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Seasonal Variability of the Water Residence Time in the Madura Strait, East Java, Indonesia

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Abstract: A Lagrangian particle tracer method embedded within a 3-D finite difference hydrodynamic model is used to study the transport and exchange processes in a semi-enclosed water of Madura Strait, East Java, Indonesia. The 3-D hydrodynamic model forcing functions consist of tidal elevation at north and east open boundary, river discharge of Brantas River estuaries, and monsoonal wind. The validated model successfully estimated the variability of residence time. The calculation results show that water residence times in Madura Strait and especially in its tributaries are mainly governed by the strength of river discharges, whereas the direction of advection is influenced mainly by monsoon wind directions and less by the tide-induced residual current.

Key words: Hydrodynamics, water residence time, Lagrangian model, Brantas River, Madura Strait.

Introduction

Coastal regions are home to large and growing populations. Nowadays, approximately three billion people or almost half of the world population live within a 200 km band of coastal waters (Creel, 2003). The environmental degradation of coastal areas is very acute in some developing countries. Although the causes of progressive coastal environment decline are complex, it is believed that anthropogenic pressure has a considerable contribution. Coastal waters turn to become repositories for immediate direct point discharge of contaminants, indirect pollutant input through diffuse land sources and atmospheric pollutant deposition. The knowledge about the dynamics of coastal waters is very important to understand the transport and the fate of the contaminants in the system and its capabilities to influence the various pollutant pathways. However, to understand the dynamics of shallow waters near coastlines is more difficult than dynamics of the open ocean. The existence of shelf friction, increase of tidal currents that have important consequences for the stratification and water movements, and the type of mixing in the surface layer as a determinant for the strength and direction of wind driven currents are some factors that distinguish between coastal waters and the open ocean. Additionally, the presence of the coasts, the variation of sea level, stratification and the terrestrial influences are some factors that make coastal seas become special. This paper discusses the characteristics of water residence time driven by dynamics of a shallow strait in Indonesia that is influenced by two open boundaries with different types of tide and strong seasonal variability.

Some authors defined the residence time as "the time it takes for water parcel to leave the water body through its outlet to the sea" (Takeoka, 1984; Dronkers and

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Zimmermann, 1982; Delhez, 2005). The residence time is a measure of the average time a substance spends within a physical system; this substance could be any particle flowing with the water. In the case of the coastal ocean, a measure of residence time can be extremely useful in determining transport and fate of contaminants and organisms in such surface water systems. Using relatively few data, knowledge on freshwater resident time can be applied, for example, to estimate the fractions of upland inputs of nitrogen that are exported or denitrified (Dettmann, 2001). The map of residence time is also useful in assessing placement of aquaculture operations, shown, for example, for Cobscook Bay, Maine (Brooks et al., 1999).

Methodologies for computing residence time and related variables have been investigated and developed using a variety of approach from the simple ones in terms of tidal prism, salinity-based estimation, or morphological relation (Rasmussen and Josefson, 2002). Such simplified models are adequate if the concern is for the average condition in an entire bay or estuary. High resolution hydrodynamic models can be used to calculate residence time in coastal estuaries in more thorough ways than by observations alone. The simplified models may be evaluated against water calculation exchange based on identification of transport components in a specific transect or hydrodynamics model of different complexity (Rasmussen and Josefson, 2002). In this paper, the use of Lagrangian tracer techniques is described to compute water residence times based on hydrodynamic information from a three-dimensional current model.

Collection of water quality and biogeochemistry data has been done during Germany-Indonesian research project SPICE (Science for the Protection of Indonesian Coastal Environment). However, knowledge of physical oceanography of this area is very rare. To our knowledge, there is no study on the dynamics of the Madura Strait. Therefore, this study can be considered as a first investigation in which the residence time in the Madura Strait is computed and discussed. Hopefully, our work can elucidate the relationship of ocean dynamics with marine ecosystem.

Description of Study Area

Madura Strait (MS) is located between East Java at the west and south, Madura Island at the north, and Bali Strait in the east (Figure 1). The strait is connected to the Java Sea through the narrow, shallow channel of Surabaya Strait (SS) that is 14 km wide at the eastern entry, 2.4 km at its narrowest part, and 4.6 km at the north exit. Surabaya Harbour is located in the centre of the channel. Surabaya, the capital city of Eastern Java, is the second biggest city in Indonesia and the main harbour in the eastern part of Indonesia. The channel is dredged regularly to maintain its depth in order to be able to provide safe shipping routes in the Indonesian archipelago. MS is relatively shallow water with the maximum depth of about 40 m located in the east. The Madura Strait can be considered as a semi-enclosed, rectangular tidal basin with a uniform width and is characterized by smooth and regular sloping bottom topography, although it is not entirely closed due to the

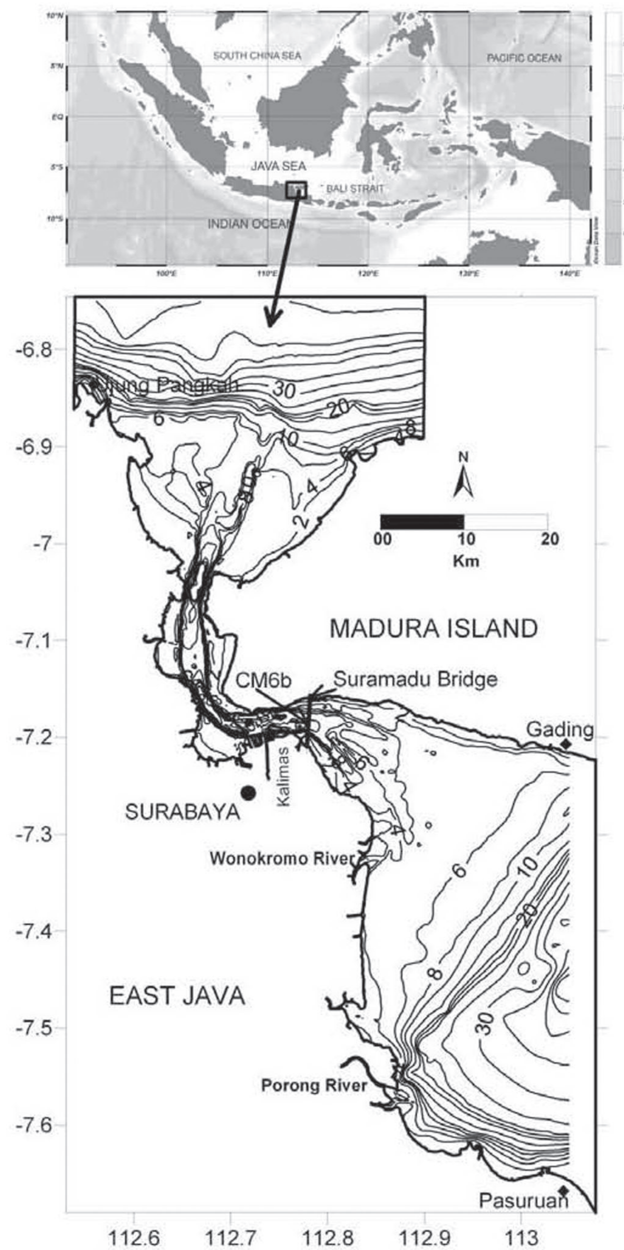

Figure 1: Location of the Madura Strait and bathymetry of the model domain.

presence of the Surabaya Strait. The tidal residual transport from the Surabaya Strait is estimated to be only 10% (0.0025 Sv) of the Madura Strait (0.022 Sv) (Hoekstra, 1989). Currents are strongest near Surabaya but gradually decrease in a southward direction.

Brantas River (BR) is the main freshwater discharge nutrient source for the MS. The river has been undergoing long-term ecosystem modifications because of anthropogenic activities such as dam construction, chemical fertilizer use, and land use modifications. The Brantas River with a length of 320 km and a catchment area of 11,050 km^2 (Figure 2, upper) is the second largest river in Java. It originates near the volcano Arjuno and diverts into three branches in the coastal lowlands. The

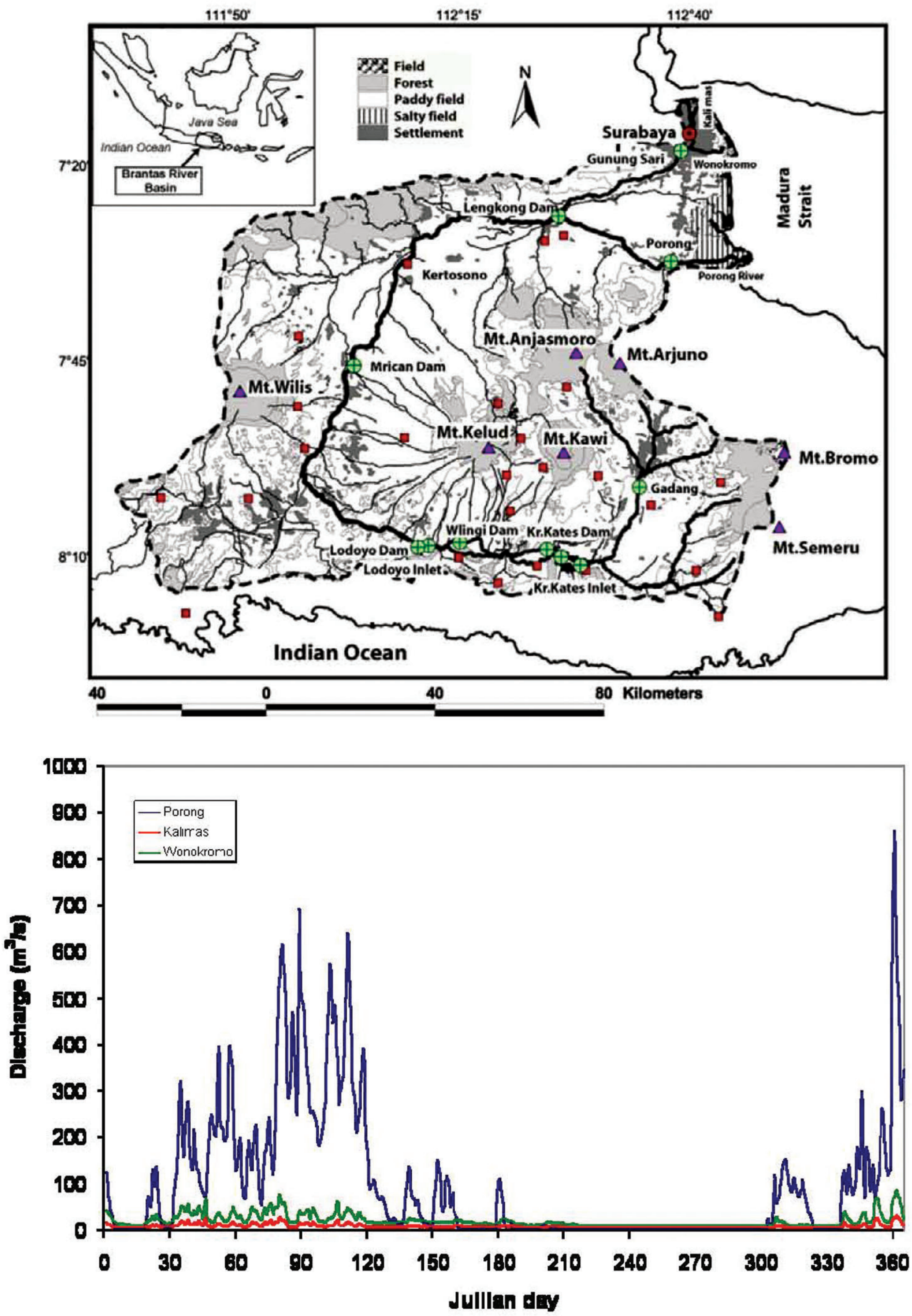

Figure 2: Brantas River basin, East Java, Indonesia. Rain gauge stations (square) as well as discharge stations (crossed circles) are marked (upper; after Aldrian et al., 2008) and daily discharge of Porong River, Wonokromo River and Kali Mas Rivers in the year 2007 (lower).

BR passes through 14 regencies and municipalities of the East Java. There are about 15 million people living in the basin (42% of the East Java Province population). The Porong and the Wonokromo are the two major branches discharging into MS, while the smaller Kali Mas discharges into SS after passing the city of Surabaya.

As easily conceivable from the aforementioned information the coastal waters of MS are heavily affected by human activities (Nugrahadi and Yanagi, 2003). The discharge of the BR plays, for example, an important role as a nutrient source. The influence of the BR to the MS can only be assessed by the combination of measurements and models. Therefore, our study is the first step to give an overview of the seasonal dynamics of the Madura Strait. The purpose of the research is to investigate water residence time in the Madura Strait using a 3D numerical model to simulate the circulation driven by the tide, wind and runoff from three principal rivers (Kali Mas River, Wonokromo River and Porong River).

Motivation and Investigation Concept

The fate of dissolved substances within certain coastal and/or estuarine environments is of high importance for management and research objectives in these areas. The spreading and advection of such water can be simulated either by Eulerian or Lagrangian numerical methods. The two methods give similar results when they are applied to simple cases such as regular basins or artificial channels (Takeoka, 1984). On the other hand, differences arise in application to basins characterized by complex geomorphology and hydrodynamics. The Lagrangian is less dissipative and therefore, better suited to look at residence time of certain water bodies. Therefore, in this investigation Lagrangian tracer techniques are used to calculate residence times in Madura Strait for different tidal and seasonal conditions.

The basic current information for the Lagrangian model is an Eulerian prognostic, baroclinic, general circulation model system for three dimensional shallow and deep water flow and transport problems. The reader refers to Duwe et al. (1983) for the standard governing equations and detailed numerical solution scheme. The model provides a broad band of applications in hydraulic engineering, environmental impact or risk assessment and decision-making for all types of natural surface waters. Most applications like transport of pollutants, spreading of heat, wind influenced circulation and sediment transport require a proper vertical resolution of the flow field. For processes which are influenced by the mass distribution (baroclinicity, stratification) like estuaries three dimensional modelling is an essential need. The model system consists of finite-difference Eulerian schemes calculating the non-linear Navier-Stokes equations (equations of motion and continuity) plus advection-diffusion equations integrated over the respective model layers defined by the discrete bathymetry and the water level elevation.

The basic idea behind the Lagrangian method is the introduction of particles as tracers, which are defined as a representative for a certain water volume. The method is similar to the “marker and cell” method of Harlow and Welch (1965). The tracers are advected by currents and turbulence; their properties such as salinity, temperature or suspended sediment concentrations are in addition influenced by sources and sinks as well as turbulence. The latter is described by dependencies to current speed and Richardson number (Talbot and Talbot, 1974; Awaji, 1982; Ghonhiem and Sherman, 1985). Generally, the approach is based on assumptions about the relationship between Eulerian and Lagrangian descriptions of current fields and their different dissipation characteristics (Longuet-Higgins, 1969; Sullivan, 1971; Zimmerman, 1979) and their approximation by Monte-Carlo methods. Estuarine applications have been described in this respect, for example, Maier-Reimer and Sündermann (1982).

The methodology is based on the description of substance distributions by a large number of particles within a flow field. This tracer ensemble is influenced by the mean current field, turbulence, and the properties as well as interaction processes of the substance in question.

Simulation Setup

The area of interest extends from 112.5° to 113.0° E and 6.7° to 7.7° S or approximately 57.6 × 101.7 km. The bottom topography (Figure 1) data in the coastal sea and Brantas River estuarine system used in this study were obtained from the Hydro-Oceanography Service, Indonesian Navy. The morphology of the Surabaya Strait has been changing rapidly due to natural impact and construction. Therefore, in order to have an updated coast line, this bathymetry is complemented by the coastline digitized from Google Earth (http://maps.google.de/maps?ll=-7.1373069,112.72958&z=11&t=h&hl=en). A 3D finite-difference grid was developed to adequately discrete the model domain. The cell size is 200 × 200 m. The horizontal grid contained 147,900 (290 × 510) cells and the vertical direction was divided into 15 layers with different intervals. Since the coastal sea is composed of tidal flats that expose to the air after tidal cycle, it is necessary to specify a drying water depth of 0.2 m and a flooding water depth of 0.3 m. The model time step is set to 900 s. The model currents start from the rest, so there is an initial spin-up period of one or two tidal cycles required for the model to come into equilibrium with the tidal sea-level height specified at the open boundary and with the initial temperature and salinity specified at each grid.

There are two open boundaries imposed at the northern part of Surabaya that represents tides in the Java Sea and in the east of the coastal water of the Brantas River estuary. There was no real measurement data at these open boundaries, therefore hourly water elevation were generated from eight tidal constituents reproduced by the WX_Tide free software (http://www. wxtide32.com/). Tidal constituents that are used in the WX_Tide are based on the old data; nevertheless it is still better than the tidal solution produced by the Oregon State University Tidal Prediction Software (Egbert and Erofeeva, 2002). The second tidal software may be good enough to give a tidal solution in the open area of the Indonesian Seas, but it has a poor resolution in the inner water such as MS.

The river discharges of the Brantas River are strongly affected by the monsoon (Figure 2, lower). The discharges and water quality data were provided by BR Authority Company Perum Jasa Tirta 1 in Malang, East Java Province. To investigate the probable influence of the wind field on sea surface current, three hourly wind data from Surabaya were acquired from the website of British Atmospheric Data Center (http://badc.nerc.ac.uk/ data/). Temperature and salinity at the open boundary were inferred from Comprehensive Oceanographic and Atmospheric Dataset in the period 1950 to 1990 (Claude Roy, 1996).

Topography of the MS is very complex; there is no consistent inflow and outflow as if in a bay or enclosed water body. Hence information about residence times in this area is not easily derived from Eulerian hydrodynamic information. Therefore, a Lagrangian particle tracer method was used to compute the advection and diffusion of water in Madura Strait. In order to compute residence time, one particle was released in each grid cell at the start of computations and thereafter the pathways were computed based on Eulerian current information from the three dimensional current model. The domains for residence time calculation are Surabaya Strait and Porong River estuary that was bounded until the water depth of 20 m.

Validation and Verification of the Model

Model calibration and verification are important steps to ascertain the model accuracy for practical application. Unfortunately, field hydro oceanography data in our study area is very limited and difficult to find. However, the model was calibrated and verified against the available data from the contribution of Badan Koordinasi Survei dan Pemetaan Nasional (Indonesian National Coordinating Agency for Survey and Mapping) to the international program Global Sea Level Observing System (GLOSS) and from Suramadu Bridge Project (2005). Prior to considering water residence time the model predicted water level was validated against the measurement in Surabaya (http://ilikai.soest.hawaii.edu/ uhslc/-htmld/0160A.html). The water level data set recorded in 1985 was chosen for validation because it is the most complete without any gap along the year. Figure 3 demonstrates that the model can accurately reproduce water level measurement. In addition, comparison of simulated currents time series were

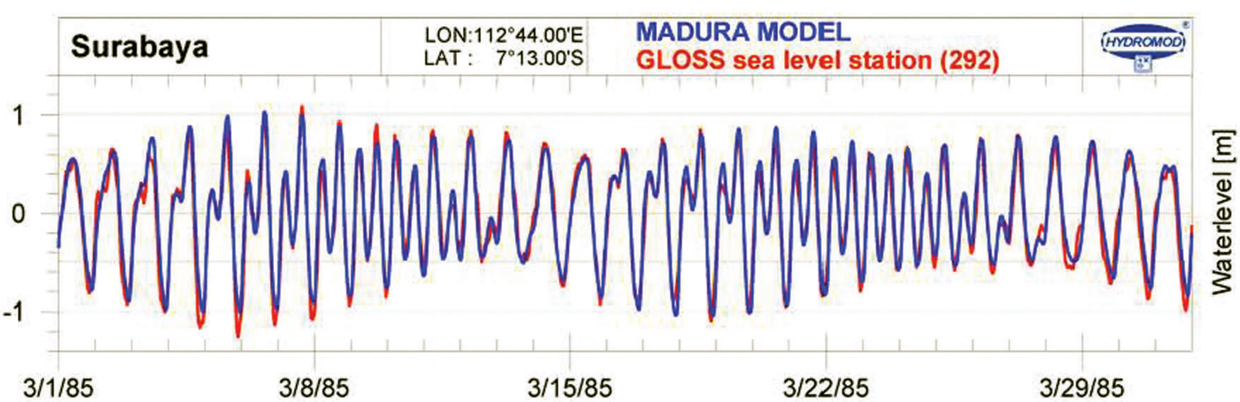

Figure 3: Comparison of simulated and measured water levels at Surabaya Harbour.

performed against measured ones in the eastern entrance of the SS shown in Figure 1 without changing the value of bottom roughness value determined in model validation. The currents compare well in the example shown for August 2005 at a position near the newly built Suramadu Bridge that connects Surabaya and Madura Islands (Figure 4). Thus, since the model can reproduce measured data of sea surface elevations and currents reasonably well, it can be concluded that the hydrodynamic model provides reliable results. Hence, we can expect that the Lagrangian simulations forced by these hydro dynamical fields are well realistic.

Results and Discussions

In this section, the result is gained from the computation of the hydrodynamic and Lagrangian particle tracking are presented and discussed. Simulation has been carried out for the whole model domain to produce the current field for the Lagrangian particle tracking. In this study, two regions of the MS have been considered in order to compare their residence time under different hydrology and meteorology-marine forcing. These regions are the Surabaya Strait and the Porong River estuary.

Currents in the Madura Strait

The simulation revealed that currents in narrow Surabaya channel are strongest with the largest speed being about 0.6 m s^{-1} and then gradually decreasing to the southeastward direction. Alternation of directions of currents in the Surabaya Strait is to the west and east with the frequency of 12 hours because of the balancing effect between the northern and eastern boundary. Clockwise eddies are found in front of the Porong River estuary. This might be caused by the relatively steep bathymetry that inhibits flow from the ocean to the coastal area. Such evidence can be obtained from AQUA-MODIS images of the strait showing the distribution of surface turbidity (Pranowo and Realino, 2004).

Seasonal Variability of the Residence Time

There are strong seasonal variations in the meteorological and hydrological conditions in the area. We investigate the various processes controlling the circulation in the MS. Although it is dominated by the tidal influence, the circulation is likely to be modified by the intensity of the turbulent mixing, freshwater input, and coastal ocean circulation and wind forcing. The processes that we consider here is the tidal range, particle release timing, wind and freshwater inflow from the Brantas River. In order to look at the variability of residence times three typical scenarios were chosen:

(a) Rainy season with high river discharges and west monsoon (March 2007).
(b) Transition period with mean discharges and variable winds (April 2007).

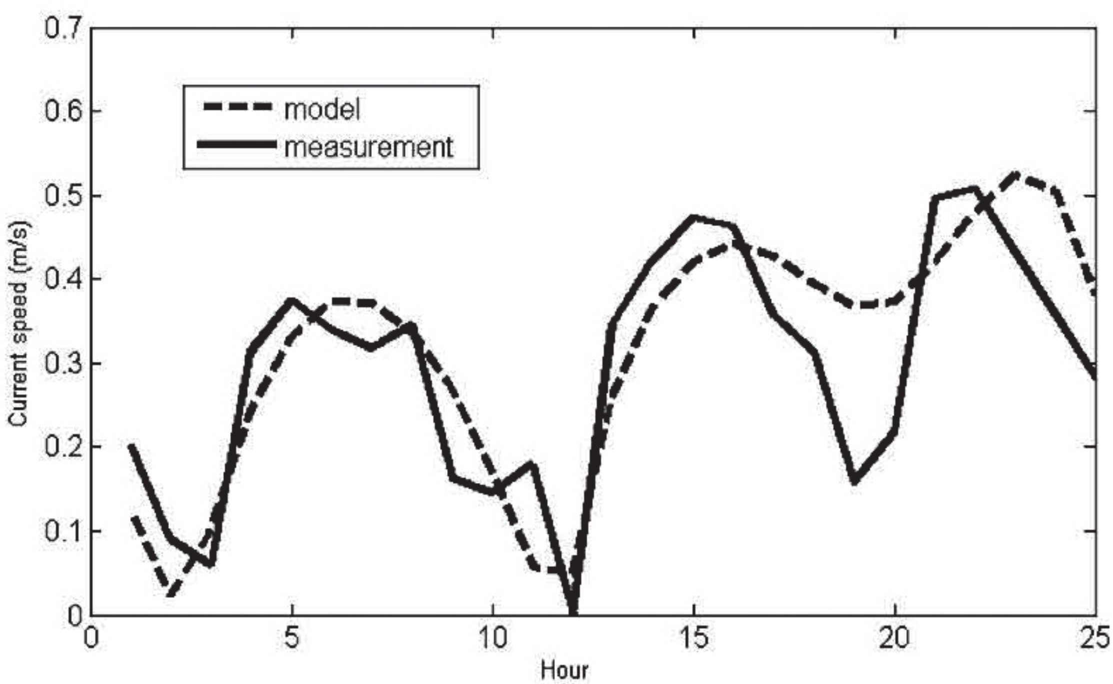

Figure 4: Comparison of simulated (dashed line) and hourly measurement current (solid line) at 3-metre depth at measurement position CM6b started on August 13, 2005 at 10 a.m.

(c) Dry season with virtually no river discharges and east monsoon (September 2007).

The residence time varies with these general conditions as well as tidal conditions when water particles enter the strait either from the open boundaries or from inflowing rivers. Figures 5 to 7 show the variations in residence times over a complete spring-neap tidal cycle (16 days) for all three scenarios and the influence of particles time release were indicated with water level conditions. Figure 5 shows daily variation of residence time over particle time released from 3 until 26 March 2007 that represent rainy season. In the rainy season with dominating semi-diurnal tides the residence time varies from below 200 hours until 250 hours. The residence time well corresponds with variation of current speed. Current speed reaches its maximum of 1.4 m/s when the semi diurnal tide is dominant, and then decreases to its minimum which is less than 0.2 m/s. The shortest residence times which are less than 200 hours occur twice when the particles were released on 18 March and 27 March, respectively. The longest residence time 250 hours occurs on 23 March 2007. Water residence time in April (Figure 6) is minimum 200 hours when particles are released on 15 April 2007 at neap tide from ebb to flood and current speed almost 1.4 m/s.

Residence time increases as the current speed becomes weaker when the tide changes from fully semidiurnal to diurnal on 21 April 2007. The longest residence time nearly 450 hours occurs on 20 April 2007 and then decreases again to 330 hours as the tide changes to semi diurnal. The influence of particle release time to residence time is more obvious in September 2007 simulation that represents dry season (Figure 7). The longest residence time occurs when the particles are released on 17 September 2007 as the current speed is weaker when the tide changes to diurnal. Afterward, the residence time decreases gently to 230 hours as the current becomes stronger when particles are released on 26 September

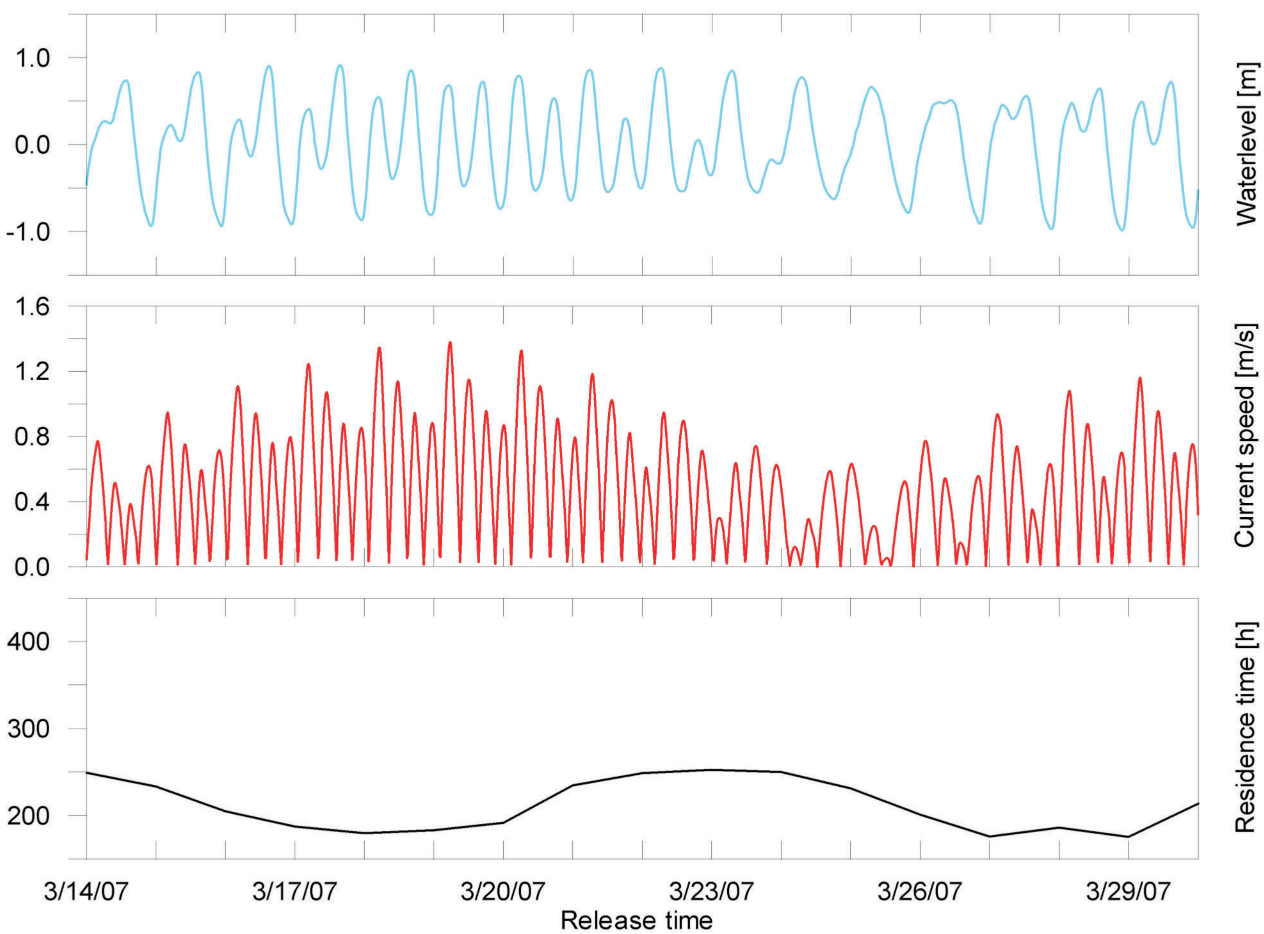

Figure 5: Rainy seasons in March 2007: Mean residence time in Madura Strait, water level and current speed in front of Surabaya Harbour.

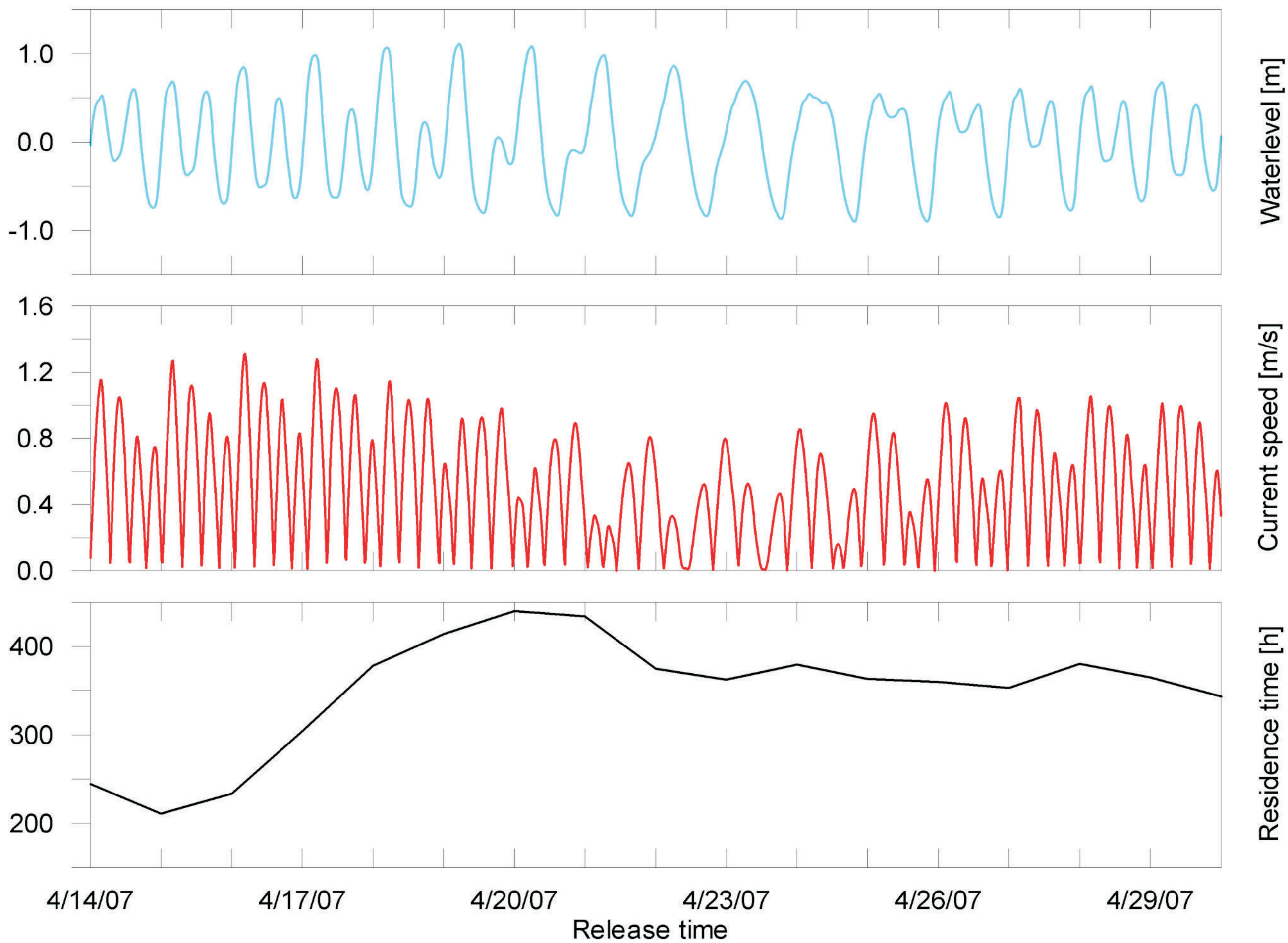

Figure 6: Transition periods in April 2007: Mean residence time in Madura Strait, water level and current speed in front of Surabaya Harbour.

2007. Our experiment shows that the change of tidal period plays a significant role on water residence time. When the tide shift from semi diurnal to diurnal, the current speed (hence residence time) becomes longer. On the contrary, when the tide shift from diurnal to semi diurnal, the current speed increases, hence water residence time becomes shorter. Water marked by tracer during strong tides does have a shorter residence time than water marked during neap tidal conditions.

Like general condition in Indonesian Archipelago, MS is subject to the monsoon. Monsoon winds generate a specific pattern of wind-driven current in the MS. In April and October and November the monsoon changes and the wind has more variable direction, but easterly winds predominate. Dry season period is from May to September, and the easterly winds prevail in this season. In the coastal area such as in the MS, the effect of monsoon is superimposed with the land-sea circulation due to the differential heating of land and water surface throughout the day, thus it creates a regular daily wind pattern (Hoekstra, 1989). To investigate the influence of wind to the particle distribution, we released the particle in the SS in the same tidal condition. Figure 8 shows distribution of particles seven hours after release under different seasonal wind. The pathways of water particles are strongly affected by winds and less by the mean tidal advection. During dry season or east monsoon (Figure 8, above right) and in intermediate period (Figure 8, bottom left) water particles are advected into Java Sea, whereas in the rainy season (west to northwest monsoon) the waters of MS are advected to the east (Figure 8, bottom right).

Residence Time in the Porong River Estuary

Variation of freshwater is one of the dominant factors controlling the transport processes (Shen and Wang,

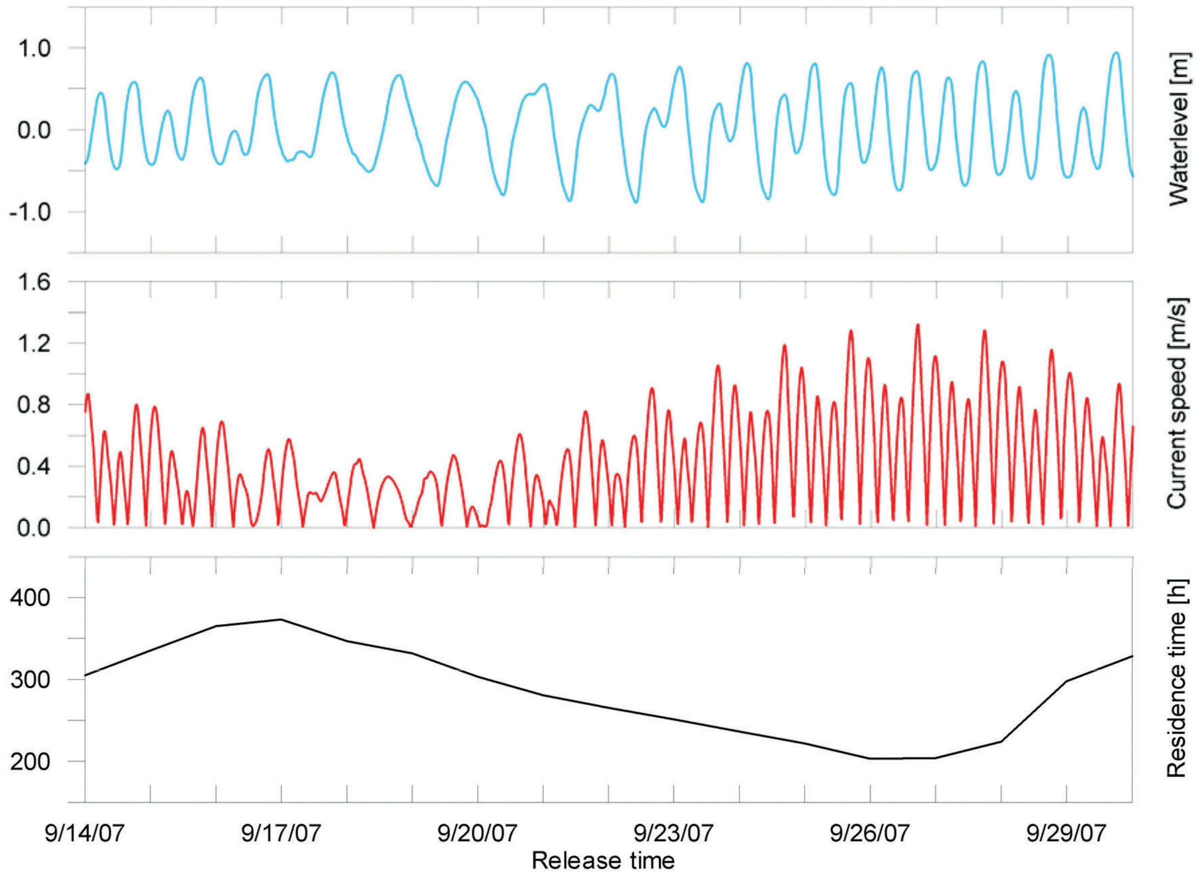

Figure 7: Dry seasons in September 2007: Mean residence time in Madura Strait, water level and current speed in front of Surabaya Harbour.

2007). Porong River supplies largest nutrients, suspended sediment and freshwater from land to the coastal water of Madura Strait (Nugrahadi et al., in submission). To address the effect of the river discharge and diffusivity strength on water residence time, an interesting case study was undertaken for water discharged by the Porong River south of MS. In Porong estuary, like measured by Hoekstra (1989), mean residual current is very small and sometime negligible. In this experiment, the particles were seeded everyday for 17 days from March 14, 2007 to March 30, 2007 and from September 14, 2007 to September 30, 2007, respectively. The residence times in this case were calculated as the time the water particle did not leave the 20 m depth mark as a measure of coastal environments.

The influence of tidal pattern (Figure 5, upper and Figure 7, upper), associated with discharge of Porong River (Figure 2, lower) to produce seasonal water residence time, can be seen from Figure 9. Water residence times during dry season and rainy season is striking. The average residence time in Porong River Estuary ranges 50-110 hours (ca. 2-5 days) and 300-350 hours (ca. 12-14 days) in the rainy and dry season, respectively. During strong tides and very high discharge as in March the residence times are short. This is shown when the particles are emitted between days 4 and 6. When the tide changes from semi diurnal to diurnal on 23 March 2007 or emission day 10, the water residence time becomes longer to be around 100 hours. In contrast, during dry season river discharge is very low. Therefore, the tide controls water residence time in Porong estuary fully. The longest residence time occurs when the tidal current is weak as the tide shifts from semi diurnal to diurnal on 17 September 2007, or emission day 4. Minimum residence time 300 hours occurs on 27 September 2007 when tide is fully semi diurnal as shown in Figure 7. However, a regression of water residence time against river discharges shows a moderate correlation ($WTR = 10.82 \times e^{(-0.0024Q)}$ $R^2 = 0.6309$). Using the three dimensional hydrodynamic model, Liu et al. (2008) studied residence time in Danshuei River estuary and compared the relationship between residence time

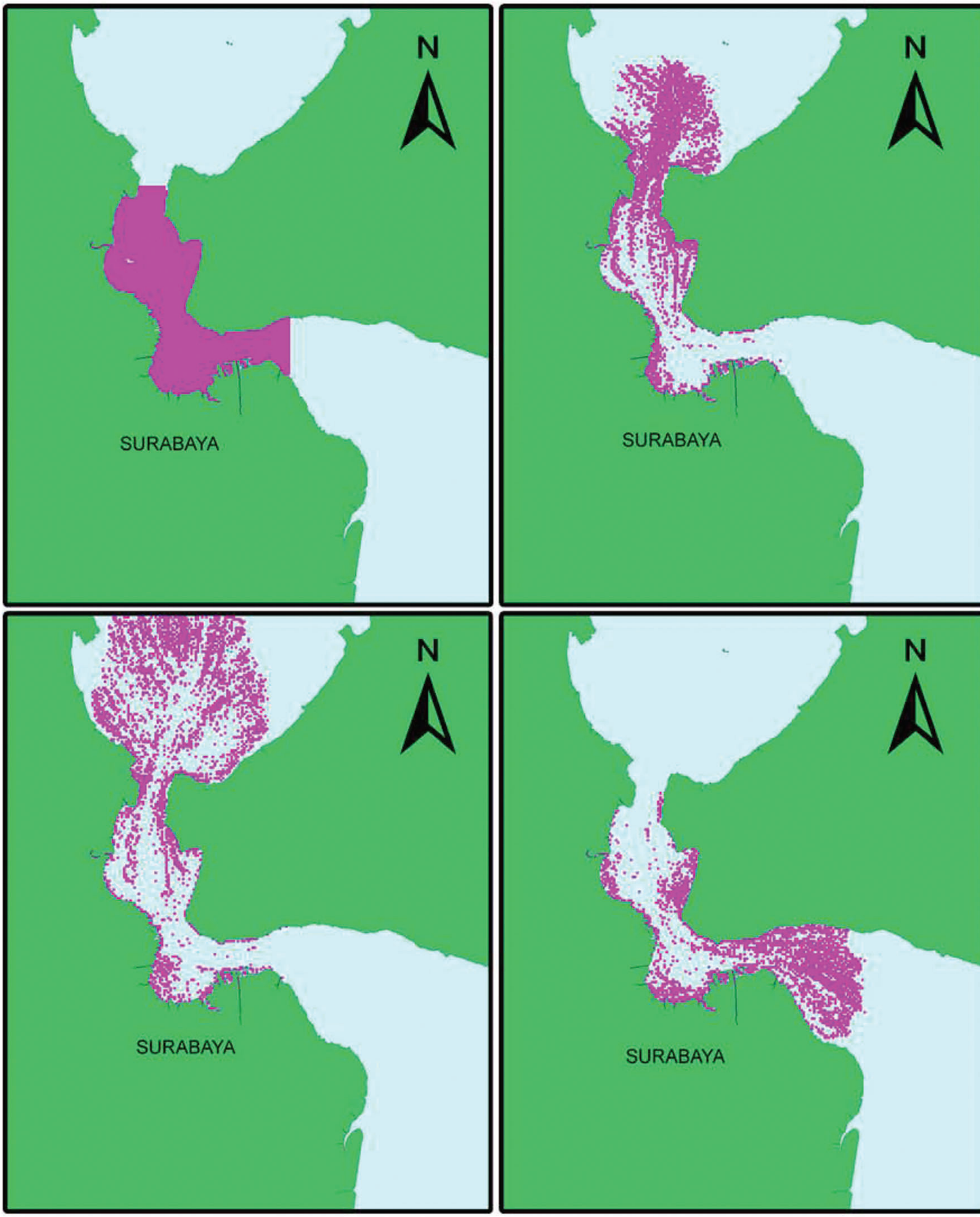

Figure 8: Distribution of water particles in Madura Strait seven hours after release: Initial distribution (picture above left), dry season (above right), transition period (bottom left), and rainy season (bottom right).

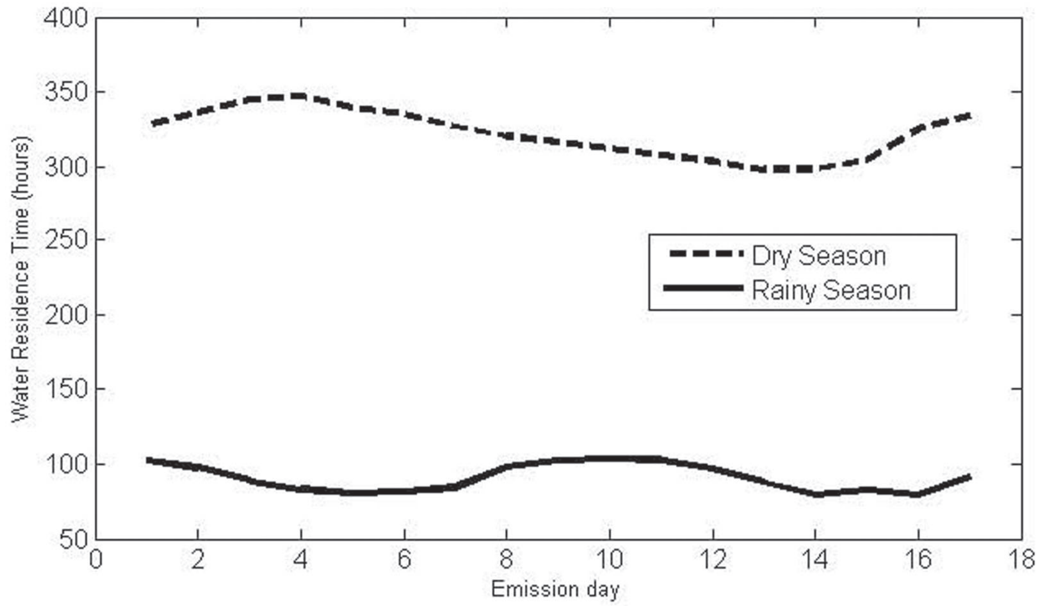

Figure 9: Daily values of residence times in the estuarine part of Porong River derived from Lagrangian tracer emissions for a 17-day period during the rainy and dry season.

and freshwater inflow with some bays and river. In comparison of the curves, the residence time of Porong River Estuary is more sensitive to the variation of river discharge than Danshuei River estuary and Narraganset Bay.

Conclusions

The use of Lagrangian particle tracer techniques results to reveal a seasonal variability of the coastal circulation and residence time as a consequence of fluctuations of its governing factors. Using a 3D hydrodynamic model driven by diurnal tides from the Java Sea at the northern boundary and semi diurnal tides from the eastern part of MS, large number of the particles is tracked over a period of one month. The effect of the tidal condition on time release, seasonal wind and freshwater inflow are investigated.

The calculation results reveal seasonal variability of movement of water particles, its residence time and its governing factors. In Surabaya Strait where the stronger current exists, the residence time and direction of particle advection are influenced mainly by monsoon wind directions and less by the tide-induced residual current. This condition occurs because Surabaya Strait is influenced by two open boundaries with different type; therefore there is a shifting period from semi diurnal to diurnal or vice versa. The contribution of river discharge from land to Surabaya Strait is weak. On the contrary, the tide-induced residual current in coastal area of Porong is weak; therefore the mean residence times are mainly governed by the strength of river discharges.

Madura Strait receives large seasonal and spatial variation of nutrient supply. Largest nutrient input is during rainy season and Porong River has the largest contribution due to high river discharge (Nugrahadi et al., in submission). In contrast, phytoplankton abundance during dry season is high in the coastal area of Porong River, despite very low concentration of nutrients (Jennerjahn et al., 2004). Thus, beside nutrient supply and light, the other physical process such as water residence time may play a very important role controlling biological activity in the coastal water of the area.

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