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Analysis of critical river discharge for saltwater intrusion control in the upper South Branch of the Yangtze River Estuary

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Abstract: Saltwater intrusion in the estuary area threatens the use of freshwater resources. If river discharge increases to a critical value, then saltwater intrusion frequency and salinity level decreases. In this study, long-term river discharge and tidal range data in the Yangtze River Estuary (YRE) and salinity data obtained in the upper South Branch of the YRE were used to analyze the characteristics of different variables and the basic law of their interactions. Two methods, namely, the material analysis method and empirical models, were applied to determine the critical river discharge for saltwater intrusion control. Results are as follows: (1) the salinity might exceed the drinking water standard of China when the river discharge was less than 30,000 m³/s. Approximately 69% of salinity excessive days occurred when the river discharge was less than 15,000 m³/s; (2) the tidal range in the YRE roughly varied in sinusoidal pattern with a 15-day cycle length. Exponential relationship existed between daily salinity (chlorinity) and daily mean tidal range. Combining these two features with the cumulative frequency statistics of tidal ranges, it was showed that notable saltwater intrusion occurred when the tidal range was more than 2.7 m at Qinglonggang station. Moreover, the critical discharge was found to be slightly higher than 11,000 m³/s; (3) various of empirical models for salinity prediction could be chosen to calculate the critical discharge. The values obtained by different models were in the range of 11,000–12,000 m³/s; (4) the proposed critical discharge to reduce notable saltwater intrusion was 11,500 m³/s. After the Three Gorges Reservoir operation, the minimum river discharge into the YRE in 2008–2017 was below the critical discharge, thereby suggesting an increase in the minimum river discharge by reservoir regulation in drought periods.

Keywords: critical discharge; saltwater intrusion control; empirical model; the Yangtze River Estuary

1 Introduction

Estuary area is commonly densely populated and economically developed. However, the estuarine regions are also the intersections of river freshwater and marine saltwater. Such

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regions are prone to saltwater intrusion. Serious saltwater intrusion may affect the industrial and domestic water use, and has a negative impact on the ecological environment (Palmer *et al*., 2015). With the impact of various natural and anthropologic factors such as rising sea level, climate changes, increased riverine water diversions, and regulations of large-scale hydro-projects in river basin, saltwater intrusions have become important issues for many estuaries in the world (Bhuiyan *et al*., 2012; Jacob *et al*., 2013; Guerra *et al*., 2019; Rodrigues *et al*., 2019). The control and mitigation the harm of saltwater intrusion in the engineering practices of water resource utilization, not only in river basins but also in estuarine areas, have drawn remarkable concerns (Kacimov *et al*., 2009; Rodrigues *et al*., 2019).

Factors affecting saltwater intrusion in the estuary include river discharge, tidal level, sea salinity, estuary geometry and riverbed resistance, wind power and wind direction, but the most decisive factors are river discharge and tidal range (An *et al*., 2009; Zhang *et al*., 2011; Cai *et al*., 2015). Observations and theoretical analyses indicate that the level of saltwater intrusion in the estuary is negatively correlated with river discharge (Palmer *et al*., 2015; Rodrigues *et al*., 2019). In certain estuaries, when the river discharge is below a certain value due to drought or excessive riverine water diversions, the frequency and level of saltwater intrusion are significantly enhanced (Huang *et al*., 2011; Magritsky *et al*., 2017). With the regulations of large-scale reservoirs in river basins, their adjustment effects can increase low flow discharge during the dry season, and alleviate the saltwater intrusion in the estuary. However, reservoirs generally have multiple objectives such as navigation, irrigation or power generation, the volume of available water resources during the dry season is limited. Therefore, the reasonable determination of the critical river discharge for the saltwater intrusion of the estuary area is essential for water resource management in basins.

The Yangtze River Estuary (YRE) is the largest estuary in China. The annual runoff of the Yangtze River into the sea exceeds 900 billion m^3. Thus, the YRE is the main freshwater source for Shanghai, the largest city in China. However, due to the uneven distribution of runoff discharge in different seasons, saltwater intrusion often occurs in the dry season (Zhang *et al*., 2011; Cai *et al*., 2015). Certain estuary freshwater reservoirs have been constructed in the YRE to ensure industrial and agricultural water use in Shanghai. These reservoirs store freshwater when the water quality is good, and supply water when saltwater invades (Xu *et al*., 2018). However, the duration of saltwater intrusion lasts a long time when the runoff discharge is severely dry. On such occasions, the limited storage capacity of these reservoirs still cannot guarantee sufficient freshwater supply (Chen *et al*., 2013b).

Since 2003, large reservoirs, such as the Three Georges Reservoir (TGR), have been impounded in the upper Yangtze River. With the regulation of TGR, increasing the river discharge and reducing the duration and frequency of saltwater intrusion in dry seasons are possible, thereby increasing the guarantee rate of the freshwater supply (An *et al*., 2009). However, many studies have suggested different values to the critical discharge for saltwater intrusion control (Gu *et al*., 2003; Chen and He, 2009; Zhu *et al*., 2010; Chen *et al*., 2011; Chen *et al*., 2014; Wang, 2016; Xu *et al*., 2018). Shen *et al*. (2002) revealed that when the river discharge is less than 25,000 m^3/s and the tidal range of Qinglonggang station (in the North Branch (NB) of the YRE) is more than 3 m, notable saltwater intrusion can occur in the South Branch (SB). Li *et al*. (2013) proposed that when the river discharge is between 6820–16,000 m^3/s and the tidal range of Qinglonggang station is 2.4–3 m, a continuous saltwater intrusion can occur in the YRE for 10–30 days. Planning report for the YRE has recommended that the river discharge should be 10,000–13,000 m^3/s to satisfy the demand of saltwater intrusion control (CWRC, 2005). The reason for the different values is that the effects of various factors such as river discharge and tidal range are interacted in the measured data, quantifying their influence independently is difficult.

To quantitatively separate the effects of different factors, an impact-response relationship among river discharge, tidal range, and saltwater intrusion should be established. The common methods are material analysis method, empirical models, analytical models and numerical models. These methods have been used widely in many estuaries around the world (Shaha *et al*., 2009; Parsa *et al*., 2011; Jacob *et al*., 2013) and in the YRE (Mao *et al*., 1993; Chen *et al*., 2011; Chen *et al*., 2013b; Hou and Zhu, 2013; Zheng *et al*., 2014). The critical discharge is considered as a river discharge value under which the salinity at a certain location (e.g., water intake of freshwater reservoir) can be maintained to satisfy the drinking water standard with high guarantee rate (Huang *et al*., 2011; Chen *et al*., 2013b). Under such a definition, the salinity change process of a specific location is a more serious concern than the detailed salinity information of the entire estuary area. Compared with the numerical model, which has large data demands, material analysis method, empirical models and analytical models have the advantages of simple forms and few parameters. They are confirmed effective in determining the types of salinity information in engineering practice and planning (Shaha and Cho, 2009; Parsa and Amir, 2011; Jacob *et al*., 2013). Therefore, the use of an empirical or analytical model is appropriate to determine the critical discharge. In the literature, many analytical or empirical models have been used to analyze the saltwater intrusion in the YRE (Zhang *et al*., 2011; Li *et al*., 2013; Zheng *et al*., 2014; Cai *et al*., 2015). However, applying these models to determine critical discharge remains difficult. First, most models focus on the predictions of the saltwater intrusion length and longitudinal salinity distribution in estuaries (Parsa and Amir, 2011; Cai *et al*., 2015). They can be used to assess the effect of human-induced or natural changes on the salt intrusion, but their ability to predict the temporal variation of salinity in a specific location were limited. Second, river discharge is the only controllable factor in saltwater intrusion control. Investigators generally treat tidal range as a range of case specific input in their models (Gu *et al*., 2003; Hou and Zhu, 2013; Li *et al*., 2013). The predictive ability of these models is limited by the requirement of tidal range predication. Third, formula structures and parameters in the empirical models proposed by different researchers are relatively different because they are based on observations of different datasets (Mao *et al*., 1993; Chen *et al*., 2013b; Sun *et al*., 2017). For a certain location, whether the results obtained using empirical methods are model independent is not confirmed.

The upper SB of the YRE is an important water source region, where several freshwater reservoirs are located. In this paper, we use the measured salinity data of more than 60 tidal cycles in the period 2009–2014 in the upper SB to estimate the critical discharge for saltwater control in this area. In addition, the study presents two aspects: (1) to clarify the relationship among river discharges, tidal ranges and saltwater intrusion levels in the upper SB by using material analysis method; (2) to examine and improve the predictive function of existing empirical models, and apply these models for the purpose of critical discharge determination.

2 Study area and data collection

2.1 Study area

The YRE (Figure 1) starts from Datong hydrological station, which is located at the tidal limit covering approximately 94% of the drainage area. Downstream of Xuliujing tidal station, which is more than 500 km from Datong hydrological station, the YRE is divided into two branches, namely, the NB and the SB by Chongming Island. SB is separated into the North Channel and the South Channel by Changxing Island and Hengsha Island. Thus, the YRE has a complicated topography with three-order bifurcations and four outlets into the sea. The maximum width of the flared opening is more than 90 km.

In the YRE, the NB and the main stream are almost disconnected, and the flow of the NB is very small (less than 5% of the main stream flow). In the upper section of SB from Xuliujing to Liuhekou, there are several freshwater reservoirs such as the Baogang Reservoir, the Chenhang Reservoir, and the Dongfengxisha Reservoir. Therefore, the upper SB is an important source region for water supply. We select the water salinity of the upper SB as the objective of saltwater intrusion control.

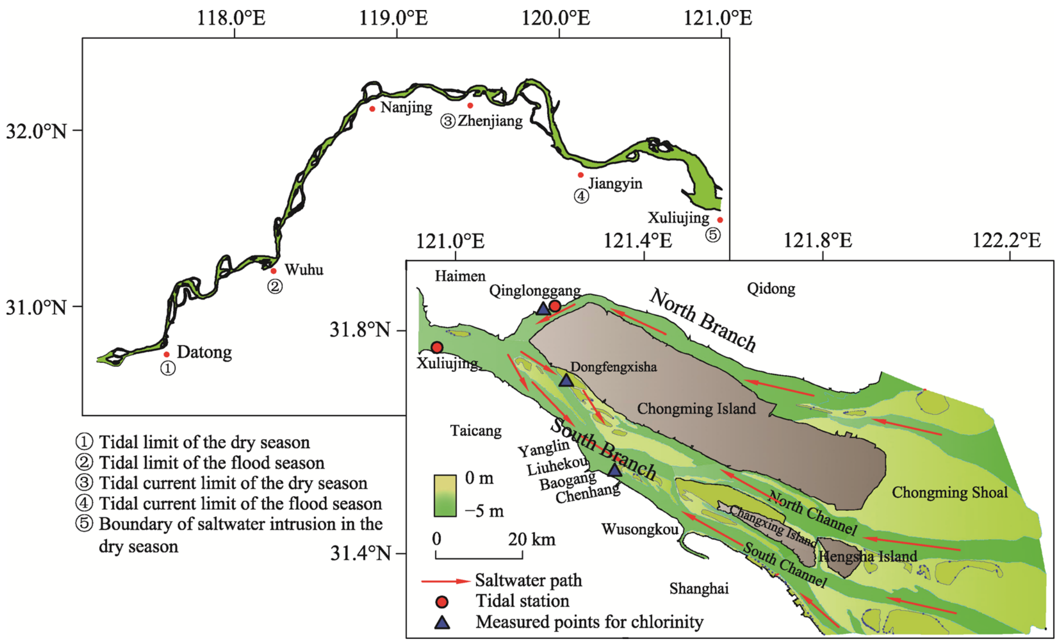

Figure 1 Sketch of the Yangtze River Estuary displaying the location of measuring stations

The scope of saltwater intrusion in the YRE is generally limited below Xuliujing (Xu and Yuan, 1994; He *et al*., 2006). The saltwater intrusion characteristics are different in the two branches. The NB of the YRE is almost perpendicular to the main channel and the freshwater discharge into the NB is very small. In addition, the upper section of the NB has a trumpet-shaped topography. Therefore, saltwater dominated the flow in this branch in the dry season. The tidal flood current can bring the high salinity water of the NB into the SB during periods of rising tide. According to previous investigations, the saltwater in the upper SB is mainly from the NB (Xu and Yuan, 1994). The saltwater from the outlet can reach the upper

SB only in very extreme drought because of the large freshwater discharge in the SB (He *et al*., 2006).

2.2 Data

Datong hydrological station, which is situated approximately 1800 km downstream of TGR, often serves as the controlling station for the measurements of the Yangtze River runoff into the sea (Zhao *et al.* 2012; Chen *et al.* 2013b). The daily discharge data of Datong in 1950–2017 are obtained in this study. This research focuses on the daily discharge data in the dry season (November to April) to investigate the saltwater intrusion changes with discharge, which has been observed to have evident seasonal changes. The TGR has redistributed the discharge into the YRE since its impoundment in 2003 and its operation with a full storage capacity started in 2008 (Zhao *et al.* 2012). Thus, 1950–2002, 2003–2007, and 2008–2017 are defined as the pre-dam, post-dam closure, and post-dam normal operation periods, respectively. The average lag time of flow between Datong and Xuliujing stations is approximately six days.

The tide near the YRE mouth is mainly semi-diurnal with a mean and maximum tidal range of 2.67 and 4.62 m, respectively. The data of the daily mean tidal range are obtained from two tidal stations, namely, Xuliujing station and Qinglonggang station. The data of Xuliujing station cover the entire years of 2009 and 2011–2014. The data of Qinglonggang station are only of several months in 2005, 2009, 2011, 2013, 2014 and 2017. We plot the tidal range data of the same day from Qinglonggang and Xuliujing stations. The results show that good correlation exists between the data of the two stations, as illustrated in Figure 2. In previous research, the tidal range of Qinglonggang station was often selected as a variable in empirical models for salinity prediction (Xu and Yuan, 1994; He *et al*., 2006; Zheng *et al*., 2014). We use the correlation in Figure 2 to interpolate from the tidal data series of Xuliujing station given the data deficiency of Qinglonggang station.

In this study, the data of salinity are mainly abtained from the Dongfengxisha observation point (intake of Dongfengxisha Reservoir), which is located in the north side of the upper SB of the YRE. The Dongfengxisha salinity data are the daily mean chlorinity, values obtained from November to April in each year of 2009–2014, totally 1,113 days. In addition to the Dongfengxisha chlorinity data, other data about saltwater intrusion duration are collected from previous studies (Xu and Yuan, 1994; Shen *et al*., 2002; Gu *et al*., 2003; He *et al*., 2006; Zhu *et al*., 2010; Chen *et al*., 2011; Wang, 2016). On the basis of the collected data, the daily changes of chlorinity, discharge, and tidal range in dry seasons of 2009–2014 are shown in Figure 3. All the data sources are presented in Table 1, and the measuring stations mentioned above are displayed in Figure 1.

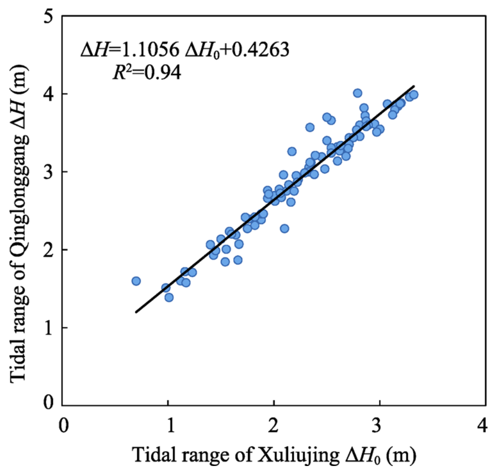

Figure 2 Correlation between the daily mean tidal ranges of Xuliujing and Qinglonggang stations

Table 1 Data sources

Data type	Station	Period	Source
Daily discharge	Datong	1950–2017	Yangtze River Hydrographic Yearbook
Daily mean tidal range	Xuliujing	2009, 2011–2014	Yangtze River Hydrographic Yearbook
Daily mean tidal range	Qinglonggang	Certain months in 2005, 2009, 2011, 2014 and 2017	Jiangsu Provincial Hydrology and Water Resources Bureau, Zheng *et al.* (2014)
Daily mean chlorinity	Dongfengxisha	2009–2014	Shanghai Water Affairs Bureau

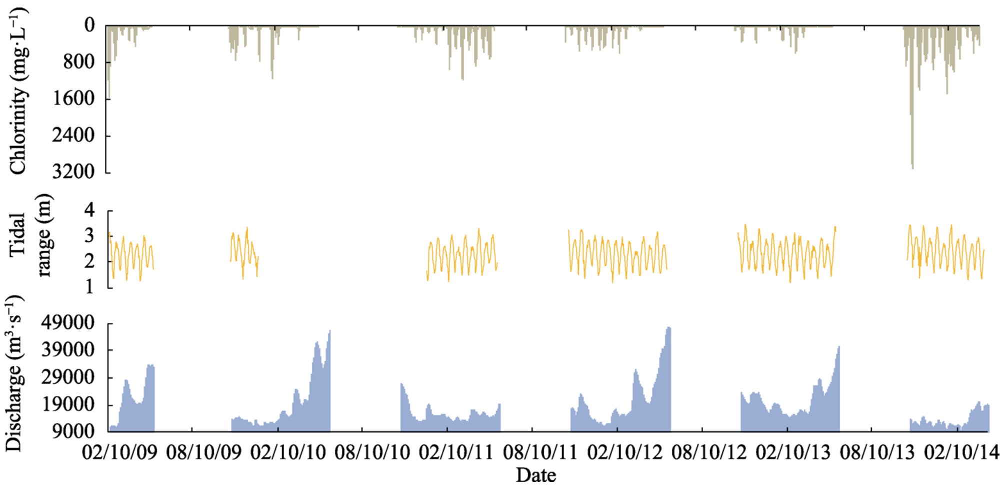

Figure 3 Chlorinity of Dongfengxisha observation point, discharge at Datong station and tidal ranges at Xuliujing station in the dry seasons of 2009–2014

3 Methodology

3.1 Research design

According to China National Standard of Water Supply (SEPAC, 2002), water quality is considered unsuitable for drinking when chlorinity is greater than 250 mg/L or salinity is greater than 0.4‰. To avoid threatening the normal operation of freshwater reservoirs (e.g., the Chenhang Reservoir) in the upper SB of the YRE, the number of salinity excessive days should not last for more than 10 days in a tidal cycle (Gu *et al.*, 2003; Tang *et al.*, 2011; Zhao *et al.*, 2012; Chen, 2014). Therefore, we use these restrictions as criteria for saltwater intrusion control.

The salinity process at a certain location is mainly determined by river discharge and tide, whereas the latter can be represented by tidal range, considering stable topography and random meteorological conditions (Parsa and Amir, 2011; Cai *et al.*, 2015; Chen *et al.*, 2017). On the basis of this understanding, we conduct an analysis and calculation work according to the following steps: (1) provision of a detailed statistics of the discharge data of Datong station in different stages of the TGR operation to reveal the characteristics of river discharge into the YRE in dry seasons; (2) qualitative and quantitive analysis of the salinity data observed in the upper SB to examine the saltwater intrusion status quo, including its occurrence rate and duration length corresponding to different river discharges; (3) determination of the critical discharge by two methods. The first approach is the material analysis method, with which the basic law of saltwater intrusion is directly identified by analyzing the observation data. The second is the empirical model method, which uses the historical data of river discharge and estuarine salinity to establish empirical formulas. We use the two methods to separately perform the estimation to ensure the reliability of the results.

The critical discharge determined in step (3) can be compared with the statistical characteristics of the discharge at Datong station. Thus, whether the river discharge can control the saltwater intrusion in the upper SB during the dry seasons after the TGR operation can be inferred.

3.2 Scheme of material analysis method

Salinity changes at a specific location are principally affected by factors of river discharge or tidal range, given that the geometrical status of the YRE generally does not vary remarkably in time. When one of the two factors is fixed, a monotonous relationship exists between the other factor and the salinity (Chen *et al.*, 2013b; Hou and Zhu, 2013; Zheng *et al.*, 2014). Therefore, the idea of variable separation can be used to determine the independent effects of river discharge or tidal range.

The river discharge generally changes on the seasonal time scale. At mid-latitudes, including the YRE, the daily mean tidal range basically varies over the 15-day spring-neap cycle. Given these relatively large time scales involved, the saltwater intrusion process generally can be regarded as in the quasi-equilibrium state on the daily time scale of 24 h (Huang *et al.*, 2011; Kuijper and Van Rijn, 2011). Based on this precondition, the following inferences can be drawn: (1) for a constant river discharge Q_c, a certain level of tidal range ΔH_c exists, and the combination effects of the two factors can maintain the daily mean salinity at a certain value C at a specific location; (2) if the river discharge remains Q_c, but the tidal range level is greater than ΔH_c, then the salinity at this location exceeds value C; (3) if the river discharge is greater than Q_c and the tidal range level remains ΔH_c, then the salinity at this location becomes less than value C. We will use the measured data to verify whether these inferences are reasonable in the upper SB of the YRE, and then we use them to estimate the critical river discharge.

3.3 Selection of empirical model

Many studies have established the quantitative relationships among river discharge, tidal level, and salinity (chlorinity) in estuaries, including analytical models and empirical models. The analytical method approximates the longitudinal spatio-temporal distribution salinity to a one-dimensional problem with a constant point source at one end (Savenije *et al.*, 2008). Given a constant tidal average flow, the analytical solution of the problem is obtained as follows:

$$S(x) = S_0 \exp\left[-\frac{Q}{\overline{A}D} f(x)\right] \tag{1}$$

where S and S_0 are the salinity at a distance of x and 0 from the sea, respectively; Q and $\overline{A}$ are the river discharge and tidal average cross-sectional area, respectively; $f(x)$ is a function of distance and geometrical factors; D is longitudinal dispersion coefficient. Despite long-term research, the determination of parameter D still relies on complicated empirical relationships (Kuijper and Van Rijn, 2011; Shaha *et al*., 2011). In most studies, D is mainly determined by the tidal cycle length and tidal flow velocity, and the latter is closely related to the tidal range (Savenije, 1993; Zhang *et al*., 2011; Cai *et al*., 2015). The empirical models obtain regression correlation from observational data. Parsa and Amir (2011) proposed a logarithmic function to predict the salinity intrusion, in which effective dimensionless parameters are used, considering the physical background. For a specific estuary, the dimensionless geometric parameter and tidal cycle length can be regarded as constants. Therefore, the function obtained by Parsa is simplified as follows:

$$x_L = A\ln\left[1+B\left(\frac{\Delta Z}{h_0}\right)^{\alpha}\left(\frac{u}{\sqrt{gh_0}}\right)^{-\beta}\right] \tag{2}$$

where x_L is the saltwater intrusion length; ΔZ is the tidal range; u is the riverine water velocity; h_0 is the tidal average water depth; and A, B, α, and β are the parameters. Considering the relationship between salinity spatial distribution and salinity intrusion length (Shaha *et al*., 2011; Zhu *et al*., 2013), equation (2) can be written as follows:

$$S(x) = S_0 \exp\left[-\frac{Q^{\beta}}{\Delta Z^{\alpha}} r(x)\right] \tag{3}$$

where $r(x)$ is a function of x, and the remaining variables have the same definition as those above mentioned. Equations 1 and 3 show that the analytical model and the empirical model have the same form. That is, the salinity of a specific location can be approximately estimated by an exponential function, in which the river discharge and the reciprocal of tidal range are the only variables.

Equations (1) and (3) are obtained from geometry without bifurcating. Their application effects have not been examined in bifurcated estuary as the YRE. In the upper SB of the YRE, certain statistical-based studies have established other types of relationship functions (Mao *et al*., 1993; Chen *et al*., 2013b; Zheng *et al*., 2014; Sun *et al*., 2017), such as the combination of polynomial and exponential functions. To verify the effects of the functions of various forms, four representative empirical models are selected from the literature (Table 2). Among them, Zheng *et al.* (2014) and Chen *et al*. (2013b) proposed similar relationships with different parameters. Mao *et al.* (1993) did not provide the specific parameter values of the empirical model. In the following section, we use the measured data in the study area to test the validity of these models, and then use them to calculate the critical river discharge.

3.4 Modes of daily mean tidal range estimation

For the functions in Table 2, the modes of tidal range estimation are required to perform salinity prediction. Generally, the tidal wave can be continuously deformed and flattened and the tidal range can decay during tidal wave propagation in estuaries (Chen and Jin, 1989). However, the theoretical analysis by Horrevoets *et al.* (2004) indicate that the influence of river discharge on the tidal range can be negligible in the reach section where channel width is much larger than that of the riverine section. In such a circumstance, the tidal range is only affected by the estuary topography and bed friction. In the YRE, the reach below

Table 2 Selected empirical models for salinity prediction in the upper South Branch of the Yangtze River Estuary

Source	Relationship	Variable explanation
Mao *et al.*(1993)	$S \sim \exp(\Delta H^{\alpha}/Q^{\beta})$	S is the salinity of Baogang; ΔH is the tidal range of Qinglonggang; Q is the discharge at Datong station.
Zheng *et al.*(2014)	$S=ae^{b\Delta H}+ae^{b\Delta H}(c_1Q^3+c_2Q^2+c_3Q+c_4)$	S is the salinity of Qinglonggang station; ΔH is the tidal range of Qinglonggang station; Q is the discharge at Datong station.
Chen *et al.*(2013b)	$S=(4.16\times10^{-9}Q^2-2.745Q+4.317)\times0.02404\times e^{0.009085\Delta H}$	S is the salinity of Chenhang; ΔH is the tidal range of Qinglonggang station; Q is the discharge at Datong station.
Sun *et al.*(2017)	$C=A\exp(a\Delta H_0-bQ)$	ΔH_0 is the tidal range of Xuliujing station; Q is the discharge at Datong station; C is the chlorinity of Dongfengxisha.

Xuliujing station is wider than that of the upstream. We plot the relationship between the daily mean tidal range of Xuliujing station and the daily discharge of Datong station, as shown in Figure 4. The figure illustrates that the correlation between the two variables is insignificant. This finding is consistent with the conclusion of Horrevoets *et al.* (2004). In addition, the simulation of Lu *et al.* (2010) reveals that at a certain location below Xuliujing, the difference of tidal ranges corresponding to different river discharges is no more than 0.2 m. Compared with the annual mean tidal range of 2.35 m at Xuliujing station, the influence of varying river discharges is small. Therefore, from the view of engineering practice, we ignore the influence of river discharge on tidal range in the upper SB of the YRE.

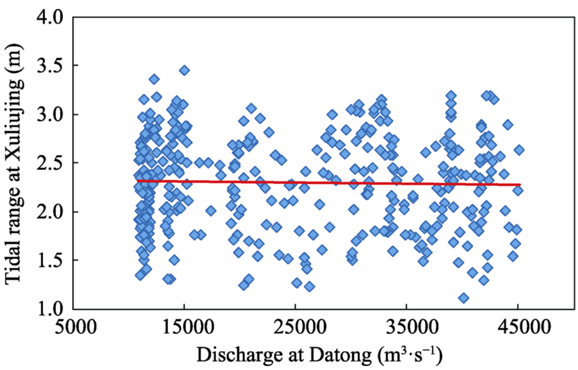

Figure 4 Relationship between the discharge at Datong station and the tidal range at Xuliujing station (Red line across the data points represents the trend line between the two variables.)

The daily mean tidal range should vary on a time scale of 15 days because the M2 tidal component generally predominates over other constituents. We plot the relationship between the tidal range and lunar calendar date in Figure 5a by using the daily mean tidal range data of Xuliujing station. The figure shows that the daily mean tidal range roughly varies in sinusoidal pattern in a 15-day cycle. The peak value appears near the 3rd and 18th day in a lunar month with an average amplitude of approximately 0.7 m. It should be noted that there is random variable amplitude of about 0.5 m apart from the cyclic amplitude. We use the following four modes to approximate the variation of tidal range for the simultaneous description of the periodic and random variations of the tidal range, as illustrated in Figure 5: (1) the upper envelope curve A, which uses the maximum tidal range of every date to determine the periodical average value and amplitude; (2) the average curve B, which uses the average tidal range of every date to determine the periodical average value and amplitude; (3) the middle curve C, which uses the trough and crest values to determine the periodical average value and amplitude; (4) the inner curve D, which uses the mean value of curves B and C. According to the correlation between the daily mean tidal range of Qinglonggang and Xuliujing stations (Figure 2), the curves of Qinglonggang station corresponding to the four modes are depicted in Figure 5b. The measured data of the daily mean tidal range of Qinglonggang station are also shown in Figure 5b. The figure shows that the variation of the daily mean tidal range of Qinglonggang station is similar to that of Xuliujing station.

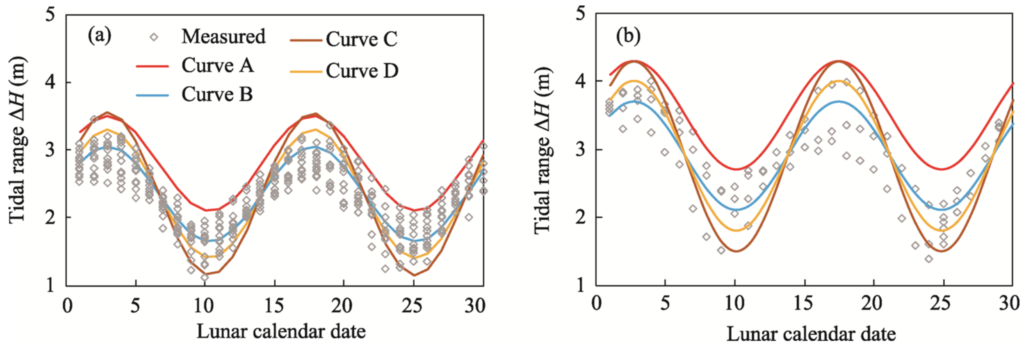

Figure 5 Relationship between lunar calendar date and daily mean tidal range at (a) Xuliujing station and (b) Qinglonggang station (Curves of different colors represent different tidal range estimation modes.)

On the basis of the four description modes, the daily mean tidal range of a certain station can be approximately estimated by the following equation:

$$\Delta H_t = \Delta H_0 + A\cos\left[\frac{2\pi}{14.75}(t-B)\right] \tag{4}$$

where ΔH_0 denotes the daily mean tidal range on the t-day in a lunar month, ΔH_0 refers to the periodic average value of the tidal range; A and B represent the periodic amplitude and phase, respectively. We use the measured data to determine parameters ΔH_0, A and B. In the following section, we use the different parameters to test their effect of tidal range estimation. By introducing function (4) into functions in Table 2, the tidal range is substituted by the lunar calendar date, and the river discharge is the only variable required in the empirical models. Thus, the empirical model has a predictive equation when only the observation data of river discharge are available.

4 Result

4.1 Characteristics of river discharge into the YRE

Due to the possible large volume of water withdrawn between Datong station and Xuliujing station along the Yangtze River, it is controversial whether the discharge of Datong station can represent the discharge into the sea (Chen *et al*., 2001; Chen *et al*., 2013a). Zhao *et al.* (2012) suggested that the water intake capacity of the diversion project between Datong and Xuliujing stations is above 20,000 m³/s, whereas the actual water intake is smaller than the water diversion capacity. The phenomenon that the discharge at Xuliujing station is less than that at Datong station occur mostly in May and June. In dry seasons, these phenomena can occur in only 20% of the days, and the discharge difference between the two stations is less than 600 m³/s (Zhao *et al.* 2012). Similarly, Zhang and Chen (2003) showed that the monthly discharge reduction between the two stations does not exceed 570 m³/s from January to March, even in drought years. Tang *et al.* (2011a) indicated that the discharge at Xuliujing station is less than that at Datong station only from March to June, and the discharge difference in March is only 341 m³/s. Based on these investigations, the discharge at Datong station in dry seasons can represent the river discharge into the sea.

Table 3 Frequency of daily discharge at Datong station in different periods

Measured time	Cumulative frequency of less than a certain value of discharge (%)			
	< 25000 m³/s	< 15000 m³/s	< 12000 m³/s	< 10000 m³/s
1950–2002	45.71	25.71	16.9	10.06
2003–2007	55.83	24.85	14.29	2.74
2008–2017	50.33	21.59	7.73	0.1

The frequency of daily discharge at Datong station is shown in Table 3. The finding indicates that the frequency of Q < 25,000 m³/s increases after the impoundment of the TGR. However, the frequencies of Q < 15,000, Q < 12,000 and Q < 10,000 m³/s decrease. In the dry months from October to April, which are prone to saltwater intrusion, the seven months averaged discharge is 16,725, 15,938, and 17,806 m³/s corresponding to the 1950–2002, 2003–2007, and 2008–2017 periods, respectively. The difference among the three periods is relatively small. For the dry seasons of the three periods, the multi-year average monthly discharge and the maximum and minimum discharge in each month are depicted in Figure 6. The figure shows that the multi-year average monthly discharge increases from December to March and decreases from October to November after the TGR operation. In every month, the maximum discharge decreases, and the minimum discharge increases. Thus, the variations in each month are reduced. The minimum discharge in each year commonly appears from December to February. The minimum values are 6300 (in 1963), 8380 (in 2004) and

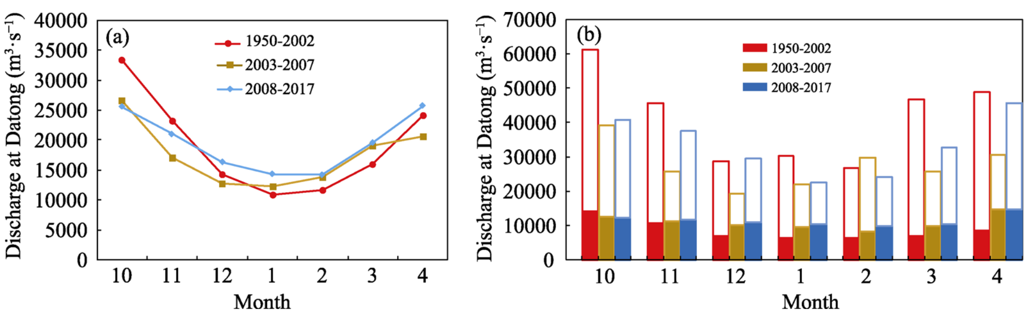

Figure 6 Characteristics of river discharge at Datong station in dry seasons of three different periods: (a) multi-year average monthly discharge; (b) the maximum and the minimum discharge in every month (Total height represents the maximum value of each month. Colored fill portion represents the minimum value of each month. Red represents the period of 1950–2002, brown represents the period of 2003–2007, blue represents the period of 2008–2017)

9927 m³/s (in 2014) in the three periods. The results indicate the increasing trend of the yearly minimum discharge with the TGR operation.

4.2 Characteristics of salt intrusion in the upper SB

The data of severe saltwater intrusion events (the daily mean salinity continually excessive for more than nine days) in the upper SB in recent decades are listed in Table 4. The table shows that a large river discharge generally indicates a short saltwater intrusion duration. However, differences are observed in the saltwater intrusion duration even under an approximately constant river discharge. Therefore, river discharge is not the only variable affecting the saltwater intrusion.

The data in Table 4 suggest that certain characteristics of saltwater intrusion in the upper SB are as follows: (1) 80% of the saltwater intrusion event occurs from November to April. During the saltwater intrusion period, 82% of the daily discharge is less than 15,000 m³/s. Thus, once the daily discharge is close to or lower than 15,000 m³/s, the probability of saltwater intrusion is large. For example, in October 2006, the saltwater intrusion was three months earlier than normal because the river discharge was significantly lower than normal (Zhu *et al*., 2010). (2) When the saltwater intrusion duration is close to or exceeds a tidal period of 15 days (e.g., the events in 1978–1979, 1987, and 1999), the daily discharge is generally less than 10,000 m³/s. These phenomena are consistent with the conclusion of Xu and Yuan (1994). They revealed that in the infrequent situations when the river discharge is less than 10,000 m³/s, the saltwater from the NB and from the outlet of the SB can meet in the upper SB, resulting in high salinity; moreover, the duration of salinity excessive in the upper SB can exceed a tidal cycle (Xu and Yuan, 1994). (3) The saltwater intrusion duration

Table 4 Statistical features of certain saltwater intrusion events in the upper South Branch of the Yangtze River Estuary in recent decades

Measured time	Observation point	Salinity excessive days (d)	Average discharge at Datong station during the salinity excessive periods (m³/s)	Data source
Winter of 1978–Spring of 1979	Wusong	64	7256	Shen *et al.*(2002)
February–March 1987	Chenhang	13	8467	Gu *et al.*(2003), Chen *et al.*(2011), Xu and Yuan(1994)
February–March 1999		25	9487	Shen *et al.*(2002), Gu *et al.*(2003)
February 2004		9.8	9479	He *et al.*(2006)
October 2006		9	14,300	Zhu *et al.*(2010)
February 2014		19	10,900	Wang (2016)
November 3–12, 2009	Dongfengxisha	10	14,030	Shanghai Water Affairs Bureau
November 15–24, 2013		10	12,240	
December 3–11, 2013		9	12,500	
December 17–25, 2013		9	11,365	
January 2–10, 2014		9	12,144	
January 30–February 22, 2014		24	11,138	

of more than 15 days and the daily river discharge greater than 10,000 m³/s at the same period are rare. For example, in addition to low river discharge, the severe saltwater intrusion in February 2014 is closely related to the northward strong wind. However, such an event only accounts for 5% of the total events, as shown in Table 4, thereby indicating that meteorological conditions may cause severe saltwater intrusion with small probability.

To identify the effects of river discharge on salinity (chlorinity), the chlorinity data observed at Dongfengxisha in dry seasons of 2009–2014 are analyzed, as illustrated in Figure 7. In Figure 7a, the relationship between river discharge and chlorinity is plotted. The figure indicates that chlorinity increases rapidly as river discharge decreases. The chlorinity does not exceed the standard of 250 mg/L when the river discharge is higher than 30,000 m^3/s. By dividing the discharge below 30,000 m^3/s into different intervals, we calculate the ratio of the number of days on which chlorinity is above 250 mg/L to the total number of days in each interval (Figure 7b). The figure shows that the over-standard probability is close to 100% when the river discharge is less than 10,000 m^3/s. The over-standard probability of chlorinity is 65% when the discharge is between 11,000 and 12,000 m^3/s. For the 301 days on which chlorinity is over-standard, the accumulated probability is as depicted in Figure 7c. The figure indicates that 97% of the over-standard days occur when the river discharge is less than 20,000 m^3/s, and 69% of the days occur when the river discharge is less than 15,000 m^3/s.

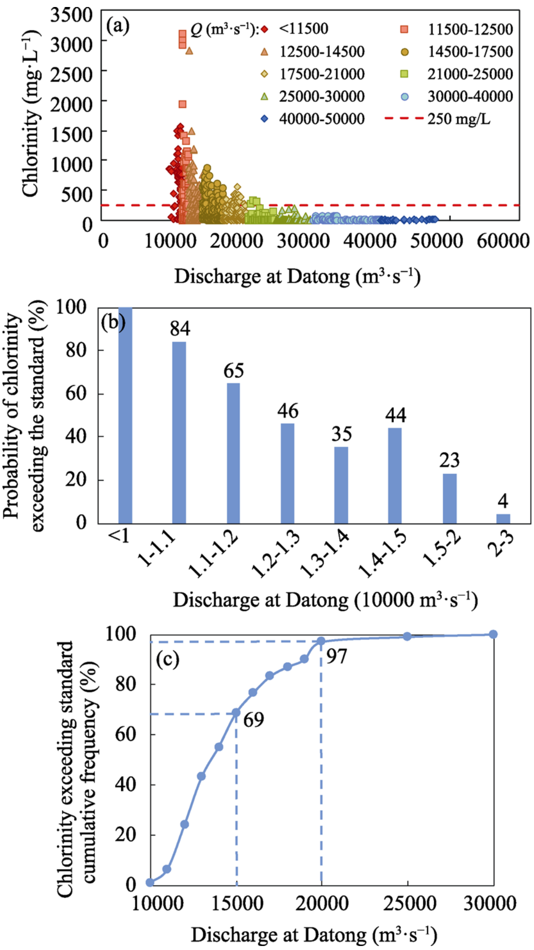

Figure 7 Characteristics of saltwater intrusion under different river discharges: (a) relationship between daily discharge at Datong station and daily chlorinity at the Dongfengxisha observation point, (b) probability of chlorinity exceeding the drinking water standard in each discharge interval, and (c) the discharge at Datong station *vs* the cumulative probability of excessive chlorinity

The analysis suggests that the phenomenon of chlorinity over standard mainly occurs when the river discharge is less than 15,000 m^3/s, especially when it is less than 12,000 m^3/s. After the impoundment of the TGR, the daily discharge at Datong station is mostly greater than 10,000 m^3/s. However, the phenomenon of chlorinity over standard still occurs. Therefore, the critical discharge for saltwater intrusion control should be above 10,000 m^3/s.

4.3 Critical river discharge determined using material analysis method

The relationship between daily chlorinity data and daily tidal range data is shown in Figure 8.

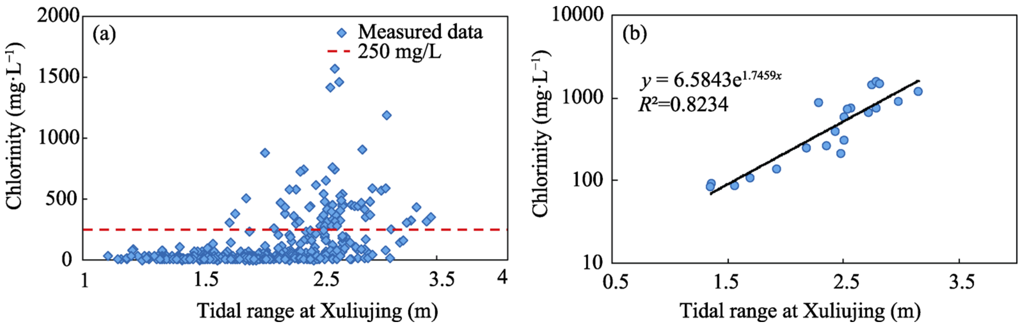

Figure 8 Tidal range of Xuliujing station *vs* chlorinity of Dongfengxisha observation point: (a) data of all discharges, and (b) data corresponding to the river discharge of approximately 11,000 m^3/s

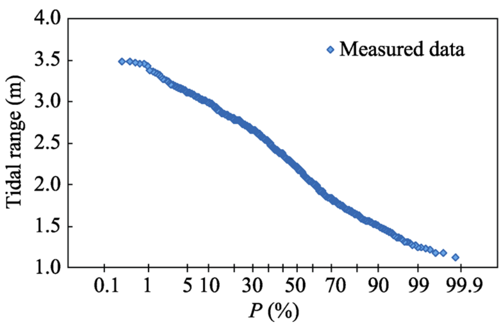

Figure 9 Accumulative frequency of the tidal range of Xuliujing station

The phenomenon of chlorinity over standard may occur when the daily tidal range of Xuliujing station is greater than 1.8 m. The probability of chlorinity over standard increases significantly when the daily tidal range is greater than 2.3 m. The data in Figure 8a are scattered due to the influence of river discharge. When data near a certain discharge are screened out, the correlation in Figure 8a can be evidently improved. For example, the data near the river discharge of 11,000 m^3/s are depicted in Figure 8b. An approximately exponential correlation is observed between daily chlorinity and daily tidal range, when the discharge has a fixed value. Similar to Figure 8b, the correlations corresponding to different discharge levels are determined. Using these correlations and given a certain river discharge value Q_c, the tidal range ΔH_c corresponding to the 250 $mg \cdot L^{-1}$ chlorinity standard is determined (Table 5).

Figure 8 displays that chlorinity only depends on tidal range if river discharge has a fixed value. Thus, chlorinity should have a 15-day periodic variation similar to the tidal range variation. That is, if the river discharge maintains a fixed value and chlorinity is over standard for more than 10 days in a tidal cycle, then the number of days that tidal range exceeds the critical value ΔH_c should be more than 10 days. In summary, a general probability of 2/3 (66.7%) is deduced for the critical tidal range ΔH_c. The tidal frequency is shown in Figure 9 using the daily tidal range data of Xuliujing station. The figure illustrates that the 66.7%

Table 5 Corresponding tidal ranges of Xuliujing station (ΔH_c) and discharges of Datong station (Q_c) to maintain the drinking water standard

Chlorinity of Dongfengxisha observation point (mg/L)	Discharge at Datong station Q_c (m^3/s)	Daily tidal range of Xuliujing station ΔH_c (m)
250	11,000	2.05
250	12,000	2.24
250	13,000	2.42
250	15,000	2.61

probability corresponds to a ΔH_c value of 2.06 m. Combining the critical tidal range value of 2.06 m with the data in Table 5, the critical river discharge should be between 11,000 and 12,000 m³/s, which is close to 11,000 m³/s.

4.4 Critical discharge determined using empirical models

4.4.1 Effects of empirical models

The selected empirical models in Table 2 are verified with measured data. Among them, the parameters in the model proposed by Mao *et al.* (1993) are determined with the chlorinity data of Dongfengxisha. The tidal range data estimated with different modes in Figure 5 are introduced into the empirical models.

The calculation results reveal that the effect of the curves B and C is always better than that of curves A and D. Specifically, the determination coefficient (R^2) in Table 6 indicates that the overall effect of curve C is the best, and the R^2 value is all above 0.5. The calculated results using curve C are compared with the measured chlorinity data in Figure 10. The good agreement in Figure 10 shows that the proposed tidal range estimation mode (curve C) can be used to predict chlorinity in empirical models. Model 2 proposed by Zheng *et al.* (2014) aims to predict salinity (chlorinity) at Qinglonggang station, which is not in the SB. Therefore, we only use models 1, 3, and 4 to perform salinity prediction in the upper SB in the following section.

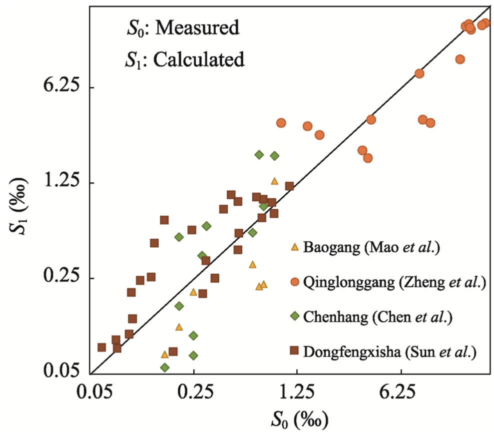

Figure 10 Comparison of the measured and calculated salinity values using different empirical models

Table 6 Determination coefficient between measured and calculated salinity using different tidal range estimation modes and different empirical salinity prediction models

Empirical salinity prediction model	Tidal range estimation mode	Determination coefficient R^2	Tidal range estimation mode	Determination coefficient R^2
Mao *et al.* (1993)	Qinglonggang station, curve B	0.45	Qinglonggang station, curve C	0.51
Zheng *et al.* (2014)	Qinglonggang station, curve B	0.85	Qinglonggang station, curve C	0.88
Chen *et al.* (2013b)	Qinglonggang station, curve B	0.7	Qinglonggang station, curve C	0.74
Sun *et al.* (2017)	Xuliujing station, curve B	0.8	Xuliujing station, curve C	0.81

4.4.2 Calculation result of critical discharge

The empirical models proposed by Mao *et al.* (1993), Chen *et al.* (2013b) and Sun *et al.* (2017) are applied to determine the critical discharge for the upper SB. Using a certain river discharge as an input, the chlorinity process can be obtained by the empirical models. For example, the chlorinity processes in Figure 11 are calculated by the empirical model of Sun

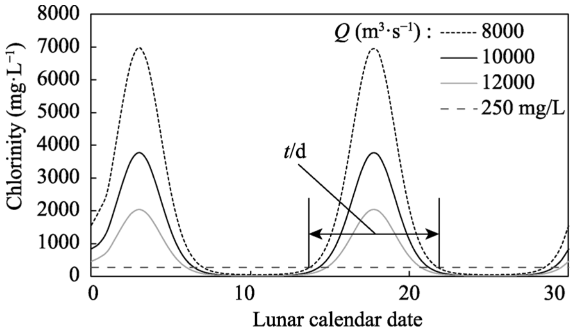

Figure 11 Calculated chlorinity processes of the Dongfengxisha observation point under different river discharges (t denotes the duration when chlorinity exceeds the required drinking water standard)

et al. (2017). The chlorinity processes in Figure 11 show that the number of days on which chlorinity is over standard can be distinguished. By repeating trial calculations, the critical river discharge can be obtained when the number of days is equal to 10.

We perform several groups of calculations with combinations of different modes of tidal range estimation and different empirical models. The results indicate that the critical discharges obtained from different modes have the general law of curve A > curve C > curve D > curve B. Evidently, if curve A is used, then the critical discharge induces waste of water resource. Curve C can fully reflect the extreme value of the measured tidal range and the critical discharge corresponding to curve C is moderate. The results obtained with curve C and the selected empirical models are listed in Table 7. The calculated critical discharges are between 11,000 and 12,000 m^3/s. Thus, the critical discharge with empirical models is 11,500 m^3/s on average.

Table 7 Critical discharges calculated using different empirical models

Empirical model	Location of chlorinity prediction	Tidal range estimation mode	Calculated critical discharge (m^3/s)
Mao *et al.* (1993)	Baogang	Curve C	12,000
Chen *et al.* (2013b)	Chenhang	Curve C	11,000
Sun *et al.* (2017)	Dongfengxisha	Curve C	11,500

5 Discussion

Our statistics and previous investigation have shown that the saltwater of the upper SB mainly comes from the NB when the river discharge into the YRE is greater than 10,000 m^3/s (Xu and Yuan, 1994). After the impoundment of the TGR, the probability of the daily river discharge less than 10,000 m^3/s is close to zero, as shown in Table 3. Thus, the complex mixing processes of saltwater from two sources generally do not occur in this region. Moreover, the quantitative description of the interactions among variables, including river discharge, tidal range, and salinity is possible by means of data analysis or simplified empirical modeling.

In engineering practices, such as tidal level forecast or tidal current modeling in the YRE, the daily tidal range varying on a time scale of 15 days is widely accepted (Chen and Jin, 1989; Lu *et al*., 2010; Hou and Zhu, 2013). In this background, considering the influence of random factors, we use the cumulative frequency in Figure 9 and the various curves in Figure 5 to describe the tidal range variation on average. Therefore, the critical criterion of "continually excessive salinity for more than 10 days" can be translated into a certain tidal range. The calculation results show that the critical discharge determined by the empirical models is very close to that of the material analysis method. This finding suggests that the simplified modes of daily mean tidal range estimation are reasonable and applicable.

In the selected empirical models, without exception, the exponential functions are used to describe the relationship between salinity (chlorinity) and tidal range. However, the function used to describe the relationship between salinity (chlorinity) and river discharge is different. For example, Chen *et al*. (2013b) and Zheng *et al*. (2014) considered the salinity and river discharge to be a polynomial relationship. Mao *et al*. (1993) and Sun *et al*. (2017) considered the relationship to be exponential. Nevertheless, the empirical models are theoretically based on the measured data statistics, and the law of interactions among variables can be fitted with different types of functions. If parameters in empirical models are appropriately calibrated, different types of models can have good simulation effects. Therefore, the calculation result shows that the proposed tidal range estimation modes indicate applicability in all the selected models, and the different types of models have obtained similar critical river discharges.

For the critical condition of notable saltwater intrusion, previous investigators had provide various of descriptions. For example, the statistics of Tang *et al.* (2011b) and Gu *et al.* (2003) indicated that the tidal flood current in the NB tends to bring high salinity water into the SB when river discharge is less than 20,000 m^3/s. Shen *et al.* (2002) showed that chlorinity in the upper SB changes gradually with river discharge reduction when the discharge is greater than 16000 m^3/s. However, chlorinity can rapidly increase with river discharge reduction when the discharge is less than 11,000 m^3/s. Li *et al.* (2013) proposed that when the discharge at Datong station is 6820–16,000 m^3/s, the saltwater intrusion can last for 10–30 days in the YRE. These descriptions of critical discharge are consistent with the proposed value. For the critical tidal range that may induce evident saltwater intrusion, Gu *et al.* (2003) pointed out that saltwater tends to spill over from the NB when the tidal range of Qinglonggang is greater than 2.5 m. Shen *et al.* (2002) proposed the value to be 3 m, whereas Li *et al.* (2013) proposed the value of 2.4–3.3 m. The results show that the critical tidal range of Xuliujing is 2.06 m. The correlation in Figure 2 reveals that the corresponding tidal range of Qinglonggang is 2.7 m, which is consistent with previous investigations. These comparisons indicate the reasonability of our results.

In addition, the reasonability of the proposed critical river discharge (11500 m^3/s) is confirmed through observations after the TGR operation. Based on data obtained from the water source region in the upper SB, the statistics conducted by Zhao *et al.* (2012) showed that even if the minimum river discharge increased to 10,500 m^3/s after 2006, the water quality was unsuitable for use for consecutively 10 days in certain drought months. In 2014, the discharge at Datong station was below 11,500 m^3/s for more than 20 days. That had induced the most serious saltwater intrusion event in recent years.

Our statistics indicated that after the impoundment of the TGR (2003–2017) the number of days on which the daily discharge at Datong station below 11,000, 11,500, and 12,000 m^3/s were 234, 349, and 480 days, respectively. The multi-year average number is 15.6, 23.3, and 32 days. Therefore, the possibility of notable saltwater intrusion in drought months still exists if the TGR regulates river discharge under the current operation scheme. To reduce the frequency of saltwater intrusion, we suggest the TGR and other cascade reservoirs in its upstream to increase the amount of downstream water replenishment during dry periods. Particularly, the minimum discharge at Datong station should be maintained above 11,500 m³/s.

6 Conclusions

The relationship among river discharge, tide and saltwater intrusion in the upper SB, which is an important freshwater source region in the YRE, is explored. Gauged daily discharge pre- and post- the TGR operation, long-term daily mean tidal range, and salinity data during the dry seasons of 2009–2014 are used to analyze the characteristics of different variables and the basic law of their interactions. In particular, the critical river discharge for saltwater intrusion control is investigated using material analysis method and empirical models. The following are the main findings of this study.

When the river discharge at Datong station is less than 30,000 m³/s, saltwater intrusion can occur in the upper SB of the YRE. The probability of saltwater intrusion dramatically increases when river discharge is less than 15,000 m³/s, and notable saltwater intrusion mainly occurs when the discharge is less than 12,000 m³/s. However, in extreme drought occasions with a discharge of less than 10,000 m³/s, a severe saltwater intrusion event lasting for more than one tidal cycle is probable.

In the YRE, even considering the influence of random factors, the daily mean tidal range is approximately independent of river discharge. It roughly varies in sinusoidal pattern in a 15-day cycle. Under fixed river discharges, exponential correlations exist between daily chlorinity and daily mean tidal range. Based on these two features and from the view of data analysis method, the critical tidal range corresponding to the criterion "chlorinity excessive for more than 10 days in a tidal cycle" is 2.06 m at Xuliujing station and 2.7 m at Qinglonggang station. The critical river discharge corresponding to that criterion is estimated to be slightly more than 11,000 m³/s.

Several simplified modes of daily mean tidal range estimation are presented to describe the periodic variation of tidal range. Several empirical models of different formula structures are also selected for salinity prediction. The predictive function of these models is improved for salinity process calculation and critical discharge determination by introducing the estimated tidal range. The critical river discharges at Datong station are calculated using different empirical models. The obtained critical discharge values are between 11,000 and 12,000 m³/s.

In summary, the critical discharge for saltwater intrusion for the upper SB is proposed to be 11,500 m³/s in engineering applications. Compared with the results of previous investigators and the measured data in recent years, our proposed value of critical discharge is reasonable. To avoid saltwater intrusion threatening the normal operation of freshwater reservoirs in the upper SB of the YRE, the minimum discharge at Datong station should be maintained above 11,500 m³/s by the TGR regulation.

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