Salt intrusion response to changes in tidal amplitude during low river flow in the Modaomen Estuary, China

Sophia Hammood, Xiaoling Yin and Xuefeng Zhao
South China University of Technology, civil and transportation school, Guangzhou, Guangdong

Abstract. Because of the increasing of water demand in the recent years, the salt water intrusion in Modaomen Estuary becomes severe which influences water supply in the surrounding regions, especially the cities of Zhongshan, Zhuhai in Guangdong Province and Macau. The variability of salt transport determines the variation of the length of the salt intrusion in an estuary. Numerical model of Delft3D flow was using to study the salt transport mechanisms and the response of salt intrusion to changes tidal amplitude. The total transport pattern shows the salt intrusion changes corresponding to spring – neap tide variations. The total transport shows a net landward transport during neap tides and seaward transport during spring tides the response of salt intrusion to change in tide amplitude depends largely on river flow. The salt intrusion length changes very little with spring-neap changes in tidal amplitude during a persistent period of low river discharge, whereas the salt intrusion changes significantly during fortnightly cycles under high flow conditions.

1. Introduction
Estuaries, in their most common form, are arms of the coastal ocean where fresh water and ocean water meet and mix [1]. Modaomen Estuary is the main estuary of the Xijiang River of the Pearl River. Many studies have been conducted to investigate the variations of salt intrusion in the estuary and the underlying driving mechanisms. Salinity distribution in an estuary depends on the estuarine response to river discharge, tidal mixing and wind over time scales ranging from days to weeks and months [2]. Salt intrusion responding to tidal amplitude have been studied extensively. The relationship between salt intrusion and tide amplitude is, for a well-mixed or salt wedge estuary, salt intrudes more landward during spring tides than during neap tides. Numerical model results have indicated that larger upstream salt intrusion happens during neap tides in partially mixed estuaries [7]. The amplitude and time response of an estuary to time variations in forcing is dependent on the sensitivity of the estuary to the forcing and time scale that by which the estuary responds to changes compared to the time scales over which the forcing varies [8]. If the response time \( \tau \) is much shorter than the time scale of variations in forcing, the estuary will remain in a quasi–steady state relative to instantaneous forcing conditions. If \( \tau \) is comparable to or longer than the time scale of forcing variations, the estuary cannot keep pace with forcing variations and the estuary remains in an unsteady [9].

2. Salt balance and estuary time response
The salt transport in an estuary is a balance between seaward flux, induced by river flow (advective transport), and landward flux associated with tides and estuarine exchange flows (dispersive transport). The subtidal, longitudinal salt balance can be expressed as an advection–diffusion equation as follows:

\[
A \frac{d}{dx} S = \frac{d}{dx} \left( Q_f S + AK \frac{dS}{dx} \right)
\]  (1)
Where $S$ is the subtidal, cross-sectionally averaged salinity at some location along the estuary; $A$ is the cross-sectional area of the estuary; $x$ is the along-estuary distance increasing in the upstream direction; and $K$ is the along-estuary salt dispersion rate. The up-estuary salt transport, expressed in the last term in Eq. (1). The response of the estuary is sensitive to changes in tide amplitude. The estuary response time is predicted to be the time it takes a water parcel, traveling at the speed of the freshwater discharge $Q_0/A$, to traverse the length of the estuary.

$$\tau = \frac{L_0 A}{Q_0}$$ \hspace{1cm} (2)

### 3. Methodology

#### 3.1 Model Setup

The model used in this study is the Delft3D software, developed by WL Delft Hydraulics. Delft3D can simulate hydrodynamic and morphodynamic processes in 3-dimensions and in any chosen time-period. Delft3D is suited for 2D and 3D computations for coastal, river and estuarine hydraulic flows, waves, sediment transports, morphology changes, water quality and ecology. Delft3D FLOW solves the continuity equations and the Navier Stokes equations for an incompressible fluid. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid. In numerical flow modelling the reliability of data is extremely important. Flow equations are well known and the Delft3D software has proven to be able to calculate hydrodynamic processes very accurately. The reliability of model results depends mainly on the efforts of the modeler and the accuracy of the data. The Modaomen channel model used in this study based on a rectangular channel model with 1000m width, 6m water depth, and 45km channel length. The estuary part which is connected with the river mouth is also obtained through generalization of the model. Mouth width is 20km, length is 10km. The schematic diagram of the model is shown in Figure 1. In this study, we do not use the actual estuary model, but based on the concept of the idealized estuary model. The main reason is the research purpose is to analyze the influence of one factor on salt intrusion to find out some new answers and solutions to salt intrusion effects. If used the actual estuary is studied, it is necessary to Considering the influence of wind, wave, Coriolis force. The advantage using a generalized model channel it is simple, do not need detailed information, is not affected by the topography of the estuary, estuarine conditions, also can eliminate the interference of terrain factors. In addition, we can neglected wind, wave, Coriolis force and other factors influence because of their minor effect in this model.

![Figure 1. Model plan and grid](image-url)
3.1.1 *A simulation conditions.* To examine the variation of salt intrusion variation the Delft3D model runs for 15 days at constant river flows of $Q = 1600 \text{ m}^3 \text{ s}^{-1}$ (low flow conditions). The model was forced with K1, O1, M2 and S2, 0.453, 0.487, 0.321, and 0.227 respectively at the coastal open boundary so as to produce an oscillation in tidal amplitude. Wind was not included.

4. **Salt intrusion variation**

The length of the salt intrusion in a partially-stratified estuary defines the extent of habitat and the limit of drinking water supply. The length of the salt intrusion and the evolution of the salt balance are determined by the magnitude and variation of salt transport along the channel of the estuary. the changes in tidal amplitude, the salt length of the estuary in the Hudson River changes very little with spring-neap changes in tidal amplitude during a persistent period of low river discharge, whereas the salt intrusion changes significantly during fortnightly cycles under high flow conditions [2]. Spring-neap fluctuations in the mechanisms of salt transport should be most evident in partially-stratified estuaries. During neap tides, the estuarine salt transport increases, and the salt intrusion moves further into the river. During spring tides, the estuarine salt transport is reduced, and the salt intrusion is moved seaward by the freshwater flow [9].

4.1 *Salt intrusion response to tide amplitude changes*  

The estuary becomes highly stratified to a partially mixed under low river flow (1600 m3/s). Salt intrusion length varies with changes spring and neap tides. The mean salt intrusion length is approximately 8.52km, while the maximum change in salt intrusion length during a fortnightly cycle is 0.871km, representing a 10.22% relative change. This indicates that, under low river flow conditions the salt intrusion changes little with spring neap variation. The total transport shows a net landward transport during neap tides and seaward transport during spring tides. The total transport pattern shows the salt intrusion changes corresponding to spring–neap tide variations. Maximum salt intrusion happens at neap tide, while minimum salt intrusion lags spring tides by 3-4 days. By take salt $L_0$ equal to 8.52 km, the cross section area $A$ equal to 6000 $m^2$ .

And assuming $Q$ is 1600 $m^3/s$ the response time calculated to be 32 days, which is longer than a fortnightly tidal cycle (15 days), and results in small variation of salt intrusion to change in tidal amplitude.

![Figure 2. Water level](image1.png)  
![Figure 3. Salt intrusion length](image2.png)
Figure 4. Salt transport components at section A-A (dash dot line signifies dispersive transport, dash line denoted the advective transport, transport, and solid line stand for total transport.

5. Conclusion
In this study, a Delft3D flow model was using to study the salt intrusion in Modaomen Estuary. The salt transport were decomposed into, advective transport, and dispersive transport associated with (tides and exchange flows) the response of the salinity intrusion to a spring-neap cycle at low flows the length of the salt intrusion changes very little over the spring-neap cycle. The ability of the salt intrusion to respond to variations of tidal amplitude is characterized by comparing a response time of the salt balance to the time scale of spring-neap variations. When the response time scale is orders of magnitude larger than the time scale of the spring-neap cycle, the length of the salinity intrusion has little variation.

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