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EVALUATION OF THE WATER AGE IN THE WESTERN PART OF JOHOR STRAIT, MALAYSIA

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Abstract: The age of water is useful for understanding the fundamental mechanisms controlling the flux of substances through an estuary. Furthermore, this variable is useful indicators of the susceptibility of estuaries to eutrophication. In this paper, an application of a three-dimensional hydrodynamic model used to evaluate water age distributions for a range of inflow conditions in the Western Part of Strait of Johor, Malaysia. As a first step, the three dimensional hydrodynamic model EFDC was calibrated and then used to evaluate the spatial distribution of water age. Numerical simulations were completed under different inflow conditions. The analysis suggested considerable spatial variation in the water age under both low and high-flow conditions. The average water age in entire system is maximum 14 days under minimum inflow, 194.4 m^3/s and minimum 4 days under maximum inflow, 541.3 m^3/s. This analysis helped in recognition of areas of the estuary most vulnerable to oxygen depletion and eutrophication.

Keywords: *Water age, EFDC, hydrodynamic modeling, estuary, Johor Strait.*

1.0 Introduction

Estuaries are coastal area where freshwater from rivers and streams mixes with saltwater from ocean and are thus characterized by a variety of complicated and complex processes (Michaelis, 1990). One significant and typical estuarine phenomenon is the mixing zone between the saline water and freshwater. With population growth and industrialization has entered agricultural pesticides, large amounts of metals, nutrients, and chemicals into the aquatic environment .These materials have the potential to reduce the water quality and unfavourable effects on the aquatic life and human health through the food chain (Kennish, 1996). An estuary also serves as a connecting bridge between the ocean and land, and receives natural and human resources of these materials. Consequently, estuaries are easily polluted or contaminated of the marine environments (Sharp *et al.*, 1982). Considering the importance of estuaries, it is imperative to understand the hydrodynamic and transport processes of water and its compounds (Liu *et al*., 2008).

The timescales associated with how long water parcels and their related suspended and dissolved materials exist in a specific water-body as a result of different transportation mechanisms (such as dispersion and advection) are important physical characteristics of that water-body. Those transportation timescales strongly impact associated chemical, biological, and physical processes. Evaluation of transportation timescales is very important for management purposes because they are strongly related to the ecological health and water quality on the different aquatic systems of the world (Lucas, 2010). Numerous metrics have been used to calculate transport timescales, containing exposure time, residence time, and age of water. The age of water is an important local scale indicator of a system's water renewal capacity. These timescales have been used in the past as an approach to investigate the processes affecting the scalar transportation between estuarine environments and their external boundaries (Camacho and Martin, 2012). The water age and residence time scales were examined in a modeling study of the Hudson River plume on its entry to the New York Bight (Zhang *et al*., 2009). Huang *et al*. (2010) investigated water age modeling on Little Manatee River by hydrodynamic model using EFDC (Huang *et al*., 2010). Li *et al*. (2011) studied influence of wind on water age distribution.

In this paper, an application of a three dimensional hydrodynamic model used to estimate water age distributions for a range of inflow conditions in Western Part of Johor Strait. The hydrodynamic model was previously calibrated by field observations to quantify the mixing and transport processes in the estuarine system under wind, tides, and freshwater inflows (Kazemi *et al*., 2014).

2.0 Materials and Methods

2.1 Study Area

The Johor Strait is an estuarine system located on the coast of the state of Johor in Malaysia. Johor Strait separates the Peninsular Malaysia to the north from Singapore Island to the south, and it lies between the Johor River estuary to the east and the Pulai River estuary to the west with a distance of about 53 km. The major river catchments which carry out into the Johor Strait include five rivers with their river tributaries. These rivers include the order catchments area of Johor River, Layang River, Tebrau River, Skudai River and Pulai River 51,372 Ha, 2,453 Ha, 24,877 Ha, 31,667 Ha, 31,124 Ha, respectively. Causeway has divided this strait which is linking mainland Malaysia to Island of Singapore into Western Strait and Eastern Strait of Johor. The Eastern part of the Johor Strait is located between Causeway and The Johor River estuary to a distance of about 20 km and the Western Part of Johor Strait is located between Causeway and

Pulai River estuary to a distance of 33 km with a minimum width of 632 m and a maximum width of 12440 m in the close estuary of Pulai (Figure 1).

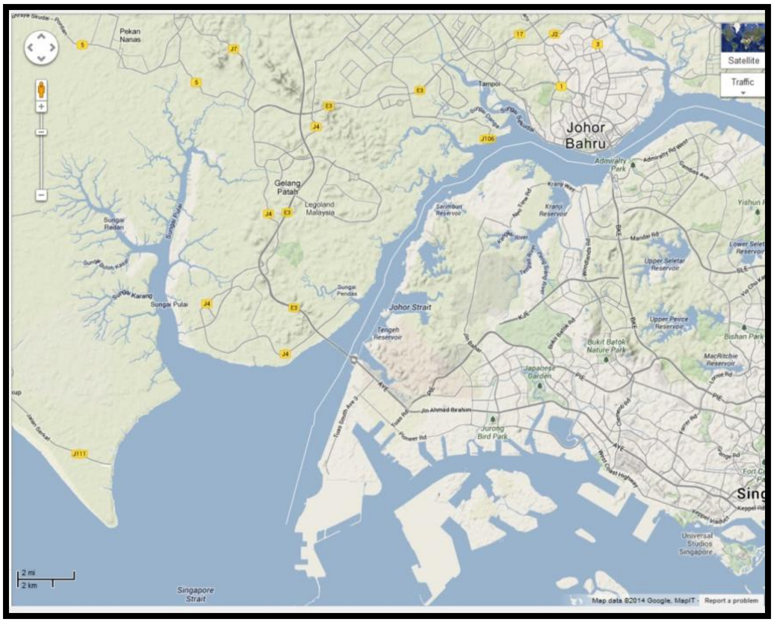

Figure 1: Study Area

2.2 *The EFDC Model*

The Environmental Fluid Dynamics Code (EFDC) model is a package that it is for the simulation of one, two, and three-dimensional transportation, flow, and processes of biology-chemical in the system of surface water, include lakes, reservoirs, rivers, estuaries, coastal regions, and wetlands (Hamrick, 1992 & 2001; Craig, 2012). The EFDC model has four main models; a hydrodynamic model, a water quality model, a sediment transportation model, and toxic model. Hydrodynamic model included six models of transportation such as dye, salinity, temperature, dynamics, drifter, and near field plume (Ji *et al*., 2001). Hamrick in 1992 and Hamrick and Wu in 1997 coupled directly various results of the dynamics model (i.e., velocity, water depth, and mixing) for the water quality, sediment transport, and toxic models (Hamrick and Wu, 1997; Ji *et al*., 2001).

The Environmental Fluid Dynamic Code is one of the most widely used hydrodynamic models and has been examined in more than 60 research model (Ji *et al*., 2001). In the recent two decades, many researchers have used widely it in the different parts of the world. Over 100 applications have existed for water bodies that include lakes, rivers, wetlands, reservoirs, coastal areas, and estuaries in environmental management and evaluation (Ji *et al*., 2001; Park *et al*., 2005; Liu *et al*., 2007; Wu and Xu, 2011; Wang *et al*., 2013). Successful applications of the EFDC model include research of tidal intrusion and its impact on larval dispersion in James River estuary (Shen *et al*., 1999), modeling estuarine front and its associated eddy (Shen and Kuo, 1999), hydrodynamic and water quality model in the Peonic Bay by Tetra Tech (1999). The hydrodynamic model for Lake Okeechobee (Jin *et al*., 2000), wetting and drying simulation for Morro Bay (Ji *et al*., 2001), optimal control of salinity boundary condition in a tidal model using an inverse variations method (Yang and Hamrick, 2005), and integrated hydrodynamic and water quality modeling shames for Wissahickon Creek (Zou *et al*., 2006).

2.3 Definition of Water Age

The age of water is a numerically derived complementary transportation time scale to residence time. Water age, as used here, has the advantage of continuously varying temporally and spatially throughout the computational domain and simulation period, in contrast to being only applicable to a discrete and selected period. Therefore, the use of water age allows determination of variations in residence time under different hydraulic conditions and meteorological (Camacho and Martin, 2012).

Zimmerman (1988) defines the age as “the time [a water parcel] has spent since entering the estuary through one of the boundaries." It also can be considered as the time a water parcel has spent in the system since the moment when its age was specified as zero. Delhez *et al.* (1999) defines the age of a parcel of the constituent as “the time elapsed since the parcel under consideration left the region where its age is prescribed to be zero."

Several methods have been used to estimate the age of water in a given system. The method introduced by Delhez *et al*. (1999) for example, has been used in different numerical model studies (Shen and Haas, 2004; Shen and Wang, 2007, Liu *et al*., 2008; Gong *et al*, 2009).

The method presented in this study can be considered a special case of the Sheng and Wang (2007) methodology and based on the method implemented in the Corps of Engineers CE-QUAL-W2 model. The method considers the age of water as an independent constituent that follows a zero-order growth model with a rate of l/day (i.e. k=l/d). The mass balance of the age of water is given.by:

$$\frac{\partial a(t,x)}{\partial t} + \nabla(\vec{u}\, a(t,x)) - k\nabla a(t,x) = 1 \tag{1}$$

Where *a(t, x)* is the age of water "concentration", *u* the velocity vector, *k* the diffusivity tensor and *k =1/d*, the rate of growth of the water age. The interpretation of the model given by (1) is straightforward. If the terms of transport by advection and diffusion are neglected (i.e. no movement at all in the system) the age of water of the estuary at the end of the first day of simulation will be 1 day, at the end of the second day will be 2 days, and so on. If the particular grid cell is flushed every day for the period of the simulation, the age will never exceed 1 day.

The procedure for computing the water age is straightforward, only requiring a transport (advection diffusion) equation for which a zeros' order kinetic rate of +1/d can be set. Then the computation requires basically the initialization of the age of water field at the Beginning of the model run to zero, and the specification zero ago for all boundary conditions throughout the simulation period, as the riverine and sea water that enters the estuary is considered to be new water for the system. Water age is then continuously simulated for the computational grid at the computational time step. It may then be evaluated discretely or averaged over space and time scales of interest.

2.4 Model Development

The Western Part of Johor Strait is bounded by a complex shoreline with shallow areas. The curvilinear orthogonal grid was created with using the Delft3D package to present the complex geometry of the Western Part of Johor Strait. The model grid consists of 2310 grid cells in the horizontal direction, with grid size ranging from 20 m in rivers and up 350 m in the Strait. The Figure 2 shows the EFDC grid with the boundary condition locations identified and labelled by boundary group. Open boundary is west of model grid and head-water of freshwater system are include Skudai River, Melayu River, Perpet River, Pendas River, and their tributaries . The Causeway along the eastern edge of the model domain in the Strait of Johor was taken as no flow boundary.

The bathymetry data used in the hydrodynamic models was the combination of surveyed data and digitized data. The bathymetry surveys in the rivers were conducted in 2002 and 2005. The bathymetry data in the Strait of Johor has been digitized from navigation maps that the Royal Malaysian Navy published it in 1999.

The atmospheric forcing factors considered in this EFDC model included air temperature, Wind speed and direction, solar radiation, and atmospheric pressure. These data was obtained from "www.underground.com" Website at the meteorological station of Senai Airport. Tidal data obtained from tide tables Malaysia 2010 for station of Pelabuhan Tanjung Pelepas (PTP).

Mathematical models of the Western Part of Johor Strait have been developed and calibrated using EFDC (Kazemi *et al*., 2014). The model's grid corresponds to curvilinear orthogonal grid discretized vertically into four layers. The hydrodynamic component of the model was calibrated to reproduce observed profiles of velocity, water surface elevations and salinity at different locations within the estuary during the periods 4th to 17th October, 2009. A detailed description of the primary results of the calibration process can be found in (Kazemi *et al*., (2014)).

The hydrodynamic model of the Western Part of Johor Strait has been updated in this study to the latest available versions of EFDC. Six constant river inflow scenarios were selected in hydrodynamic model simulations to examine water ages in the Western Part of Johor Strait. For each constant inflow scenario, hydrodynamic models simulation was conducted. Table 1 shows flow data for six scenarios.

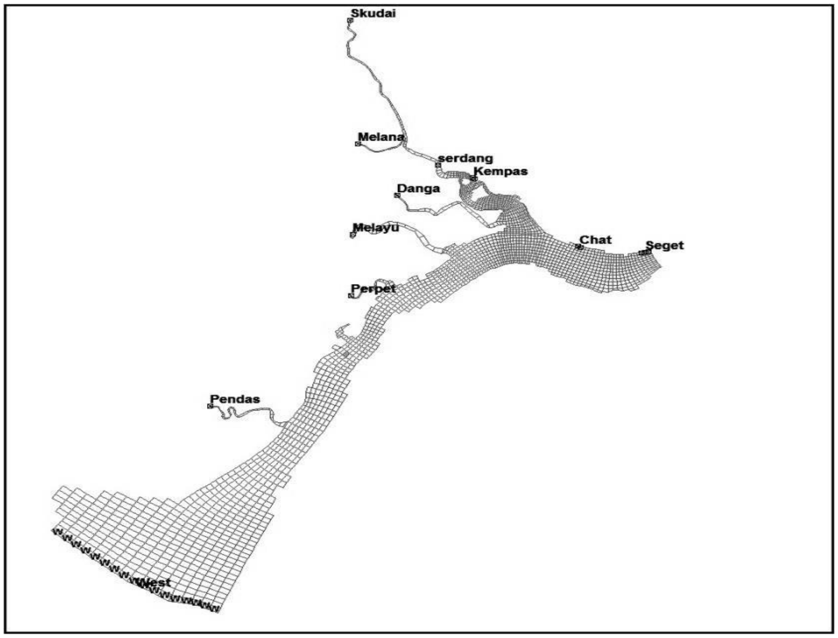

Figure 2 : The model grid and location of boundary condition in the EFDC hydrodynamic model

Table 1: Inflow data for six scenarios

Return period (Years)	Flow Skudai (m^3/s)
2	194.4
5	270.1
10	335.9
20	392.0
50	471.7
100	531.4

3.0 Results and Discussion

The water age is implemented in the Western Part of Johor Strait as a strategy to evaluate the local-scale impacts of freshwater inflows and tides. It was computed for each modeling scenario presented in Table 1 using Equation (1). For each simulation the model was run for 180 days defining as the initial condition an age of water of zero in every cell of the model domain. As boundary condition a zero value was also prescribed at the head-waters of the freshwater systems and at the open boundary. This condition physically means that the water that enters the system through any boundary is considered new water.

The age of water is an indicative measure of the estuary's water renewal capacity at a local scale. The regions characterized by high water age value are therefore 'stagnant zones' associated with limited circulation, whereas the regions characterized by low water age values are zones of high circulation. This type of characterization is also useful for management purposes because it allows the identification of the areas in the estuary that as a result of the low circulation capacity are more vulnerable to water quality degradation. The results of the water age analysis along with the analysis of biological or chemical decay rates can also be used to generate spatially varying risk maps.

Six constant river inflow scenarios were selected in hydrodynamic model simulations to examine water ages in the Western Part of Johor Strait. For each constant inflow scenario, hydrodynamic models simulation was conducted.

Water ages nonlinearly vary in term of distance along the main channel. This is due mainly to the velocity variations along the channel as the results of the changes in cross section area. In addition, the transport time not only depends on the advection transport by velocity, but also is affected by nonlinear diffusive transport. The maximum water age, more than 50 days, occurs at the near causeway under the inflow from Skudai River, 194.4 m3/s (Figure 3).

Figure 3 also illustrates that higher values water age are located near Causeway. Whereas the limited circulation near Causeway may be caused by low freshwater inflow and the limited of circulation in the central strait can be affected by the strait shape and river configuration.

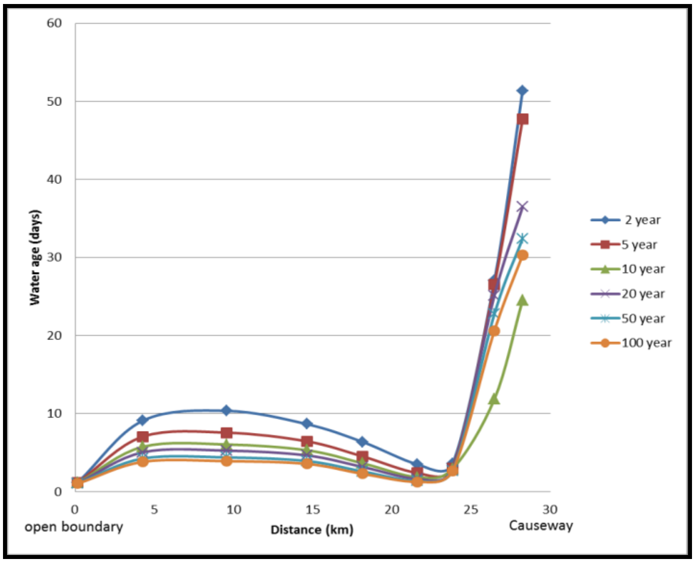

Figure 3 : Spatial variations of water age throughout the Western Part of the Strait of Johor

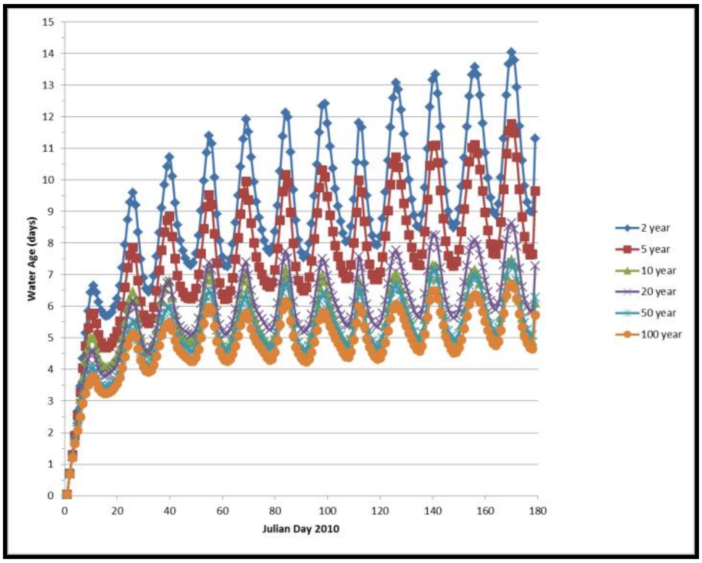

Figure 4 :Temporal variation of daily average age of the entire system

Figure 4 shows that the average water age in entire system is maximum 14 day under minimum inflow, 194.4 m^3/s and minimum 4 days under maximum inflow, 541.3 m^3/s. The results indicate that under prolonged low flow conditions, the flushing potential or water renewal capacity of the estuary is high.

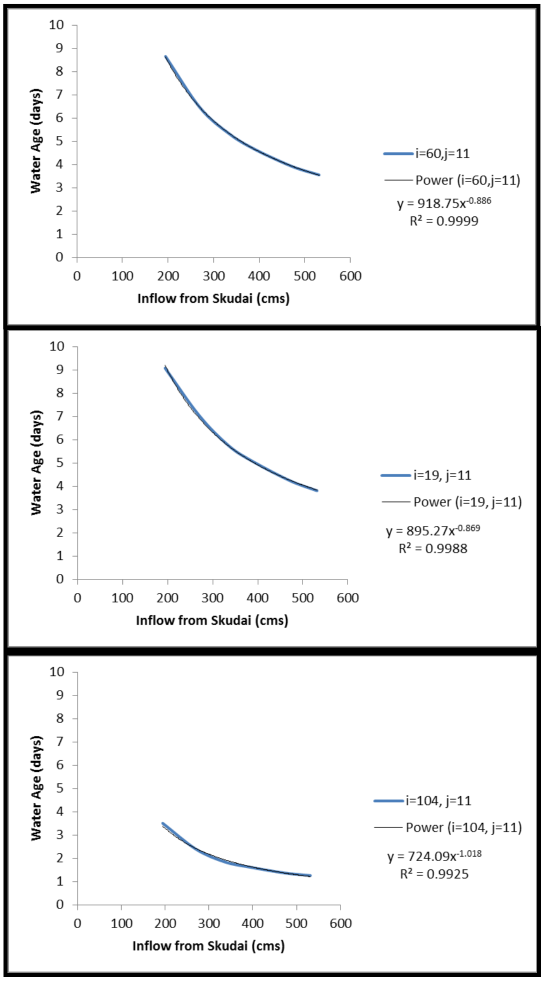

Figure 5 : Tidally-averaged water ages T (days) in responses to river inflows Q (cms) at different location

In order to evaluate the correlation between water ages and inflows, water ages at three locations were plotted against inflows as shown in Figure 5. Empirical best fitting equations were obtained in forms of power law. The power-law empirical equations fit well with the water ages resulted from the hydrodynamic model simulations, with correlation R-squared values above 0.99 in all three locations.

It is important to point out however, that the use of the water age is not a strong strategy for the selection of minimum flow criteria. It requires to be accompanied by chemical and biological studies to identify the desired ecological conditions to be protected. Once these conditions including concentration limits of specific determinants, transformation and accumulation rates are established, they can be used to evaluate healthy water ages for estuary, and therefore, the required freshwater inflows conditions to support such as condition using a relation of the form presented in Figure 5.

4.0 Conclusions

A three dimensional hydrodynamic model was used to evaluate the transport time-scales in the Western Part of Johor Strait. The age concept of water parcels provides a useful time scale to quantify the transport processes in estuaries. The characteristics of transportation and mixing of dissolved pollutant depend primarily on low frequency and mean motions of water. This paper attempts to investigate the impacts of freshwater inflow on age distribution of a water parcel. The amount of water age is more between estuary of Skudai River and Causeway. The lack of flow in this area is the reason of high of water age. This analysis helped in recognition of areas of the estuary most vulnerable to oxygen depletion and eutrophication.

The hydrodynamic model can be readily used to predict water ages under any given time series of unsteady inflows conditions. The simulated results provide useful information for understanding transport processes and can be used to estimate the waste assimilative capacity in the Johor Straits estuary.

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