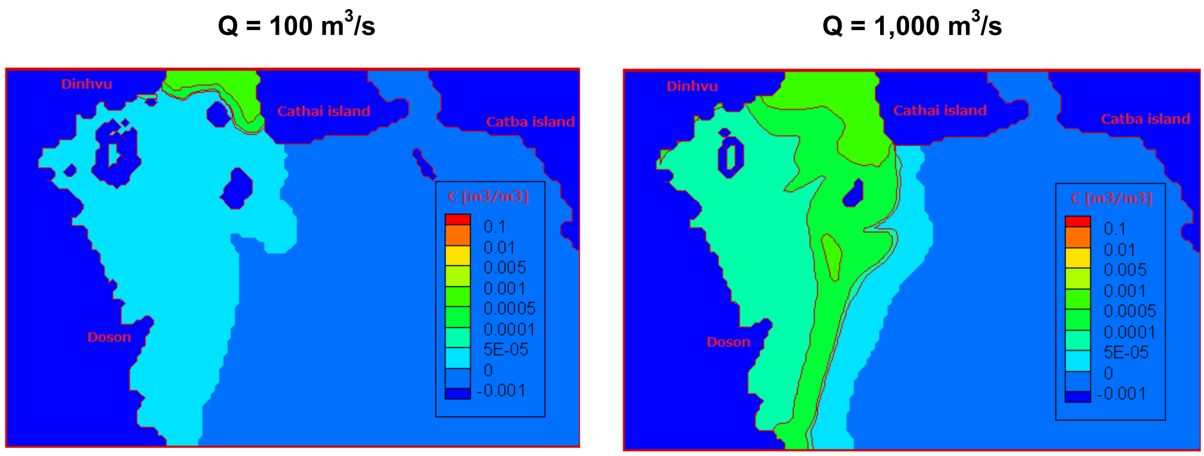

Figure 7 Simulated volumetric concentration [m^3/m^3] after 15 days for the smallest discharge case [100 m^3/s] and the largest discharge case [1,000 m^3/s].

4. CONCLUSIONS

By using observed values of sea levels, wind, and river discharge, we have numerically simulated the time-dependent velocity and sediment structures in the Hai Phong estuary for several scenarios. The results of the simulation have provided new insight into the physical processes involved in the near-shore circulation and sediment transport. The computed velocity fields show the differences in flow direction at two river mouths, Nam Trieu and Lach Huyen, across Cat Hai Island. This finding is consistent with observations and is an important physical process that contributes to water management in Hai Phong Bay. In addition to circulation produced by tidal and wind-induced currents, the numerical study was extended to transport processes of suspended sediment in the estuary. Our simulation result showed that sediment concentration near coasts is very high, even in the absence of wind. The total amount of river discharge is important in changing the sediment distribution. The substantial variation in sediment field caused by small discharge is significant at Do Son beach, where water turbidity has recently increased.

5. REFERENCES

Barth, A., *et al.* (2007), *Multigrid state vector for data assimilation in a two-way nested model of the Ligurian Sea*. J. Marine Sys., 65, 41-59.

Beckers, J.-M. (1991), *Application of the GHER 3D general circulation model to the Western Mediterranean*, J. Marine Sys., 1(4), 315-332.

Dinh V.U. (1981), *Wind stress on the sea surface with wave*, Marine research journal, II-2, Nhatrang, 117-122 (In Vietnamese).

Dinh V.U. *et al*. (2006), *Development and Application of the Environmental Hydrodynamic 3D Model for Computation and Forecasting of Oil Pollutions in Coastal Marine Environment*, Annual Report of FY 2006 of CUP between JSPS and VAST, 191-200.

Dinh V.U. *et al*. (2007), *Development of system of Hydrodynamic-environmental models for coastal area (Case study in Quang Ninh-Hai Phong region)*, Journal of Science, Earth Sciences, T. XXIII, No.1, 59-68.

Dinh V.U. (2007), *Towards a coastal ocean monitoring and prediction system for Vietnamese Sea Waters, The 4th Seminar on Environmental Science and Technology issues related to the Sustainable development for urban and coastal area*, The 7th General Seminar of CUP between JSPS and VAST, Danang, 148-153.

Dinh V.U. and Ha T.H. (2008), *Hydrodynamic modeling in tidal dominated estuarine regions*, Journal of Science, Earth Sciences, T. XXIIII, No.3, 33-38.

Dinh V.U. (2009), *Application of the sediment transport and bottom morphological change model for a marine estuarine area of Hai Phong port*, Journal of Science, Earth Sciences, T. XXV, No.1S, 133-139. (In Vietnamese)

Grant, W.D. and Madsen, O.S., (1979), *Combined wave and current interaction with a rough bottom*, J. Geophys. Res. 84, 1797-1808.

Jansen, P.A. (1992), *Experimental evidence of the effect of surface waves on the air flow*, J. Phys. Oceanogr. 22, 1600-1604

Nguyen D.C. (1999), *Space narrowing of tidal zone in Bach Dang estuary as a key factor causing Haiphong port shipping channel siltation, Journal of Marine Resources and Environment*, VI, 54-69. (In Vietnamese)

Van Rijn L.C. (1984), *Bebload transport–Part 1*, Journal of Hydraulic Engineering, vol 110, No. 10, 1431-1456.

WAMDI Group. (1988), *The WAM model - the third generation ocean wave ocean wave prediction model*, J. Phys. Oceanography, 18, 1775-1810.