Journal of Environmental Science and Engineering A 4 (2015) 67-78
doi: 10.17265/2162-5298/2015.02.002

Characteristics of Suspended Particulate Matter and the Coastal Turbidity Maximum Areas of the Mekong River

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Abstract: This paper presents the results of application of a 3D (three-dimensional) numerical model to study on MTZ (maximum turbidity zone) in the coastal zone of Mekong River Delta. In this study, a 3D system model with combination of hydrodynamics—wave and suspended sediment transport was set up and validated with measured data in the study area. Based on calculated scenarios for the flood and the dry season, the results have shown appearance of MTZs in the coastal zone of Mekong River with suspended sediment concentration prevalent of 0.04-0.07 $kg \cdot m^{-3}$ (the dry season) and 0.05-0.1 $kg \cdot m^{-3}$ (the flood season). The position and MTZs scale change with the interaction between fresh water and tidal oscillations. The MTZ occur more in the dry seasons compared to the wet season. The MTZs are prevalent located far away from estuaries about in 12-22 km (in the dry season), and 5-15 km in the flood season.

Key words: Modelling, maximum turbidity zone, suspended sediment transport, Me Kong river coastal area.

1. Introduction

The picture of the suspended sediment transport is very important in predicting the movement of pollutants in coastal estuaries. A phenomenon related to the suspended particulate matter transport in estuaries which has the influence of tide is "MTZ (maximum turbidity zone)". This phenomenon has been observed quite early [1-3]. The formation mechanism and the role of MTZ, however, have just been researched in recent years. The MTZs are characterized by higher suspended particulate matter content than normal mutation in comparison with inside the river and outside the coastal areas.

The formation and movement of the MTZs in the estuaries are a complex process of dynamic integrated geo-hydro [4, 5]. They depend on the tidal dynamics, the discharge of water from the river, the erosion or deposition processes of suspended particulate matter as well as sediment resuspension process from the bottom and the volatility (in space and time) of salinity due to the influence of the tide [6, 7]. The study results have shown that MTZ is not only a place of deposition and accumulation of material from the continent, nutrient enrichment, but also a place of accumulation of toxic chemicals and heavy metals [8-11]. These pollutants are absorbed into plankton, through the food chain, affecting the entire ecosystem area. On the other hand, MTZ is a place which has an abundant source of food for the settling and laying eggs of fish and other organisms [12, 13]. Therefore, research of this issue has not only a scientific sense but also a practical meaning.

Mekong is the largest river system in Vietnam and the tenth rank in the world (flow discharge). The annual river discharge/sediment are quite large combining with unregulated semi-diurnal regime lead to complex hydrodynamic-sediment conditions. They create favorable condition for the appearance of MTZ. However, studies relating to MTZ in this area have been quite new. Based on the observation and application of mathematical modeling tools, this article will provide further understanding of the

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formation and fluctuation of MTZ in the coastal areas of the Mekong River.

2. Data and Methods

2.1 Data

In this study, collected data include:

- Flow data and the content of suspended particulate matter at some survey points (Fig. 1) in Mission International Cooperation in science and technology under the Protocol Vietnam-United States (2013-2015 period) named "Interaction between hydrodynamics process Bien Dong (East Sea) and Mekong River" also have been assembled and tackled to serve correcting the reliability of the hydrodynamic model;
- Depth and shoreline data of the Mekong coastal region have been digitized from the map published by Department of Survey and Mapping Viet Nam in 2005. The depth of the outward sea has used database from GEBCO (General Bathymetric Chart of the Oceans)-1/8. These are topographic data that have a 0.5-minute resolution processed from satellite images and the bathymetric data [14];
- Meteorological data involve wind data observed for many years in Vung Tau stations and Con Dao stations. Water level data used to adjust the model have been the measurement results of water level (1h·obs^{-1}) in Vung Tau. The offshore tidal harmonic constants have been collected from the database [15];
- Data on temperature and salinity of sea water in the Mekong estuaries and the outward ocean have been collected from the relevant research results in these areas. Data on temperature and salinity of offshore area have been collected from the database WOA13 with a 0.25 degrees resolution [6];
- Observed water discharge of river in the dry and flood season at Can Tho and My Thuan station has been collected, processed to establish the river boundary data.

2.2 Methods

In this study, the main methods used are as follows:

- GIS (geographic information system) method has been used for digitizing, processing and updating topographic data. The GIS softwares also have been used to integrate the coastal terrain data with topographical data in topographic databases GEBCO-1/8 of offshore area;
- Data extraction method from WOA13 salt heat database and tidal FES2004 in order to provide the necessary data for the open boundary conditions for offshore hydrodynamic model (with outside the model domain) has been stored in Netcdf file [6, 15];
- Nesting method used in this study is to create the open sea boundary conditions of the model. To create the file for the open sea boundary conditions of the model with detailed net (for coastal areas of the Mekong River), a model which has the coarser net with the same calculable time and the same type of calculable net in outside area was performed. Coarse-mesh model has 210 × 156 calculated points and uses curved orthogonal grid (Fig. 1). The size of grid cells varies from 166-22,666 m. According to vertical, this model has been divided into four deep layers in σ coordinate. Open sea boundary of this model has been divided into different sections, each section has used the harmonic constants in FES2004 database and mean monthly temperature and salt data in WOA13 database [6];
- The method applies mathematical model.

The hydrodynamic conditions, waves and sediment transport have been modeled by Delft 3D-flow module (combined with the waves, sediment module simultaneously) in Delft3D model system [4].

Hydrodynamic model for the coastal estuaries of the Mekong River has used curve orthogonal grid with calculated range including: the waters of Soai Rap estuary, Tieu estuary, Dai estuary, Ba Lai estuary, Ham Luong estuary, Co Chien, Cung Hau, Dinh An and Tran De. Calculated domain's size is approximately 485 km east-southwest and 100 km north-south, divided into 424 × 295 calculated points. The grid cell size varies from 43.9 m to 11,488.9 m (Fig. 1).

According to vertical, the entire water column has been divided into four depth classes based on σ coordinate. The depth grid has been set up based on the grid calculation and terrain map.

Hydrodynamic model has been set up and run for two typical seasons in 1 year: 3-month flood season (September-November 2012) and 3-month dry season (March-May 2012). Run-time step of the model is 0.2 min.

Initial conditions of the status quo scenarios are the calculated results after 1 month of the dry and flood season in the restart files. Data for the open sea boundary are the calculated results from the outside model then using NESTHD to create the temperature, salinity, water level data files at the boundary points. This tool is used to create time serial boundary condition of detail model (inside) from overall model (outside) in the Delft3D to generate nested time-series boundary conditions of the temperature, salinity and water level data files at the boundary points. This is time serial data with a frequency of 1 $h \cdot obs^{-1}$. For the river boundary, salinity and temperature data for boundary conditions have been characterized monthly. Water discharge used for the river boundary conditions is the chain of data calculated from the measured data with a frequency of 1 $h \cdot obs^{-1}$ at Can Tho and My Thuan station. Wind data introduced into the calculable model for the status quo scenarios are the observation data in Con Dao in month March-May and month September-December in 2012 with a frequency of 6 $h \cdot time^{-1}$.

Wave model in this study has been set up to run at the same time (online coupling) with hydrodynamic model and suspended particulate matter transport model. At each time of calculation (time step), the wave model will use the grid calculation, wind data, the results of depth, the water levels, and the flow of hydrodynamic model.

- Open boundary conditions of wave model have used the wave result of WAVE CLIMATE [16] for the South China Sea and consulted additionally the wave monitoring data in Con Dao in 2012;
- The bottom friction in the wave model selected in this study has been from the JONSWAP (Joint North Sea Wave Observation Project) spectrum with coefficient value to be 0.067. B & J model [17] has been selected to calculate the effects of shallow water where the wave break process appears.

The other parameters are calculated by the model:

- The bottom roughness in this study has been

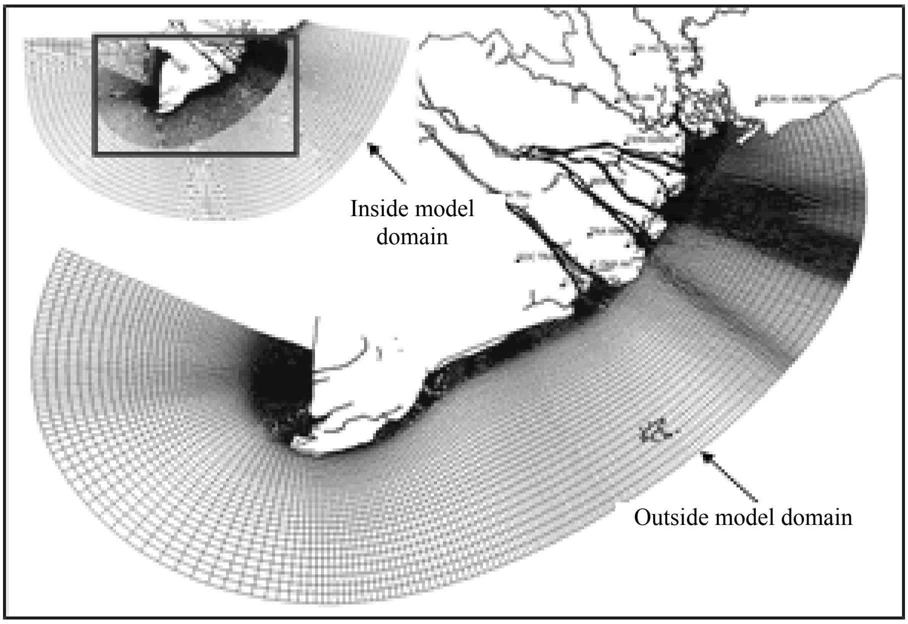


Fig. 1 Grid model (inside model domain and outside model domain).

chosen to use the Manning coefficients (n) that alter according to space with value from 0.018 $m^{-1/3} \cdot s^{-1}$ to 0.023 $m^{-1/3} \cdot s^{-1}$ [17, 18];

- The values relating to turbulence condition in this model have been calculated using the method which has HLES (large eddy simulation horizontal) approach in Delft3D model system based on the theory of Uittenbogaard [19] and Van Vossen [20].

The parameters are calculated by the suspended sediment model:

- The accumulation speed of suspended particulate matter selected has varied from 0.05-0.12 $mm \cdot s^{-1}$. Stress criteria for erosion process of sediment has been 0.25 $N \cdot m^{-2}$ [21]. Stress criteria for the deposition process of sediment has been 0.1 $N \cdot m^{-2}$ [21]. Initial natural erosion rate is assumed to be 10^{-3} $kg \cdot m^{-2} \cdot s^{-1}$.

The calculated results of model have been verified by comparing with the observed data. Comparing the calculated results of water level from the model with observed water level at stations in Vung Tau, Binh Dai, An Thuan and Binh Hoa, it is shown that they are quite suitable for phase and amplitude (Figs. 2a and 2b). Mean square error between the calculated and measured water levels at these stations has ranged 0.18-0.25 m. The values of flow monitoring have been analyzed into sectors meridian (u) and latitude (v) before comparing with the calculated results from the model. After the final adjustment, the comparison results have shown that a relative consistence between the measured data and the calculated data in this area has been reliable (Fig. 2c). Comparing the observed content with the calculated content of suspended particulate matter at some outside points of the Mekong River Estuary, the particular correspondence between calculation and observation has been also discovered (Fig. 2d).

3. Results and Discussion

3.1 Distribution of Suspended Particulate Matter in the Coastal Areas of the Mekong River

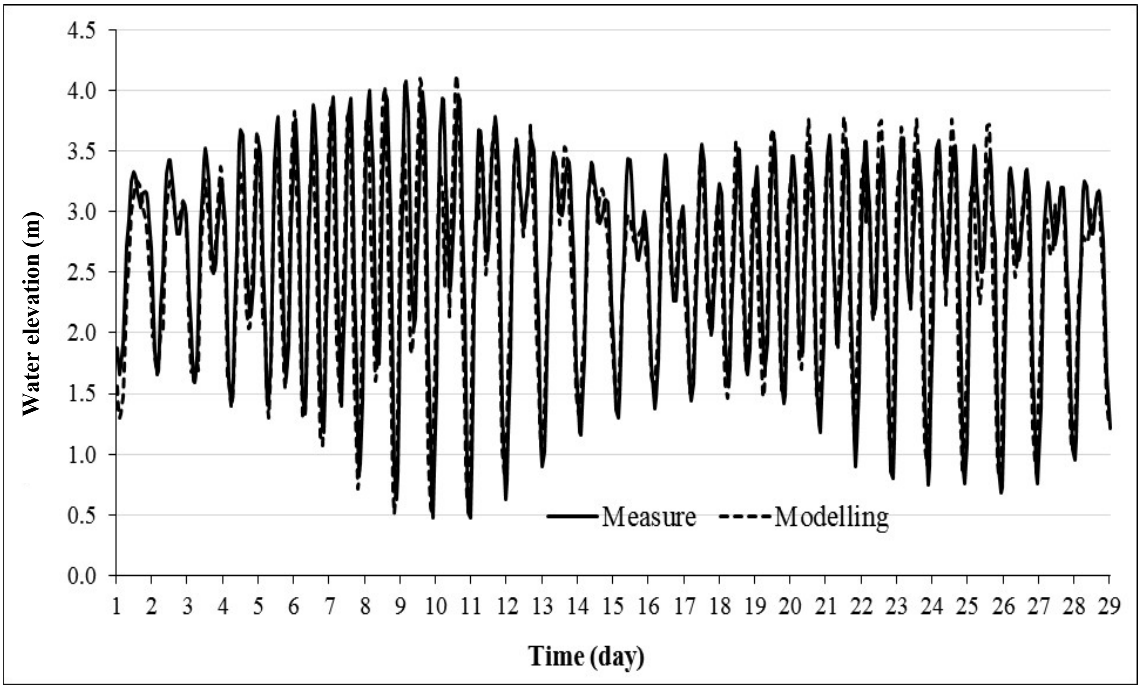
The research results of MTZ which have used a calculated tool-model [2, 22-26] have shown that the circulation density due to differences ratio between freshwater and saltwater, the deposition of suspended particulate matter and resuspension by eroding the bottom under the action of tidal current are three main causes of shaping MTZ.

The calculated results have shown that aside from the dynamic regime, distributable characteristics and thermal-salt structure, the appearance of MTZs in the coastal zone of the Mekong Delta relating to the distribution of suspended particulate matter has depended on the fluctuating water levels and the seasonal variation of stream sediment from the continent.

In the low tide phase, stream sediment from the river has the fastest growing outward sea. In the flood season, the water with content of suspended particulate matter about 60 $mg \cdot L^{-1}$ may appear away from the estuary around 25-30 km with the surface and 20-25 km with the bottom. The water with high content of suspended particulate matter above 100 $mg \cdot L^{-1}$ on the surface extends about 10-15 km away from the estuary, while at the bottom it is only 8 km wide. In the dry season, the content and discharge of mud and sand given by river both reduce, so the content is quite small with most values below 70 $mg \cdot L^{-1}$.

In the high tide phase, while the mass of water with high content of suspended particulate matter from continent is still given, the mass of seawater with high salinity moves towards the continent. The interaction between these two ones causes the remarkable narrowing of the incidence of water mass with the high content of suspended particulate matter in comparison with the low water. This also makes the appearance of turbidity areas more clearly.

At the time of high water, the influence of the sea water mass on the continent is maximum. In the flood season, the river water with the high content of suspended particulate matter is driven into outside the estuaries. The interaction between the halocline with suspended particulate matter flow still pushed out by the river has contributed to establish some maximum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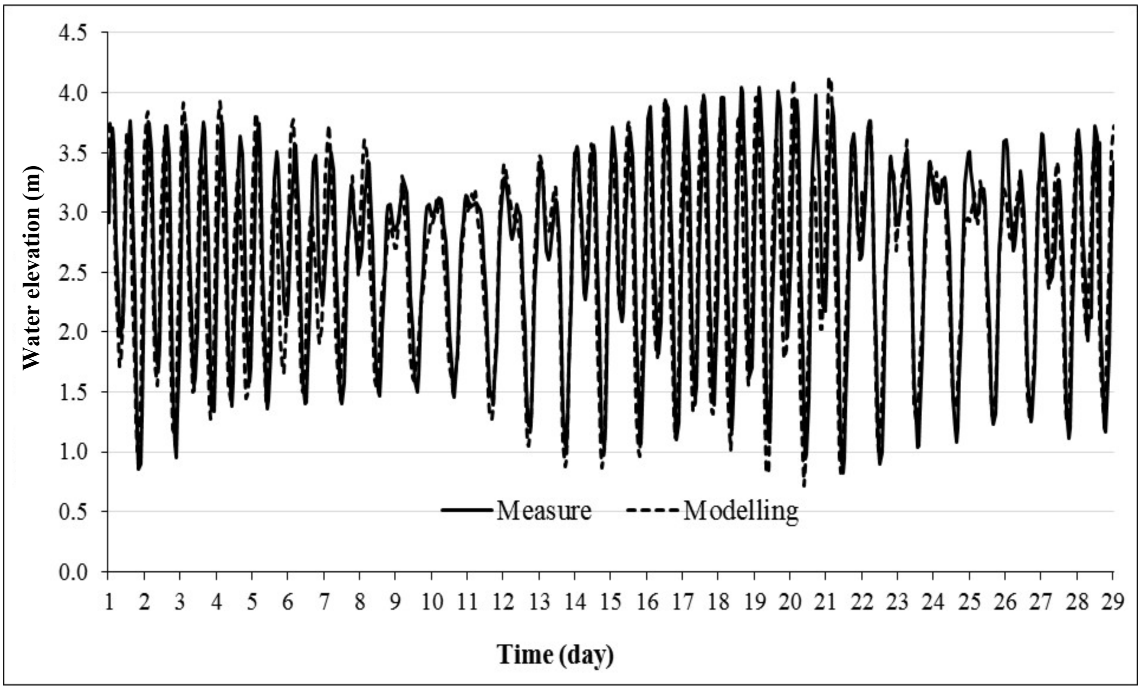
Time (day)

(a)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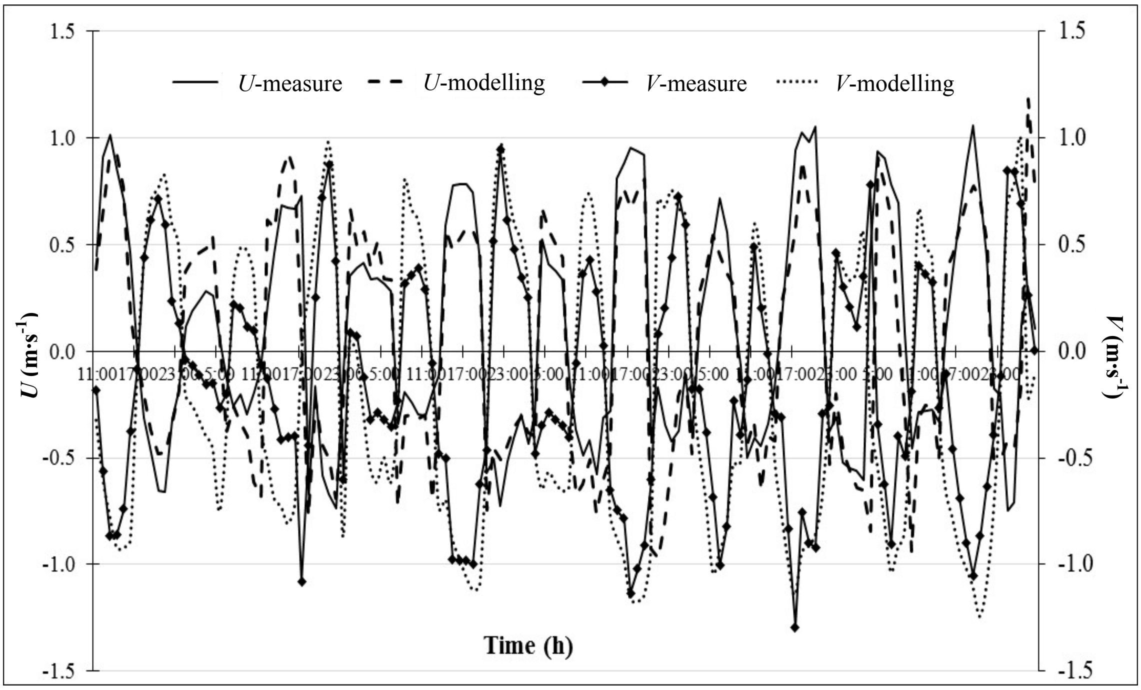

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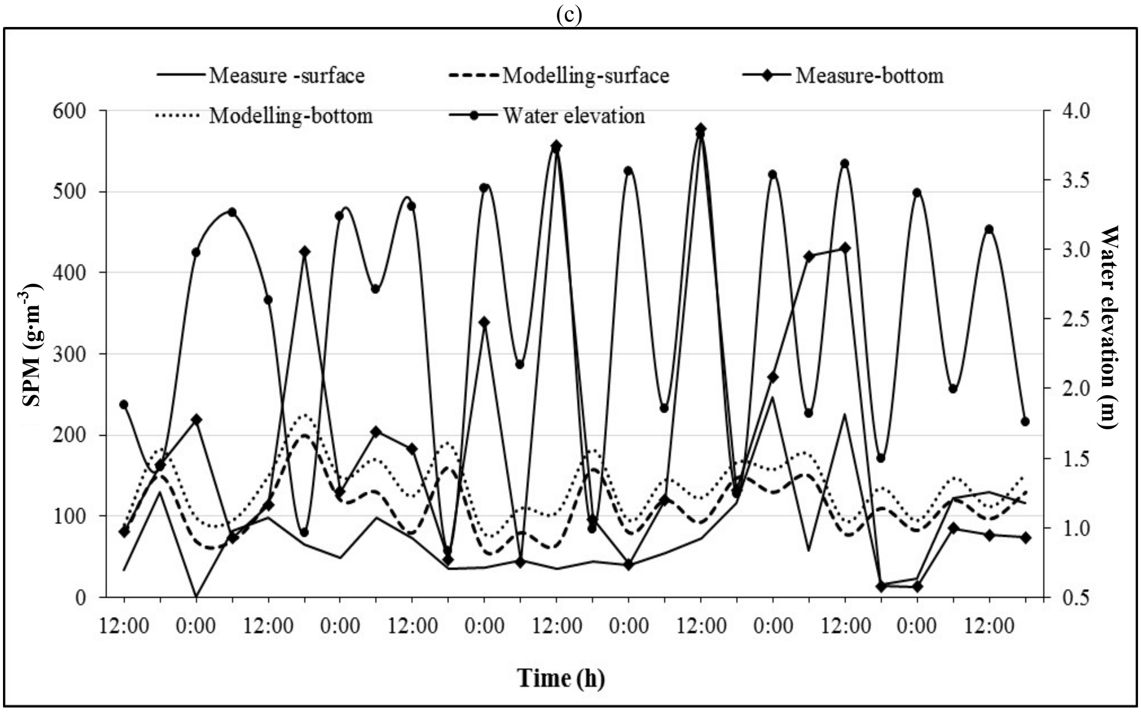


(d)

Fig. 2 Comparison between modelling results and measurement: (a) water elevation at Vung Tau in April 2012; (b) water elevation at Vung Tau in September 2012; (c) componential current in middle layer in Xoai Rap mouth (September 14-20, 2013); (d) SPM (suspended particulate matter) in outside Tran De mouth (September 14-20, 2013).

turbidity areas in most major estuaries in the region. In the dry season, when suspended particulate matter flow from the continent is not great, the influence of sea water mass has absolute dominant in the high tide phase, making the deeper MTZ appearance inside the estuaries and the smaller content of suspended particulate matter in comparison with one in the flood season.

3.2 The Maximum Turbidity of the Coastal Areas of the Mekong River Delta

The analytic results have shown that the MTZs in coastal estuaries of the Mekong Delta closely depend on the fluctuating water levels and the source of sediment supply, and river water fluctuates in season. Compared with the Bach Dang River estuary, the fluctuation of MTZs (in space and time) between flood tide and low tide in this area is smaller [27].

In the dry season, because the content and discharge of suspended particulate matter given into the coastal areas by river through the estuaries is relatively small, it is easy for seawater to go into the estuaries deeply, the formation of MTZs happens clearly in the estuaries.

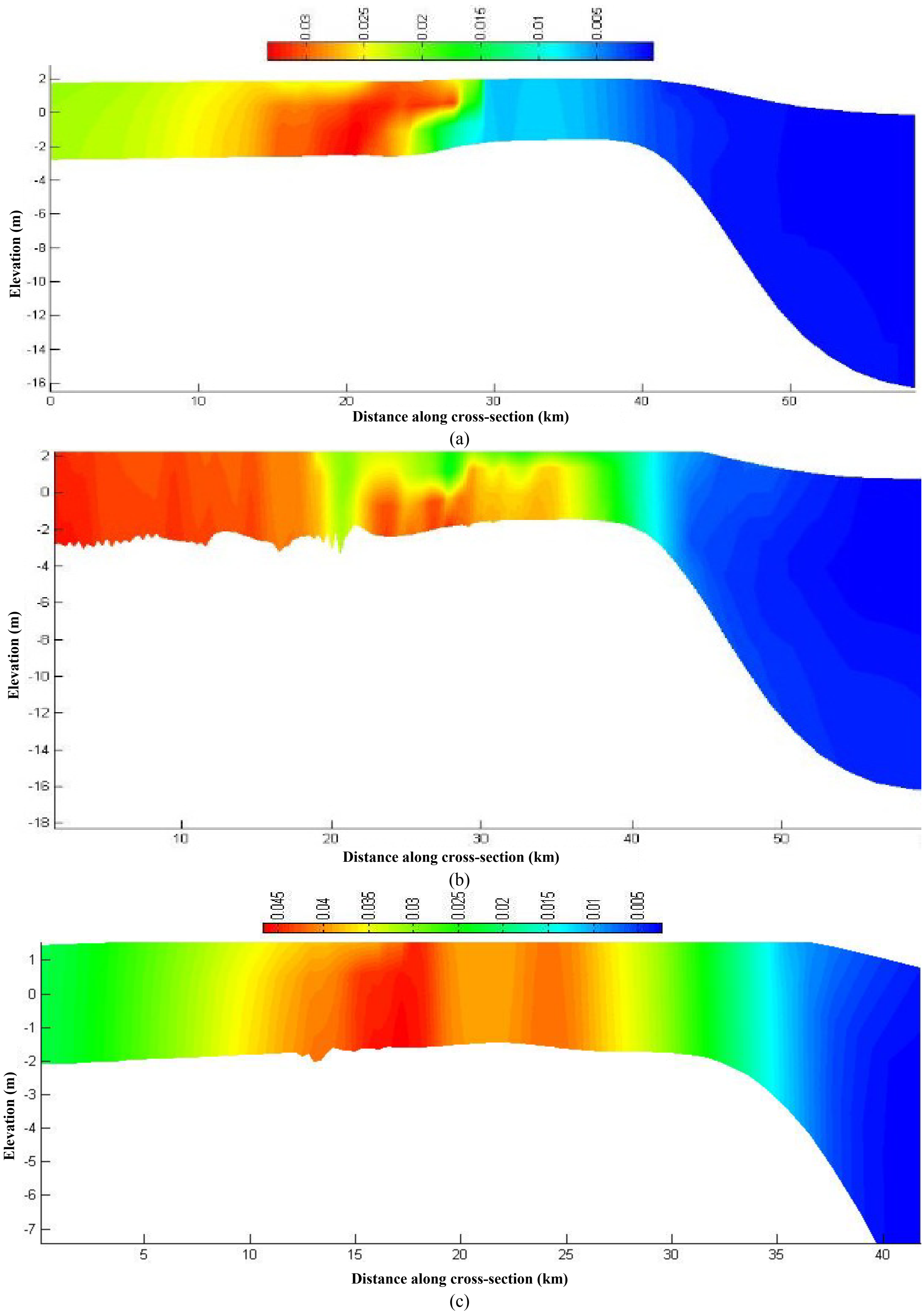
In the low tide phase, the influence of water mass with high content of suspended particulate matter is maximum. The interaction of two river-sea water mass is shown on the vertical profiles of suspended particulate matter from outside the estuaries to outwards. On the profiles, there are appearances of areas with higher content of suspended particulate matter than others. The vertical profiles of suspended particulate matter uniform fairly inside the estuaries (over 22 km away from the estuaries), but areas that are adjacent sea (about 5-22 km away from the estuaries) have the strong fluctuations in depth (the content of suspended particulate matter is higher than that in the surface and relatively small in the bottom) due to the influence of halocline. Because of the difference of the location and topography of estuaries, the level of formation of MTZs as well as the incidence of suspended particulate matter outwards from the estuaries are also various. The influences of sediment from the estuaries such as Dinh An, Cua Dai, Tran De are bigger than others.

The shape and appearance of MTZs are very clear in the high tide phase and the high water when having the interaction between seawater and riverwater. In Dinh An estuary, MTZ moves between 18-22 km (compared to the estuary) with the content of suspended particulate matter to be about 0.04-0.07 $kg \cdot m^{-3}$ (Fig. 3a). Meanwhile, in Cung Hau estuary, MTZ concentrated away from estuary approximately 15-20 km and the content of suspended particulate matter in this turbidity area uniform fairly vertically with the value of 0.04-0.06 $kg \cdot m^{-3}$ (Fig. 3c). In the outer Ham Luong estuary, MTZ reaches the maximum of 0.05-0.07 $kg \cdot m^{-3}$ with location about 12-17 km from the estuary (Fig. 3e). In Cua Dai estuary, MTZ is located about 15-20 km from the estuary with the content of suspended particulate matter about 0.035-0.06 $kg \cdot m^{-3}$ (Fig. 3g).

The fluctuation and formation trend of MTZs in the flood season are basically similar with the dry season. However, because the dynamic river in the flood season is much larger than that in the dry season, the MTZ characteristics in the coastal estuaries of the Mekong River have changed significantly compared to the dry season (Figs. 3b, 3d, 3f and 3h). These changes are:

- Location of MTZs in the flood season moves closely towards the estuaries approximately 3-8 km as with the dry season. This shows the stronger influence of dynamic river compared to dynamic sea;
- The content of suspended particulate matter of MTZs in the flood season is higher than that in the dry season with the common values between 0.05-0.1 $kg \cdot m^{-3}$;
- The appearance of MTZs in the flood season in the estuaries of the Mekong River does not occur as frequently as in the dry season. It appears mainly in the high tide and high water. The maximum turbidity zone also appears less on these days which have load of water from rivers. This means when the load of water is so huge to reduce the penetration of seawater (salinity) into estuaries, the freshwater and suspended particulate matter thrive outwards strongly and limit the formation of MTZs in the estuaries.

Because of the difference of topography and dynamic conditions, MTZs in the estuaries of the Mekong River appear more pronounced than that in Bach Dang River, especially at the end of the flood season and the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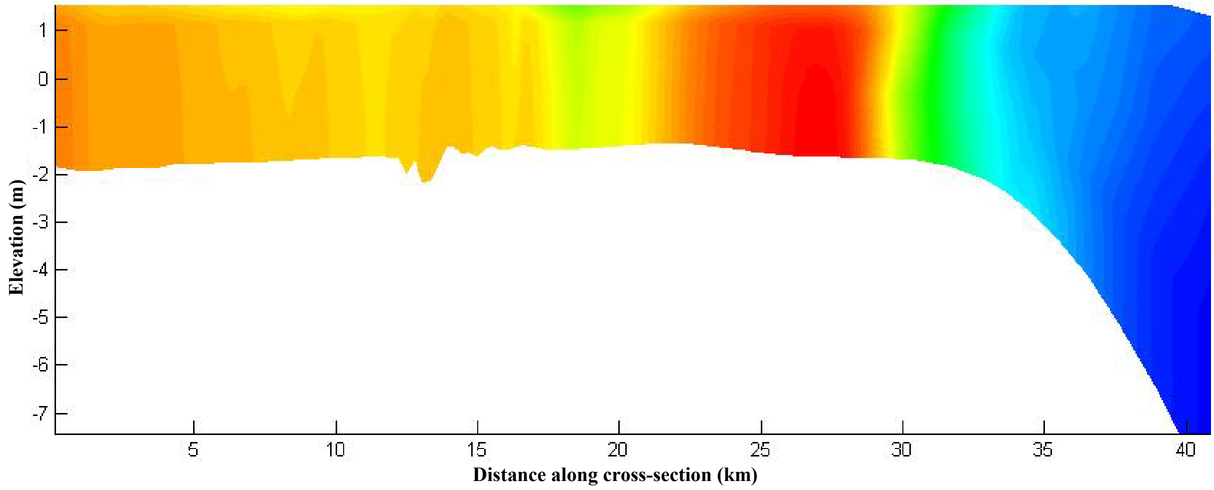
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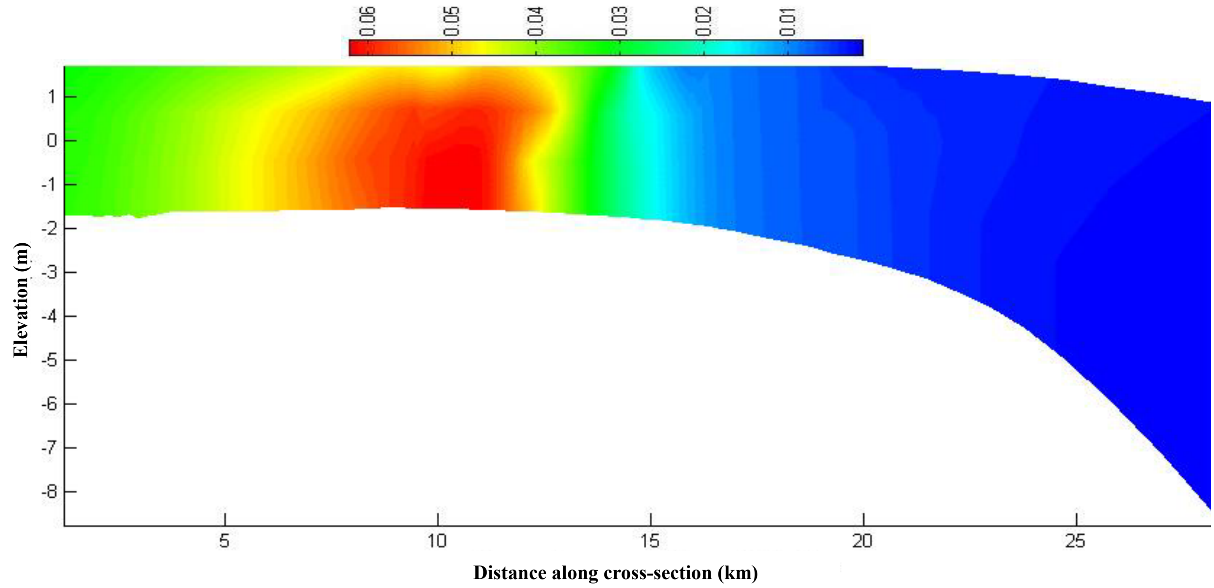
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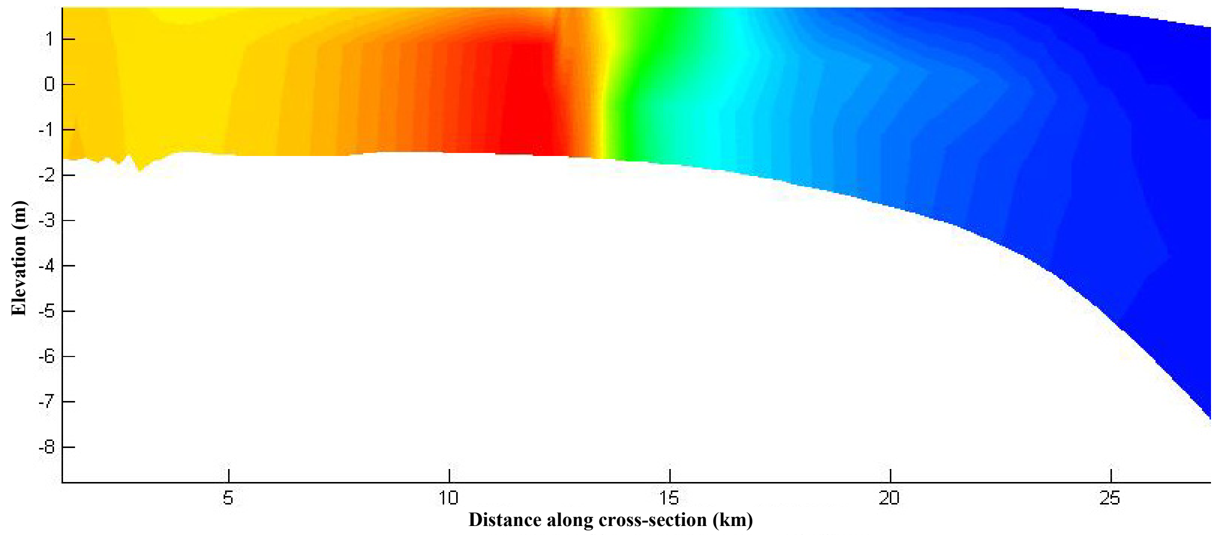
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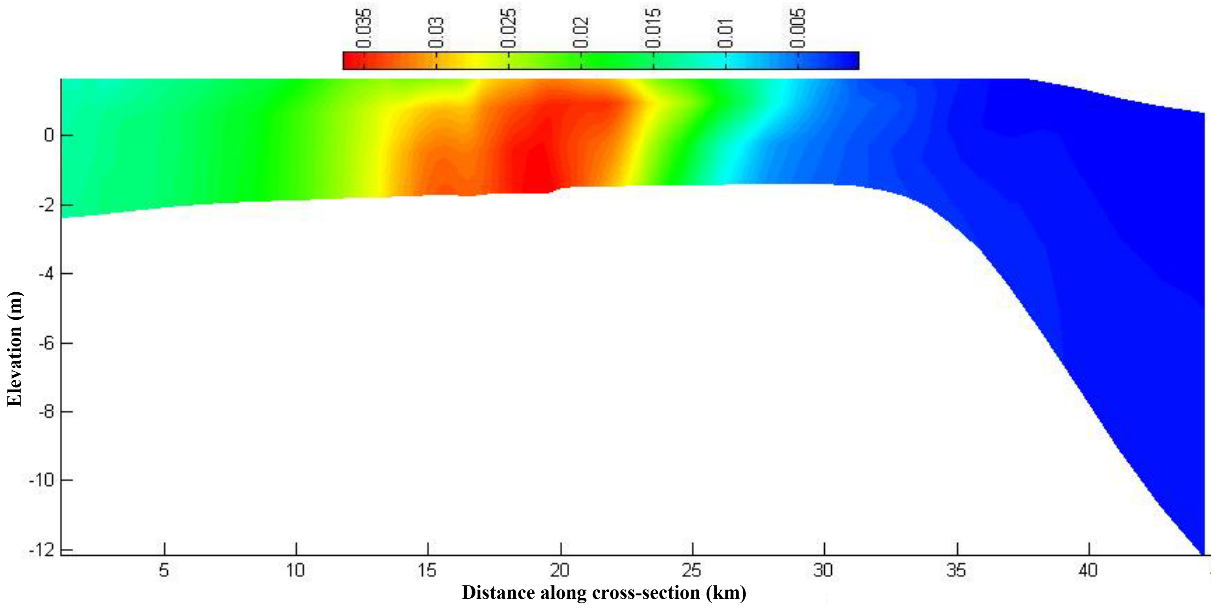

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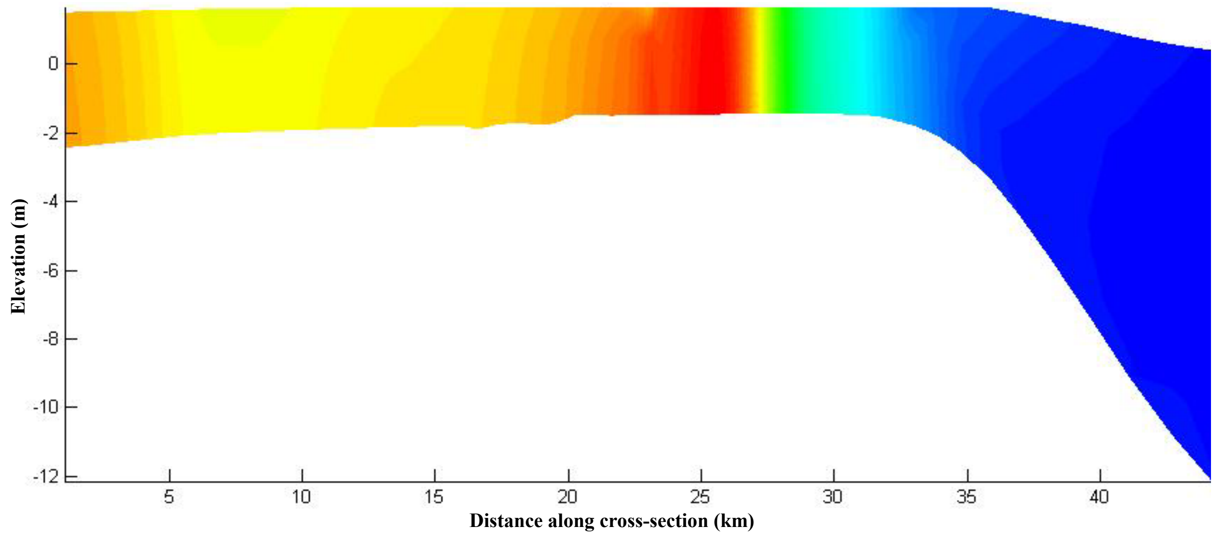

(h)

Fig. 3 SPM (kg·m^{-3}) profile in long sections: outside Dinh An estuary ((a) dry season; (b) wet season)); outside Cung Hau estuary ((c) dry season; (d) wet season)); outside Ham Luong estuary ((e) dry season; (f) wet season)); outside Dai estuary ((g) dry season; (h) wet season).

dry season. Most location of MTZs in this area located deep inside the estuaries, while at Bach Dang estuary, the maximum turbidity zones occur mainly outside the estuaries (Nam Trieu estuary) [27].

4. Conclusions

One of the results of the simultaneous interaction between river-ocean dynamic conditions in the coastal areas of the Mekong Delta is the formation of MTZs inside the estuaries in this area. The appearance and scale of MTZs closely depend on river flow and tidal oscillation. In the study area, MTZs appear more in the dry season and the high water-high tide phase, at different locations inside the estuaries. The position of MTZs located about 12-22 km (dry season) and 5-15 km (flood season) from the estuaries.

MTZs move along the profile from the estuary to the sea. However, in the moving process, they form the accumulation of mud, sand and buring nutrients, pollutants from the mainland. The results in this paper are only the first step. There should be more survey data on environmental conditions to verify the results of the calculated model.

Acknowledgments

This work was financed by the science and technological cooperation programme between the Vietnam and USA (2013-2015), the project “Interaction between Hydrodynamical Process Bien Dong (East Sea) and Water Mekong River”. It also benefited from the support given by VAST.ĐLT.06/15-16 project.

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