Response to referees, followed by paper with marked-up changes

Authors' response to referees

Referee 2

Comment: “The use of Q_{t-7} in the statistical model is quite important. This relies on the assumption that travel time from Datong to Gaoqiao is 7 days, which was from Zhang et al (2012). In reality the travel time is likely to be a function of discharge, although the travel time might not vary much over the range of discharge of interest. A comment on this could be provided.”

Response: It is true that the travel time is likely to vary with discharge. However, the discharges are very highly auto-correlated, with an average change in discharge from one day to the next of only 0.0094 per cent. So any error involved in this assumption is very small.

In the paper: The point is acknowledged on lines 140-142 of the unmarked manuscript and lines 147-149 of the manuscript with marked changes.

Referee 1

Referee 1 makes five comments, which we address in turn.

Comment 1 “The paper uses a statistical model to represent the relationship between salinity and discharge, rather than a physics-based model, such as that of Zhang et al (2011).”

Response: Zhang et al. (2011) informed our work. That model is designed to estimate salinity along the separate branches of the estuary and at different distances from the sea, which is a different problem from that which we confront. Our problem combines frequent observations of discharge, infrequent observations of salinity and the task of estimating salinity and its duration at a point, Shanghai’s Qingcaosha storage intake. Whereas Zhang et al. could calibrate their model parameters from observations on one day and then evaluate the model with observations on only another two days, we sought a method that combined the known data [over 300 observations] with a search for more robust estimates of chlorinity. We believe that it is important that there exist different methods for approaching the task of predicting the risk of saline intrusions. Our method is attuned to duration, and its probabilistic nature accords with incomplete knowledge about the dynamics of the Yangtze estuary.

In the paper: Our response to this comment in the resubmitted paper is subsumed under our response to this referee's comment 3.

Comment 2 “It is a bit hard to see the innovation of this paper. The application of a complex autoregressive function is not really the innovation. So the innovation lies in the combination of a salinity-discharge relation with a Monte Carlo simulation method to construct high intrusion periods, and to analyse which of these have a critical duration.”

Response: Precisely! Unlike all previous analyses of saline intrusions in the Yangtze River, we estimate not only their chlorinity, but also their duration. Because we know daily discharges for over 60 years, we can estimate the probability of critical discharges, below which saline intrusions are highly likely and we can estimate the probability that these intrusions last for more than specified lengths of time. We can demonstrate that intrusions are a continuous function of discharge, for example.

In the paper: We have emphasised this contribution in lines 104-106 and 112-115 of the manuscript with marked changes and lines 98-100 and 105-108 of the unmarked manuscript.

Comment: 3 “Because the authors have used an auto-regressive function that lacks physical foundation, the risk is that this model works well for the calibration period, but fails during the critical periods the method has been designed for.”

Response: The calibration period includes observations from five separate years. In all of those observations, discharges lay in the range 6000 – 16000 $m^3 s^{-1}$, which is precisely the range within which chlorinity is variable. No lower discharges have ever been recorded; at higher discharges, saline intrusions are demonstrably unlikely. The calibration intervals are precisely those that are the critical periods for saline intrusions. Of course, the model may fail outside the calibration period. But our calibration period extends over five separate years and more than 300 observation.

In the paper: Nevertheless, we have acknowledged this risk and discussed it in the revised paper. See lines 426-437 of the resubmitted manuscript and lines 436-447 of the manuscript with marked-up changes.

Comment: 4 'The authors mention that: "All of these modifications (physical interventions) will affect the probability of salt intrusions in the estuary and it is important to calculate their effects". Only a physics-based model will be capable of simulating the effects of these interventions (dredging, sea level rise, changing seasonality, etc.), whereas the statistical method cannot.'

Response: The editor also asked that we address this comment, by using the model to predict the effects of management interventions on the probability of long duration salt intrusions into the estuary. This we have done, by calculating the change in the probability of long durations of chlorinity 250 mg L^{-1} under the operations of the Three Gorges dam, and the abstractions that are likely for the South-North Water Transfer Project and local abstractions in the Yangtze delta by 2030.

In the paper: This major revision to the paper:

(1) adds a new context to the paper – lines 50-59 of the resubmission [54-63 of the marked-up manuscript];

(2) adds a new aim – lines 98-100, 104-108 of the resubmission [104-106, 113-115 of the marked-up manuscript];

(3) requires discussion of an additional data set – lines 184-197 of the resubmission [191-204 of the

marked-up manuscript] + new figure 3 + Appendix A;

(4) leads to a new set of results – lines 317-349 of the resubmission [327-359 of the marked-up manuscript], including new table 4 and new figure 8;

(5) requires additional discussion – lines 390-412 of the resubmission [400-422 of the marked-up manuscript].

Comment: 5 “Finally, as an aside, the main problems of salinity near the intakes for Shanghai, are the result of relatively saline water from the North Branch spilling into the South Branch during low flows. This effect is impossible to take into account in this statistical model, while it is this phenomenon that is most probably critical for the water supply of Shanghai.”

Response: The paper mentions that this is what actually happens during an intrusion. Our model is in effect a method for identifying when this occurs. The Zhang et al. model is not a model of this spill-over effect, either.

In the paper: We have addressed this comment in discussing the risk that the calibrated statistical model fails outside the calibration period – lines 426-437 of the resubmitted manuscript [436-447 of the marked-up manuscript].

~~A METHOD FOR CALCULATING~~Impact of Three Gorges Dam, South-North Water Transfer Project and water abstractions on the duration and intensity of salt intrusions in~~:~~ the Yangtze River estuary

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Abstract

This paper assesses the impacts of the Three Gorges dam, the South-North Water Transfer Project and other water abstractions on the probability of long duration salt intrusions into the Yangtze River estuary. Studies of intrusions of salt water into estuaries are typically constrained by both the short duration of discharge records and the paucity of observations of discharge and salinity. Thus studies of intrusions of salt water into estuaries typically seek to identify the conditions under these intrusions occur, using detailed observations for periods of 20 – 60 days. The~~is~~ paper therefore first demonstrates a method by which to identify the conditions under which intense intrusions of long duration occur and then applies that method to ~~the Yangtze River estuary~~analyse the effect of the three projects. The paper constructs a model of the relationship between salinity and discharge and then employs Monte Carlo simulation methods to reconstruct the probability of observing intrusions of differing intensities and durations in relation to discharge. The model predicts that the duration of intrusions with chlorinity ≥ 250 mg L^{-1} (or ≥ 400 or 500 mg L^{-1}) increases as the number of consecutive days with discharge ≤ 12 000 m^3 s^{-1} (or ≤ 8 000 m^3 s^{-1}) increases~~; consecutive days of discharges ≤ 8 000 m^3 s^{-1} predict the duration of intrusions with chlorinity ≥ 400 or 500 mg L^{-1}~~. ~~In 26 of the 64 years analysed, the probability of an intrusion of at least 60 days at ≥ 250 mg L^{-1} is greater than 1 in 1000; in 17 years is greater than 1 in 100; and in ten years is greater than 1 in 10.~~ The model predicts that in 1950-2014, the number of consecutive days with chlorinity ≥ 250 mg L^{-1} averaged 21.34 yr^{-1}; if the three projects operate according to their normal rules, that average would rise to 41.20 yr^{-1}. For a randomly selected year of discharge history from the period 1950 – 2014, under normal operating rules for these projects the probability of an intrusion rises from 0.25 (30 days) or 0.05 (60 days) to 0.57 or 0.28, respectively.

Keywords

Salt intrusion, Yangtze River, discharge, salinity, ~~simulation~~Three Gorges dam, South-North Water

Transfer Project

1 Introduction

Shanghai's industries and the more than 24 million people who live in the municipality now principally depend on the Yangtze River for their water supply. Yet, like other large estuaries (Gong 2013), the estuary of the Yangtze River is affected by salt intrusions (Shen et al. 2003). The latest occurred in 2014 (CNTV 2014), the longest since 1993. So two storages have been built in the estuary to store water against the threat of salt intrusions (see Fig. 1 for locations): Chenhang reservoir supplies about 23 per cent of the municipality's public water; Qingcaosha reservoir supplies about 54 per cent (Li *et al.* ~~forthcoming~~2014). Qingcaosha's storage capacity is said to be equivalent to 67 days of Shanghai's current consumption. The probability of long duration salt intrusions in the Yangtze estuary is thus of considerable social importance.

However, the discharge and tidal characteristics of the Yangtze estuary are now being modified. Water is increasingly being abstracted from the river, for the South-North Water Transfer Project (SNWTP) as well as for more local uses (Chen 2013; Zhang *et al.* 2012), tending to increase the length and the intensity of periods of low discharge (Li *et al.* 2014). The Yangtze River is increasingly being dammed for large hydro-electric projects, that cumulatively can now store about 25 per cent of the annual flow; this capacity is planned to double by 2050 (Li *et al.* 2000). The largest of these is the Three Gorges Dam. As hydro-electric dams, these constructions have limited effects on annual discharge, but do affect its seasonal distribution (Finlayson *et al.* 2013). All of these modifications will affect the probability of salt intrusions in the estuary and it is important to calculate their effects.

Intrusions of salt in estuaries have been widely studied, by both numerical and theoretical methods. Most studies of the Yangtze estuary have been numerical (Kuang *et al.* 2009; Li *et al.*

2012; Liu *et al.* 2013; Xue *et al.* 2009). However, Zhang *et al.* (2011) ~~have~~ applied Savenije's (1986, 1993) theoretical model. As Fig. 1 indicates, the Yangtze estuary is complex, with four outlets to the sea. Nevertheless, these studies confirm that salt water intrusions are primarily governed by a combination of low discharge and spring tide conditions, but are also influenced by wind speed and direction. The discharge of the Yangtze R is highly seasonal, with average discharges below 12 000 $m^3 s^{-1}$ in January and February, compared to over 40 000 $m^3 s^{-1}$ in June – August (Chen 2013; Finlayson 2013). In dry years, discharges in December through March are less than 12 500 $m^3 s^{-1}$ (Wang *et al.* 2008). It is this period, December – March, in which intrusions are most likely to occur. When spring tides occur in December – March, intrusions are common: the lower the discharge and the higher the tide, the more intense the intrusion, especially when accompanied by strong south-easterly winds.

Figure 1 Map of the Yangtze estuary

The principal problem for these studies has been to examine the conditions under which oceanic water intrudes far up the estuary. They seek to predict an event – the observation of water with chlorinity exceeding 250 mg L^{-1} (ppm, equivalent to 0.45 on the Practical Salinity Scale), which is the Chinese standard for drinking water (National Standard GB 5749-2006). Since the usual treatment technologies in Shanghai's water plants do not remove chlorides, it is also the standard for raw water that is to be processed into tap water (Surface Water Quality Standards GB 3838-2002).

However, the duration of this event is also significant, especially for residents of Shanghai. An intrusion of a few days, no matter how intense, has little social significance, compared to an intrusion of a few months. ~~Li *et al.* (2014) demonstrate that the duration of intrusions is positively related to their intensity (chlorinity); unfortunately, Li *et al.* have only 11-13 data points to support~~

~~this conclusion.~~ Chen *et al.* (2013) ~~also~~do address duration, but they, like others (Chen *et al.* 2001; Gu and Yue 2004; Wang *et al.* 2008; Yang 2001; Zhao *et al.* 2009), identify a single threshold discharge below which intrusion is likely and above which intrusion is unlikely. In fact, salt intrusions may occur at a variety of discharges (Fig. 2), with a probability that varies inversely with discharge.

The difficulty is that, while long discharge records for many rivers are generally available, measurements of salinity are not routinely collected by state agencies. Salinity thus needs to be measured for a specific purpose, such as a research project. Measurements of salinity are therefore expensive and not available in long records. It is thus important to find a method for using historical data about discharge to generalise the limited observations of salinity, and so obtain a long record of salinity, which identifies both the duration of a saline intrusion and the relative frequency of occurrence of such intrusions. It is this method that this paper presents, and then employs to calculate both the probability of long duration salt intrusions in ~~illustrates from the case of~~ the Yangtze River estuary and the impact of human modifications of the river on that probability.

~~This~~Specifically, the paper therefore addresses the following problems: how can the probability of long duration (up to 60 days) salt intrusions in the Yangtze estuary be identified? What is that probability? ~~Subsequent questions, to be addressed in a later paper, concern the impact of~~What is the effect on that probability of increasing water abstraction from the Yangtze basin, the SNWTP and the ~~increasing~~ construction of the Three Gorges ~~hydro~~ dam~~s, climate change and sea level rise on this probability~~?~~.~~ It is our calculation of the probability of long duration salt intrusions and our prediction of the impact on that probability of human modifications to discharge that sets this paper apart from other studies of salt intrusions in the Yangtze estuary.

2 Method

This paper is statistical and predictive. We do not model the estuary dynamics, either theoretically or numerically, but estimate statistical relations between discharge and salinity to identify the probability of long duration salt intrusions. The paper draws on ~~two~~three ~~principal~~ sources of data.

First, it employs published data about discharge and salinity for various periods to estimate the relationship between discharge and salinity. The salinity data refer to the Gaoqiao gauging station in the estuary (Fig. 1), the nearest station to Qingcaosha and are from Li *et al.* (2014). The discharges are measured at Datong, the nearest g~~u~~auging station which has a long record of discharge data. The observations refer to the periods 1 January 1979 through 30 April 1979 [120 observations]; 13 February 1984 through 30 March 1987 [47 observations]; 1 January 1987 through 17 April 1987 [107 observations]; 24 January 1999 through 17 February 1999 [25 observations]; 16 February 2007 through 4 March 2007 [17 observations]. All 316 observations lie in periods in which the probability of low discharges and therefore of salt intrusions is high. Figure 2 illustrates the discharge and salinity conditions in these periods.

Figure 2 Salinity and discharge conditions in the periods of observation

These observations are neither logically nor statistically independent. They are not taken on a random sample of days between 1 January 1979 and 4 March 2007, and so are not logically independent. A casual observation of Fig. 2, confirmed by statistical tests, reveals that there is a pronounced lag structure to the salinity measures, so they are not statistically independent either. An appropriate estimate of the relationship between discharge and salinity must recognise this non-independence of the observations. Although an Artificial Neural Network could be constructed to model this relationship, we chose to estimate an equation of the form:

$$G_t = \text{function}\ [G_{t-1}, Q_{t-7}], \qquad 1$$

in which

$G_{t,}$, G_{t-1} denote the salinity measure at Gaoqiao on day t and t-1, respectively

Q_{t-7} denotes the discharge at Datong on day t-7.~~;~~ A~~a~~t average discharges, it takes seven days for water to flow from Datong to Gaoqiao (Zhang *et al.* 2012); the travel time is likely be be less at high discharges, though the fact that the average change in discharge from one day to the next is only 0.0094 per cent renders this point moot.

Such a model has a straightforward, intuitive meaning. Observations are numbered 1, 2, …, n within years, and the estimates are made through a generalised estimating equation (Garson 2013). After testing a variety of functional forms for Eq. 1 and assumptions about the distribution of residuals, the specific estimated equation is:

$$\log G_t = \alpha_0 + \alpha_1 \log G_{t-1} + \alpha_2 (\log G_{t-1})^2 + \alpha_3 Q_{t-7} + \alpha_4 \log Q_{t-7} + \alpha_5 (Q_{t-7} - Q_{t-8}) + r_t \qquad 2$$

in which the residuals, r_t, are assumed to follow an inverse Gaussian distribution with autocorrelated variance structure, and α_0 , …, α_5 are parameters to be estimated. There are 312 usable observations, since the first day of each sequence is lost through the lag specification.

There are four known sources of error in the data that have been used to construct this equation. First, unknown, but variable, amounts of water are extracted from the river or drain into the river between Datong and the salinity gauging station at Gaoqiao. Zhang *et al.* (2012) estimate that net abstractions are highest in periods of spring tide, in September, October and November and in years of drought (see also Dai *et al.* 2011). These differences are systematic, though with imperfectly understood characteristics, which create errors of estimation. Secondly, the influence of spring and neap tides is not included (Tong *et al.* 2010 illustrate these effects). However, the partial autocorrelation plots of the residuals from Eq. 2 do not reveal any significant autocorrelations beyond day 1. Third, there has been a rise in the long term level of the sea. Cai *et al.* (2009) estimate that the rate of relative sea level rise in the Yangtze delta has been accelerating and in the past few decades was 6.6 mm yr^{-1}. Over the period 1950-2010, this implies a rise of up to 40 cm, which may influence the probability of an intrusion at any given discharge. Fourth are errors of measurement within and differences in methods between the data sources, which are not known.

The second data set consists of the record of daily discharges at Datong. These are available for the period 1950 through 2007 from the published yearbooks of the Changjiang Water Commission, with gaps that were kindly infilled by Klaus Fraedrich, and from 2004 through 30 September 2014 at the website of the Changjiang Shuiwei Guangli Xitong (Changjiang Water Level Management System, http://yu-zhu.vicp.net/). The record is converted from calendar years into "river years", which run from 1 August for 305 days; in a normal year, the sequence ends on 1 June; in a leap year on 31 May. Intrusions have never been observed in June and July. Once the parameters of Eq. 2 were estimated, those parameters and the distribution of residuals were used to create 1024 simulations of the corresponding salinities for each year t, using random numbers generated from the inverse Gaussian distribution of the estimated residuals, r_t. Thus, from the simulations we can then calculate for a year with the discharge characteristics of year t, the probability of observing 1, 2, …, n consecutive days with salinity above the critical values of 250 mg L^{-1} (the upper limit of drinking water, according to the standard), 400 and 500 (values chosen to reflect the possibility of building water plants in Shanghai that can treat saline water to obtain drinking water). Repeating this calculation for each year provides the critical information which this paper seeks to present. The analysis concludes by illustrating the discharge characteristics of years in which the simulations reveal that the probability of long duration intrusions is high.

Thirdly, the paper relies on published information about the volumes and operating rules of local abstractions, the SNWTP and the Three Gorges dam. In each case, we investigate the effect of two scenarios: the first, “normal operating rules”, which represent our best estimate of abstractions out of the basin and discharges from the Three Gorges dam; the second, “conservative operating rules”, which assume that abstractions and changes in discharge are less severe than under normal operating rules. In both cases, it is assumed that current plans for the years 2030-2035 are followed. The details of these rules and the sources from which they were calculated are described in Appendix A; their effect on discharge into the estuary, net of return flows, is illustrated in Fig. 3. The impact of these modifications on the probability of long duration intrusions is then calculated as follows: first, for the 64 river years 1950-1951 to 2013-2014, what is the probability of an intrusion of given duration and chlorinity? Second, if the Three Gorges dam, SNWTP and local abstractions planned for 2030-2035 had operated in 1950-1951 to 2013-2014, what would have been the probability of an intrusion of given duration and chlorinity? The difference in probabilities is ascribed to the three modifications to the river.

Figure 3 Net changes to discharge from Three Gorges dam, SNWTP and local abstractions under normal and conservative operating rules

The principal limitation of this analysis is the short duration of the time series of daily flows. There are only 64 river years of data from 1 January 1950 to 30 September 2014. Long periods of saline intrusion are relatively rare events, perhaps occurring no more than five times per century, so this record is clearly an insufficient basis from which to draw robust conclusions about the relationship between low frequency, long duration intrusions and river discharge.

3 Results I: Discharge and salinity

Table 1 about here

The model estimates and goodness of fit criteria are contained in Table 1. The effect of all variables is significant at $p < 0.05$, and the likelihoods are appropriately low. At the ranges of discharges to which the model was fit (6 0~~5~~00 ≤ discharge < 16 000) salinity is negatively associated with discharge and positively associated with the previous day's salinity. The proportion of the variance in log G that is accounted for by the model is 0.8893. Residuals are not significantly different from normal, according to a one-sample Kolmogorov-Smirnov test; furthermore, the residuals are not correlated with the predicted values and their variance is approximately constant (Fig. 4~~3~~).

Figure ~~3~~4 Distribution of residuals, with Weibull fit

Note: one-sample Kolmogorov-Smirnov test: most extreme deviation = 0.044; asymptotic significance = 0.200, after Lilliefors correction.

The model predicts a close relation between discharge and mean salinity, especially when discharge falls for long periods below about 10 000 m^3 s^{-1}. In 43 of the 64 years, the model predicts that there were periods in which mean salinity exceeded 250 mg L^{-1}, ranging in length from 1 through 97 days; in 30 years there were periods in which mean salinity is predicted to have exceeded 400 mg L^{-1}, ranging in length from 1 through 80 days; and in 25 years there were periods in which mean salinity is predicted to have exceeded 500 mg L^{-1}, ranging in length from 1 through 70 days (Fig. 4). The model predicts that in ten years – 1955, 1956, 1958, 1962, 1966, 1967, 1971, 1978, 1979 and 1986, mean salinities of over 500 mg L^{-1} lasted more than 30 days. The model suggests that the ~~Changjiang~~Yangtze has become less liable to long duration intense intrusions since 1986: no mean salinity of more than 500 mg L^{-1} is predicted to have exceeded ten days since then. However, the complete model is probabilistic, with a frequency distribution of residuals around these mean predictions, as illustrated in Fig. 4~~3~~, so it is important to use these probabilistic predictions in order to understand the probability of encountering long duration intense intrusions under the discharge characteristics of the various years in the sample.

Figure 4 Frequency distribution of years, classified by number of days with high chlorinity

4 Results II: Discharge and intrusions

This model, with its known frequency distribution of residuals (Fig. 4~~3~~), is therefore used to simulate salinity intrusions. These simulations follow Monte Carlo methods, in which the frequency distribution of residuals is repeatedly sampled, in conjunction with the other parameters of Eq. 2, in order to identify the probability that intrusions of given intensities and durations will occur. The results are first illustrated in detail for 1962, the year with the longest duration intense intrusion on record. Figure 6~~5~~ reveals the frequencies with which salinities of 250, 400 and 500 mg L^{-1} for different lengths of time were observed in the simulations. Superimposed on the frequencies is a Weibull distribution, fitted by least squares. The most common intrusion of 250 mg L^{-1} lasts for 74 days, but even intrusions of at least 91 days occur with a probability of 0.05 and of at least 97 days occur with probability of 0.01. An intrusion of at least 73 days is as likely to occur as not. The most common intrusion of 400 mg L^{-1} lasts 67 days, while intrusions of at least 77 days have a probability of occurring of 0.05 and of at least 85 days occur with a probability of 0.01. Intrusions of 55 days are as likely to occur as not. The most common length of an intrusion of 500 mg L^{-1} is 67 days, but intrusions of 69 days occur with a probability of 0.05 and of 77 days occur with a probability of 0.01. Intrusions of 47 days are as likely to occur as not. These are the model predictions of the duration of salinity intrusions for years in which the discharge characteristics are those of 1962.

Figure 6~~5~~ Frequency distributions of numbers of consecutive days with chlorinity above 250 (upper left), 400 (upper right) and 500 (lower left) mg L^{-1}, fitted with Weibull distributions, 1962 data

Similar calculations have been made to determine the probability of occurrence of various durations of intrusions of 250, 400 and 500 mg L^{-1} for every other year. Table 2 provides the simple correlations between the simulated frequencies of three durations (30, 50 and 60 days) and a variety of characteristics of discharge for all the years of record. The probability that in a year chlorinity ≥ 250 mg L^{-1} for at least 30 days consecutively is correlated with a variety of measures of low flow, especially the number of days for which discharge ≤ 12 000, 10 000 or 8 000 m^3 s^{-1}. However, the probabilities of longer duration intrusions of ≥ 250 mg L^{-1} and the probabilities of higher salinity intrusions are best predicted by measures of the number of days for which discharge ≤ 8 000 m^3 s^{-1}. Across all the durations and chlorinity levels, the best predictor of the probabilities of duration-chlorinity pairs is the maximum number of consecutive days for which discharge falls below 8 000 m^3 s^{-1}. Worryingly for planners, no measures of discharge before the event predict long duration, high intensity intrusions.

Table 2 about here

Figure 7~~6~~ reveals in more detail how the probability of observing duration-chlorinity pairs depends on the duration of discharge less than 8000 m^3 s^{-1}. These graphs are the ~~central~~first result~~s~~ at which this method is aimed.

Figure 7~~6~~ Relationship between long duration, high intensity intrusions and duration of low discharges

The upper graph in Fig. 7~~6~~ illustrates how the probability of 30, 40 and 50 day intrusions of ≥ 250 mg L^{-1} in a year varies in relation to the number of consecutive days in that year in which discharge ≤ 8 000 m^3 s^{-1}. ~~If there are no such days in a year, then the probability of there occuring at least 30 days with chlorinity ≥ 250 mg L^{-1} varies between 0 and 0.4; in fact, o~~Only if there are at least 20 consecutive days in a year with discharge ≤ 8 000 m^3 s^{-1} does the probability of at least 30 days with chlorinity ≥ 250 mg L^{-1} rise above 0.025. As the number of consecutive days in a year with discharge ≤ 8 000 m^3 s^{-1} rises from 0 to 20, the probability of ~~there occuring~~ at least 30 days with chlorinity ≥ 250 mg L^{-1} rises to 0.55 – 0.9. When the number of consecutive days in a year with discharge ≤ 8 000 m^3 s^{-1} rises to 30 and then to 40 – 50, the probability of ~~there occuring~~ at least 30 days with chlorinity ≥ 250 mg L^{-1} is 0.9 and 0.99, respectively. Longer duration intrusions of chlorinity ≥ 250 mg L^{-1} are also closely related to the number of consecutive days with discharge ≤ 8 000 m^3 s^{-1}. If in a year the number of such days is less than eight, then 50 or 60 day intrusions of chlorinity ≥ 250 mg L^{-1} have probability less than 0.2; when the number of such days is between nine and 30, then the probability of 50 days of ≥ 250 mg L^{-1} lies between 0.1 and 0.5 and of 60 days lis between 0.1 and 0.3.

The central graph in Fig. 7~~6~~ illustrates how intrusions of chlorinity ≥ 400 mg L^{-1} vary in relation to the number of consecutive days in a year with discharge ≤ 8 000 m^3 s^{-1}, while the lower graph illustrates the same information for intrusions of ≥ 500 mg L^{-1}. In both cases, the probability of 30 day intrusions rises linearly as the number of consecutive low discharge days increases. In both cases, too, the probability of a longer intrusion (50 or 60 days) is less than 0.1 unless the number of consecutive days in a year with discharge ≤ 8 000 m^3 s^{-1} exceeds 30. In t~~he record there are no years in which the number of consecutive days in a year with discharge ≤ 8 000 m^3 s^{-1} lay between 30 and 40; but in t~~he two years in which more than 44 consecutive days exhibited discharge ≤ 8 000

m^3 s^{-1}, the probability of 50-day or 60-day, chlorinity ≥ 400 mg L^{-1} intrusions lay between 0.5 and 0.7 or lay between 0.25 and 0.5, respectively. The probability of 50-day or 60-day, ≥ 500 mg L^{-1} intrusions is a little lower; even so, the probability of 50-day intrusions of chlorinity ≥ 500 mg L^{-1} is 0.25 or 0.47 if a year has 44 or 50, respectively, consecutive days with discharge ≤ 8 000 m^3 s^{-1}. This event occurred twice in the 64-year long record.

This information is summarised in Table 3.

Table 3 about here

5 Results III: Impact of Three Gorges dam, SNWTP and local abstractions on intrusions

The net effect of the three modifications is to reduce the discharge of the Yangtze River at the estuary for most of the year (Fig. 3). The operations of the Three Gorges dam cause net decreases in discharge when it it being filled (October and early November), but nil effects or net increases throughout the rest of the year, including in the periods of lowest flow (December – February). However, these effects are offset by abstractions for the Middle and Eastern Routes of the SNWTP and by abstractions in the delta region. In aggregate, discharge is reduced throughout the year, except when normal operating rules raise discharges from the Three Gorges dam above inflows (in April and May).

The consequence is an increase in the risk of long duration salt intrusions. We illustrate the calculations by examining the probabilities of intrusions of chlorinity ≥ 250 mg L^{-1} for 30, 50 and 60 days (Table 4). The probability, calculated over 1024 simulations for the discharges observed in 1950 – 2014 and the abstractions identified in Fig. 3, of a 30-day intrusion of ≥ 250 mg L^{-1} was 0.25

under then current conditions, would rise to 0.40 under conservative rules by 2030-2035 and to 0.57 under normal rules. Likewise, the probabilities of 60-day intrusions of ≥ 250 mg L^{-1} rise from 0.05 to 0.14 and 0.28 under the three conditions.

Table 4 about here

More light is shed on the risk of intrusions in Fig. 8. These graphs reveal the proportion of years in which the probability of an intrusion of chlorinity ≥ 250 mg L^{-1} for 30, 50 and 60 days lies in the specified range. The upper graph indicates that 0.55 of years have a probability of less than 0.1 that an intrusion of ≥ 250 mg L^{-1} will last at least 30 days under then-current historical discharges. Under conservative operating rules, that proportion falls to 0.42, while 0.42 of years have a probability of at least 0.5 of an intrusion of ≥ 250 mg L^{-1} lasting at least 30 days. Under normal operating rules, 0.56 of years have a probability of at least 0.5 of an intrusion of ≥ 250 mg L^{-1} lasting at least 30 days. Similar changes in the probabilities of intrusions are revealed by the central (intrusions of at least 50 days) and lower (intrusions of at least 60 days) graphs.

Figure 8 Frequency distribution of years by the probability of an intrusion of chlorinity ≥ 250 mg L^{-1} for 30, 50 and 60 days, under three operating rules

6 Discussion

Unlike previous studies of intrusions of salt water into the estuary of the Yangtze River, this paper has sought to identify the conditions under which intense intrusions of long duration occur. Constrained by both the shortage of the discharge record and the paucity of observations of discharge and salinity, the paper has constructed a model of the relationship between salinity and discharge and then employed Monte Carlo simulation methods to reconstruct the probability of observing intrus~~t~~ions of differing intensities and durations in relation to discharge. The model predicts that the duration of intrusions with chlorinity $\geq$ 250 mg L^{-1} increases as the number of consecutive days with discharge $\leq$ 12 000 m^{3} s^{-1} increases; consecutive days of lower discharges ($\leq$ 8 000 m^{3} s^{-1}) predict the duration of intrusions with chlorinity $\geq$ 400 or 500 mg L^{-1}.

In 51 of the 64 years analysed, the probability of an intrusion of at least 30 days at chlorinity $\geq$ 250 mg L^{-1} is greater than 1 in 1000; in 37 years, is greater than 1 in 100; and in 15 years it is greater than 1 in 10. In 26 years, the probability of an intrusion of at least 60 days at $\geq$ 250 mg L^{-1} is greater than 1 in 1000; in 17 years is greater than 1 in 100; and in ten years is greater than 1 in 10.

In 26 years, the probability of an intrusion of at least 30 days at chlorinity $\geq$ 500 mg L^{-1} is greater than 1 in 1000, in 19 years it is greater than 1 in 100; and in 10 years it is greater than 1 in 10. The most extreme event analysed in this paper, an intrusion of $\geq$ 500 mg L^{-1} for more than 60 days occurs with a probability greater than 1 in 1000 in 6 years, and is greater than 1 in 100 and 1 in 10 in only one year.

Existing~~Typically,~~ estimates in the literature of discharges at which salinity intrusions occur in the Yangtze estuary are point estimates: they seek to identify a discharge below which intrusions are likely and above which intrusions are unlikely. Serious intrusions occurred near Chenhang Reservoir in 1978-79, 2001-02 and 2006-07, when the maximum average monthly discharges in January and February were 7 103 m^{3} s^{-1}, 10 165 m^{3} s^{-1} and 11 777 m^{3} s^{-1}, respectively, leading Chen *et al.* (2013) to suggest that the critical discharge into the estuary is at least 11 777 m^{3} s^{-1}. Gu and Yue (2004) suggested that a monthly mean Datong discharge of 11 000 m^{3} s^{-1} was critical and Wang *et al.* (2008) identified 13 000 m^{3} s^{-1}. Data in Li *et al.* (2014) demonstrate that mean salinity levels near Qingcaosha are a negative exponential function of discharge at Datong seven days earlier; at discharges less than 11 500 m^3 s^{-1}, mean salinity exceeds 250 mg L^{-1}. These results are broadly consistent with those reported in this paper, though the estimate of Wang *et al.* (2008) is high. However, they are misleading in the sense that there is no critical discharge: at all discharges ≤ 16 000 m^3 s^{-1}, the lower the discharge and the longer that low flow persists, the higher the probability of longer and more intense salt intrusions. The relationship between discharge and salinity is probabilistic as well as continuous.

The second principal result of the paper is the measurement of the effect of the Three Gorges dam, the SNWTP and local water abstractions in the delta on the probability of long duration intrusions. The calculations were presented for intrusions of chlorinity ≥ 250 mg L^{-1}, since this is the legal standard for drinking water in China and, given the absence of desalinisation treatment in Shanghai, the *de facto* standard for water intakes into treatment plants. Our results indicate that, for a randomly selected year of discharge history from the period 1950 – 2014, the probability of an intrusion rises from 0.25 (30 days) or 0.05 (60 days) to 0.40 – 0.57 or 0.14 – 0.28 (depending on the operating rules), respectively. The proportion of years for which the probability of an intrusion exceeds 0.50 rises from 0.22, 0.05 and 0.03 for 30, 50 and 60-day intrusions, respectively, to 0.42 – 0.56, 0.20 – 0.36 and 0.13 – 0.27, depending on the operating rules.

Others have also pointed out that the Three Gorges dam, the SNWTP and local abstractions will affect the probability of salt intrusions into the Yangtze estuary. In general, the operations of the Three Gorges dam tend to reduce the probability of saline intrusions, since under normal operating rules the reservoir discharges more than inflow during the periods of lowest natural discharge in December – February (An et al. 2009). However, the SNWTP and local abstractions both reduce discharge into the estuary, tending to create "high likelihoods" of salt water intrusions in December to February of a dry year and January and February of a normal year (Chen et al. 2013); likewise Zhang et al. (2003, 2012) estimate the effects on discharge of local abstractions, though without calculating their impacts on the probability of an intrusion of salt water. None of these, however, has calculated the changes in the probability of intrusions caused by these abstractions nor sought to apply their methods to the entire historical record of discharge, much less sought to identify the likely duration of saline intrusions.

~~Nevertheless, t~~The literature does identify other conditions besides discharge that affect the occurrence of salt intrusions, notably tide and wind conditions (Kuang et al. 2009; Li et al. 2012; Liu et al. 2013; Xue et al. 2009; Zhang et al. 2011). As noted in Appendix A, Zhang et al. (2012) also demonstrate that water abstractions from the Yangtze River below the gauging station at Datong are a significant proportion of total discharge, especially if years of relatively low discharge are also years of low rainfall in the estuary region. These are factors that an analysis of discharge data for the entire period 1950 – 2014 cannot take into account. In addition, there are concerns that rainfall patterns in the Yangtze basin may be changing under the influence of climate change (Jiang et al. 2008; Tao et al. 2012), which may alter the discharge characteristics of the river; furthermore, sea-levels off the Yangtze estuary have been rising and this will have effects similar to a reduction in discharge (Cai et al. 2009). The paper has not accounted for these factors.

Finally, we should comment on our choice of method. The risk of using a statistical model is that it works in the calibration period, but fails outside that time; we sought to minimise this risk by calibrating the model with data from five separate years from 1979 through 2007 and spanning discharges in the entire range 6 000 – 16 000 m^3 s^{-1}. No lower discharges have ever been observed and at higher discharges saltwater intrusions are unlikely. The principal change that is likely to modify the observed relationship between salinity and discharge is an alteration in the morphology of the channel – deepening it or widening it, for example. Our calculations and predictions are therefore subject to the proviso that such changes in the morphology of the estuary do not occur. If the morphology of the estuary is not changed, then the discharge conditions under which salt water from north of Chongming Island (the North Branch) spills over into the South Branch will remain constant, and the calibrated relationship between discharge and salt water intrusions will continue to hold.

6 Conclusion

This paper has demonstrated a new method for calculating the probability of occurrence of long duration salt intrusions of specified chlorinity. The method shows that the relationship between discharge and the intensity and duration of salinity intrusions is probabilistic and continuous. At discharges $\leq$ 16 000 m^3 s^{-1}, the lower the discharge and the longer that low flow persists, the higher the probability of longer and more intense salt intrusions. Combining this result with the known frequency of periods of low discharge during the period 1950 – 2014, the paper calculates that saline intrusions (chlorinity $\geq$ 250 mg L^{-1}) of at least 30 days occur with $p \geq 0.01$ in 37/64 years and with $p \geq 0.1$ in 15/64 years. Saline intrusions (chlorinity $\geq$ 250 mg L^{-1}) of at least 60 days occur with $p \geq 0.01$ in 17/64 years and with $p \geq 0.1$ in 10 years. Intrusions that can disrupt the supply of water to Shanghai's residents are not rare events.

Furthermore, they will become even less rare as the Three Gorges dam, the SNWTP and local water abstractions in the delta begin to affect discharge into the Yangtze estuary. The proportion of years for which an intrusion is more likely than not rises from 0.22, 0.05 and 0.03 for 30, 50 and 60-day intrusions, respectively, to 0.42 – 0.56, 0.20 – 0.36 and 0.13 – 0.27, depending on the operating rules of the three projects. However, these predictions do not account for ongoing changes in precipitation or rises in sea level, both associated with climate change. If climate change does not have the effect of increasing discharge in the winter months, then operating rules will have to be revised during years of low discharge or Shanghai will have to find alternative sources of water to prevent the disruptions to supply that these calculations predict.

~~However, the discharge and tidal characteristics of the Yangtze estuary are now being modified. Water is increasingly being abstracted from the river, for the South-North Transfer Project as well as for more local uses (Chen 2013; Zhang *et al.* 2012), tending to increase the length and the intensity of periods of low discharge (Li *et al.* 2014). Sea levels are rising on account of both global warming and the sinking of the Yangtze delta (Cai *et al.* 2009), which has an effect on intrusions that is equivalent to reductions in discharge. Finally, the Yangtze River is increasingly being damned for large hydro-electric projects, that cumulatively can now store about 25 per cent of the annual flow; this capacity is planned to double by 2050 (Li *et al.* 2000). As hydro-electric dams, these constructions have limited effects on annual discharge, but do affect its seasonal distribution (Finlayson *et al.* 2013). All of these modifications will affect the probability of salt intrusions in the estuary and it is important to calculate their effects.~~

Appendix A Data sources and assumptions: dams and diversions

1 Dams

The largest dam on the Yangtze is the Three Gorges dam. Other dams are being built above Three Gorges, but we assume that any effects of their operation on discharge at Datong will be regulated through the Three Gorges dam. There are also dams on other tributaries which join the Yangtze below the Three Gorges dam, but their effect is not separately considered here, though it is present in the discharge record.

Chen et al. (2001) describe the plans for the operation of the Three Gorges dam. The reservoir is planned to store water from October each year, tending to decrease flows below the dam. In a dry year, the water storage process may have to be extended to November. Then, during the dry season (December to April), the water level in the reservoir will need to be dropped to meet the needs of the hydropower plant. The plan is that minimum water levels will be attained at the end of September. Guo et al. (2011, Figures 3 and 8) provide more details: in June, July and August, the reservoir water level is maintained at 145 m asl, to provide for flood control during the wet season. In October, the water level is raised to 175 m asl, the planned maximum level, and it is maintained at as high a level as possible (and above 155 m asl to facilitate navigation) until the end of April, when it is again reduced to 145 m asl. According to Zhang et al. (2012, Table 3), the Three Gorges reservoir holds ~21.5 10^9 m^3 more water at its planned maximum level than at its planned minimum level.

Given estimates that it takes 14 days for water to flow from the dam site to Datong, Zhang et al. (2012) estimate that the reservoir's operation would be: in a dry year (eg 2001-2002) fill from 15 September to 31 October; in an extremely dry year (eg 1978-1979) fill from 1 September to 15 November.

We assume as follows. Under normal rules, the reservoir is filled in October, which reduces flow at Datong from 15 October through 14 November by 8000 m^3 s^{-1}. Under conservative rules (corresponding to dry year operations) the reservoir is filled from mid-September through to the end of October, which reduces discharge at Datong from 29 September through 14 November by 5400 m^3 s^{-1}. Following Guo et al. (2011, Figure 8), in normal operation, the reservoir is assumed to maintain its maximum water level until the end of January, that is having no effect on discharge at Datong until 14 February; and then to progressively discharge at rates above inflows from February through the end of April, increasing discharge at Datong from 14 February through 14 May by 900, 1800 and 2700 m^3 s^{-1} in each 30-day period; in May, the reservoir level is reduced to 145 m asl, which implies an increase in discharge at Datong from 14 May through 14 June of 2700 m^3 s^{-1}. For the remainder of the year there is no net storage or release of water. A more conservative rule is for the reservoir to discharge at constant rates above inflow in December through August, which increases discharge at Datong from 15 December to 14 August by 916 m^3 s^{-1}. For the remainder of the year, there is no net storage or release of water.

Zhang et al. (2012) state that the dam first began to affect discharges in 2006-2007, when experiments began to fill it. These experiments continued until 2010. Thereafter, the dam has functioned normally. Therefore the assumed modifications to discharge at Datong are not applied to years 2010-2011 onwards.

2 South – North water diversion project

The South – North water diversion project (SNWDP) project involves three routes: a western route, a middle route and a third route, taking water from the Yangtze to northern China. The western route is still in the planning stages and the volume of water to be diverted is still uncertain; it will not be operation until at least 2020. It is not considered any further here**, though it can be assumed that it will exacerbate the situation described in this paper**. The central and the eastern routes are now operating, however.

The eastern route is planned to transfer 8.9 billion m^3 yr^{-1}, 10.6 billion m^3 yr^{-1} and 14.8 billion

m^3 yr^{-1} in successive stages, according to official sources (Office of the SNWDP nd). However, a recent report (Nan 2014) indicates that only about 3.6 billion m^3 yr^{-1} is currently being delivered to northern provinces. Wet seasons have reduced the demand for Yangtze water, some distribution pipes to individual cities have yet to be constructed, and provinces are not using much diverted water because they face difficulties reconciling its relatively high price with the lower prices of local water. Nevertheless, both Chen et al. (2013) and Zhang et al. (2012) indicate that by 2030 it is planned to transfer 800 – 1000 m^3 s^{-1} by this route (25.2 – 31.5 m^3 yr^{-1}).

We assume as follows. By 2030 the eastern route will be transferring 900 m^3 / s. This is a reduction in discharge that occurs below Datong gauging station.

It is planned that the middle route will divert 12 – 14 billion m^3 yr^{-1} in normal years and 6.2 billion m^3 yr^{-1} in dry years (Office of the SNWDP nd). The water is sourced from the Danjiangkou reservoir, located on the Han River, a tributary of the Yangtze. We assume that these conditions will hold in 2030. These imply reductions in discharge at Datong of 410 m^3 s^{-1} under normal rules and 200 m^3 s^{-1} under conservative rules.

3 Other diversions

In addition to the SNWDP, water is also diverted from the lower Yangtze (below Datong) to cities and agricultural areas. The history, current status and some projections of these diversions are comprehensively described by Chen et al. (2001), Zhang et al. (2003) and Zhang et al. (2012). Zhang et al. (2003) provide historical data about the capacity of water extractions from 1958 through 2000, and also indicate net water extractions for November, January and March in the 1980s and by 2030. Chen et al. (2001) provides a summary of the findings of Zhang et al. (2003).

Zhang et al. (2012) update the information provided by Zhang et al. (2003); in addition, they provide estimates of daily net abstractions for the dry seasons of four years.

These data indicate that the capacity to extract water from the Yangtze downstream of Datong has increased rapidly since the 1950s. However, the available data do not indicate that the net quantity of water abstracted from the Yangtze has increased over time, controlling for discharge, tides and local precipitation. Regression estimates of net abstractions (according to Zhang et al. 2012, Figure 4A) indicate that, net of tidal conditions, these depend on the sequence of the observation within the river-year (tending to decrease and then rise), on the discharge (tending to rise with discharge) and on the year (tending to decrease slightly over time). These data imply that the estimates of discharge at Datong are biased estimates of discharges at the estuary; but also that there is no evidence that this bias has changed over time.

However, Chen et al. (2013) indicate that new abstractions are planned. These imply an additional net reduction in discharge of 670 $m^3 s^{-1}$. (They consider this a low estimate of the new abstractions.) Zhang et al. (2003, Table 1) estimate that the net water abstractions from the Yangtze River will increase by about 830 – 940 $m^3 s^{-1}$ over current levels of abstraction, after including the effects of the eastern route of the SNWDP. Zhang et al.'s estimates (360 – 470 $m^3 s^{-1}$ net of the eastern route transfer) are low, but they do note that an additional 210 $m^3 s^{-1}$ of extractions are planned. We assume approximately this pair of estimates, 650 $m^3 s^{-1}$; but supplement this with a conservative rate of abstraction of 550 $m^3 s^{-1}$.

4 Summary

Thus there are three modifications to the discharge of the Yangtze River at its estuary, estimated under two conditions – conservative rules and normal rules. The discharge at Datong is modified by the operation of the Three Gorges hydropower station (except during the years after 2010-2011, when it was actually in operation) and by the operation of the middle route of the SNWDP); both have normal year and conservative rules of operation. Below Datong, additional water is extracted by the eastern route of the SNWDP and by more local abstractions (the latter of which also have normal and conservative rules of modification). The resulting implications for discharge at the estuary are illustrated in Figure 8 of the paper.

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References

An, Q., Wu, Y. Q., Taylor, S. and Zhao, B.: Influence of the Three Gorges Project on saltwater intrusion in the Yangtze River estuary, Environ. Geol. 56, 1679-1686, 2009.

Cai, F., Su, X. Z., Liu, J. H., Li, B. and Lei, G.: Coastal erosion in China under the condition of global climate change and measures for its prevention, Prog. Nat. Sci., 19, 415-426, 2009.

Chen, D., Webber, M., Finlayson, B., Barnett, J., Chen, Z. Y. and Wang, M.: Impact of water transfers from the lower Yangtze River on water security in Shanghai, Appl. Geogr. 45, 303-310, 2013.

Chen, X. Q., Zong, Y. Q., Zhang, E. F., Xu, J. G. and Li, S. J.: Human impacts on the Changjiang (Yangtze) River basin, China, with special reference to the impacts on the dry season water discharges into the sea, Geomorphology, 41, 111-123, 2001.

Dai, Z. J., Chu, A., Stive, M., Zhang, X. L. and Yan, H.: Unusual salinity conditions in the Yangtze esuary in 2006: impacts of an extreme drought or of the Three Gorges Dam?, Ambio, 40, 496-505, 2011.

Finlayson, B. L., Barnett, J., Wei, T. Y., Webber, M., Li, M. T., Wang, M. Y., Chen, J., Xu, H. and Chen, Z. Y.: The drivers of risk to water security in Shanghai, Reg. Environ. Change, 13, 329-340, 2013.

Garson, G. D.: Generalized Linear Models / Generalized Estimating Equations, Statistical

Publishing Associates, Asheboro NC, 2013.

Gong, W. P., Shen, J. and Jia, L. W.: Salt intrusion during the dry season in the Huangmaohai Estuary, Pearl River Delta, J. Marine Syst., 111–112, 235-252, 2013.

Gu, Y. and Yue, Q.: Analysis and prediction of saltwater intrusion in Chenhang water source region in Yangtze River Estuary, Public Utilities, 18, 19-20, 2004.

Guo, S. L., Chen, J. H., Li, Y., Liu, P. and Li, T. Y.: Joint operation of the multi-reservoir system of the Three Gorges and the Qingjiang cascade reservoirs, Energies, 4, 1036-1050 2011.

Jiang T, Kundzewicz Z W and Su B D 2008 Changes in monthly precipitation and flood hazard in the Yangtze River basin, China Int. J. Climatol. 28: 1471-1481

Kuang, C. P., Sun, B. and Liu, S. G.: Approach of moving boundary and its application in 3D tidal current simulation of Changjiang River Estuary based on ECOMSED model, Acta Oceanol. Sin., 28, 78-85, 2009.

Li, C. A., Yin, H. F. and Yu, L. Z.: Silt transform characteristics and latent effect on fluvial system environment in Yangtze River, Resour. Environ. Yangtze Basin, 9, 504–509, 2000 (Chinese with English abstract).

Li, L., Zhu, J. R. and Wu, H.: Impacts of wind stress on saltwater intrusion in the Yangtze Estuary, Sci. China Ser. D, 55, 1178-1192, 2012.

Li, M. T., Chen, Z. Y., Finlayson, B., Wei, T., Chen, J., Wu, X., Xu, H., Webber, M., Barnett, J., Wang, M.: Water diversion and sea-level rise: potential threats to freshwater supplies in the Changjiang River estuary, Estuar. Coast. Shelf S., 156, 52-60, 2014.

Liu, S., Zhong, G., Kuang, C., Sun, B., Gou, H. and Huang, W.: Effects of South-To-North Water Transfer Project on salinity intrusion in Yangtze Estuary, Coast. Hazards, 119-128, doi: 10.1061/9780784412664.012, 2013.

Office of the SNWDP: South-to-North Water Diversion, http://www.nsbd.gov.cn, nd. Accessed 6 August 2015.

Savenije, H. H. G.: A one-dimensional model for salinity intrusion in alluvial estuaries, J. Hydrol., 85, 87-109, 1986.

Savenije, H. H. G.: Predictive model for salt intrusion in estuaries, J. Hydrol., 148, 203-218, 1993.

Shen, H. T., Mao, Z. C. and Zhu, J. R.: Saltwater Intrusion in the Changjiang Estuary, China Ocean Press, Beijing, 2003. (Chinese, with English summary).

Tao, H., Gemmer, M., Jiang, J. H., Lai, X. J. and Zhang, Z. X.: Assessment of CMIP3 climate models and projected changesof precipitation and temperature in the Yangtze River basin, China, Climatic Change, 111, 737-751, 2012.

Tong, C. F., Zheng, J. H., Zhang, C. and Guilbaud, C.: Salinity response to the runoff from Yangtze River basin at Qingcaosha reservoir area in Yangtze estuary, Proc. ASME 2010 29th Int. Conf.

Ocean, Offshore Arctic Eng., 4, 2010

Wang, D. and Sun, S.: Impact and its countermeasure on small hydropower in Huaian city from the east route of the South-to-North Water Transfer project. Small Hydro Power, 6, 33-35, 2006. (Chinese).

Wang, Y. G., Huang, H. M., and Li, X.: Critical discharge at Datong for controlling operation of South-to-North Water Transfer Project in dry seasons, Water Sci. Eng., 1, 47-58, 2008.

Xue, P. C., Chen, P., Ding, R. C., Beardsley, H., Lin, H., Ge, J. and Kong, Y.: Saltwater intrusion into the Changjiang River: A model-guided mechanism study, J. Geophys. Res., 114, doi:10.1029/2008JC004831, 2009.

Yang, G.: Impacts of the construction of key water conservancy projects in the Yangtze River and sea level rise on water quality of Shanghai water intake, Acta Geogr. Sin., 21, 123-129, 2001.

Zhang, E. F., Chen, X. Q. and Wang, X. L.: Water discharge changes of the Changjiang river downstream Datong during dry season, J. Geogr. Sci., 13, 355-362, 2003.

Zhang, E. F., Savenije, H. H. G., Wu, H., Kong, Y. Z. and Zhu, J. R.: Analytical solution for salt intrusion in the Yangtze Estuary, China, Estuar. Coast. Shelf S., 91, 492-501, 2011.

Zhang, E. F., Savenije, H. H. G., Chen, S. L. and Chen, J. Y.: Water abstraction along the lower Yangtze River, China, and its impact on water discharge into the estuary, Phys. Chem. Earth, 47-48, 76-85, 2012.

Zhao, R., Yang, Z., Sun, T., Chen, B., and Chen, G.: Freshwater inflow requirements for the protection of the critical habitat and the drinking water sources in the Yangtze River Estuary, China, Commun. Nonlinear Sci., 14, 2507-2518, 2009.

Table 1 Parameter estimates and goodness of fit

Parameter	B	Std Error	95% Wald Confidence Interval		Hypothesis test	df	Significance
			Lower	Upper	Wald Chi-square		
Intercept	4.923	1.761	1.471	8.374	7.814	1	0.005
Year = 1979	-0.015	0.0148	-0.044	0.014	0.972	1	0.324
Year = 1984	-0.067	0.0069	-0.080	-0.054	95.507	1	<0.001
Year = 1987	-0.085	0.0087	-0.102	-0.068	95.230	1	<0.001
Year = 1999	0.010	0.0032	0.004	0.016	10.084	1	0.001
Year = 2007	0*						
Q_d	3.20E-005	1.59E-005	8.04E-007	6.32E-005	4.042	1	0.044
Log Q_d	-0.483	0.208	-0.890	-0.076	5.405	1	0.020
Q_dDiff	2.95E-005	1.15E-005	6.94E-006	5.21E-005	6.562	1	0.010
Log Glag	0.220	0.0185	0.184	0.256	141.042	1	<0.001
Log Glag^2	-0.008	0.002	-0.012	-0.004	17.497	1	<0.001
Scale	0.001						

* Set to zero, as parameter is redundant.

Corrected Quasi Likelihood Goodness of Fit: 20.341.

Table 2 Correlations between probabilities of chlorinity above stated levels for stated lengths of time and selected discharge characteristics, annual scale

Indicator	Chlorinity > 250 for > (days)			Chlorinity > 400 for > (days)			Chlorinity > 500 for > (days)		
	30	50	60	30	50	60	30	50	60
Aug-May av Q_d	-	-	-	-	-	-	-	-	-
Dec-Mar av Q_d	-*	-	-	-	-	-	-	-	-
Nov av Q_d	-	-	-	-	-	-	-	-	-
Dec av Q_d	-	-	-	-	-	-	-	-	-
Dec-Feb av Q_d	-*	-	-	-	-	-	-	-	-
Jan-Feb av Q_d	-*	-	-	-	-	-	-	-	-
No days $Q_d < 16000$	+	+	+	+	+	+	+	+	+
NC days $Q_d < 16000$	+	+	+	+	+	+	+	+	+
Av flow $Q_d < 16000$	-*	-	-	-	-	-	-	-	-
No days $Q_d < 14000$	+	+	+	+	+	+	+	+	+
NC days $Q_d < 14000$	+*	+	+	+	+	+	+	+	+
Av flow $Q_d < 14000$	-**	-	-	-	-	-	-	-	-
No days $Q_d < 12000$	+	+	+	+	+	+	+	+	+
NC days $Q_d < 12000$	+***	+*	+	+*	+	+	+	+	+
Av flow $Q_d < 12000$	-***	-*	-	-*	-	-	-	-	-
No days $Q_d < 10000$	+***	+*	+	+	+	+	+	+	+
NC days $Q_d < 10000$	+****	+**	+*	+**	+	+	+*	+	+
Av flow $Q_d < 10000$	-***	-*	-	-**	-	-	-*	-	-
No days $Q_d < 8000$	+***	+****	+***	+****	+**	+*	+***	+*	+
NC days $Q_d < 8000$	+***	+****	+****	+****	+***	+**	+****	+**	+*

~~Note: the average flows for Q_d < 16 000, 12 000, 10, 000 or 8 000 are computed for the period from the first discharge < the stated value to the last discharge < this value.~~Note: the average flows for Q_d < 16 000, 12 000, 10 000 or 8000 are computed for the period from the first discharge < the stated value to the last discharge < this value.

NC: number of consecutive days.

-, +: sign of the correlation coefficient.

* absolute value r ≥ 0.6. ** absolute value r ≥ 0.7. *** absolute value r ≥ 0.8. **** absolute value r ≥ 0.9.

Table 3 Probability of intrusion duration and intensity in relation to length of periods of low discharge

Duration of period discharge ≤ 8 000 m^3 / s	No. of years with this duration discharge	Average probability of intrusion ≥ 250mg/L lasting		
		30 days	50 days	60 days
0 days	42	0.050	0.004	0.001
1-7 days	7	0.289	0.034	0.011
8-17 days	10	0.703	0.261	0.129
19-29 days	3	0.910	0.431	0.168
44-50 days	2	0.998	0.916	0.792
		Average probability of intrusion ≥ 400mg/L lasting		
		30 days	50 days	60 days
0 days	42	0.003	0.000	0.000
1-7 days	7	0.041	0.001	0.000
8-17 days	10	0.267	0.030	0.007
19-29 days	3	0.585	0.062	0.010
44-50 days	2	0.944	0.590	0.343
		Average probability of intrusion ≥ 500 mg/L lasting		
		30 days	50 days	60 days
0 days	42	0.001	0.000	0.000
1-7 days	7	0.024	0.001	0.000
8-17 days	10	0.143	0.012	0.003
19-29 days	3	0.361	0.014	0.000
44-50 days	2	0.853	0.360	0.173