

Guarantee rate of freshwater in a river mouth intruded by saltwater with respect to the joint impact of runoff and tide

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ABSTRACT

Saltwater intrusion is detrimental to water utilization. It is of vital significance to study the joint impact of runoff and tide on salinity and the risk of saltwater intrusion. To analyze the risk of saltwater intrusion, this paper proposes two concepts: critical runoff–tide level line and guarantee rate of freshwater. Taking Nandu River Estuary in China as a study case, a three-dimensional (3-D) hydrodynamic and salinity numerical model is built. Critical runoff–tide level lines are obtained to determine the occurrence of saltwater intrusion. To quantify the guarantee rates of freshwater, copula joint distribution is utilized, which connects the numerical model and daily hydrological characteristics. Guarantee rates of freshwater are obtained under different amounts of water intake (0, 10 m³/s, 20 m³/s, 30 m³/s). In addition, critical locations of water intake that satisfy different guarantee rates (80%, 85%, 90%, 95%, 99%) are identified. All the results will provide technical support for risk evaluation of saltwater intrusion and decisions on water intake location.

Key words | 3-D hydrodynamic and salinity numerical model, critical runoff–tide level line, guarantee rate of freshwater, joint probability distribution, Nandu River Estuary, saltwater intrusion

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INTRODUCTION

Saltwater intrusion is a global issue. It not only has a significant impact on river and wetland ecosystems (Suen & Lai 2013), but also influences the survival and development of mankind (Khan *et al.* 2011). Many large cities are situated at river mouths where freshwater resources are crucial to the local citizens. Due to the influence of saltwater intrusion, locations of water intake are important for drinking water safety (Werner *et al.* 2013). Research on risk and uncertainty management relating to guarantee rate of freshwater are becoming increasingly important. It is of vital significance to accurately assess the risk of saltwater intrusion and select feasible water intake locations regarding human activities.

In estuary areas, water salinity is affected by the joint impact of runoff and tide (Yang *et al.* 2015). The transportation of salt depends on a variety of factors including runoff, tide, estuary topography, etc. (Rice *et al.* 2012). The

freshwater source is supposed to be the dominant influencing factor on the saltwater intrusion, salinity structure, vertical stratification, and saltwater intrusion length (Zhou *et al.* 2012). A higher flow provides substantial dilution to reduce the salt concentration and vice versa during low flow regimes (Prairie & Rajagopalan 2007). Tide is another important factor that exerts considerable influences on water salinity. A rising tide favors the convection and diffusion of saltwater from the sea. It will aggravate the saltwater intrusion, and make the isohaline and intrusion length move upstream (Rice *et al.* 2012). The response of salinity in the river to runoff and tide is complicated. Some linear, polynomial, exponential relationships have been put forward between freshwater runoff, tide, and salinity intrusion length for specific research areas (Huang & Spaulding 2000; Becker *et al.* 2010; Rice *et al.* 2012; Yu *et al.* 2013; Yang *et al.* 2015). However, there is still no universal formula

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and more work is needed to study the joint impact of runoff and tide on salinity.

From the perspective of research methods, studies on saltwater intrusion are divided into statistical analysis and numerical simulation. A considerable amount of research has been done in the field of saltwater intrusion for a long time based on the statistical analysis of measured data (Uncles *et al.* 2000; Huang & Foo 2002; Hall *et al.* 2004; Aris *et al.* 2012; Liu *et al.* 2014). With the rapid development of computer technology, numerical simulation has been widely employed in the study of saltwater intrusion due to its high computation speed, low cost, and high stability. There are some mature and widely used three-dimensional (3-D) numerical models, including the HD model (Bhuiyan & Dutta 2012), EFDC model (Xu *et al.* 2008; Jeong *et al.* 2010), HEM-3D model (Rice *et al.* 2012), ECOM model (An *et al.* 2009; Qiu & Zhu 2013), FVCOM model (Wang *et al.* 2012), etc. The MIKE 3 model was developed by DHI Water and Environment, and has proven its accuracy and reliability in large-scale and long-term numerical simulations (Rasch *et al.* 2005; DHI 2009; Myrberg *et al.* 2010; Sharbaty 2012). In previous research on salinity intrusion, typical hydrological conditions (e.g., average flow, high flow, low flow, average tide level, high tide level, low tide level, etc.) are often extracted to perform numerical simulation (Jeong *et al.* 2010; Rice *et al.* 2012; Das *et al.* 2012; Bhuiyan & Dutta 2012; Li *et al.* 2013). Extensive research on saltwater intrusion has been carried out in the area of conclusive research under typical hydrological conditions, but study concerning accurate quantification of saltwater intrusion risk and guarantee rate of freshwater is still insufficient.

Nandu River is the largest river of Hainan Island. The estuary has long been influenced by saltwater intrusion which suffers a trend of exacerbation because of sand-excavating in recent years (Li 2007; Gong *et al.* 2012; Zhao *et al.* 2013). Water intakes in the estuary are frequently affected; hence, a new site locating strategy is imperative. At present, little attention has been paid to Nandu River Estuary. Gong *et al.* (2012) only qualitatively studied the salinity stratification in the timescales of the intratidal to the intertidal based on measured data, which were insufficient for quantitative analysis. Li (2007) calculated the relationships between runoff discharge and intrusion length using

a 2-D model in which salinity stratification could not be considered. Zhao *et al.* (2013) studied the temporal and spatial variations of salinity during dry and wet seasons. Although results under different runoffs and tides were obtained, it still was not possible to support site locating. Therefore, a comprehensive study about the joint impact of runoff and tide on saltwater intrusion is necessary for Nandu River Estuary. In this paper, methods of quantifying saltwater intrusion risk and guarantee rate of freshwater are proposed. A 3-D numerical model based on MIKE 3 is built to analyze water salinity considering the joint impact of runoff and tide. Critical runoff–tide level lines are proposed and obtained to determine the occurrence of saltwater intrusion. With critical runoff–tide level lines, a copula joint probability distribution of runoff and tide level is established to accurately quantify the guarantee rate of freshwater. Finally, critical locations of water intake satisfying different guarantee rates of freshwater are identified. All the results will be a good support for risk evaluation of saltwater intrusion and decisions about water intake location.

This paper is organized as follows. The case study area, Nandu River Estuary, and daily runoff and tide data are described in the next section. The following section elaborates on the research methods, including study framework, numerical modeling and simulation, methods of joint impact and guarantee rate, and so on. Results and discussion are presented based on critical runoff–tide level lines, joint distribution of runoff and tidal level, and guarantee rates of freshwater. Finally, conclusions are drawn.

CASE STUDY AREA AND DATA COLLECTION

Case study area

Haikou City is the capital of Hainan province, but also the political, economic, technological, and cultural center. As shown in Figure 1, Nandu River, as the largest river in Hainan Island that flows through Haikou City into the sea, offers almost the entire water source for Haikou City and northeastern Hainan Island. Longtang Dam is located 26 kilometers away from the river mouth. According to the overall plan of Haikou City, the water demands of agriculture, industry, and urban living on the Nandu River

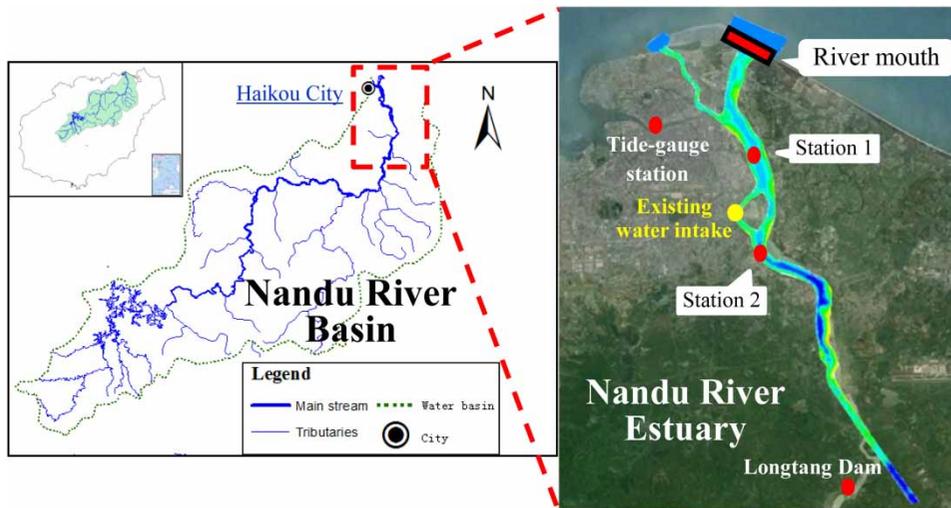


Figure 1 | Location map of Nandu River Estuary. Stations 1 and 2 are salinity and velocity monitoring stations.

Estuary will remain stable in the range of 20 to 30 m³/s by the year 2020.

Saltwater intrusion occurs easily in the Nandu River Estuary, which seriously affects the existing water intake which lies 8 kilometers upstream from the river mouth. According to some statistics, water salinity presents as high under low runoff of Longtang Dam. Saltwater intrusion has greatly hampered the development and utilization of water resources in this region. Therefore, it is necessary to find a new and feasible water intake location.

Data collection

Terrain data used for numerical modeling are the digital elevation model data of the original terrain with 30 m resolution measured in 2013. Daily runoff data from 1/1/1980 to 12/30/2012 were provided by Longtang hydrometric station. Daily runoff ranges from 6.5 to 8,670 m³/s. Daily tide data from 1/1/1980 to 12/30/2012 measured by Haikou tide-gauge station, including typical daily tide process, daily high tide level, and low tide level, were also collected. Daily high tide level ranges from -0.72 to 3.05 m. Tide process during the period 6/16/2009 1:00 a.m. to 6/17/2009 1:00 a.m. is selected as typical daily tide process. The reasons for it are described as follows. First, there is little rainfall during this period. Second, tidal range, the duration of tide falling and rising on that day are close to the average level

for many years. Third, the event is the latest of the above states (Chen *et al.* 2000).

METHODS

Study framework

This research includes four main steps. First, a 3-D hydrodynamic and salinity model for Nandu River Estuary is built. Second, salinity intrusion lengths under various scenarios of runoff and tide are calculated, and critical runoff-tide level lines of multiple sections are obtained. Third, a joint distribution of runoff and tidal level using copula is established. Finally, and crucially, based on the critical runoff-tide level lines and joint distribution of runoff and tidal level, guarantee rates of freshwater and critical locations of water intake are obtained. The study framework of the paper is shown in Figure 2.

3-D hydrodynamic and salinity numerical model

Model solution

A 3-D hydrodynamic and salinity model for the Nandu River Estuary from Longtang Dam to the river mouth is developed

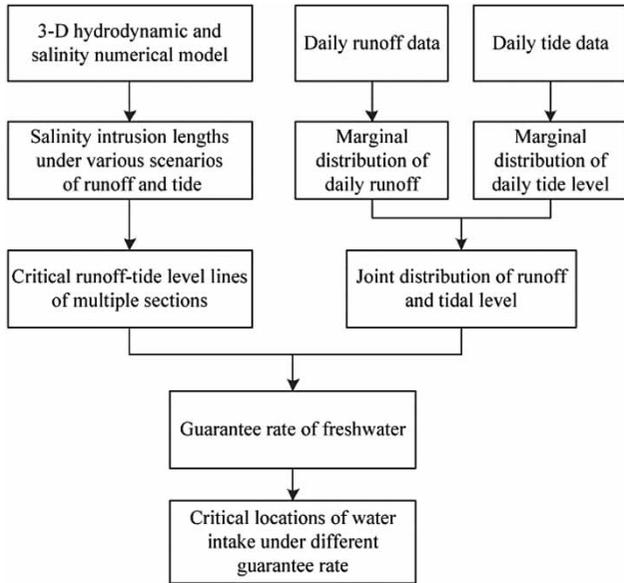


Figure 2 | Study framework of this paper.

by MIKE 3 Flow Model (FM) modeling system. The model is based on the three-dimensional incompressible Reynolds averaged Navier–Stokes equations (DHI 2009), which are expressed as Equations (1)–(3). The model is solved by discretization in solution domain using a finite volume method. In the vertical direction, the water is divided into multilayers while unstructured meshes are used in the horizontal domain.

Local continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = S \tag{1}$$

Two horizontal momentum equations for the x- and y-component, respectively:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial wu}{\partial z} = fv - g \frac{\partial \eta}{\partial x} - \frac{1}{\rho_0} \frac{\partial p_a}{\partial x} - \frac{g}{\rho_0} \int_z^\eta \frac{\partial \rho}{\partial x} dz - \frac{1}{\rho_0 h} \left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y} \right) + F_u + \frac{\partial}{\partial z} \left(v_t \frac{\partial u}{\partial z} \right) + u_s S \tag{2}$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial wv}{\partial z} = -fu - g \frac{\partial \eta}{\partial y} - \frac{1}{\rho_0} \frac{\partial p_a}{\partial y} - \frac{g}{\rho_0} \int_z^\eta \frac{\partial \rho}{\partial y} dz - \frac{1}{\rho_0 h} \left(\frac{\partial s_{yx}}{\partial x} + \frac{\partial s_{yy}}{\partial y} \right) + F_v + \frac{\partial}{\partial z} \left(v_t \frac{\partial v}{\partial z} \right) + v_s S \tag{3}$$

Convection diffusion equation of salinity:

$$\frac{\partial s}{\partial t} + \frac{\partial us}{\partial x} + \frac{\partial vs}{\partial y} + \frac{\partial ws}{\partial z} = F_s + \frac{\partial}{\partial z} \left(D_t \frac{\partial s}{\partial z} \right) + s_s S \tag{4}$$

where t is the time (s); x , y , and z are the Cartesian co-ordinates (m); η is the surface elevation (m); d is the still water depth (m); $h = \eta + d$ is the total water depth (m); u , v , and w are the velocity components in the x , y , and z direction (m/s); $f = 2\Omega \sin \varphi$ is the Coriolis parameter (N); Ω is the angular rate of revolution and φ is the geographic latitude; g is the gravitational acceleration (m^2/s); ρ is the density of water (kg/m^3); s_{xx} , s_{xy} , s_{yx} , and s_{yy} are components of the radiation stress tensor; ν_t is the vertical turbulent (or eddy) viscosity (m^2/s); p_a is the atmospheric pressure (pa); ρ_0 is the reference density of water (m^3/s); S is the magnitude of the discharge due to point sources (m^3/s), and (u_s, v_s) is the velocity by which the water is discharged into the ambient water (m/s).

Model description

The modeling scope covers from the Longtang Dam spillway to the river mouth, a total length of 26 km. Triangle meshes are generated according to the digital elevation model data. Terrain boundaries are the channel embankment. As shown in Figure 3, averaged mesh size is 50 m, some areas with complex terrain and irregular boundaries are refined to 20 m. The total number of mesh is 8,141. The computational time step is set as 2 seconds.

Model calibration

Model calibration is carried out for parameters, including roughness height and salinity diffusion coefficient.

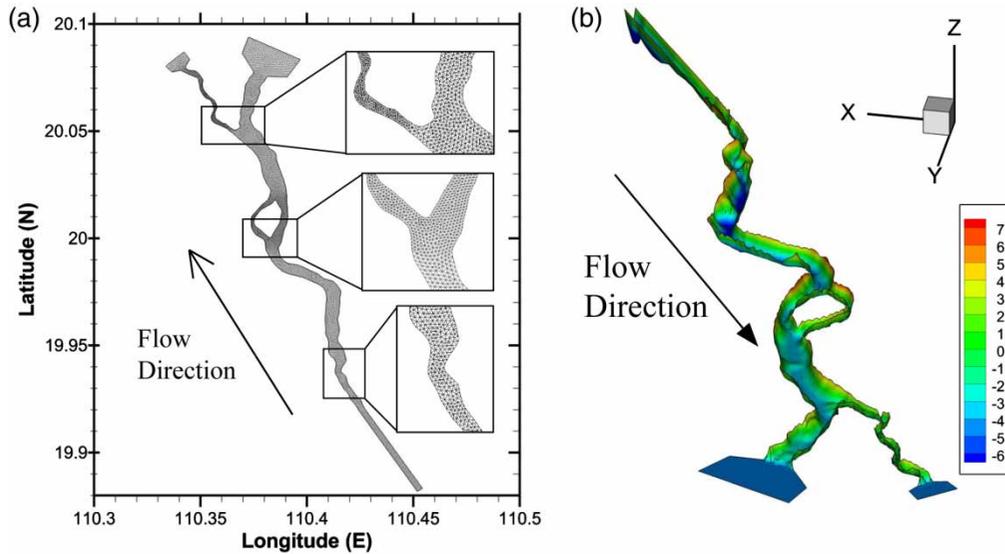


Figure 3 | 3-D hydrodynamic and salinity numerical model of Nandu River Estuary: (a) for 3-D model mesh and (b) for the topographical map with an overhead view.

The simulated water level, velocity and its direction, and salinity are compared with data measured in the flood (18/10/2010), neap tide (2/7/2009 9:00 a.m. to 2/8/2009 10:00 p.m.) and spring tide (2/11/2009 10:00 a.m. to 2/12/2009 11:00 p.m.) (Li 2007; Gong et al. 2012; Zhao et al. 2013). After referring to the relevant authority and repeated adjustment, the roughness heights are set as 0.002 ~ 0.005 m. Values of upstream are larger than those of downstream, and values of bottomland are larger than those of the main channel. Horizontal and vertical salinity diffusion coefficients are set as 0.12 m³/s and 0.0001 m³/s.

Many model evaluation statistics have been proposed, among which Nash–Sutcliffe efficiency (NSE) and root-mean-square error (RMSE) observations standard deviation ratio (RSR) were recommended by Moriasi et al. (2007). In general, model simulation can be judged as satisfactory if NSE > 0.50 and RSR < 0.70. NSE and RSR are calculated as in Equation (5):

$$\text{NSE} = 1 - \frac{\sum_{i=1}^n (X_i^{\text{obs}} - X_i^{\text{sim}})^2}{\sum_{i=1}^n (X_i^{\text{obs}} - X^{\text{mean}})^2},$$

$$\text{RSR} = \frac{\text{RMSE}}{\text{STDEV}_{\text{obs}}} = \frac{\sqrt{\sum_{i=1}^n (X_i^{\text{obs}} - X_i^{\text{sim}})^2}}{\sqrt{\sum_{i=1}^n (X_i^{\text{obs}} - X^{\text{mean}})^2}} \quad (5)$$

where X_i^{obs} is the i th observation for the constituent being evaluated; X_i^{sim} is the i th simulated value for the constituent being evaluated, X^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

In this paper, NSE and RSR are chosen to test the goodness-of-fit of the simulation model. Calibration results, NSE and RSR values are presented in Figures 4–6.

As shown in Figures 4 and 5, NSE values are larger than 0.75, RSR values are smaller than 0.50. As to the 12 scenarios of salinity calibration, all but one of the scenarios can be judged as satisfactory. The errors may result from the errors of measurements.

Considering the multiplicity and complexity of impacting factors in estuary areas, fitting results are satisfied,

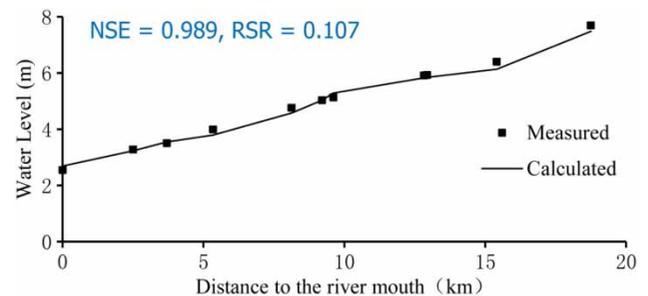


Figure 4 | Comparisons of calculated and measured water level. The line represents calculated values while the squares represent measured values.

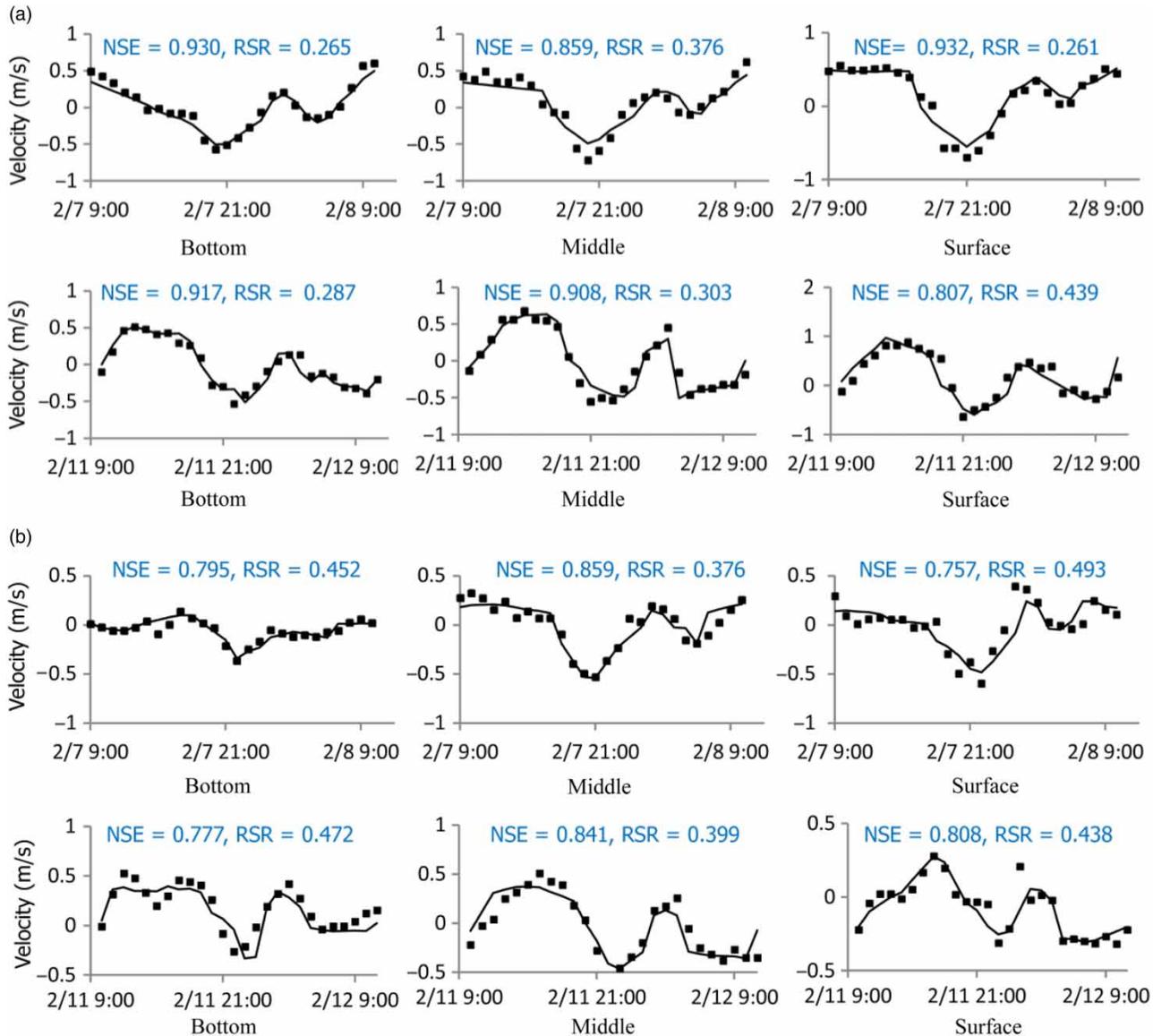


Figure 5 | Comparisons of calculated and measured velocity. Lines represent calculated values while squares represent measured values. Positive value indicates the flow direction toward the sea. (a) Station 1 and (b) Station 2.

which means the numerical model can properly reflect temporal and spatial distribution of hydrodynamics and salinity.

Model scenarios

For the 3-D hydrodynamic and salinity field simulation, 290 model scenarios are proposed according to the characteristics of daily runoff and high tide level. Every scenario contains a daily runoff process as the inflow boundary condition and a daily tide process as the open boundary. For the

Nandu River Estuary, runoff does not change in a day due to the regulation of Longtang Dam. Therefore, daily runoff process can be set as a constant. For model scenarios, the constant is set as the following 29 values: 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000. Daily tide processes are proposed by homogeneous enlargement of typical daily tide process according to high tide level. High tide level is set as the following 10 values: -1, -0.5, 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5.

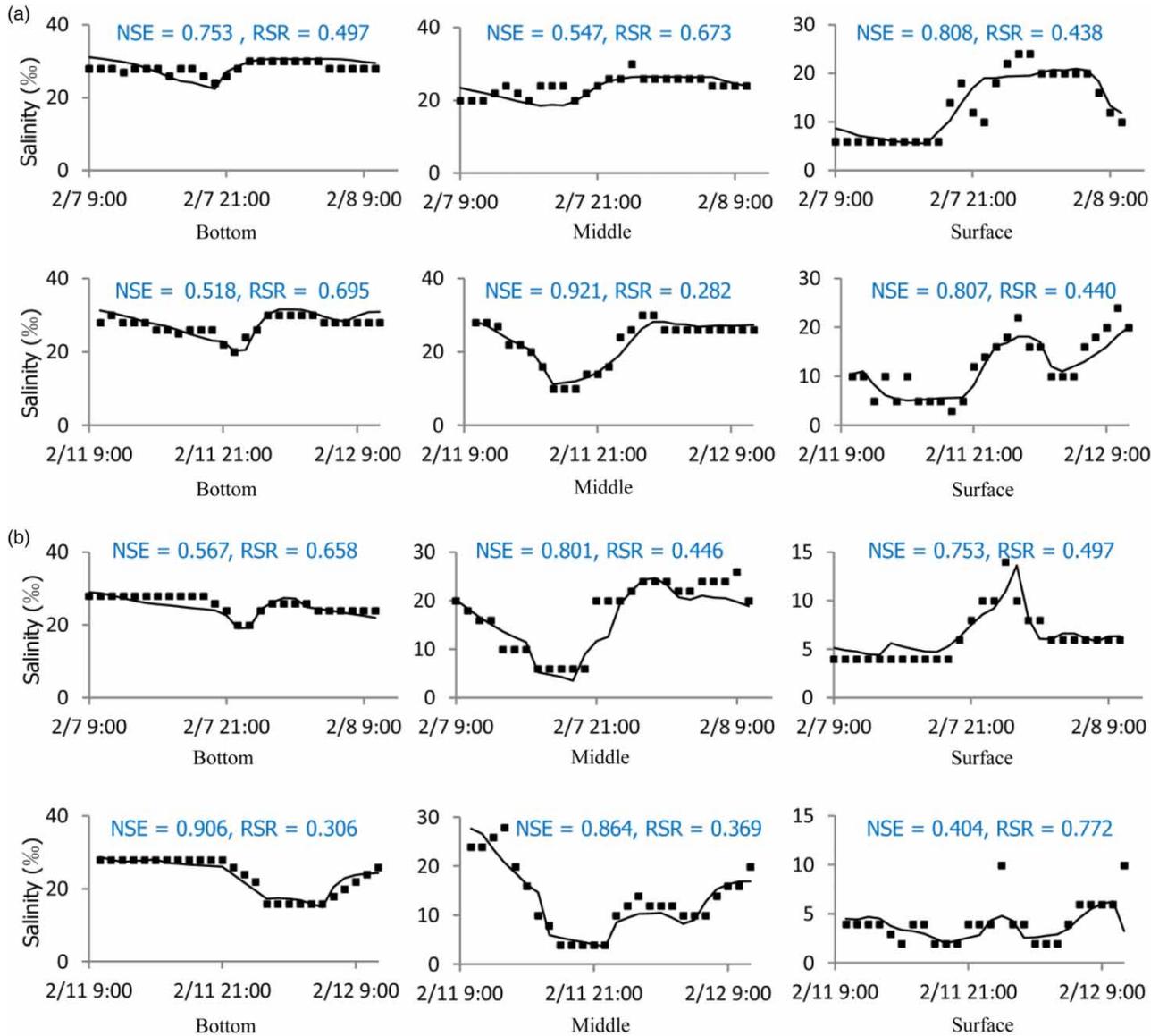


Figure 6 | Comparisons of calculated and measured salinity. Lines represent calculated values while squares represent measured values. (a) Station 1 and (b) Station 2.

Critical runoff-tide level lines

According to water quality standards for drinking water and correlational research (WHO 2011; Qiu & Zhu 2013), 0.45‰ is set as the threshold of standard-exceeding salinity. In the vertical direction, density variation causes salinity stratification, bottom salinity is higher (Becker et al. 2010); the saltwater intrusion length is shown in Figure 7.

Critical runoff-tide level line is the criterion used to judge whether saltwater intrusion occurs. According to

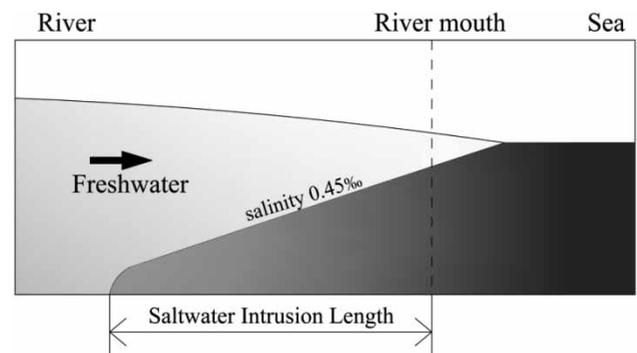


Figure 7 | Schematic diagram of saltwater intrusion length in the estuary.

this line, the safety area of runoff and tide level for salinity is defined, as shown in Figure 8. Based on the numerical model, saltwater intrusion lengths of all scenarios can be calculated. As for different river sections, critical runoff-tide level lines can be obtained.

Joint probability distribution of runoff and high tide level

Marginal distribution of runoff and high tide level

Before the establishment of joint probability distribution, marginal distributions of runoff and high tide level should be developed. Long-term records of runoff and high tide level are analyzed by mathematical fitting method. Marginal distribution curves are fitted by classic models such as linear, Gaussian, binomial, polynomial, Gompertz, etc. To test the fitting result of marginal distribution functions, quantitative statistics NSE, RSR and coefficient of determination (R^2) are used.

Joint probability distribution using copula

Joint probability distribution is an effective method of multivariate hydrological analysis. Copula function can describe the correlation structure of random variables and put marginal distributions together to form a joint probability distribution (Favre et al. 2004; Genest et al. 2007). Owing

to its simplicity and practicability, it has been widely used in risk assessment of extreme floods (Fiorentino et al. 2007; Lian et al. 2013; Xu et al. 2014), which provides the possibility and convenience to study the guarantee rate of freshwater in river estuaries. The relationship between copula function and joint probability is presented in Equations (6) and (7).

$$\Pr(Q < q, H < h) = F(q, h) = C(F_q(q), F_h(h)) \quad (6)$$

$$F_q(q) = \Pr(Q < q), \quad F_h(h) = \Pr(H < h) \quad (7)$$

where q is the runoff (m^3/s); h is the high tide level (m); $\Pr(Q < q, H < h)$ is the probability that runoff presents lower than q and tide level presents lower than h ; $F(q, h)$ is the joint distribution of runoff and tide level; $F_q(q)$ and $F_h(h)$ are marginal distributions of runoff and tide level; $C(F_q(q), F_h(h))$ is the joint probability distribution of runoff and tide level using copula.

Frequently used copula functions include Clayton, Frank, Gumbel, t Copulas, etc. The functions are described specifically in the Appendix (available online at <http://www.iwaponline.com/jh/017/038.pdf>).

To choose the best copula function, the Akaike information criterion (AIC) is used (Yamaoka et al. 1978; Pan 2001). With the value of AIC becoming smaller, the fitting result gets better. The AIC equation is presented in Equation (8).

$$\text{AIC} = n \ln \left[\sum_{i=1}^n (X_i^{\text{sim}} - X_i^{\text{obs}}) / n \right] + 2k \quad (8)$$

where X_i^{obs} is the i th observation for the constituent being evaluated, X_i^{sim} is the i th simulated value for the constituent being evaluated, n is the total number of observations, and k is the number of variables.

To test the fitting result of joint distribution functions, quantitative statistics NSE, RSR, and coefficient of determination (R^2) are used.

Guarantee rate of freshwater

Guarantee rate of freshwater is the probability of the safety area for salinity. For a specific section k km upstream

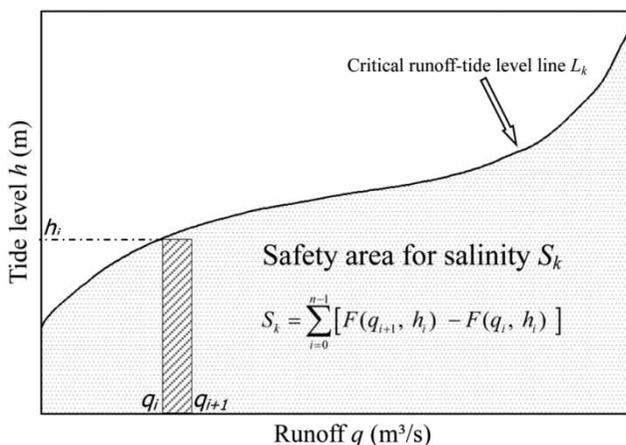


Figure 8 | Schematic diagram of critical runoff-tide level line L_k and the safety area for salinity S_k . $\Pr(S_k)$ is the probability of safety area for salinity, i.e., the guarantee rate of freshwater. $F(q, h)$ is the joint probability distribution of runoff and tide level.

from the river mouth, guarantee rate of freshwater is defined as the probability that salinity is lower than 0.45‰ , or intrusion length is less than k .

Based on critical runoff–tide level lines, scenarios of runoff and tide not suffering from saltwater intrusion can be defined. Probability of the safety area for salinity, i.e., guarantee rate of freshwater (GRF), can be calculated through joint probability distribution, as shown in Figure 8 and Equation (9).

$$\begin{aligned} & \Pr(\text{GRF of river sections } k \text{ km} \\ & \text{upstream from the river mouth}) \\ &= \Pr(\text{salinity} \leq 0.45) \\ &= \Pr(\text{Saltwater intrusion length less than } L_k) \\ &= \Pr(S_k) \approx \sum_{i=0}^{n-1} (F(q_{i+1}, h_i) - F(q_i, h_i)) \end{aligned} \quad (9)$$

where L_k is the critical runoff–tide level line of section k km upstream from the river mouth; S_k is the safety area for salinity of section k km upstream from the river mouth, as shown in Figure 8; $F(q, h)$ is the selected joint probability distribution; n is the number of subsections of runoff, when it is big enough, Equation (9) turns to

$$\Pr(S_k) \approx \sum_{i=0}^{n-1} (F(q_{i+1}, h_i) - F(q_i, h_i)).$$

The critical location of water intake is where the guarantee rate of freshwater exactly meets the requirements. When water intake is located upstream of the critical location, freshwater resources from the water intake can satisfy the design guarantee rate of freshwater. After calculating the guarantee rate of freshwater, critical locations of water intake satisfying different guarantee rates (80%, 85%, 90%, 95%, 99%) can be obtained.

RESULTS AND DISCUSSION

Obtaining critical runoff–tide level lines

Processes of saltwater intrusion under different model scenarios are simulated by 3-D numerical model. Salinity intrusion lengths are obtained and presented in Figure 9. According to the isoline distribution, critical runoff–tide level lines of multiple sections are shown in Figure 10.

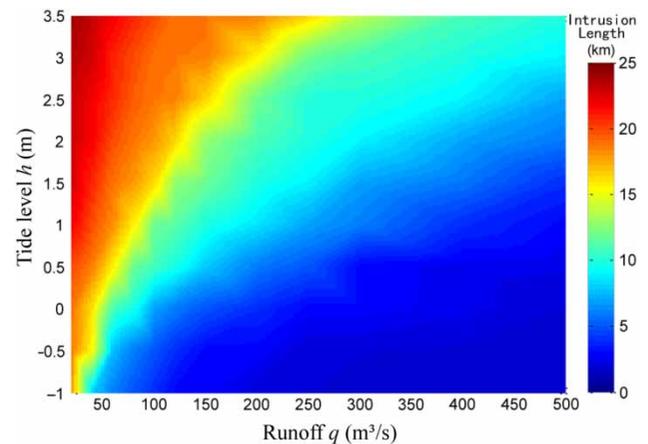


Figure 9 | Saltwater intrusion lengths in Nandu River Estuary under various scenarios of runoff and tide level.

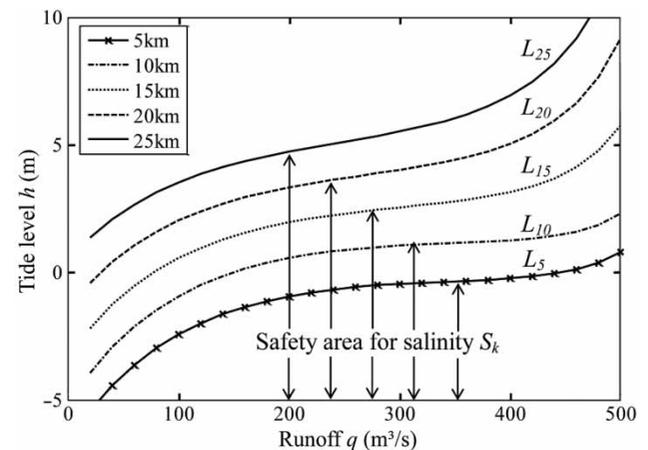


Figure 10 | Critical runoff–tide level lines of multiple sections.

Establishment of joint probability distribution of runoff and high tide level

Marginal distribution of runoff and high tide level

Marginal distribution curves of runoff and high tide level are analyzed and fitted by nonlinear models. The Gompertz model was a practical predictive tool in demography originally (Johnson 1990; Mueller et al. 1995) and has been used in hydrology recently (USGS 2012). The cumulative frequency curve of log-values of daily runoff fits well with the Gompertz model. The NSE, RSR, and R^2 values are 0.998, 0.047, and 0.971, respectively. Considering the giant sample size (more than 10,000), the model can perfectly

reflect the characteristic of daily runoff. The regression equation is presented in Equation (10) and the fitting result is presented in Figure 11. By shifting the current runoff marginal distribution curve, a new curve reflecting the situation of after-water-intaking is formed. The shift range is in direct proportion to the amount of water intake.

Joint probability distribution using copula

Joint distributions can be obtained based on marginal distributions. Copula functions used include Clayton, Frank, Gumbel and *t* copulas. Copula parameters are calculated using maximum likelihood approach. Copula parameters

$$\Pr(Q \leq q) = F_q(q) = \begin{cases} 0.9999 & (8700 < q) \\ 0.9957 \exp\{-\exp[-3.1942(x - 1.82695)]\} + 0.0001 & (5 < q \leq 8700) \\ 0.0001 & (q \leq 5) \end{cases} \quad (10)$$

where $x = \lg(q + N)$, N is the amount of water intake. When N equals 0, the current runoff marginal distribution curve is derived.

Probability density function of daily high tide level fits well with the Gaussian distribution with mean 1.24 and standard deviation 0.27. The NSE, RSR, and R^2 values are 0.997, 0.057, and 0.955, respectively. Considering the giant sample size (more than 10,000), the Gaussian distribution can fully reflect the characteristic of daily high tide level. The regression equation is presented in Equations (11) and (12), with the fitting result shown in Figure 11.

$$h \sim N(\mu, \sigma^2), \mu = 1.24, \sigma = 0.27 \quad (11)$$

$$\Pr(H \leq h) = F_h(h) = \int_{-\infty}^h \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\mu)^2}{2\sigma^2}} dt, -\infty < h < +\infty \quad (12)$$

and goodness-of-fit test of four copula functions are listed in Table 1.

On the principle of minimum AIC, the Gumbel copula function with the parameter θ set as 1.28 best fits the joint distribution of average daily runoff and high tidal level. The NSE, RSR, and R^2 values are 0.997, 0.059, and 0.959, respectively. The selected copula function can perfectly represent hydrological joint distribution characteristics of daily high runoff and high tide level.

According to parameters calculated in Table 1 and the formula in Equation (A1), the Gumbel copula fitting the joint distribution $F(q,h)$ for Q and H is expressed in Equation (13):

$$F(q, h) = \exp\{-[(-\ln F_q(q))^{1.28} + (-\ln F_h(h))^{1.28}]^{1/1.28}\} \quad (13)$$

Calculation of guarantee rate of freshwater

Based on critical runoff-tide level lines of multiple sections and joint probability distribution, guarantee rates of

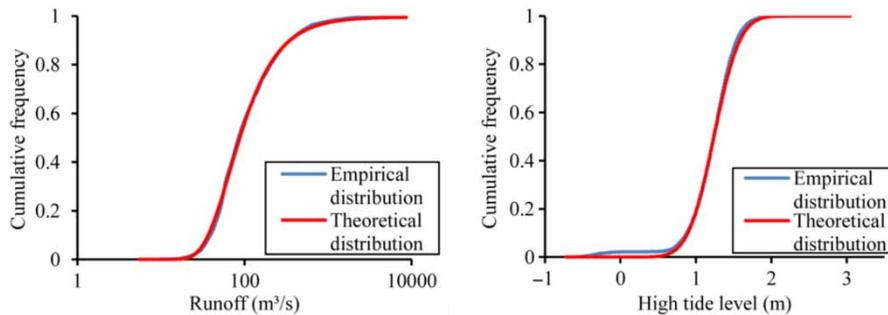


Figure 11 | Comparisons of empirical and theoretical cumulative frequency distribution for the daily runoff and high tide level.

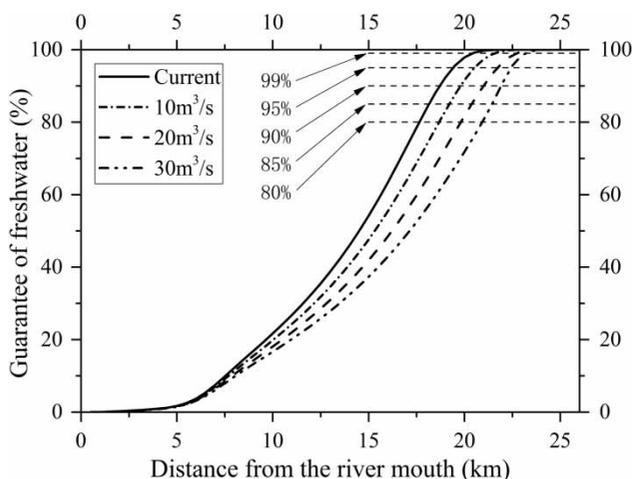
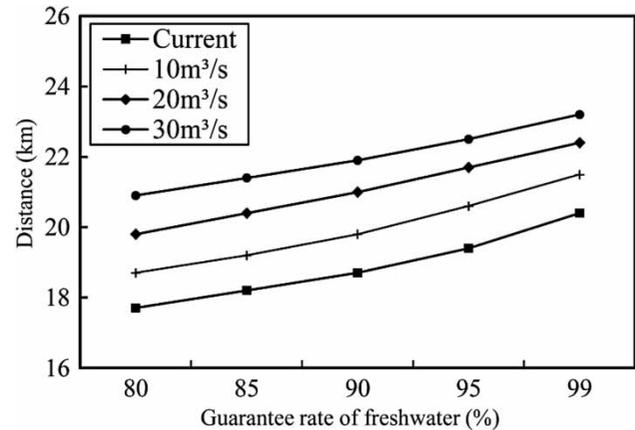
Table 1 | Parameters and goodness-of-fit test of copulas

Copulas	Gumbel	Frank	Clayton	t copula
Parameters	$\theta = 1.28$	$\theta = 2.07$	$\theta = 0.57$	$\rho = 0.34$
AIC	-105,154	-98,182	-90,576	-99,475
NSE	0.997	0.995	0.991	0.996
RSR	0.059	0.068	0.094	0.065
R ²	0.959	0.912	0.864	0.916

freshwater are calculated under different amounts of water intake (0, 10 m³/s, 20 m³/s, 30 m³/s), as presented in Figure 12.

Within the river channel 5 km from the river mouth, guarantee rate of freshwater remains lower than 5%. The persistent high salinity may result from diffusion and accumulation of salt in water. With an increase of the amount of water intake, downstream runoff decreases, and corresponding salinity and intrusion length increase. In general, a decrease in runoff will increase the risks of salinity and decrease the guarantee rate of freshwater.

Critical locations of water intake under different guarantee rates (80%, 85%, 90%, 95%, 99%) are determined and presented in Figure 13. These four lines are almost parallel. Under identical guarantee rate of freshwater, the distance from the critical location to the river mouth is in proportion to the amount of water intake. When the amount of water intake is 0 and guarantee rates of freshwater are set as 80%, 85%, 90%, 95%, 99%, critical locations of water intake lie 17.7 km, 18.2 km,

**Figure 12** | Guarantee of freshwater (GRF) in Nandu River Estuary under different amounts of water intake (0, 10 m³/s, 20 m³/s, 30 m³/s).**Figure 13** | Critical locations of water intake satisfying different guarantee rates.

18.7 km, 19.4 km, and 21.3 km from the river mouth, respectively. When the amounts of water intake increases to 10 m³/s, 20 m³/s, and 30 m³/s, critical locations of water intake move 1.1 km, 2.2 km, and 3.0 km upstream on average. This indicates that the critical location of water intakes moves 1 km upstream on average when the amount of water intake increases by 10 m³/s. For Haikou City, when freshwater demand is 20 m³/s, critical locations of water intake are 19.8 km, 20.4 km, 21 km, 21.7 km, 22.4 km from the river mouth under different guarantee rates (80%, 85%, 90%, 95%, 99%). When freshwater demand is 30 m³/s, critical locations of water intake are 20.9 km, 21.4 km, 21.9 km, 22.5 km, 23.2 km from the river mouth under different guarantee rates (80%, 85%, 90%, 95%, 99%). Based on the results above, location of water intake can reasonably be selected according to the amount of water intake and guarantee rate of freshwater.

CONCLUSIONS

Freshwater resources are crucial to estuary regions. However, the security of these resources has been threatened by saltwater intrusion. Extensive research on saltwater intrusion has been done under typical hydrological conditions, but study about the risk of saltwater intrusion is currently lacking. In the Nandu River Estuary, a comprehensive study about the joint impact of runoff and tide on saltwater intrusion is needed to provide adequate support for site locating strategy. This paper performs a risk probability analysis of saltwater intrusion, and quantifies the guarantee rate of

freshwater. The work consists of four main parts: (a) establishment of a 3-D hydrodynamic and salinity model; (b) obtainment of critical runoff–tide level lines; (c) construction of joint probability distribution of runoff and tidal level using copula; and (d) calculation of guarantee rates of freshwater and critical locations of water intake.

In this paper, the concepts of critical runoff–tide level line and guarantee rate of freshwater are proposed. Critical runoff–tide level line refers to a criterion used to judge whether saltwater intrusion occurs. It involves the joint impact of runoff and tide on salinity. The guarantee rate of freshwater is the probability of freshwater. It is closely linked to the risk of saltwater intrusion and site locating strategy of water intake. The two concepts are practical in the risk research on saltwater intrusion for river estuaries. Focusing on the Nandu River Estuary, this paper has obtained the critical runoff–tide level lines of multiple sections, and quantified guarantee rates of freshwater. Results reveal that as the amount of water intake increases at the rate of $10 \text{ m}^3/\text{s}$, critical locations of water intake move 1 km upstream on average. It shows a good linear relationship between the river channel length satisfying the guarantee rate of freshwater and the amount of water intake. For another guarantee rate of freshwater or amount of water intake, the location of water intake can be determined by interpolation method. The result is very practical both for the risk analysis of saltwater intrusion and the site locating of water intake.

In this study, the impact of many factors including runoff, tide, terrain, and human activities have been taken into consideration to quantify the risk of saltwater intrusion, which provides a new strategy for the research on risk management regarding the guarantee rate of freshwater. This research can be the reference for other water bodies in estuary areas. Within the field of development of ocean exploitation, research into risk management regarding saltwater intrusion will be a major focus of future studies.

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