# HYDRODYNAMICS IN MANGROVE ESTUARY

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## ABSTRACT

The field surveys in Bujang Estuary conducted by Universiti Sains Malaysia (USM) provided some interesting features peculiar to a mangrove estuary system; that is, the asymmetric variation of tidal flow observed at an estuarine mouth, stratification and vertical mixing. They depend on tidal amplitude, rainfall, inundation and entrapping in swamps. In order to simulate such physical phenomena, a set of new mathematical model has been developed to apply the tidal flow and salt intrusion in creeks as well as inundation in swamps. The proposed model was built up the coupling of a three dimensional baroclinic flow model for creeks and a two-dimensional depth-integrated model for swamps. Comparison of the computed data with field data obtained in Bujang Estuary clarifies the hydrodynamic features in mangrove-fringed estuaries.

## KEYWORDS

mangrove estuary, creek and swamp system, field survey, mathematical modeling, tidal flow

## INTRODUCTION

Although a large number of rsearchers including biologist, ecologist and so on, has been carried out in mangrove estuary system, there has still remained unsolved. The mangrove estuaries consist of creek and swamp system. A creek corresponds to a river channel, while a swamp does a flood plain. At low tide, water is confined to the creek. However, as tide rises, water overflows its bank and progressively floods into the swamp with mangrove vegetation. Only during extreme high spring tide the entire area of mangrove swamp is flooded. After high tide changes to the low tide, the ebb current occurs in creeks, but the inundation water remains in the swamp to flow out into the creeks slowly. These events cyclically occur depending on the change of tide elevation. Field surveys have clarified that the magnitude of peak ebb current becomes larger than that of peak flood current at an estuarine mouth. With each tide a varying amount of dissolved and suspended matters is transported from the mangrove flats into the estuary and to the sea. Other findings are the change of mixing type in spring or neap tide, gravitational circulation, the heavy rainfall in the rainy season, meandering effects of creeks on flow and so on.

The present study focuses on the hydrodynamics in the Bujang Estuary, which is one of branches of the Sungai Merbok Estuary in the West Malaysia. It is about 4 km with 18 bends and 50 m wide and 8 m deep at the mouth. Therefore, the size of Bujang Estuary is very convenient for field surveys. The field surveys were carried out by researchers of USM for understand the physical proccsses, while those of Osaka University have already started to discuss the flooding of swamps in meandering channels and also the asymmetric changes in the velocity fluctuation at the estuarine mouth due to the flood water entrapped in the swamps (e.g. Nakatsuji et al., 1996). These discussions, however, were based on depth-integrated two-dimensional (2-D) numerical experiments. For better understanding of the phenomena, especially for the large precipitation periods during rainy seasons, it is necessary to apply a three-dimensional (3-D) numerical simulation taking the density change in the creek into account.

## FIELD SURVEY

A field survey in Bujang Estuary was carried out by USM. As shown in Fig. 1, the basin is surrounded by farmland, and a drainage outlet with a slice gate is located at the upper reach of the estuary. Three current meters and one conductivity-temperature chain deployed on 17 November. One at mid-depth in the top station and two at the mouth, one near the surface and another 1.5 meters from the bottom. The conductivity-temperature chain was deployed at the mouth station. Two tide gauges were deployed on 18 November, one at the top station and the other at the mouth station. The bottom mouth station stopped recording midway. Two sampling of water were also carried out, one during neap tide (from 19 November to 20 November) and another during spring tide (from 26 November to 27 November). The measuring stations are shown in Fig. 1.

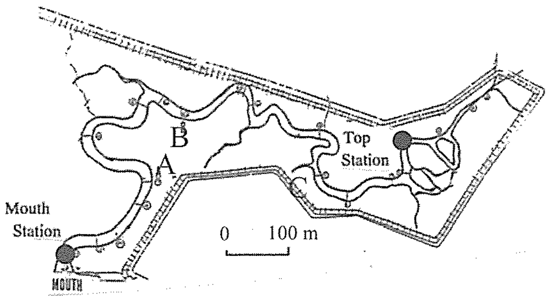



**Fig. 1 Topological map of Bujang Estuary and location of measuring stations**

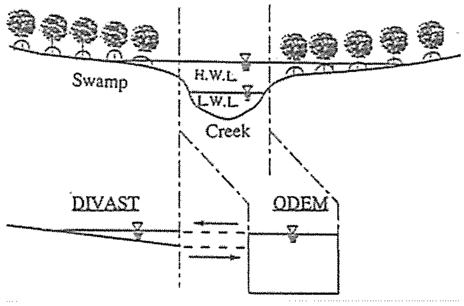



**Fig. 2 Modeling of cross-sectional creek and swamp system**

## MATHEMATICAL MODELILNG

The mangrove estuaries consist of a creek and swamp system as shown in Fig. 2. A creek corresponds to a river channel, while a swamp does a flood plain. The flow in the creek are affected by the density gradients in both longitudinal and vertical directions; hence the flow shows a complicated, three-dimensional behaviours. In contrast, overflowing water inundates in swamps with shallow water depths. It is, therefore, meaningless to apply a 3-D model to the swamps, where the water flow is determined by the balance between the slope of the water surface and the resistance of the roots of mangrove trees which grow there densely. The model is required to exactly represent the frontal phenomena of overflowing water between dry and wet beds in swamps.

In the present study, a 3-D baroclinic flow model is applied to the flow in creeks where the flow behaves three-dimensionally, while a depth-integrated, a 2-D flow model is applied to the flow in swamps where the front of flooding water changes depending on the tide. For proceeding the numerical simulation, ODEM-code developed at Osaka University (Nakatsuji et al., 1988) was used for the flow in creeks, and DIVAST-code developed at Bradford University (Falconer, 1991) was used for the flow in swamps. The 2-D models were connected at the boundary between the creek and the swamp together trying to reproduce the entire flow in the mangrove estuary.

### Connecting the Two Models

The flows from creek to swamp or from swamp to creek are connected at the bounary between both water areas as shown in Fig. 2.

*From ODEM to DIVAST;*
The water level in the creek obtained by the ODEM is given as the boundary condition of the DIVAST. The salinity computed by the ODEM is added to the boundary conditions of the DIVAST only when overflowing water from the creek inundates in the swamp.

*From DIVAST to ODEM;*
Using the flow rate flux at the boundary of the swamp computed by the DIVAST, the values of change in the water level is computed and then corrected. The salinity is added as the salinity flux to the top layer mesh in the creek at the boundary. The above method of connecting the creek and the swamp takes no account of the transportation of momentum. This is justified by the fobservation results that the flow between the creek and the swamp in the real estuary is induced by the slope of the water surface.

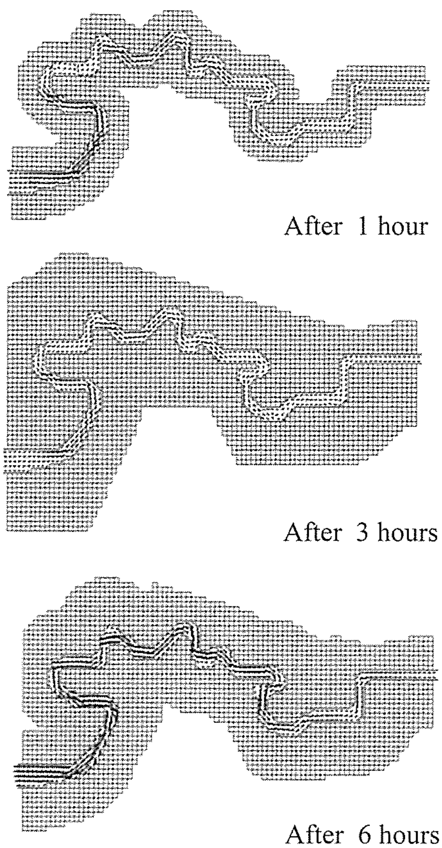
### Computation Conditions
The computation meshes for the creek and the swamp are 20 m x 20 m on a horizontally rectangular coordinates. The slope of the swamp is set to 3/1000 on the basis of field surveys. The thickness of vertical layers in 3-D model for the flow in creeks are 2 m in the surface upper layer and 1 m in others. It is because the tidal changes must be included in the surface layer. There were 8 layers at the deepest area. Measured data in the field surveys are used as salinity boundary conditions.

## COMPARISON BETWEEN COMPUTED AND MEASURED DATA

### Inundation of Overflowing Water into Swamps
Accompanying with water rising due to tide elevation, the water in creeks overflows beyond a bank to inundate into mangrove swamps. From the physical viewpoint, the flow in mangrove swamps is dependent on water surface slope, resistance on estuarine bed, complicated vegetation. A vegetated-induced friction is strongly related with inflow pattern.

Figure 3 shows the inundation of overflowing water into mangrove swamps in a case of spring tide, the tidal amplitude of which is about 1.5 meter. The time is defined at 0 hour when a tidal level becomes 0.0. Flowing from creeks to swamps has already started at around 1 hour. Then, over-flowing water inundates into almost whole area after 3 hours when the tide elevation attains at the highest at the estuarine mouth. There is a few velocites in current at the maximum ebb tide after 6 hours passing when the water levels in creeks and swamps should be zero. However, inundated water still remains in the mangrove swamps. Accompanied with decreasing tide level, a part of overflowing water will fall down into creeks in a slow speed. This phenomena is called as "entrapping in mangrove swamps".

In a case of neap tide, which is not shown due to lack of space, the volume exchanging between creeks and swamp is smaller than that of spring tide. There are not difference in the level between creeks and swamps.




**area and velocity vector in the case of spring tide**

## Asymmetric Pattern of Tidal Flow at Estuary Mouth

Figure 4(a) shows a comparison of observed and computed values of the velocity at the estuarine mouth at spring tide. The observed and computed values match very well. The two velocity peaks appear in the flood tide, however, dose not appear clearly in the computation. Although this computation use a constant slope for the swamp and a constant roughness coefficient in the whole domain, the slope of the swamp varies from location to location in real estuaries and the roughness coefficient changes with time depending on the water level. These factors enhance the trapping effect, and also increase the time difference between the first peak caused by the slope of the surface in the creek and the second peak caused by the flood into the swamp.

In case of neap tide as shown in Fig. 4(b), since the variations in the observation data and the computed velocity are all small, it is difficult to give a strict comparison. Roughly speaking, the results of observation and computation show good agreement. The computation results exhibit the asymmetry of the larger ebb current velocity than the flood current velocity. Although it is slight, the phenomenon of two velocity peaks in the flood current can be reproduced in the computation results. Velocity of 0.0 m/s means that the observation did not done due to accedents in observation.

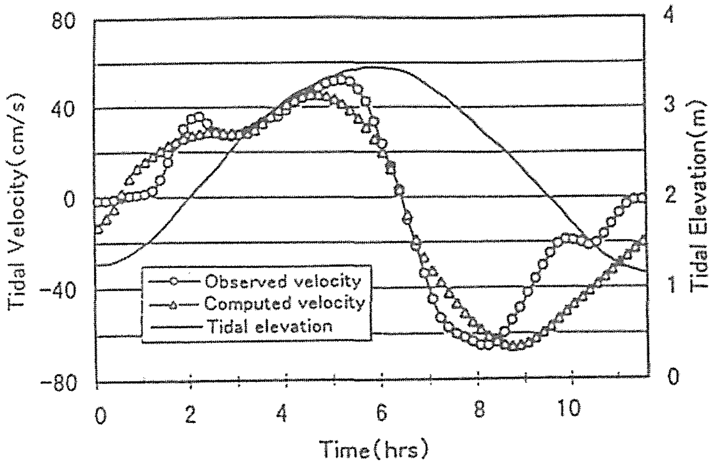



Fig. 4(a) Comparison of observed and computed velocities aat the estuarine mouth in spring tide

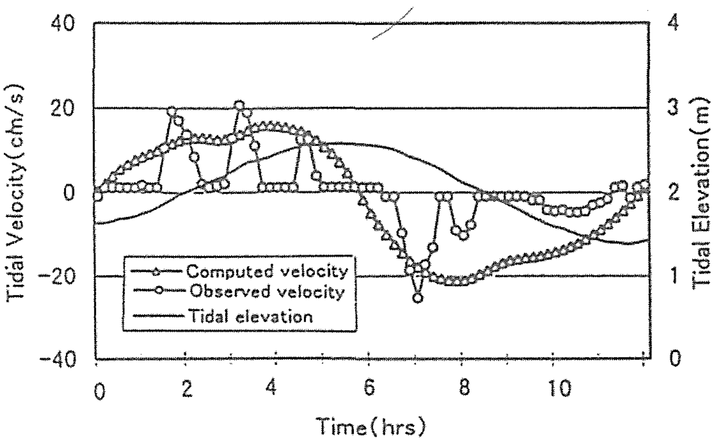



Fig. 4(b) Comparison of observed and computed velocities aat the estuarine mouth in neap tide

## Computed Salinity Intrusion Along Creek

The observation results reported in the the above section show that the flow is well-mixed at spring tide and it is stratified at neap tide. Through the comparison of observation results, the density structure (salinity distribution) in the creek of Bujang Estuary is reproduced by numerical computation. Since fresh water inflows from drainage outlets of the farmland are observed when the tide flows out at spring and neap tides, water volume from the outlet was taken into account.

Figure 5 shows the salinity distribution in the longitudinal direction. A, B and C in the figure corres-pond to observation points indicated in the topographic map of Fig. 1. Time zero is set when the change of tide level at the estuarine mouth is 0 m. Through the middle to the lower reaches of the estuary, the the slope of salinity increased notably while the tide is ebbing, showing a stratification as shown in Fig. 5(b). This computation therefore reproduces the characteristics of the neap tide successfully. Compared to the neap tide, the sea water intruding distance at spring tide is large with extremely high salinity concentration at high tide even around the upper reach in Fig. 5 (a). At low tide, water with low salinity concentration reaches the estuarine mouth. This intense cycle of inflow and outflow of sea water can be confirmed in the observation results. Both figures suggest that sea water with high salinity flows in through the whole cross-section of the flow from the upper to lower layers at high tide and low-density water with low salinity flows out faster from the upper layers at low tide. The notably precision of the vertical salinity distribution around the upper reach is not good for both spring and neap tides case. Since the water is shallow there and only one or two vertical layers were available for numerical computation, it is difficult to represent the vertical slope of salinity accurately.

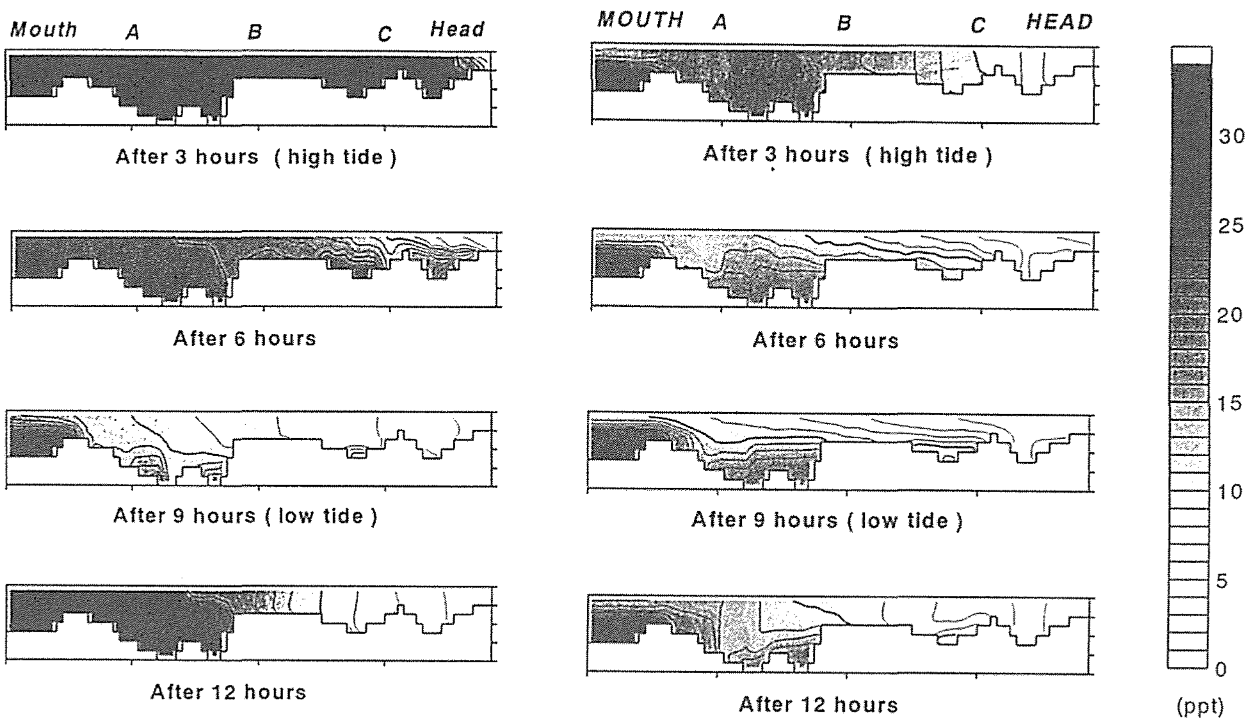



Fig. 5 Longitudinal distributions of computed salinity in Bujang estuary:
(a) in spring tide (left figure) and (b) in ebb tide (right figure).

## CONCLUSIONS

The present paper described the results of field survey and numerical simulation conducted in the Bujang Estuary, a branch of the Sungai Merbok Estuary in the north-west Peninsular Malaysia. Our attention is paid to two physical phenomena generally observed in mangrove estuary, which is related with mass transport processes. One is the asymmetric flow pattern observed at the mouth of mangrove estuaries, where the velocity of flood current is larger than that of ebb current. The other is that the density structure by the intrusion of freshwater shows different mixing patterns at the spring and neap tides: a well-mixing pattern at the spring tide and a weakly-mixed pattern with stratification at the neap tide.

In the present study a new mathematical model is developed for clarifying the hydrodynamics in creek and mangrove swamp system in tropical mangrove estuary. The proposed mathematical model contains a 3-D baroclinic flow model (ODEM) for tidal flow and transport of salinity and nutrient in creeks, combined with a depth-integrated 2-D barotropic flow model (DIVAST) for inundation flow in swamps. In the case study of the Bujang Estuary, computation results show good agreement with the observation data, while clearly reflect some characteristics peculiar to the mangrove estuaries obtained by field survey. The model also is applied to the Sungai Merbork Estuary. It is possible to quantitatively understand the physical characteristics which has been estimated qualitatively so far. However, there are lack of fundamental field data of not only physical data but also biological, ecological and chemical data in mangrove swamps. Further improvement of ecosystem maybe depend on more reliable field data.

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