Numerical simulation of the fortnight change of salt intrusion based on numerical model of Modaomen estuary, Pearl River

Sophia Hammood, Xiaoling Yin¹, Xuefeng Zhao and Ying Zeng

School of civil engineering and transportation, South China University of Technology, Guangzhou, 510640, China

¹ arxlyin@scut.edu.cn

Abstract. To investigate the respond of salt intrusion in Modaomen estuary to variations of river flow and fortnight tidal cycle in dry season, numerical simulation was applied to a simplified estuary model based on the geometries of Modaomen. Like many other estuaries, the intrusion length decreases as river flow increases. During neap tides the stratification is strong and exchange flow is remarkable in a longer intrusion length while during spring tides the minimum stratification occurs owing to enhanced turbulence in a shorter intrusion length. The salt transport presents landward during neap and seaward during spring. The advection timescales are smaller than fortnight period apparently for dry season flows and thus the intrusion responds to the spring-neap variation quickly in spite of some days lag. High flows result in shorter adjustment times which is reflected in smaller differences of intrusion lengths between neap and spring than low flows.

1. Introduction

The estuary is the intersection of the oceans and rivers, fresh water and ocean water meet in such semi-enclosed coastal waters. Many studies have been conducted to explore the variations of salt intrusion and the saline movement mechanisms in the estuary [1, 2]. Salinity distribution in an estuary depends on flow discharge, tidal mixing and wind over time scales ranging from days (river flow pulse and wind) to weeks (spring-neap tide) and months (seasonal river flow change) [3]. The relationship between tide and salt intrusion has been studied extensively [1, 2]. For a well-mixed estuary, salt water is easier to invade in the spring tide [1, 3]. In partially mixed estuaries, numerical model results shown that larger upstream salt intrusion happens during neap tides [4, 5, 6]. Study salt transport near the mouth is essential in predicting the extent of salt intrusion and provides insight into the dispersal of other substances [7]. Salt transport is divided into a seaward transport of salt due to the river flow (advective transport) and landward salt transport (dispersive transport) which consists of two mechanisms, the estuarine salt transport and tidal oscillatory transport, respectively [8]. According to Lerczak et al. [9], the variability of salt transport determines the variation of salt intrusion length. Also there is a time lag in an estuary’s response to changes in river flow, tidal, and wind mixing [10]. It has been proved that estuarine response to changing forcing depends on the contrast between estuarine advection timescale $\tau$ and the time scale of forcing variation. The estuary advection timescale depends on the mean forcing about which the variations occur and the background state of the estuary itself (Hetland and Geyer 2004; MacCready 2007) [6, 10]. Hetland and Geyer [10] further noticed the asymmetry of the response time of the estuary to increasing and decreasing river flow. Lerczak et al. [7], developed a linear model to study the response of salt intrusion length to river flow and tidal
variations. A linearized equation describes the advection timescale $\tau$ for a parcel released at salt intrusion limit for escaping from the estuary. So the estuary advection timescale $\tau$ 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 [6, 10].

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

where $Q_0$ is the runoff discharge, $A$ is the average cross-sectional area and $L_0$ the intrusion length.

If an estuary’s $\tau$ is shorter than the timescale of forcing variations, the estuary will remain in a quasi-steady state relative to instantaneous forcing conditions. However, if $\tau$ is comparable to or longer than the time scale of forcing variations, the estuary remains in an unsteady, time-dependent state [6, 7, 9].

The circulation and stratification of estuaries are a result of the interactions of the tides, river flow, density difference between the river and the ocean/sea, coastal sea level fluctuations, winds and the bathymetry [11, 12]. The stratification in estuaries, quantified by the buoyancy frequency $N^2$ at which a parcel of fluid vertically displaced from its equilibrium position in a stable environment, will oscillate due to buoyant and gravitational forces where viscous and mixing effects are neglected. The buoyancy frequency can be defined as a function of the mean density gradient in a stratified flow as:

$$N^2 = -\frac{g}{\rho^0} \frac{\partial \bar{\rho}}{\partial z}$$ \hspace{1cm} (2)

where $g$ is gravitational acceleration, $\rho$ is density, the buoyancy frequency is a quantity describing the density gradient of stably stratified fluids, and it has to be greater than zero for stably stratified situations. With an increasing density gradient, the buoyancy frequency increases.

Turbulence is responsible for the efficient mixing of quantities such as momentum and scalars. In order to properly understand the mixing processes in estuaries it is first necessary to understand the turbulence properties of these systems. The nature and intensity of mixing processes within an estuary are driven, to a large extent, by the dynamically important gradients of density and velocity. Shear instabilities resulting from perturbations in the velocity profile large enough to overcome the ambient density stratification provide the primary mechanism for turbulence generation and mixing [13]. Turbulent mixing is generated by tides which propagate over a rough bottom, thus the magnitude of mixing depends on the magnitude of tidal forcing. In most estuaries the spring-neap cycle modulates the tidal range, producing a variation in the strength of vertical mixing.

In a fluid of constant density, velocity shear considers a source for the generation of turbulence and instability. Stable stratification within a fluid has the opposite effect, providing a stabilizing influence to the flow. In a stratified shear flow, both of these mechanisms are important and a balance is struck between the two. The nature of the balance can be quantified by the gradient Richardson number, $Ri$ is the ratio of the square of the buoyancy frequency to the square of the vertical velocity shear:

$$Ri = N^2 \cdot (\partial u / \partial z)^2$$ \hspace{1cm} (3)

where $u$ is velocity. Miles [14] and Howard [15] demonstrated analytically that at values of $Ri > 1/4$ the density gradient is strong enough to suppress the development of turbulence, and that a value of $Ri < 1/4$ was a necessary, but not sufficient, condition for the generation of turbulence. Thorpe [13] supplemented this work by demonstrating experimentally that a value of $Ri = 1/4$ was a good indicator for the onset of stratified turbulence, and establishing this threshold as a sufficient condition for turbulence in a laboratory shear flow. The gradient Richardson number is an important parameter in describing stability and understanding turbulent mixing in stratified flows [16].
The buoyancy Reynolds number \( R_{eb} \) (dimensionless) quantifies the energy level of stratified flows and is defined as:

\[
R_{eb} = \frac{\varepsilon}{\nu N^2}
\]

where \( \varepsilon \) is the dissipation rate and \( \nu \) is the vertical eddy viscosity. It is commonly used in oceanography because it is absent of kinetic energy, a difficult parameter to measure [17]. The previous studies show that \( R_{eb} > 100 \), the mixing is described as strong turbulence, \( 7 < R_{eb} < 100 \), intermediate regime and \( R_{eb} < 20 \), the flow is controlled by molecular effects and although stirred, it is essentially laminar [18]. It is generally taken that \( R_{eb} \) must be greater than 20 for active turbulent to exist [19].

Modaomen estuary is a main waterway for Xijiang, the greatest runoff tributary of Pearl River, to get into South China Sea. The salt intrusion of the estuary in recent years is of great concern because of fresh water supply problems. However, the detailed dynamics and influencing processes are still in investigation and discussions due to diversity and complexity of the estuary physics. Here, a numerical simulation is applied in our study to contribute in understanding the estuarine salt intrusion.

2. Methodology
The modeling tool used in this study is the flow module of Delft3D software that was developed by WL Delft Hydraulics [20]. As shown in figure 1, the tidal river geometries are simplified but based on the average true conditions of Modaomen, including a prismatic horizontal channel of 300km long and with a rectangular cross-section of 1200m wide and 6m~8m deep in average. For the open sea, 30m of water depth is taken as on the furthest boundary, linearly varied according to the actual average coastal bed slope. For Manning's coefficients, 0.020 is taken as offshore and 0.025 is taken as within the mouth. k-\( \varepsilon \) Turbulent model is adopted for flow field calculation. On the upstream runoff boundary, salinity is set as zero, while on the open boundary downstream, salinity is set as 30ppt. After 1 month modeling with cold start, simulation calculations begin for another 1 month with hot start. The lateral variation is neglected here and wind and wave effects were also neglected.

3. Results and discussion

3.1. Salt intrusion response to tidal and river flow changes
Tide and river flow are two main forcing factors controlling estuarine circulation [21]. Six river flows were considered in our simulations, over a spring/neap tidal cycle, 1600m\(^3\)/s, 1800m\(^3\)/s, 2000m\(^3\)/s,
2400\text{m}^3/\text{s}, 2800\text{m}^3/\text{s} and 3000\text{m}^3/\text{s}. Figure 2a shows how salt intrusion varies with river flow changes. It is clear that when river flow increases, the intrusion length decreases. And, the differences between minimum intrusion length occurred in spring and maximum in neap also decrease. The tide range drives the flow which causes different mixing mechanisms in estuaries. In an estuary mixing originates from shear mixing. Figure 2b shows the variation of intrusion length with tide ranges. The delft-3D model forced with 2000 m$^3$/s river flow and run for 30 days with hot start under different tide range obtained from multiplying the original values of tide constituents by the factors of 0.5, 0.75, 1.0, 1.25, 1.5 and 1.75. It can be seen that salt intrusion tend to be smaller with increased of tide range. The increased of tide range enhancing mixing, which decreased stratification and increased the effect of river flow on salt intrusion length.

![Figure 2a and 2b](image-url)

**Figure 2.** The state of fortnight salt intrusion under different (a) river flows and (b) tide ranges.

3.2. Salt intrusion response to fortnightly variations.

3.2.1. Stratification and mixing. To examine the fortnightly salt intrusion variations of Modaomen, three river flows of 1600\text{m}^3/\text{s}, 2000\text{m}^3/\text{s} and 3000\text{m}^3/\text{s} were chosen to represent low, normal and high flow, respectively in this article. Model was forced with four tidal constituents K1, O1, M2 and S2 at the coastal open boundary so as to produce a simple fortnightly oscillation in tidal amplitude. The result obtained indicated that, the stratification is strong and exchange flow is high when vertical mixing is small during neap tide. The minimum stratification occurred during spring tides produce enhanced turbulence, which increases mixing and leads to a nearly well-mixed water column. Variations in river flow cause large variations in stratification. It can be seen that buoyancy frequency decreased from neaps to springs. As in figure 3, low $N^2$ values and Richardson numbers, $Ri < 1/4$ become more frequent during spring tides, as compared to neap tides. $Re_b$ values fall between energetic and intermediate regimes. Few fall in diffusive regime, below the threshold of active mixing , suggesting that the flow is primarily turbulent [22]. This indicates that even though turbulent mixing was weak, it was rarely suppressed completely.

3.2.2. Advection time and salt transport. In the simulations, salt intrusion length varies with changes of tide range, increasing from neap to spring but decreasing from spring to neap, during a fortnight tidal cycle. During neap tides, when vertical mixing is weaker, the salt transport increases, and the salinity intrusion moves further into the river. During spring tides, when vertical mixing is stronger, the salt transport is reduced, and the salinity intrusion is moved seaward by the river flow. As in figure 4, during low flow conditions maximum salt intrusion lags neap tide by 1-5 days, while minimum salt intrusion lags spring tide by 3-4 days. Under normal flow conditions, maximum salt intrusion lags neap tides by 1-3 days, while minimum salt intrusion lags spring tides by 3-5days. Under high flow conditions maximum salt intrusion lags neap tide by 1-2 days, while minimum salt intrusion happened near the end of spring tides. The advection timescales are 1.4, 0.9 and 0.5 days for low, normal and
high river flow respectively. It can be seen that the advection timescales are smaller than fortnight period apparently and thus the intrusion responds to the spring-neap variation quickly in spite of some days lag. Higher flows result in shorter adjustment times. The salt transport components were examined at cross section located at 12 km from estuary mouth. The total salt transport presents a landward transport during neap tides and seaward during spring tides. This result suggested that the estuary gained salt during neap tides and lost salt during spring tides.

![Figure 3](image)

Figure 3. (a) water elevation, the change of (b) buoyancy frequency (c) Richardson number and (d) Buoyancy Reynolds number under river flow variations.

4. Summary and conclusions
A Delft-3D module was used to set up a numerical model of simplified estuary in this study to examine the response of salt intrusion length to variations of river flow and the tidal ranges in dry season of Modaomen estuary. The stratification was strong during neap tides while it was weak during spring tides. During high stratification period turbulence mixing was suppressed and weakened. The turbulence intensity ranges between energetic and intermediate regimes. Few values falls in diffusive regime, indicating that even though turbulent mixing was weak, it was rarely suppressed completely by stratification. The increase of river flow moves salinity gradient seaward and lead to an increase of stratification. The salt intrusion length recedes with increased river flow and advances with decreased river flow. The maximum salt intrusion length delayed few days after neap tides, while minimum salt intrusion length lag spring tides by few days. The length of the salt intrusion increases after neaps when the estuarine circulation still dominants and results in salt transport landward inside the estuary, and decreases after the spring tides when vertical diffusions enhance upward salt transport and consequently the river flow advects the salt out of estuary. Therefore, the total salt transport presents a
landward transport during neap tides and seaward during spring tides. This result suggested that the estuary gained salt during neap tides and lost salt during spring tides. Salt intrusion tends to be smaller with increase of tide ranges owing to the enhancing mixing, which decreased stratification and increased the effect of river flow on salt transport and salt intrusion length.

Figure 4. (a) The series of water elevation (b) salt intrusion response under different river flow (c)-(e) salt transport under different flow conditions

Acknowledgment
The project is financially supported by National Natural Science Foundation of China (No. 11572130) and National Key Research and Development Program of China (No. 2016YFC0402601).

References
[1] Uncles R, Stephens J 1996 Seasonal variability of fine-sediment in the tamar estuary.
[2] Prandle D. 2004 Saline intrusion in partially mixed estuaries Estuarine Coastal & Shelf Science 59(3) 385-97
[3] Wenping Gong, Jian Shen 2011 The response of salt intrusion to changees in river discharge and tidal mixing during dry season on the Modaomen Estuary, China Continental Shelf
Research 31 769–88

[4] Walter R K and Woodson C B, Arthur R S, Fringer O B Monismith S G 2012 Nearshore internal bores and turbulent mixing in southern monterey bay Journal of Geophysical Research Oceans 117(C7) 7017

[5] Lerczak J A and Geyer WR& Ralston D K 2009 The temporal response of the length of a partially stratified estuary to changes in river flow and tidal amplitude Journal of Physical Oceanography 39(1) 1-25

[6] Maccready P 2007 Estuarine adjustment. Journal of Physical Oceanography 37(8) 2133-45

[7] Bowen M M, Geyer W R 2003 Salt Transport and the time-dependent salt balance of a partially stratified estuary Journal of Geophysical Research Atmospheres 108(C5) 249-60

[8] Geyer W R, Chant R 2006 The hudson river estuary: the physical oceanography processes in the hudson river estuary

[9] Lerczak J A and Geyer W R Chant RJ 2006 Mechanisms driving the time-dependent salt flux in a partially stratified estuary* Journal of Physical Oceanography 36(12) 2296-311

[10] Hetland R D and Geyer WR 2004 An idealized study of the structure of long, partially mixed estuaries* J.phys.oceanogr 34(12) 2677-91

[11] Dyer K R Wiley 1973 Estuaries: A physical introduction Earth-Science Reviews 9(4) 388

[12] Fischer H B 1972 Mass transport mechanisms in partially stratified estuaries Journal of Fluid Mechanics 53(4) 671-87.

[13] S Thorpe 1973 Turbulence in stably stratified fluids: A review of laboratory experiments Boundary-Layer Meteorol 5(95)

[14] Miles J W 1961 On the stability of heterogeneous shear flows Journal of Fluid Mechanics 10 496-508

[15] Howard L N 1961 Note on a paper of John W Miles Journal of Fluid Mechanics 10 509-12

[16] Kundu P K 1990. Fluid Mechanics. Academic Press SanDiego 628pp

[17] Ivey G and Winters K, Koseff J 2008 Density stratification, turbulence, but how much mixing Annual Review of Fluid Mechanics 40(1) 169

[18] Yamazaki H, Osborn T 1990 Dissipation estimates for stratified turbulence Journal of Geophysical Research Oceans 95(C6) 9739–44

[19] Itsweire E C and Kose J R, Briggs D A, Ferziger J H 1993 Turbulence in stratified oceanography shear flows implications for interpreting shearinduced mixing in the ocean Journal of Physical 23(7) 1508-22

[20] WL. Delft Hydraulics 2015 12 User manual Delft3D-flow (the Netherlands).

[21] Savenije H H G 1986 A one-dimensional model for salinity intrusion in alluvial estuaries Journal of Hydrology ELSEVIER 85 85-109

[22] Imberger J and Ivey G N 1991 On the nature of turbulence in a stratified fluid part ii: application to lakes Journal of Physical Oceanography 21(5) 659-81