# A MODELLING STUDY OF WATER AGE IN A TIDE-DOMINATED ESTUARY

**Yuheng Ren[1], Binliang Lin[2,1], Jian Sun[3]**

[1]School of Engineering, Cardiff University, UK, Cardiff CF24 3AA
[2]Department of Hydraulic Engineering, Tsinghua University, China, Beijing, 100084
[3]School of Mechanical Engineering, Tianjin University, China, Tianjin, 300072
E-mail: yuheng.ren58@gmail.com

## Abstract

The main aim of this study was to determine the age of water (AW) in a tide-dominated large estuary, i.e. the Pearl River Estuary (PRE), China, using a passive conservative tracer as a surrogate. With multiple river discharges, four in the east side and four in the west side of the estuary, the seasonal variation of flow current is significant. Based on the age concentration method developed by Delhez et al. (1999), the AW distribution of the whole PRE estuary was predicted by considering tracer released from the eight tributaries. The AW distribution due to tracer release from each tributary was also predicted. The influences of the freshwater inflow rate, salinity stratification and variations of tide at the offshore on AW have been investigated. It has been shown that these factors play an important role in the transport mechanism for the pollutant. The model predictions indicated that an increase in river discharges resulted in larger residual currents, especially in the middle deep channel, which caused a decrease of AW in the whole area and an increase in gravitational circulation. The tracer discharged into the PRE was transported out more quickly. The gravitational circulation enhanced the salinity stratification and thus raised the AW difference between the surface and bottom layers in the inner estuary. However, it caused a decrease in the AW difference between the upper and lower parts of the estuary. When constant mean river discharges were applied, the results showed a seasonal variability of the AW, which could be attributed to the variations of tide at the offshore region.

## Introduction

From the literature of estuarine water exchange studies, it becomes clear that appropriate time scales are needed for representing the information of water transport processes for the assessment of environment impacts and estuarine environment problems such as the increase in the volume of algal biomass and the rise of the numbers of eutrophication incidents. Various time scales, e.g. age, residence time, transit time, turnover time, flushing time, have been associated with the exchange of estuarine water (e.g. Gillibrand, 2001; Monsen et al., 2002; Delhez et al., 2004; Shen and Hass, 2004; Wang et al.,2004; Anouk et al., 2010). These time scales are referred to different definitions and formulations in terms of calculations by different authors. The “age of water” (AW) is identified as a fundamental technique for understanding the relative importance of natural water change and anthropogenic disturbances, and is also frequently used as an independent variable in analysing estuary systems (J.M. Beckers et al., 2001; Nancy et al., 2002; Jian et al., 2004; Jian et al., 2007). Bolin and Rodhe (1973) summarized previous studies of time scales and introduced more rigorous definitions and formulations for these time scales, including the concept of AW (Bolin and Rodhe, 1973). Zimmerman (1976) applied the concept of AW to the Dutch Wadden Sea and introduced the name of residence time as the complement of age to represent the transport of individual water parcels in a spatially varying situation (Zimmerman, 1976). Based on Bolin, Rodhe and Zimmerman’s definitions, residence time is the time a water parcel takes from the present position until it leaves the study domain and AW is the time elapsed since the water parcel departed from the region where the age is prescribed to be zero. This region could be zero- to three-dimensional, i.e. a point, a curve, a surface or a volume, depending on the study requirement. In this paper, we use the transport of a dissolved tracer released at the headwater of an estuary to calculate the AW distribution. The age is zero at the headwater and age at other positions indicates the time of the tracer being transported from the initial location.

The present approach to compute age distribution is based on a three-dimensional numerical model over an Eulerian framework. Deleersnijder et al. (2001) introduced the Eulerian theory of AW by simulating technetium-99 released from La Hague nuclear fuel reprocessing plant in the English Channel through a three-dimensional model (Deleersnijder et al. 2001). Beckers et al. (2001) showed a method which can provide details about the propagation of younger and older material at a given location and the age fluid dynamics properties in a homogeneous environment (Beckers et al. 2001; Jian et al. 2007).

There is an increasing concern on the environmental management of estuaries and coastal seas due to the more dominant influence and pressure from anthropogenic forcing. Many estuarine systems in the world are experiencing problems due to increase of nutrients inputs and become more eutrophic. In some regions, the economic development has resulted in an adverse impact on ambient environment.

The hydrodynamic processes of estuary are influenced by the local bathymetry and geometry thus the flow and associated water circulation are usually highly three-dimensional. The processes then significantly affect mass transport around various estuaries and coastal sea structures, and dredged material disposal mounds. Hence, three-dimensional water quality models are often used in estuarine environmental studies in order to more accurately simulate complicated dynamics of boundary layers and the complex geometry, bathymetry (Wen-Cheng et al., 2008). In the PRE, the complicated geographic and topographic features exert dynamic influences on water exchange and consequently affect water quality and its ecosystem. In this study, a three-dimensional high-resolution hydrodynamic and solute transport model, namely MIKE3, was applied to simulate the water surface elevation, salinity and AW distributions in the Pearl River Estuary (PRE) of China.

## Site Description

The Pearl River Estuary (PRE) is the largest estuary in Southern China. It is situated along the south coast of Guangdong, facing the South China Sea. Figure 1 shows the location of the PRE. The PRE delta region is one of the fastest developing and densely urbanized regions in Asia. In the past few decades, it was one of the main hubs of China's economic growth. The total population in this delta is about 50 million in 2009 and is still growing. The Pearl River plays a key role in supplying fresh water to the large cities in this region, including Macau, Hong Kong, Zhuhai, and Zhongshan. The River is 2,214km long and its annual water discharge is approximately 10,524 $m^3/s$ (Kedong et al. 2008). The Pearl River system consists of three rivers originating from different directions: the West, North and East Rivers. They branch into a network of small rivers and merge into eight tributaries, four in the west (Medaomen, Jitimen, Hutiaomen, Yamen) and four in the east (Humen, Jiaomen, Hongqimen and Hengmen). It can be seen from Figure 1 that the four eastern tributaries (50-55% of river flow) are connected with the PRE (Ling Ding Yang in Chinese) and then flow into the northern part of the South China Sea.

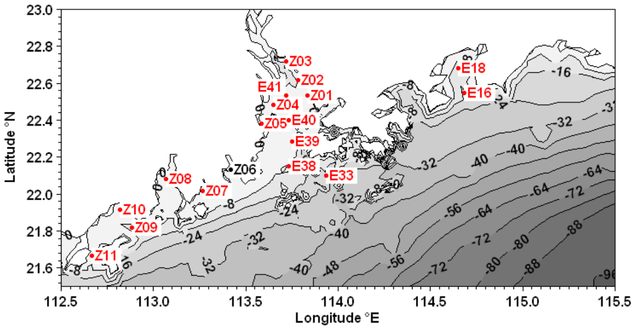


Figure 1: Map of the Pearl River Estuary

The PRE has a bell-shape area with an N-S distance about 49 km, the width in E-W direction varies from 4 km (around mouth Humen) to 60 km (between Lantau islands and Macau at the southern end. The tidal range at the mouth ranges from 1 to 2 m and the tidal current speed is generally less than 2 m/s. The depth of the PRE varies from 0 to 30 m. There are two deep channels on two sides along the PRE. The east channel is deeper than the west channel. The largest freshwater discharge is from Humen. During the 2006-2007 season the peak discharge at Humen is 3831.6 $m^3$, recorded in July, 2006, which is about 1/3 of the total Pearl River discharge. The lowest discharge of Humen is 932 $m^3$, recorded in December, 2006.

The interaction between the fresh and marine water is very strong in the summer due to the south and south-east wind. In dry seasons, the salt wedge can enter into the channel mouth and marine seawater covers the whole PRE. In the past decades more human activities resulted more waste water flows into the area. The pollutants are transported from the PRE through the interaction with tides and rainfall runoff discharge from the rivers. Thus an understanding of AW, as water exchange time scale, is very necessary. In this study we set up an AW model for the PRE base on MIKE3.

## Methods

### Three-dimensional Hydrodynamic and Transport Model

In nature water flow, in essence, is three-dimensional movement. But in some situations, for example, when the depth of water we study is relatively small, the order of magnitude of horizontal movement is much greater than that in the vertical direction. Under this situation, the water movement can be considered as shallow water flow, and we can use a one-dimensional, or a two-dimensional model to study these cases. In the current study, the topography is very complex, and the depth of center line is quite deep with two significant deep grooves. Therefore, we decided to use a three-dimensional model named MIKE3 FM, to analyse the hydrodynamic and solute transport processes in the PRE.

MIKE3 FM is a three-dimensional model with a flexible mesh developed by the Danish Hydraulic Institute (DHI). It is applicable to the simulation of hydraulic and related phenomena in lakes, estuaries, bays, coastal areas and seas where stratification, or vertical circulation, is important. Figure 2 shows the PRE model grid, the flexible mesh can better represent the complex shorelines of the PRE including all the unconnected islands. Details of MIKE3 can be found in MIKE3 manuals and other papers which have set up three-dimensional models successfully using MIKE3 (http://www.mikebydhi.com/)

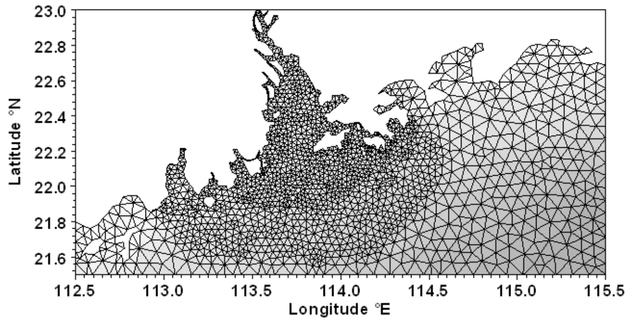


Figure 2: Model grid of the Pearl River Estuary

**Age of water calculation**

In many estuaries more than one pollutant sources are discharged into the study water body. These pollutant sources could be rivers, lateral flows or point sources. In the PRE, there are eight tributaries. AW is the time that has elapsed since a substance is transported to a concerned location from discharge sources. Several methods have been introduced for describing the theory of AW (Bolin and Rodhe, 1973; Zimmerman, 1976; Takeoka, 1984; Delhez et al., 1999; Deleersnijder et al., 2001; Beckers et al., 2001). Delhez et al. (1999) introduced a general theory for AW based on a tracer concentration depending time $\mathrm{t}$, space $\vec{\mathrm{x}}$ and age $\tau$. Through predicting the age concentration and tracer concentration, we can get spatially varying age distributions in estuarine water. The tracer concentration in one position can be calculated by::

$$\mathrm{c}(\mathrm{t},\mathrm{x}) = \int_0^\infty \mathrm{c}(\mathrm{t},\vec{\mathrm{x}},\tau)\mathrm{d}\tau \qquad (1)$$

Age concentration can be calculated from the tracer concentration:

$$\alpha(\mathrm{t},\mathrm{x}) = \int_0^\infty \tau\mathrm{c}(\mathrm{t},\vec{\mathrm{x}},\tau)\mathrm{d}\tau \qquad (2)$$

The mean age $\mathrm{a}(\mathrm{t},\mathrm{x})$ at time $\mathrm{t}$ and space $\mathrm{x}$ is given by:

$$\mathrm{a}(\mathrm{t},\mathrm{x}) = \frac{\alpha(\mathrm{t},\vec{\mathrm{x}})}{\mathrm{c}(\mathrm{t},\vec{\mathrm{x}})} = \frac{\int_0^\infty \tau\mathrm{c}(\mathrm{t},\vec{\mathrm{x}},\tau)\mathrm{d}\tau}{\int_0^\infty \mathrm{c}(\mathrm{t},\vec{\mathrm{x}},\tau)\mathrm{d}\tau} \qquad (3)$$

Assuming that there is only one tracer discharged into the estuary and no other sources and sinks of this tracer within the estuary, the transport equations for calculating the tracer concentration and age concentration can be written as:

$$\frac{\partial \mathrm{c}(\mathrm{t},\mathrm{x})}{\partial \mathrm{t}} + \nabla\big(\mathrm{uc}(\mathrm{t},\vec{\mathrm{x}}) - \mathrm{K}\nabla\mathrm{c}(\mathrm{t},\vec{\mathrm{x}})\big) = 0 \qquad (4)$$

$$\frac{\partial \alpha(\mathrm{t},\mathrm{x})}{\partial \mathrm{t}} + \nabla(\mathrm{u}\alpha(\mathrm{t},\vec{\mathrm{x}}) - \mathrm{K}\nabla\alpha(\mathrm{t},\vec{\mathrm{x}})) = \mathrm{c}(\mathrm{t},\vec{\mathrm{x}}) \qquad (5)$$

Where u is the velocity field, K is the diffusivity tensor, t is time, and $\vec{\mathrm{x}}$ is space.

In this case, (3), (4), (5) were used to compute the age of water using the ECO Lab module of MIKE3.

**Model calibration and validation**

The model was discretized into 3000 grid cells in the surface layer and 10 sigma layers vertically. The lateral grid size varies between 1km - 8km. The main parameter of calibration was the eddy viscosity. Horizontally, a constant Smagorinsky coefficient was specified as 0.28 $\mathrm{m^2s^{-1}}$ and vertical eddy viscosity was specified based on $\mathrm{k}-\varepsilon$ formulation. By selecting $\mathrm{k}-\varepsilon$ formulation, the eddy viscosity is determined as function of the turbulent kinetic energy (TKE), k and the dissipation of TKE, ε. The solution of $\mathrm{k}-\varepsilon$ formulation is automatically invoked. The model was numerically integrated with a time step of 30 s and was calibrated by using water-surface elevation data collected during 2006 and 2007. In July and October of 2006, water surface elevations were measured at stations H1, H2, H3, E38, E41, at last two depths, surface and bottom water currents were measured as well. In July and October of 2006, March of 2007, the salinity was measured during each month. The model was verified with these data. The detailed positions of these measured stations in the PRE and adjacent coastal areas are shown in Figure 1. Figure 3 presents the comparisons between the measured and predicted water levels, velocity at monitoring stations H1, H2, H3, respectively. Figure 4 presents the comparisons etween the measured and predicted surface and bottom velocity at station E38. There are strong agreements between the observed and predicted data.

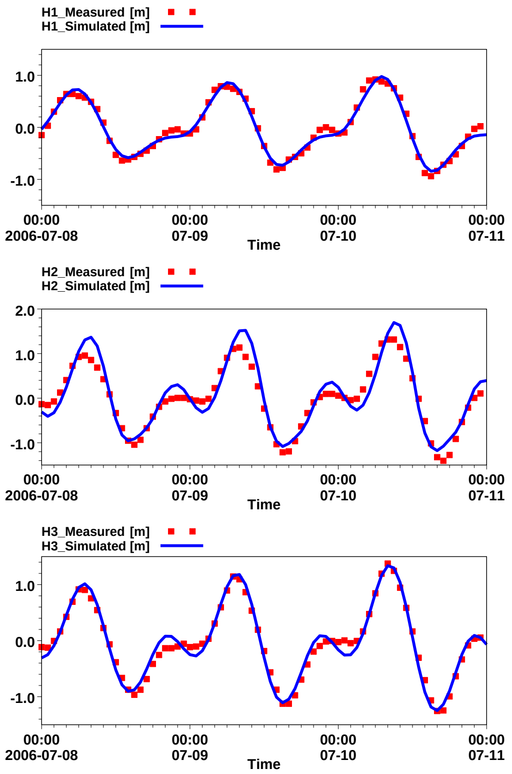


Figure 3: Comparisons between the measured and simulated water elevations at station H1, H2, H3

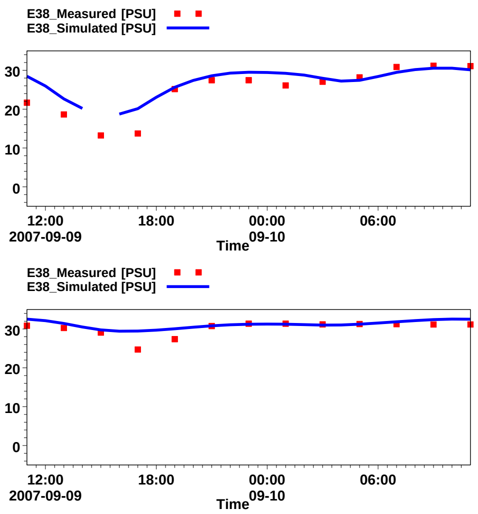


Figure 4: Comparisons between the measured and simulated salinities at Stations E38

## Model Results

Depending on the identity of AW, $\alpha(t, x)$ spatially varies with time and positions. The AW is not the time necessary for a single particle to reach the location examined from its release point, but rather should be interpreted as the time needed for a marked change in the characteristics of the source to affect significantly the conditions at this point (Delhez and Carabin, 2001). In our case, the values of AW were calculated by releasing a tracer along with freshwater continuously from the mouth of each tributary. Monthly changed flow rates for eight tributary were applied in the model for 2006 and 2007. The estuary AW distribution changes with time depending on the amount of freshwater. From the AW time series distribution at E38, two days were chosen to present the AW of the PRE in summer season and winter season, respectively. Through comparisons of the surface and bottom AW of the PRE, the influence of salinity stratification on AW can be seen. The separate change influences on the PRE from eight individual tributary can be concluded from their own AW distributions. Figure 5 shows the time series of the Humen's AW of Station E38 middle layer (see Figure 1) which is near the PRE mouth from January 2006 to February 2007. It can be seen that the age varies with time, from 8.5 to 104.1 days with an average age of 32.2 days. The largest AW value of 104.1 days was in 19th February, 2007 and the smallest value of 8.5 days was in 11th July, 2006. These two days were selected to show the spatial AW distributions as representatives of the maximum and minimum age distributions. The estuary AW distribution changes with time depending on the amount of freshwater discharge and other forcing conditions like the wind, the offshore boundaries. Because in our model a constant flow rate is used for model simulation in every month and no wind forcing is applied to the surface, the age variation in every month can be attributed to the variations of tide and salinity simulation at the offshore.

The surface AW distribution of Humen shows a tongue-shaped pattern with low age in the middle of the PRE both in February and July. This result suggests that materials are transported out of the estuary more rapidly in the middle of the channel where the flow rate is high. It is thought to be connected with the residual current distribution (Jian and Harry, 2007). We can also see from Figure 6, the AW in February is relatively higher than July. In July, more freshwater inflow discharges into the PRE, which results in the increase in water exchange and the estuary salinity stratification. From the model results, under both high and low flow conditions, the east four tributaries AW of the PRE area are much lower than the AW of west four tributaries. It means that the freshwater discharges of east four tributaries influent more on the residual current of the PRE and play more significant roles in the water exchange of the PRE region than the west four. The contours of the west four tributaries AW distribution are mostly N-S direction and west tributaries influent the west half side of the PRE more than the other half.

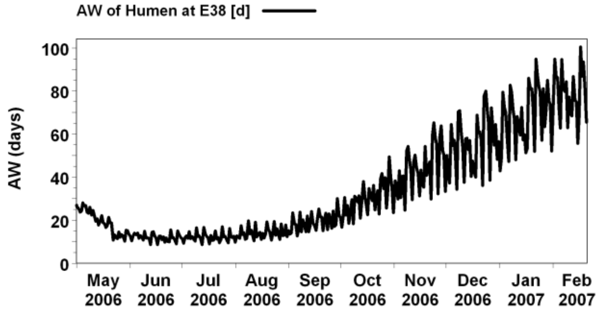


Figure 5: Time series distribution of Humen AW near the PRE mouth at Station E38

## Conclusions

AW is used as a long-term timescale to study the solute mixing and transport in the PRE in this paper. In the PRE, the freshwater discharges from eight tributaries and density-induced circulation play a significant role in controlling the pollution transport and water exchange process. A three-dimensional model was set up and used to predict the AW distributions. The model results represent the spatial AW distributions along the deep channel and the AW variations at specified positions under different dynamic conditions. The middle layer value of AW at station E38 near the PRE mouth varies from 8.5 to 104.1 days under the high and low flow conditions, respectively. Under the high flow condition, the gravitational circulation increases and leads to a stronger residual current. The freshwater comes from the eight tributaries can leave the PRE more rapidly through the surface layer when the PRE becomes more stratified. At the estuary mouth the AW value near the bed is higher than the water surface, with the difference being around 20 days. For the whole estuary the AW is much smaller under the high flow in July than low flow in February. In February, though the vertical difference is quite small, especially in the upper estuary. Even in deep water near the mouth of the PRE, the difference is only around 5 days.

This study demonstrates that the AW methodology is a useful tool to assess the water exchange process and the accumulative influences caused by seasonal freshwater discharge variations, the salinity stratifications and other factors.

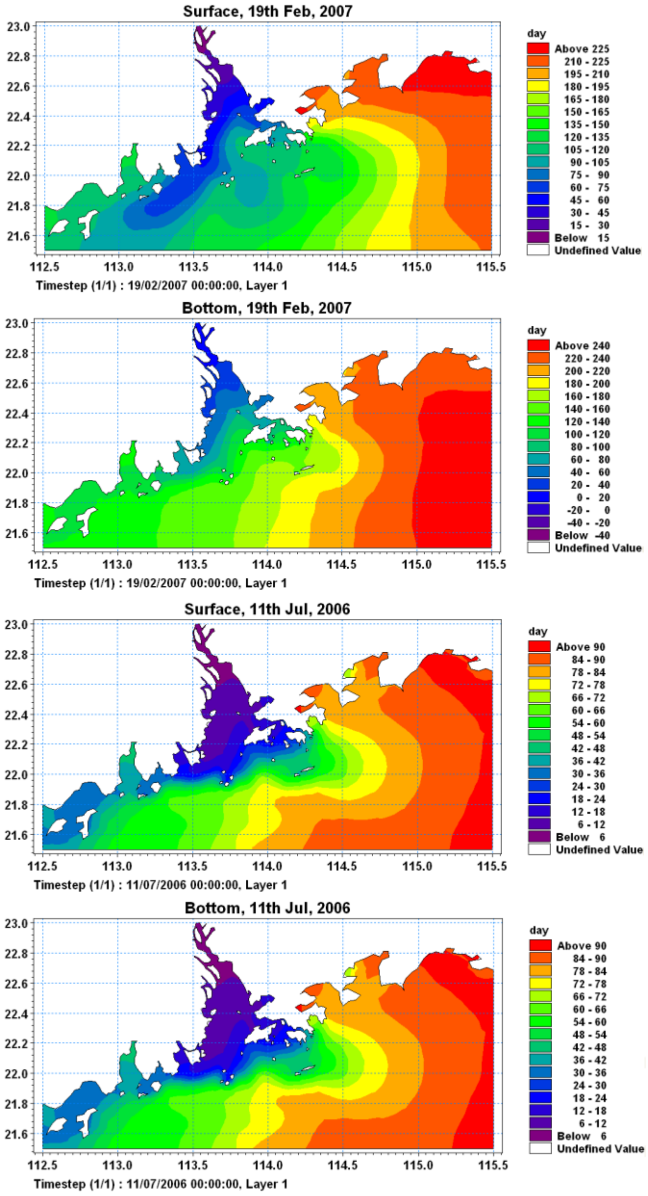


Figure 6: Distributions of AW of Humen at the surface and the bottom in 19th Feb, 2007 and 11th Jul 2006

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