RESEARCH ARTICLE

Study of an abnormally strong saltwater intrusion in the Humen Channel of the Pearl River estuary

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Abstract

Saltwater intrusion in estuaries has become a serious environmental problem, such as in the Pearl River estuary (PRE). In this study, we used a fully validated three-dimensional hydrodynamic model EFDC to numerically investigate the saltwater intrusion in the PRE during the dry season of 2007–2008. Based on the measured salinity, an abnormally strong saltwater intrusion occurred in the Humen Channel in February 2008. The saltwater intrusion occurred twice a month to varying extents, with each saltwater intrusion happening 1–3 days before spring tide, and the stronger saltwater intrusion always occurred at the beginning of the month. Our model results show that caused by a long-term northerly wind during the dry season, the increased steady shear term in the salt transport flux were responsible for the abnormally strong saltwater intrusion in the Humen Channel. The abnormally strong saltwater intrusion has features of long duration, far-reaching upstream distance and great hazard to freshwater resources. The wind effects were revealed to mainly influence the bottom salinity in the middle reach of the PRE, especially near the Humen outlet.

Keywords: Saltwater intrusion, EFDC, Pearl River estuary, Humen Channel

1 Introduction

Saltwater intrusion is the process of high salinity water from the ocean to intrude upstream along the tidal channel of an estuary. It is a natural phenomenon in river estuaries, occurring mostly during dry seasons or droughts (Chen and Zong 1999; Uncles et al. 1997). In recent years, human activities have become more extensive, and the anthropogenic alteration of riverbeds and channels in estuaries has led to enhanced saltwater intrusion (Sun et al. 2012), with serious economic losses and negative social impacts. The PRE has encountered such problems as well. Over the past two decades, the high-frequency, long-term and long-distance saltwater intrusion in the Pearl River Estuary (PRE) have exerted tremendous pressure on the social, economic and environmental development of the surrounding areas (Liu and Bao 2008). The government has implemented the “Emergency Water Diversion Program for the Pearl River” to alleviate the water supply shortage in Zhuhai and Macao (Ying et al. 2008; Kong et al. 2010). It is necessary to study the variations in saltwater intrusion in the PRE to understand the main driving mechanisms.

Previous studies have shown that the main factors affecting saltwater intrusion are river discharge, wind, tides and estuary topography, and the associated physical mechanisms are very complex (Shen et al. 2003). Haddout et al. (2018) proposed that river discharge is the main factor in saltwater intrusion, which controls the salinity structure, vertical stratification and the extent of saltwater intrusion. In addition, the changes in river discharge have a greater impact on the surface layer than the bottom layer (Xu et al., 2018). Tides and winds have a greater impact on saltwater intrusion when the river discharge...
is low (Ospino et al. 2018). Through using 3D numerical simulation, Ospino et al. (2018) suggested that when the river discharge decreases, the vertical salinity stratification and mixing situations of the estuary would change significantly under the influence of tides and winds. For well-mixed estuaries, the increased tidal strength promotes the convection and diffusion of the saline water masses, shifting both the isohaline and saltwater intrusion toward upstream, ultimately increasing saltwater intrusion (Rice et al. 2012). For partially and highly stratified estuaries, the strong tidal mixing will have an opposite effect to decrease the saltwater intrusion (Bowen 2003). Downestuary/upestuary wind would lower/elevate the water level of the estuary, enhance/reduce the bottom circulation, and strengthen/weaken the saltwater intrusion, while the remote wind (a downwelling-favorable wind in the PRE) would strengthen the vertical mixing, resulting in a significant increase in the surface salinity and a slight increase in the bottom salinity (Gong et al. 2018). Chen and Sanford (2009) pointed out that a moderate downstream wind along the estuary enhances saltwater intrusion, while an upstream wind always attenuates it. To signify the wind effect on the subtidal flow and stratification, a nondimensional parameter, the Wedderburn number ($W$), representing the relative importance of wind strength and baroclinicity, has been proposed (Gong et al. 2018; Chen and Sanford 2009). With the sea level rises due to global warming, saltwater intrusion will become increasingly severe (Hong and Shen 2012, Hong et al. 2020; Mimura 2013), making prevention and management of saltwater intrusion more difficult.

In the past decades, the saltwater intrusion in the PRE has become more frequent and severe. Prior to 1990, the measured annual average salinity data of Humen, Modaomen, Jitimen, and Yamen showed a general decreasing trend in chlorinity at all representative stations in the PRE (Zhou 1998). In contrast, serious saltwater intrusion occurred in the PRE several times after 1990, affecting 45,333 ha of farmland and about 15 million people in 1999, with annually direct economic losses amounting to 100 million yuan (Huang 1999). During the dry season from 2003 to 2004, saltwater intrusion caused water shortages in Zhuhai, Macao and Guangzhou, with the intensity and duration of the intrusion far exceeding the levels in the same period in previous years (Xu and Luo 2005). In recent 10 years, the saltwater intrusion in the PRE is seen to aggravate more (Lin et al., 2019).

Saltwater intrusion is influenced by many factors, and using the observation data alone can not differentiate the main factors. With the limitation of measured data, previous studies are often to study one aspect of forcings, such as river discharge, tidal current, and wind, making it difficult to identify the dynamics of saltwater intrusion as a whole (Lin et al. 2020; Li and Li 2011; Ataie-Ashtiani et al., 1999). In addition, less studies have been conducted on the mechanisms and hazards of abnormally strong saltwater intrusions. The aim of this study is to analyse the mechanisms for strong saltwater intrusions in the PRE and reveal its risk to upstream freshwater supply. Specifically, we analyse the intensity of saltwater intrusion under northerly winds to determine the extent of the hazard which is posed to the middle and upper reaches of the PRE. Furthermore, we effort to apply our study results to the management and prevention of strong saltwater intrusion.

This paper is organized as follows. Section 2 introduces the study area. The research methods are briefly described in Section 3. The results are presented in Section 4. And Section 5 and 6 present the discussion and conclusions.

### 2 Study area and data sources

The PRD consists of three tributaries, namely Xijiang, Beijiang, and Dongjiang, with a total catchment area of approximately 440,000 km$^2$. The PRE has an extensive and complex river network, with a total of eight outlets from east to west, namely Humen, Jiaomen, Hongqili, Hengmen, Maodaomen, Jitimen, Hutiaomen and Yamen, forming a distinctive river-network and estuarine system (Yao et al. 2003). The main study area in this paper is the Humen Channel within the PRE. The long solid line in Fig. 1b shows the main stream of the Humen Channel, which is 120 km long, and the short solid line in Fig. 1b is the Humen Bridge, which is the shortest cross-section at the head of the PRE.

The simulation area covers the PRE and its adjacent sea area. The open boundary extends from the PRE to the South China Sea to exclude the uncertainties of the specifications of open boundary conditions. A 10-layer sigma ($\sigma$) coordinate was used in the vertical direction to provide higher resolution near the surface and bottom layers. The input data were based on the realistic conditions of the PRE in 2007 and 2008, including topography, wind field, river discharge, etc. The tidal harmonics data driving the open boundary was obtained from the Ohio State University Tidal Prediction Software (OTPS). The temperature and salinity data of the open boundary were taken from the World Ocean Database. Wind field data collected at Hong Kong Airport in 2007 and 2008 were used to represent the surface winds. The river discharge data were obtained from the upper Pearl River stations of Shijiao (Beijiang), Gaoyao (Xijiang) and Boluo (Dongjiang) for 2007 and 2008, and the ratio of freshwater distribution among eight outlets (Cheng 2001) were used.
to determine the distribution of river discharge in each outlet.

3 Methods

3.1 Numerical model
In this study, we used the Environmental Fluid Dynamics Code (EFDC) model to conduct simulations. EFDC is a three-dimensional hydrodynamic model developed by the Virginia Institute of Marine Science. It is a multi-parameter finite-difference model. The EFDC model uses curvilinear, orthogonal horizontal coordinates and sigma vertical coordinates to represent the physical characteristics of a water body. The EFDC model has been widely used in estuarine hydrodynamic studies in the Pearl River estuary, the Yangtze River estuary, the Chesapeake Bay, and Perdido Bay Estuary (Hong and Shen 2012; Hong et al. 2020; Shen and Haas 2004; Meng et al. 2011). In this study, we used a boundary curve fitted grid in the horizontal direction and a σ-coordinate system in the vertical direction with 10 layers.

The EFDC model of the PRE has been fully calibrated by (Hong and Shen 2012; Hong et al. 2020). After calibration for water level, salinity and flow velocities at various time scales, the estuarine dynamics of the PRE was robustly reproduced under realistic forcing. The same external forcing field and model configuration as by Hong et al. (2020) are used in this study. The model was run from 1st, January, 2007 to 31st, May, 2008 with a hot start from the model results obtained at the end of 2006. To examine the mechanisms for the abnormally strong saltwater intrusion, we ran several model simulations: with and without winds. In this way, the effects of winds and tides on saltwater intrusion can be obtained, and the reasons for the abnormally strong saltwater intrusion are identified. In order to exclude the disturbance of river discharge variability, the model used a uniform river discharge rate of 2500 m³/s from November 2007 to April 2008 (shown in Fig. 2) and the model outputs for this period, which cover the entire dry season, was stored for subsequent analyses. The configurations for different cases are listed in Table 1.

3.2 Data analysis
The timeseries of river discharge in the PRE and the bottom salinity at the Sishengwei Station, which is located in the upstream of the Humen Channel, are displayed in Fig. 2. In Fig. 2a, we also show the threshold river discharge of 2500 m³/s as a red solid line. From the data, an abnormally strong saltwater intrusion was observed in the PRE from 3rd, February to 5th, February, 2008 under high river discharge.

To examine the saltwater intrusion, we chose the longitudinal profile of Section 1 to investigate the salinity variations along the transect.

We calculate the salt flux to analyze the effects of estuarine circulation and tidal mixing on saltwater intrusion. The total salt flux \( F_s \) can be decomposed into the advection term \( F_0 \) caused by river discharge, the steady shear term \( F_E \) caused by the estuary circulation and salinity stratification, and the tidal oscillation term \( F_T \) caused by the tidal asymmetry between ebb and flood (Lerczak et al. 2006; Gong and Shen 2011), which is calculated as follows:
where $F_S$, $F_0$, $F_E$, and $F_T$ represent the total salt flux, the advection term, the steady shear term, and the tidal oscillation term, respectively. $u_0$, $u_E$, $u_T$ and $s_0$, $s_E$, $s_T$ are the flow velocity and salinity corresponding to the advection, steady shear and tidal oscillation terms separately, $Q_f$ is the volume flux corresponding to the advection term, $u$ is the velocity component in the $y$-direction of the orthogonal curve coordinate, $A$ is the area of each grid of the profile, $s$ is the salinity of the section grid, <> denotes spatially average, and {[]} denotes tidally average.

4 Results

4.1 Tidal effects on saltwater intrusion

The most critical factors affecting saltwater intrusion are river discharge and tidal mixing, whose interaction result in the distribution and change of estuary salinity (Zhang et al. 2014). Based on the observed data (Fig. 2b), the abnormally strong saltwater intrusion occurred in February 2008. The decrease in river discharge during the dry season is one of the reasons for the enhanced saltwater intrusion. However, it is seen from Fig. 2a that the actual river discharge in early February, when the strong saltwater intrusion occurred, is much higher than the rest of the dry season, with a maximum of over 7000 m$^3$/s. It indicates that it was not the decreased river discharge that caused the abnormally strong saltwater intrusion in early February 2008. Therefore, we turned to the tidal effects. The variation of bottom salinity along the Section 1 is plotted in Fig. 3. It shows that there exists a good relationship between the tidal range and saltwater intrusion (Fig. 3a, c), which is consistent with previous findings (Yi and Gong 2015). The strong saltwater intrusion always occurred before the spring tides and occurred twice a month, with a stronger intrusion and a weaker one, coinciding with the greater and the weaker neap tidal ranges.

$$F_s = \int (u_0 + u_E + u_T)(s_0 + s_E + s_T)dA 
\approx \int (u_0s_0 + u_Es_E + u Ts_T)dA = Q_fs + F_E + F_T,
F_0 = Q_fs = u_0 * s_0 \{\{A\}\} 
F_E = \{u_E * s_E \{\{A\}\}\} 
F_T = \{\{u_T * s_T \{\{A\}\}\}\}
$$

$$u_0 = \{\{u_0s\} \{\{A\}\}\} - \{\{u_0s\} \{\{A\}\}\} \{\{A\}\}$$

$$u_E = \{\{u_Es\} \{\{A\}\}\} - \{\{u_Es\} \{\{A\}\}\} \{\{A\}\}$$

$$u_T = u - \{\{u_Es\} \{\{A\}\}\}$$

$$s_0 = \{\{s_0s\} \{\{A\}\}\}$$

$$s_E = \{\{s_Es\} \{\{A\}\}\} - \{\{s_Es\} \{\{A\}\}\} \{\{A\}\}$$

$$s_T = s - \{\{s_Es\} \{\{A\}\}\}$$

Table 1 Model configurations for different cases

| River discharge (m$^3$/s) | Wind | Tide | Section |
|--------------------------|------|------|---------|
| Case1 2500               | √    | √    | 4.1, 4.2, 5.2 |
| Case2 2500               | ×    | √    | 4.1, 4.2, 5.1 |

Fig. 2 a River discharge of the PRE from 1st, November 2007 to 9th, April 2008. b The salinity of the bottom layer of Sishengwei Station. Observation data is taken twice a day from 30th, January, 2008 to 9th, April, 2008

Fig. 3 a Tidal variations of salinity. b Tidal variation of bottom salinity. c The tidal range of the PRE.
tides, respectively. This feature is caused by the super-
imposition of two diurnal (K1, O1) and two semi-diurnal
(M2 and S2) tidal constituents. It is also noted that the
bottom salinity was significantly higher in early Febru-
ary than in the rest of the dry season, though the river
discharge was much high then. The reasons are explored
below.

4.2 Wind effects on saltwater intrusion
Both wind speed and direction influenced the flow velo-
city and the strength of mixing and stratification in the
PRE, thus affecting the intensity of saltwater intrusion
(Li et al. 2012). Figure 3b shows the changes in the bot-
tom salinity along the Humen Channel under the wind
effects. The results demonstrate that the effects of winds
were most pronounced at 40 km-80 km of the longitudi-
dinal section, which is the middle reach of the estuary.
Significant changes in bottom salinity were not observed
in the lower reach of the estuary after accounting for the
effects of winds, while a significant increase in bottom
salinity was observed in the middle reach of the estuary
and a small increase in bottom salinity was noted in the
upper reach.

To analyze the effects of wind-driven circulation on dif-
ferent river reaches during spring and neap tides, the 50 h
averaged currents and salinity along the Section 1 during
the neap (from Jan 31 to Feb 2) and spring (from Feb 6 to
Feb 8) tides obtained from the model results are shown in
Fig. 4. During the spring tide, the estuary was well mixed
and the estuarine circulation was weak. The flow veloc-
ities of the surface and bottom layers were much weaker
than those during the neap tide. On the other hand, the
estuarine circulation was strengthened due to the sig-
nificant stratification and high baroclinic pressure gra-
dient in the estuary during the neap tide, resulting in an
increased upstream movement of salt water. When the

Fig. 3  a The water elevation at Humen Outlet. Times of spring and neap tides are marked. b Changes in bottom salinity along the Section 1 from January 1st to February 29th, 2008, showing the spring-neap variations of salt intrusion (see Fig. 1b for the location of Section 1). c Changes in bottom salinity without wind along the profile
Wind forcing was taken into account, the salinity of the estuary increased significantly during both the spring and neap tides. Particularly, during the neap tide, the estuarine circulation was significantly enhanced especially in the middle reach of the estuary and the water column was highly stratified compared to the spring tide under the northerly wind, leading to a stronger saltwater intrusion in the neap tide.

During the neap tide, the longitudinal salinity gradient was smaller than that during the spring tide, as the spring tide suppressed the salt intrusion by increased mixing. Following Chen and Sanford (2009), we calculate a non-dimensional number, the Wedderburn number (W). The Wedderburn number represents the relative importance between wind stress and baroclinic pressure gradient force (Monismith 1986)

\[
W = \frac{\tau_{wx} L}{\Delta \rho g H^2}
\]  

The Wedderburn numbers for the neap tide and spring tide are 0.51 and 0.22, respectively, again indicating that the northerly wind has a greater impact on saltwater intrusion during the neap tide.

For a better presentation of the variations in estuarine circulation and salinity induced by the northerly wind, we compare the surface and bottom salinities as well as the currents during the spring tide and the neap tide in the Lingding Bay (Figs. 5 and 6). It is clear that during the spring tide there was little difference between the surface and bottom salinities, while during the neap tide, under the influence of estuarine circulation, fresher water flowed seaward and the bottom saline water obviously advected upstream. And there is a very prominent tongue of high salinity in the East Channel (shown in Fig. 6b). The surface velocity increased significantly when the effect of strong northerly winds was taken into account and the surface residual flow was gradually turned westward with strong currents outside the estuary, while the plume water was transported towards the east coast (see Figs. 5c and 6c). The salinity of the water column on the east coast was significantly increased by the Ekman transport under the influence of northerly winds. Particularly, there was a high salinity water mass at the mouth, which is related to the strong mixing and Ekman landward transport by northerly wind in the shelf (shown in Fig. 6c).

Figure 7 shows the variation of the positions of the 10/13/15 ppt isohalines at the bottom of the Humen Channel under wind and windless conditions. The wind speed and direction from January, 2008 to April, 2008 are shown in Fig. 7b. From January 25th to February 8th, the wind direction was basically northerly for a long period. Without wind, the variation of the upstream distances of the isosaline corresponded well with the cycles of spring and neap tides. There was a significant upstream movement of saltwater intrusion 1-3 days before the spring tide each month. When the wind effects were included, the isohalines for different salinities were moved upstream. The distance of saltwater intrusion was much greater in February than in January, which was due to the influence of the prolonged northerly winds from mid-January to mid-February. The winds had a greater effect on the lower salinity isohaline. Water mass with a salinity of 10 ppt were shifted upstream much further under the influence of winds than that with a salinity of 15 ppt. Nevertheless, significant upstream movement of high salinity
water was observed under sustained northerly winds. As a result, the bottom salinity at a chosen station (point A, upstream of the confluence point), remained at 10 ppt for a prolonged period in February. The extent of saltwater intrusion in February was thus severer and longer-lasting compared to January. Moreover, the isohalines travelled a greater distance upstream during neap tides than during spring tides, and the northerly winds had a greater influence on saltwater intrusion during neap tides. Based on the salinity variations at point A and at the Humen Bridge in Fig. 7c, it can be concluded that in the tidal river of the PRE, upstream from the Humen Bridge, the bottom salinity increased significantly and saltwater intrusion was much severer than during the rest of the dry season under the persistent northerly winds. Strong saltwater intrusion persisted at river discharge above 7000 m$^3$/s (Fig. 2a), showing a significant threat to upstream freshwater supply.

5 Discussion
5.1 Salt flux decomposition
Saltwater intrusion is the process by which high salinity water from the offshore sea advances upstream along the estuary. Salt transport can be decomposed into many flux components according to different methods of salinity flux decomposition (Zeng 2010). The salt flux
is decomposed into an advection term $F_0$, a steady shear term $F_E$ and a tidal oscillation term $F_T$ according to Eq. (1). The three components of the salt flux were calculated for cross-section Section 2 at Humen Bridge, and the results are shown in Fig. 8. It can be seen that the variations of the steady shear term and the tidal oscillatory term have a good periodicity. At the Humen Bridge, a period of stronger steady shear term occurs at the beginning of each month, due to the fact that the stratification and the estuarine circulation are strong during the period when the neap tides transit to the spring tides, which is consistent with the previous study by Gong et al. (2018). The tidal oscillatory term is related to the spring and neap tidal cycles, with large values during spring tides and small values during neap tides, resulting in a significant increase in the tidal oscillatory term during spring tides each month. The advection term, on the other hand, is related to runoff and does not have a significant periodicity.

To provide a more visual comparison of the three components as a proportion of the total salt flux, each salt flux term at Section 2 was averaged laterally and moving averaged over 25 h, as shown in Fig. 9. It can be seen that the tidal oscillatory term is much less variable and...
negligible compared to the advection and steady shear terms. Therefore the advection and steady shear terms are considered to be the main causes of the changes in the extent of saltwater intrusion. We also note that the advection term is always negative and seaward while the steady shear term is always positive and landward. There is a more pronounced variation in the steady shear term with a periodicity. There existed a peak in the steady

**Fig. 7**

(a) Water elevation at Humen Outlet; (b) Measured wind speed and wind direction in the PRE; (c) Intrusion length of different isohalines with and without winds. The red dashed line at 88 km is the upstream confluence point A, and the line at 60 km is the Humen Bridge.

**Fig. 8**

Decomposition of cross-sectional salt flux from January 1st to February 29th, 2008 at Section 2 (see Fig. 1b for the location). 0 km on the coordinate is the west bank, and 3 km is the east bank.
shear term in each month, which occurred just before the spring tide at the beginning of the month and was much larger than at other times within the month, which coincided with the neap-spring tidal variations. This phenomenon coincided perfectly with the occurrence of abnormally strong saltwater intrusion. The same peak of the steady shear term existed in January, but the magnitude was less than in February.

Therefore, it can be concluded that the steady shear and advection terms were the main agents governing the saltwater intrusion, and the reason for the abnormally strong saltwater intrusion in February was the larger steady shear term in early February, the magnitude of which is closely related to the estuarine circulation (Lerczak et al. 2006; Bowen 2003). The intensity of estuarine stratification and mixing changes with the spring and neap tides (Wong 2003). The combination of the effects of tidal mixing and northerly wind results in the abnormally strong saltwater intrusion. Under the influence of the northerly wind, the saltwater continued to move upstream, extending its range of influence to upstream freshwater treatment plants and lasting for nearly a month, which posed a great threat to the upstream freshwater supply and seriously affected the economic development of the region.

5.2 Wind effects on different regions
Figure 7 shows that the effects of winds on saltwater intrusion were most pronounced in the middle reach of the estuary. We therefore selected four locations: 20 km, 40 km, 60 km and 80 km, and calculated the difference in salinity between the surface and bottom layers in the presence and absence of winds, as shown in Fig. 10. The variation of surface-bottom salinity difference without wind was well related to the spring and neap tidal cycles. During neap tides the tidal mixing was weaker, stratification increased and saltwater intrusion intensified. During spring tides the tidal mixing became stronger, stratification decreased and saltwater intrusion was less pronounced. As it took time for salt transport in the PRE to adjust to the changes in tidal mixing, the time when stratification was the strongest was continuously delayed from 20 km to 80 km, becoming closer to the spring tide at more upstream locations.

When the effects of wind were taken into account, the increase in salinity at different stations in the middle of each month was basically the same. At the beginning of February the increase in salinity was most pronounced at 60 km and 80 km, with 60 km showing a greater increase in salinity than both 80 km and 40 km. We assume that at 40 km, the salinity gradient was relatively small, and an increase in the bottom landward flow can only induce a moderate salinity increase, while at 80 km the upstream river flow inhibited the increase in salinity. It can be seen that due to the prolonged northerly winds, the high salinity water were continuously transported upstream by the strong bottom circulation in the estuary.

6 Conclusion
In this study, the phenomenon of an abnormally strong saltwater intrusion in the PRE was identified from the observation data, and systematically investigated through the EFDC model simulations. The main conclusions are drawn as follows:

1) During the dry season, strong saltwater intrusions were observed twice a month in the PRE, which occurred 1-3 days before the spring tide with a stronger intrusion and a weaker one. This pattern is closely related to the changes in tidal range.

2) Decomposition of the salt fluxes shows that the steady shear term and the advective term were the main components on the intensity of saltwater intrusion, with the steady shear term being the largest term which determined the occurrence of the abnormally strong saltwater intrusion.

3) The intrusion distances of the 15 ppt, 13 ppt and 10 ppt isohalines are analysed in the presence and
absence of winds and it indicates that the northerly winds during the dry season had a greater impact on the intrusion distances of low salinity water masses and cause severer saltwater intrusion. The northerly winds have a greater impact on saltwater intrusion during neap tides than during spring tides. Prolonged northerly winds increased the surface-bottom salinity difference, intensified the stratification, and enhanced the estuarine circulation. It can intensify the saltwater intrusion and keep the upstream water column in a strongly stratified state for a long time.

As the abnormally strong saltwater intrusion is induced by the combination of weak tidal mixing in neap tides and northerly wind, it is hard to prevent it by releasing freshwater from upstream. The cost of managing this strong saltwater intrusion by increasing river discharge is enormous. Forecasting the occurrence of such strong saltwater intrusion and establishing relevant prevention measures other than solely releasing freshwater from upstream would be required.

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Authors’ contributions
Conceptualization, B.H; methodology, B.H. and J.W; validation, B.H. and J.W; formal analysis, J.W, B.H. and W.G; investigation, J.W. and B.H.; resources, B.H.; data curation, J.W; writing—original draft preparation, J.W., B.H. and W.G.; writing—review and editing, B.H. and W.G.; visualization, J.W.; supervision, B.H. and W.G.; project administration, B.H. and W.G.; funding acquisition, B.H. and W.G. All authors have read and agreed to the published version of the manuscript.
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Availability of data and materials
Due to restrictions, data are available upon request. These data are not publicly available due to privacy concerns. The author, Mrs. Bo Hong (bohong@scut.edu.cn) can be contacted for access to the data.

Declarations

Competing interests
The authors declare no competing interests.

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