Impact of sea level rise on estuarine salt water intrusion—A numerical model study for Changjiang Estuarine

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Abstract. A 3D and high-resolution salinity transport numerical model of Changjiang Estuary with unstructured mesh was established using the MIKE3. The salinity transport model results were tested and verified by the observed data in Changjiang Estuary, the statistics of correlation coefficient are in good values. And then, the verified salinity transport model was used to study the impact of sea level rise on saltwater intrusion in the Changjiang Estuary. The results show that the entire North Branch was flooded with high saline water and a large amount of salt water spill over from the North Branch into the South Branch, which caused the South Branch with a high-low-high saddle-shaped distribution. With the rise of sea level, salt rocks such as the North Branch, the South Branch, and the North Channel moved upstream to varying degrees, strengthening the saltwater intrusion in the eastern Changjiang River. The high saline waters from North Branch spill over into South Branch also increased. The isohaline of North Branch South Branch and North Channel move to upstream, and move downstream in South Channel, North Passage and South Passage. The high salt water from the North Branch into the South Branch increased the salinity of the upper section of the South Branch.

1. Introduction

Global climate change has been one of the hot topics for scientists in recent years; Sea level rise (SLR) is one of the most significant impacts of global climate variability. The Inter-Governmental Panel on Climate Change (IPCC) has projected that the rate of global sea level rise during the 21st century is between 1.0 mm/year and 2.0 mm/year with a central value of 1.5 mm/year [1-4]. China Sea Level Gazette statistics of 2014 show that from 1980 to 2014, China’s average sea level rise was 3 mm/year. In the Yangtze River Delta, the relative sea level rise in the past decades is 6.6 mm / year, and it will reach 7.9-8.4 mm / year by 2050[5-8]. The IPCC provides sufficient evidence that our freshwater resources could be severely affected by sea level rise [9-10]. SLR could push saltwater further upstream in estuaries. Severe saltwater intrusion can damage local water supplies and threaten aquatic plants and animals. According to Chen's research, saltwater invasion in the Changjiang Estuary could have significant impact on four large drinking water reservoirs, which provide drinking water to about 50 million people. [11-13] Better understanding of saltwater intrusions caused by SLR plays an important role in government strategies to mitigate the effects of rising sea levels.
The Changjiang Estuary, which exhibits multilevel bifurcations, is 120 km long and 90 km wide (Fig. 1) and it discharges $9.24 \times 10^{11}$ m$^3$ of freshwater into the East China Sea each year [14]. The tide in the estuary exhibits semidiurnal, diurnal, and fortnightly spring–neap signals. It is a mesotidal estuary with a mean tidal range of 2.66 m at the mouth[15]. The river discharge is recorded at the Datong gauge station, which is situated at the dry season tidal limit of the Changjiang Estuary. River discharge exhibits pronounced seasonal variation, with the lowest monthly mean value of 11,200 m$^3$ s$^{-1}$ in January and the highest monthly mean value of 49,700 m$^3$ s$^{-1}$ in Jul[16].

Many scholars previously studied the saltwater intrusion in the Changjiang estuary. Li et al[17] show that the NONC is an important source of saltwater intrusion in the NC and it has severe threatens on the freshwater usage. Qiu et al[18] applied ECOM-si to study the effect of wind on vertical mixing in Changjiang estuary.

However, the impact of SLR on the saltwater intrusion in the Changjiang Estuary has not been reported so far. Therefore, based on MIKE3, a three-dimensional mathematical model of hydrodynamic and salinity transport in the Changjiang Estuary is established to analyze the response characteristics of saltwater intrusion in the Changjiang Estuary to sea level rise.

2. Methods

A 3-dimensional model based on a MIKE3 Flow Model (FM) finite volume model, developed by the DHI Group (DHI, 2014). The system is based on the numerical solution of incompressible Reynolds-averaged Navier–Stokes equations with the Boussinesq assumption and hydrostatic pressure distribution. Spatial discretization of the primitive equations is performed using an element-centered finite volume method. The governing equations and details could be found in the MIKE User Manual[20].

2.1 Model setup and area

The computational domain contains the entire Changjiang Estuary, Hangzhou Bay, Zhoushan Archipelago and their surrounding seas. It extended to 124.5°E in the east, 33.5°N in the north, 29.7°N in the south, about 430 km in the east-west direction from Datong gauge station in the west to East China Sea, and 340 km in the south-north direction from Jiang Su to the Zhe Jiang(Fig. 2), with 10 uniform sigma layers in the vertical.
Fig. 2. Study area of Changjiang Estuary

The open boundary was driven by 8 astronomical constituents (M\(_2\), S\(_2\), N\(_2\), K\(_2\), K\(_1\), O\(_1\), P\(_1\), Q\(_1\)). The river boundary was specified in the form of volume flux by data measured at Datong for model validation or by a constant value for analysis. The river discharge rate at Changjiang was given as volume flux data measured at Datong. Qiantangjiang used the average river flux about 1000m\(^3\)/s during this simulation. The roughness height valued from 0.00025 to 0.0013m. The horizontal vortex viscosity coefficient of the model is calculated using the Samagorinsky coefficient, valued as 0.28.

2.2 Model verification

Model performance can be evaluated quantitatively by a statistical analysis for the agreement between model results and measurements. So, the measured salinity data on Feb, 2003 in the Changjiang Estuary are employed to validate the salinity model (positions shown in Fig.1). The verification of salinity at survey stations are showed in Fig.3. The model–observation data comparisons were assessed via the root mean square error (RMSE), and the skill model. The RMSE and skill model are defined as [19]:

\[
\text{RMSE} = \left[ \frac{\sum (D_{\text{mod}} - D_{\text{mes}})^2}{N} \right]^{1/2}
\]

\[
\text{skill} = 1 - \frac{\sum_{i=1}^{N} |D_{\text{mod}} - D_{\text{mes}}|^2}{\sum_{i=1}^{N} (|D_{\text{mod}} - D_{\text{mes}}| + |D_{\text{mes}} - D_{\text{mes}}|)^2}
\]

Where, \( D_{\text{mod}} \) are the predictions by the model; \( D_{\text{mes}} \) are the measurements; \( D_{\text{mes}} \) is the mean of the measurements; and \( N \) is the number of observations.

The RMSE and correlation coefficient were listed in Table 1. It can be seen that the computed results match the measured values very well.
Fig. 3. Comparisons of modelled and measured salinity.

Table 1. Model-observation statistics for salinity.

| Statistics | Layer | 1#  | 2#  | 3#  | 4#  | 5#  |
|------------|-------|-----|-----|-----|-----|-----|
| RMSE(psu)  | Surface | 0.76 | 0.77 | 0.73 | 0.85 | 0.82 |
|            | Bottom  | 0.58 | 0.60 | 0.54 | 0.83 | 0.78 |
| Skill      | Surface | 0.25 | 0.30 | 0.22 | 0.18 | 0.20 |
|            | Bottom  | 0.89 | 1.26 | 1.99 | 0.90 | 0.85 |

3. Result
In this section, the established and well-validated model considered with the runoff of Changjiang set to 11200m$^3$/s in dry season[16-17] was used to simulate and calculate the salinity plane distribution of the tidal cycle during normal tide during normal sea level and a rise of 25 cm, the longitudinal salinity profile distribution of the North Channel and South Passage, and the salinity process lines of some typical points. The statistical analysis of the planar distribution of salinity changes during a tidal cycle when sea level rises by 25 cm, the profile distribution of longitudinal salinity changes in the North Channel and the South Passage, and the salinity change process lines of some typical points.

3.1 Simulation of saltwater intrusion under normal sea level conditions
Fig 4 shows the salinity distributions of mean spring tidal depth-averaged in the Normal Sea Level(NSL).
In the vertical during the spring tide, the North Branch was occupied with high saline water which the water with salinity greater than 20 from the open sea, and a small part of high saline waters to appear in bifurcation. Near the Chongtou, salinity ranged from 10 to 3. A large amount of salt water from the North Branch spillover into the South Branch at the bifurcation strongly, resulting in a salinity higher than 1 in the upper South Branch. There was fresh water with salinity less than 0.5 presences in the middle of South Branch near Changxing island. Therefore the South Branch shows a high-low-high saddle-shaped distribution due to the existence of the North Branch spillover. The salt water spillover from North Branch together with oceanic water intrusion in the lower reaches, are the two sources of saltwater intrusion in the South Branch. The monthly average salinity in the South Branch was mostly less than 0.5psu. The monthly average salinity of North Channel is relatively high, which is 1-5psu. In the South Passage, North Passage and North Channel, saltwater intrusion from open sea was severely. The scope of saltwater intrusion in the offshore waters is mainly in the reach below the bifurcation of the South and North Channel. From the distance of the reach of isohaline 10psu, North Channel is farther from the South Channel. This indicates that the intensity of freshwater dilution from North Channel is higher than that from the South Channel. However, the distance from the reach to the upstream of isohaline 5psu point shows that the north port is farther than the south. Therefore, from this perspective, the intensity of the saltwater intrusion in the North Channel is higher than the South Channel. The invasion of the North Passage lies between the South Channel and the North Channel. In summary, the salinity gradient of the South Passage is significantly higher than that of the North Channel, which should be related to the direction of the tide wave propagation outside the Yangtze River Estuary. The South Channel is facing the direction of the tide wave propagation, and the North Passage form an angle with wave propagation. The Hengsha channel is an important channel for the exchange of water between the North Channel and the North Branch. The saltwater intrusion in the North Channel comes from the Hengsha channel in addition to its own channel. Therefore, the northern part of North Channel has higher salinity than the south.

In the longitudinal, salinity on the north side of the channel is generally higher than on the south side. In areas directly invaded by the open sea, high saline waters are carried upstream by rising tides. Due to the Coriolis force, the flow paths in the river trough diverge, and the rising tide on the north side of the river trough is dominant, which often forms a tide trough. Therefore, the distance of the high saline on the north side of the channel is larger than that on the south side, and the south side is significantly affected by freshwater dilution, so the salinity is high on the north side and low on the south side. In the area affected by the north branch saline irrigation, the salinity on the north side of the flume is also higher than that on the south side, which is mainly determined by the geographical location of the bifurcation of the north and south branches of the invasion.
In order to analyse the salinity distribution of each channel in the Changjiang Estuary, four sections of a, b, c, and d are arranged in the four channels of the Changjiang Estuary respectively representing the North Branch, the North Channel, the North Branch, and the South Branch (the section shows in Fig. 1).

It can be seen from the Fig.5 that section A is flooded with high saline water during the high tide, and the horizontal and vertical directions are relatively uniform. Only at the upper end of the section, that is, the area near the south branch is slightly lower in salinity. The increase in salinity in the middle and lower sections is due to the weakening of the North Branch backflow after the tide, but it did not disappear immediately. The North Branch water continued to backflush the South Branch, which caused the high salt water in the downstream to continue to move upstream, and the vertical mixing was better.

In the section B, there is a freshwater group with a lower salinity than isohaline of 0.5psu near Qingcaosha. The isohaline of 10psu is located at 35-42 km, and the bottom salinity is higher than the surface layer.

Sections C and sections D are similar. The isohaline of 10psu is located around 20km. The saltwater intrusion is significantly stronger than that of the North Channel, and the saltwater intrusion in the South Passage is stronger than that in the North Passage.

Fig.6 shows P1 and P2 vertical mean salinity process lines under NSL. Calculating salinity shows that salinity also has significant half-moon characteristics. The salinity reached a maximum during the spring tide and decreased during the neap tide.
3.2 Simulation the changes in saltwater intrusion under SLR

Fig. 7 shows the salinity distributions of mean spring tidal depth-averaged in the Sea Level Rise (SLR). Fig. 8 shows the planar distribution of the depth-averaged salinity difference between SLR and NSL.

It can be seen that under the condition of SLR of 25cm, Chongming Eastern Shoal was submerged by 0.4-0.8 increased significantly, and the salinity of the entire North Branch increased by 0.5 ~ 1. At the boundary of South Branch and North Branch, the overflow of saline from North Branch to South Branch is much larger than the NSL scheme. Although the salinity in the upstream and central part of the South Branch doubled, salinity in most areas of the South Branch remained below 0.45psu.

Fig. 7. Distributions of depth-averaged salinity under SLR

Fig. 8. Changes in distributions of depth-averaged salinity under SLR
Fig. 9 shows the distribution change of four sections of A, B, C, and D. The saltwater invasion in the open sea has increased, and the salinity value of North Channel has increased by 0.1-0.5psu, and the salinity of the North Branch has increased by about 0.5-1psu. The north-south trough salinity value decreased, and some areas reached above 0.5psu. The upper branch of the South Branch is affected by the saline irrigation of the North Branch. The increase in salinity is 0.1-0.2psu, and the saline irrigation increases significantly when the sea level rises by 25 cm.

Along the longitudinal section of North Channel, the salinity within the entrance was significantly increased by about 0.3-0.5psu, while outside the entrance, the salinity decreased slightly due to the influence of the southern water. The salinity of the north-south trough showed a downward trend, and the decline in the middle of the north trough was the most obvious, above 0.5psu. The 0.5psu salinity line on the lower part of the south branch and the north part moves about 2-3 km, and the fresh water range is between 24-53 km. The range of the second salinity line in the lower segment is larger, and the salinity increase can reach 0.6psu in the 60 km area. The southern freshwater area of the South Branch decreased by about 3 km to 35-43 km, and the salinity difference in the lower section was about 0.2psu.

Fig. 10 shows P1 and P2 vertical mean salinity process lines under SLR. Calculating salinity shows that salinity also has significant half-moon characteristics. The salinity reached a maximum during the spring tide and decreased during the neap tide.
4. Conclusions

Sea level rise is one of the most significant impacts of global climate variability, which could push saltwater further upstream in estuaries. Increased saltwater intrusion in Changjiang Estuary will affect drinking water safety for 50 million people. In this study, a 3D salinity transport numerical model of Changjiang Estuary was established using the MIKE3, and the salinity transport numerical model was verification by the observed salinity date in Changjiang Estuary. In the dry season, the salinity of Changjiang Estuary under the condition of normal sea level and sea level rise are simulated separately, to study the effect of sea level rise on saltwater intrusion in the Changjiang estuary.

The modelled results show that, during flood period, the North Branch was flooded with high saline water from the open sea, and a large amount of salt water from the North Branch flooded into the South Branch at the diversion mouth, as the time become to ebb, high saline waters moving downstream with the ebb current, therefore the South Branch shows a high-low-high saddle-shaped distribution due to the existence of the North Branch back-irrigation during the high tide in the dry season, which paly a very important impact on Changjiang Estuary's saltwater intrusion.

Under the sea level rise, the saltwater was strengthened in Changjiang Estuary, The isohaline of North Branch, South Branch and North Channel move to upstream, and move downstream in South Channel, North Passage and South Passage. That is to say, the salinity of North Branch, South Branch and North Channel increased significantly.

The high saline waters from North Branch back-irrigation to South Branch increased; therefore, the high salt water from the North Branch into the South Branch increased the salinity of the upper section of the South Branch. The isohaline of South Channel, North Passage, South Passage move downstream, and the salinity decreased a little.

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