Characteristics of saltwater intrusion in the Modaomen waterway in the dry season of 2017-2018

Huang Shuqin¹, Yin Xiaoling¹,*
¹School of Civil Engineering and Transportation, South China University of Technology, 510640, Guangzhou, Guangdong, China
* Corresponding author: arxlyin@scut.edu.cn

Abstract. Based on the observations of the Modaomen waterway in the dry season of 2017-2018 and the hydrometeorological data collected, the influence of runoff, tide and wind on the daily maximum intrusion length is analyzed here in order to research the characteristics of saltwater intrusion in the Modaomen waterway in the dry season. Compared the daily maximum intrusion length calculated by formula with the observation, it can be found that the two were consistent. Through the correlation coefficient between intrusion length of saline water and flow rate, tide difference and wind, it is found that the movement trend of salinity borderline is determined by the stability of the upstream runoff. Under the condition that the upstream runoff is relatively stable, the movement trend of the salinity borderline is dominated by tide when discharge is high, and when discharge is low, the movement trend of salinity borderline is dominated by the interaction between tide and runoff. And the northerly wind promotes and accelerates the intrusion of the saltwater.

1. Introduction
Most of the previous studies on the saline water intrusion in Modaomen estuary were based on the early observation data combined with numerical simulations. It is considered that runoff is the most direct factor affecting the saline water intrusion, determining the speed and length of the saline water intrusion and the tide, on the other hand, determines the periodic movement of the salinity borderline which intrudes in the neap tide and retreats in the spring tide¹²³. In addition to the effects of runoff and tide, the influence of wind on the saline water intrusion in the Modaomen estuary is also important. Previous studies have shown that the northerly wind and the northeast wind can promote the saline water intrusion³⁴⁵. In recent years, human activities in the Pearl River Basin have been frequent, aggravating the saline water intrusion in Modaomen waterway⁶⁷. The early observation data are not enough to reflect the changes of saline water intrusion movement in recent years. This paper analyzes the recent saline water intrusion in Modaomen waterway through the observations in the dry season of 2017-2018, and briefly analyzes how the change of external dynamic action affects the saline water intrusion in the Modaomen waterway.

2. Method and results of observation
The dates of observation are from 14 October to 30 October, from 16 November to 2 December and from 2 January to 18 January, and ship-mounted observations of tracing salinity front at the highest tide level of the day are conducted. Considering that the time of daily maximum intrusion length lags behind the time of highest tide level by 1-2 hours, determining the time of highest tide level of...
Denglongshan station as the starting time of the observation, taking Zhuhai Bridge as the starting point, the observations of vertical sections are carried out upstream along the thalweg of Modaomen waterway. The vertical salinity and velocity are measured every other distance until the salinity at the bottom of the observed section is less than 0.5 ppt, and the state of flow is converting (the bottom velocity is less than 0.15 m/s, and the degree of direction is about 200°). From this the daily maximum saline water intrusion length can be measured. In order to ensure the accuracy of the measured salinity borderline, the total daily observation time is controlled within 1-2 hours. The velocity is measured by Riversurveyor (RS), and the temperature, salinity and water depth are measured by Optical Back Scattering (OBS). Using the GPS positioning to locate the observation point, the instruments are connected with computers correspondingly, and the observation data is monitored in real time. Finally the daily maximum intrusion length of the saline water can be obtained according to the salinity and longitude and latitude of the observed section. The schematic diagram of the observation route is shown in Figure 1.

As shown in Figure 3(d), the average fortnight discharge of Tianhe station in October, November and January is 3207 m³/s, 2393 m³/s and 2910 m³/s, respectively, and during the observation period, the variation of upstream discharge in November is small, and the change of upstream discharge in January is the largest. From Figure 2. From October 2017 to January 2018, the most wind direction was northern wind and the rate was 44%, followed by eastern wind and its rate was 18%, and the remaining wind direction was mainly northward. As can be seen from Figure 3(e), the maximum tidal range is 1.51 m and the minimum tidal range is 1.01 m in October; the maximum tidal range is 2.15 m and the minimum is 0.87 m in November, and the maximum tidal range is 1.67 m and the minimum is 0.91 m in January. There is no significant difference in the tidal range between spring tide and neap tide in October. The monthly runoff, tidal range and wind speed and direction are different. In order to understand the dominant action of these three external forces when affecting the movement of the saline water, the correlation coefficients between intrusion length of saline water and average daily discharge at Tianhe station, tidal range at Denglongshan station and the northward wind speed of Macau are calculated respectively, as shown in Table 1.

3. Discussions

3.1. Movement of the salinity borderline

Ippe[8], Savenije[9] and WU M W[10] developed different formulas of saline water intrusion length under different conditions. In order to make full use of the observed data, according to the study of CHEN S S[11], the Equations (1) ~ (3) are used to calculate the daily maximum intrusion length of salinity borderline here.

\[
A = A_o \exp(-\beta\chi) 
\]

\[
\ln \frac{S}{S_0} = -\frac{Q}{\beta K A_o} \left[ \exp(\beta\chi) - 1 \right] 
\]

\[
L = \frac{1}{\beta} \ln \left\{ 1 - \frac{\beta K A_o \ln \left( \frac{S}{S_0} \right)}{Q} \right\} 
\]

The explanation of the equations is detailed in reference [11].

Taking Zhuhai Bridge as the mouth of the estuary (where \(\chi=0\)), the intrusion length is the distance from Zhuhai Bridge, and the estuary shrinkage coefficient \(\beta = 0.08\), and salinity of the section \(S=0.5\) ppt. The relationship between \(\ln (S/S_0)\) and \(\exp(\beta\chi)\) is a linear function, the fitting results of linear functions are shown in Figure 4. The relative error between the observed values and the calculated values are listed in Table 2, and the error is less than 10% which is within the allowable range, so it is shown that the maximum daily intrusion length of salinity borderline during the observation period is basically consistent with the calculated value of Equations (1) ~ (3).
3.2. Influencing factors of the movement of salinity borderline

3.2.1 Runoff

Earlier studies thought of the relationship between intrusion length (L) and river discharge (Q) as power-law relations $L \sim Q^n$. According to the previous observation data over the years of the salinity borderline[3], the power-law relations between the average intrusion length and upstream discharge is shown in Figure 5(a) and the exponent $n$ is about 0.92. As can be seen from Figure 5 (b) and (c), the sensitivity of the movement of salinity borderline to the upstream discharge in the spring tide is less than that in the neap tide.

As shown in Table 1, the correlation coefficient between intrusion length of saline water and discharge is the smallest in October while it is the largest in January. According to the correlation coefficients, the movement of salinity borderline is mainly affected by upstream discharge and the influences of tide and wind is basically not reflected. The saline water in the neap tide from 9 January to 11 January should have been in the intrusion period and the intrusion length is the largest, but due to the sudden increase of upstream discharge, the salinity borderline retreats towards the sea, and the intrusion length is the smallest on the day of the minimum tidal range in a fortnight period. Therefore, under the condition that the upstream discharge does not change much, the intrusion and retreat of the...
saline water are determined by the tidal range; if the upstream discharge increases or decreases rapidly, the saline water also retreats and intrudes accordingly.

![Figure 3](image-url)

**Fig. 3.** The results of observation. (a), (b), (c) is wind speed and direction of Macau in October, November and January respectively; (d) is the average daily discharge at Tianhe station; (e) is the tidal range at Denglongshan station; (f) is the intrusion length of salinity borderline.

**Table 1.** Correlation coefficients between salinity borderline and external dynamic actions.

| Month    | Correlation coefficients |
|----------|--------------------------|
|          | Salinity borderline - discharge | Salinity borderline - tidal range | Salinity borderline - northward wind speed |
| October  | -0.069                    | -0.667                        | 0.215                                      |
| November | -0.643                    | -0.613                        | 0.138                                      |
| January  | -0.654                    | 0.541                         | -0.346                                     |
Fig. 4. The relationship between $\ln (S/S_0)$ and $\exp (\beta x)$ in the day of maximum tidal range and the day of minimum tidal range.

Table 2. The relative error between the observed values and the calculated values.

| Date       | Calculated values /km | Observed values /km | Relative error /% |
|------------|------------------------|---------------------|------------------|
| 2017-10-23 | 6.76                   | 6.84                | 1.22             |
| 2017-10-30 | 28.16                  | 26.4                | 6.66             |
| 2017-11-21 | 16.15                  | 16.8                | 3.84             |
| 2017-11-28 | 26.1                   | 26.04               | 0.25             |
| 2018-01-02 | 14.66                  | 13.38               | 8.71             |
| 2018-01-10 | 2.86                   | 3.15                | 9.21             |

Fig. 5. (a) is the power-law relations between the average intrusion length and upstream discharge based on the previous observation data over the years of the salinity borderline. (b) is the power-law relations between the observed intrusion length and upstream discharge in spring tide and (c) is the power-law relations in neap tide. (The discharge $Q$ is the sum of the discharge at Sanshui station and the discharge at Makou station, and the intrusion length $L$ is the distance from Zhuhai Bridge.)
3.2.2 Tidal range.
The variations of discharge in October and in November both smaller than that in January. The law of salinity borderline movement is basically intruding in neap tide and retreating in spring tide. As shown in Table 1, the influences of tidal range in October and November on the saline water movement are the most obvious. Compared with the lower runoff in November, discharge in October is high and the salinity borderline movement in November is controlled by the interaction between upstream runoff and tide and it's difficult to determine who is the dominant force. So when the state of runoff is stable and the average discharge is high, the trend of the salinity borderline movement is determined by the tidal range.

3.2.3 Wind
On October 14th and October 15th, the discharge are the highest but their intrusion lengths are larger than that when the discharge is low. The reason may be that the strong northerly wind over the past two days drives the saline water to intrude upstream. Meanwhile, in the Figure 3(f), the intrusion lengths of 30 October, 19 November, 24 November and 7 January increase relatively quickly, and the hours of the northerly wind in these four days are more than 12 h and the wind speed is more than 5 m/s. It indicates that the northerly wind can accelerate the intrusion of the saline water.

4. Conclusions
The observation method of tracing the salinity front at the time of the highest tide level of the day can measure the maximum daily intrusion length basically, and the observations satisfies the equations mentioned in the early study.

The discharge not only determines the distance and speed of the intrusion, changing discharge also changes the periodic movement of the saline water, and the sensitivity of the saline water movement to the discharge in the neap tide is higher than that in the spring tide.

Under the condition of stable runoff, when the discharge is high, the dominant force driving the movement of saline water is mainly tide, and when the discharge is low, the dominant force is the interaction between runoff and tide.

Northerly wind plays an important role in promoting and accelerating the intrusion of saline water under the control of runoff and tide.

Acknowledgments
The research is financially supported by the Natural Science Foundation of China (No. 11572130) and the Open Research Foundation of Key Laboratory of the Pearl River Estuarine Dynamics and Associated Process Regulation, Ministry of Water Resources (2017KJ02).

References
[1] SU B, HE Y, LU C, et al, 2013. Salt tide invasion and saltwater tide control for the Modaomen waterway. Beijing: China Water & Power Press.
[2] LIU J B, BAO Y, HUANG M Y, 2010. Contrast of movement law of saline intrusion in Modaomen waterway in the wet year and the dry year[J].Chinese Journal of Theoretical and Applied Mechanics. 42(06):1098-1103.
[3] SU B, LIU J, et al, 2012. A preliminary study on the wind effect in the salt tide of the knife-knife[J]. PEARL RIVER. 33(S1):21-25.
[4] WEN P, CHEN X H, et al, 2007. Analysis of Tidal Saltwater Intrusion and Its Variation in Modaomen Channel [J]. JOURNAL OF CHINA HYDROLOGY. (03):65-67.
[5] LIU H, WU C Y et al, 2008. Research on the Modaomen estuarine circulation under a winter monsoon [J]. THE OCEAN ENGINEERING. (02):102-111.
[6] HAN Z Y, TIAN X P, et al, 2010Study on the causes of intensified saline water intrusion into Modaomen Estuary of the Zhujiang River in recent years[J]. JOURNAL OF MARINE SCIENCES. 28(02):52-59.
[7] HAN Z Y, TIAN X P, et al, 2010. Impacts of Large-scale Human Activities on Riverbed Morphology and Tidal Dynamics at Modaomen Estuary[J]. SCIENCE GEOGRAPHICA SINICA. 30(04):582-587.

[8] Ippen, A. T. and Harleman, D. R. F. 1961. Analytical studies of salinity intrusion in estuaries and canals, phase1: one-dimensional analysis, Technical Bulletin #5, Committee on Tidal Hydraulics, U.S. Army Corps of Engineers.

[9] Brockway R, Bowers D, Hoguane A, et al, 2006. A note on salt intrusion in funnel-shaped estuaries: Application to the Incomati estuary, Mozambique[J]. Estuarine Coastal and Shelf Science. 66(1-2):1-5.

[10] WU M W, LU C, et al, 2012. A experimental study on the movement of saltwater in the sink[J]. PEARL RIVER. 33(S1):49-51.

[11] CHEN S S, FANG L G, et al, 2007. Saltwater intrusion analysis and experiential model for Pearl River estuary, south China: A case study in Modaomen watercourse[J]. ADVANCES IN WATER SCIENCE. (05):751-755.