A framework for determining lowest navigable water levels with nonstationary characteristics

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Abstract

The lowest navigable water level (LNWL) is an important indicator used for navigation design to balance the relationship between navigation safety and economic benefits of a waterway. However, it is a challenge of accurately estimating LNWLs due to the nonstationary characteristics of observed water level data series. In this study, a comprehensive framework was developed for handling this issue. In this framework, inter-annual variabilities in both the mean and variance of water level series were described by decomposing original series and were eliminated by composing new series. Intra-annual variability was determined by detecting indicators describing intra-annual water level distributions. Considerations of inter- and intra-annual variabilities were combined by designing annual water level processes for the past and current environments. Shipping risks during both annual and multi-annual periods were considered in the framework as well. The framework was demonstrated in estimating LNWLs at the Gaodao and Shijiao stations in the North River basin, southern China. The recommended LNWLs at the Gaodao station were 22.32 m for 95% guaranteed rate and 21.84 m for 98% guaranteed rate; LNWLs at the Shijiao station were 0.27 m for 95% guaranteed rate and 0.15 m for 98% guaranteed rate. The impact of variance variability on estimations of LNWLs was also evaluated. Results indicated that the recommended LNWLs would have errors of 0.11~0.48 m at the Gaodao station and 0.03~0.04 m at the Shijiao station if the variance variability was not considered. The proposed framework was then compared with nonstationary synthetic duration curve (NSDC) method, and results illustrated that the duration curves plotted by NSDC method were unreasonable, leading to inaccurate design values. Overall, the developed framework is more reasonable and suitable for designing LNWLs of waterways where the variabilities of the water levels at different time scales are different or where the historical water level data contain various variations.

Keywords: lowest navigable water level; water level processes; nonstationary hydrological design; intra-annual variability; inter-annual variability; variance variability

1. Introduction

Inland waterways play an important role in the global transportation system, providing economic benefits with low-cost and environmentally friendly freight transportation modes (Oztanriseven and Nachtmann, 2017; Willems et al., 2018). However, inland waterways are vulnerable to climate variability (Jonkeren et al., 2011; Christodoulou et al., 2020) and human activities (e.g., dam operation and waterway modification) (Valle and Kaplan, 2019) as waterway capacities largely depend on the water levels of rivers (Wang et al., 2020). For example, in the dry period waterways are adversely affected by the resultant lowered water levels (Linde et al., 2017). Since the navigation safety is threatened in such situation, the load amounts must be restricted or shipping must be interrupted to wait for the water levels to rise again (Jonkeren et al., 2014), leading to increases in transport costs and decreases in shipping efficiency.

To guarantee efficient inland navigation, concepts related to navigable depth/water level are adopted with which to define safe and effective channel bottom criteria. Among them, the lowest navigable water level (LNWL) has been used as an important navigation standard for inland waterways (Zhao et al., 2018; Yang et al., 2019), especially in China. However, the design of LNWLs requires long-term water level series, which usually show characteristics of nonstationarity under changing environments (Milly et al., 2008). These nonstationary characteristics appear not only in water levels at different timescales (e.g., annual, seasonal, dry or wet period, month, and day) but also in intra-annual distributions of water levels (Shiau and Wu, 2007; He et al., 2019; Yao et al., 2020). Under this circumstance, the LNWLs designed in the past or based on stationary assumptions may be unreasonable. An overestimated LNWL can reduce economic benefits, as the potential of the waterway capacity is not fully exploited. If the LNWL is underestimated, the risks of ship grounding and the costs of dredging (Kling et al., 2003) will increase. Therefore, methods for designing reasonable LNWLs under conditions of nonstationarity are required.

Presently, many approaches for nonstationary hydrological frequency analysis have been proposed, and they include two main types: direct estimation approaches using nonstationary probabilistic models, and indirect estimation approaches with reconstructions of original series (Liang et al., 2017; Zhao et al., 2018; Feng et al., 2020). Among them, mixed distribution models (e.g., Singh and Sinclair, 1972; Waylen and Woo, 1982; Yan et al., 2016), time-varying moments models (e.g., Strupczewski et al., 2001a, 2001b; Strupczewski and Kaczmarek, 2001; Villarini et al., 2009; Cannon, 2009; Vogel et al., 2011; Jiang et al., 2015; Liu et al., 2014; Ahn and Palmer, 2016; Li et al., 2019), and conditional probability distribution models (e.g., Singh et al., 2005) are typical models in the first type, and these models have been widely used and improved. However, previous studies (e.g., Montanari and Koutsoyiannis, 2014; Milly et al., 2015; Zheng et al., 2018; Jiang et al., 2019) have pointed out that these models may have too many parameters to estimate, resulting in estimation errors and uncertainties (especially when input data series are short). Additionally, the return periods and risk estimates for nonstationary conditions are different from those corresponding to stationary conditions, and the design values can thus be uncertain for a given exceedance probability (Salas and Obeysekera, 2014; Rosner et al., 2014; Jiang et al., 2015; Sarhadi et al., 2016). Although some risk-based nonstationary design strategies such as "expected waiting time" (Salas and Obeysekera, 2014), "design life level" (Rootzen and Katz, 2013) and "equivalent reliability" (Hu et al., 2018) have been proposed for estimation, the reliability of the final design values may need further improvement by considering uncertainties.

The second type of approaches requires reconstructing the historical series to meet the requirement of "stationarity". These approaches assume that a nonstationary time series is composed of nonstationary deterministic parts (Maidment, 1993) and a stationary stochastic part (Yevjevich, 1972; Guttman and Plantico, 1989; Milly et al., 2015; Stojković et al., 2017). Therefore, in these methods, the original series is first decomposed into different parts and then a new same-length stationary series is composed for estimations. For example, Gau et al. (2007) decomposed groundwater level series into three components by the additive model performed by STATISTICA (Statsoft Inc., 2003). Wavelet analysis is also used to decompose and reconstruct hydrological series by wavelet transform (Wang et al., 2015). Hu et al. (2015) proposed the concept of expected vibration center (EVC), separated the original series by a novel optimal segmentation technique, and used the EVC to reconstruct the original hydrological series. Gado and Nguyen (2016a, 2016b) removed trends in both the mean and standard deviation from the original series to obtain transformed "stationary" time series for subsequent calculations. Liang et al. (2017) proposed a modified reservoir index (MRI(t)) and reconstructed annual maximum flow series by multiplying the scalar factor $1/(1-\mathrm{MRI}(t))$. Ren et al. (2018) used seasonal-trend decomposition based on loess (STL) (Cleveland et al.,

1990) to decompose the components of monthly streamflow series and then recombined them. Zhao et al. (2018) used several methods to detect abrupt changes, trends and periodicities in observed series, and then used an additive model to compose a new series with a time-invariant mean.

Compared to the first type, the second type of approaches has relatively fewer parameters for estimations. Another theoretical advantage is that identifying deterministic components of historical series allows for a better interpretation of the temporal variability present in the series and the physical causes of the nonstationarity. However, this type of approaches mainly concerns the variability in the mean, but lacks deep considerations of abrupt changes, trends and periodicities in the variance and high-order moments. Overall, both types of approaches have not been widely used to analyze nonstationary water levels, let alone to design LNWLs with nonstationary characteristics.

The nonstationary synthetic duration curve (NSDC) method has been proposed for designing LNWLs (Zhao et al., 2018), which belongs to the second type described above. However, this method has some limitations. First, it only detects and deals with the inter-annual variability in annual average water level series. However, water levels at different timescales during the year may respond differently to the changing environment (López-Moreno et al., 2013; Palleiro et al., 2014), and therefore variabilities in low water levels can be exaggerated or overlooked during the design, leading to unreasonable LNWL estimations. Besides, the navigable guaranteed rate used in the NSDC method only reflects the daily average navigable probability during the multi-year period, lacking the consideration of annual shipping risks. Furthermore, some studies (e.g., Tu et al., 2015; Ren et al. 2018; Cui et al., 2020) have evaluated indicators reflecting the characteristics of intra-annual flow regime alterations such as the complete accommodation coefficient (C_c), concentration degree (C_d) and non-uniformity coefficient (C_n), and have pointed out the existence of intra-annual variability in streamflow. Whereas the variability in distributions of intra-annual water levels was not considered in the NSDC method either, leading to inappropriate duration curves and unreasonable estimations of LNWLs. Therefore, how to handle the intra-annual variability of water level and how to combine the considerations of inter- and intra-annual variabilities in the design process require further study.

The objective of this paper is, therefore, to build a more comprehensive framework for designing the LNWL. This framework consists of the following improvements to the NSDC method. First, considering the advantages of the second type of approaches listed above, the idea of decomposition and composition is also employed in this study, and the deficiency of only handling mean variations in most previous studies is overcome. Thus, reconstructed series with time-invariant means and variances can be obtained for subsequent design. Second, the variabilities in annual water level process, including variabilities in low water levels and intra-annual water level distributions, are considered together. By considering these variations, the impact of nonstationarity on the estimations of LNWLs can be minimized. Another advantage of this framework is that it considers not only the annual shipping risks occurring in the multi-year duration (expressed by the "exceedance probability"), but also the guaranteed navigable days at annual scales (expressed by the "annual navigable guaranteed rate"). The application of the framework is demonstrated in estimating the LNWLs at Gaodao and Shijiao hydrological stations located in the North River Basin, southern China. The daily water level data used from 1955 to 2016 at Gaodao station and from 1952 to 2017 at Shijiao station are used for this study.

2. The proposed framework for designing LNWLs

The proposed framework of designing LNWLs includes the following parts (see Fig. 1): (1) Water levels at multi-temporal scales are detected to identify the inter-annual variabilities in the means and variances, and each series is decomposed into abrupt changes, trends, periodic components, and stochastic remainders; (2) Each water level series is reconstructed under the assumed environment. Then, designed water levels at multiple time scales for a given "exceedance probability" are calculated based on the new series. (3) Annual series of C_d, C_n, C_c, and GI, which characterize the intra-annual water level variabilities, are calculated and detected. (4) All the change-points are used to split the time period, and the typical year of each sub-period is selected. (5) The designed intra-annual water level hydrograph under each environment is derived by scaling the benchmark water level hydrograph of the typical year. (6) The duration curve is drawn based on the designed intra-annual water level hydrograph, and the LNWL is estimated for a given annual navigable guaranteed rate.

<Figure 1>

2.1 Characterization of intra-annual water level distribution

The concentration degree (C_d), non-uniformity coefficient (C_n), and complete accommodation coefficient (C_c) are the indicators commonly used for characterizing the intra-annual flow regime alterations. In this section, these indicators along with the Gini coefficient (*GI*) are used to describe the characteristics of intra-annual water level distributions. The larger the C_d, C_n and C_c are, the more uneven the intra-annual water level process is. However, *GI* is negatively correlated with the non-uniformity. By detecting these indicators simultaneously, the intra-annual variability of water levels can be reliably obtained.

C_d is calculated based on the premise that the daily water level is a vector with a unique direction and magnitude. The direction represents the corresponding circular date and the magnitude is the value of the water level (Gumbel, 1954; Magilligan and Graber, 1996; Magiligan and Nislow, 2005). Therefore, the calendar date (i) can be transformed into the circular date (θ), such that:

$$\theta_i = \frac{2i-1}{2} \times \frac{360^\circ}{n} \tag{1}$$

where n is the number of days in the year, θ_i is the circular date of the i^{th} day, and i ranges from 1 to n. C_d is expressed as follows:

$$C_d = \frac{Z}{\sum_{i=1}^{n} Z_i} \tag{2}$$

$$Z = \sqrt{\left(\sum_{i=1}^{n} Z_i \cos\theta_i\right)^2 + \left(\sum_{i=1}^{n} Z_i \sin\theta_i\right)^2} \tag{3}$$

where Z is the module of the resultant vector of all daily water levels; and Z_i is the magnitude of the water level of the i^{th} day.

C_n can measure the dispersion of data points around the mean value and is calculated as:

$$C_n = \frac{\sigma}{\bar{Z}} \tag{4}$$

$$\overline{Z}=\frac{1}{n}\sum_{i=1}^{n}Z_i \tag{5}$$

$$\sigma=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z_i-\overline{Z})^2} \tag{6}$$

where $\overline{Z}$ is the annual average water level, and σ is the standard deviation of the daily water level series. The formula of C_c is shown below:

$$C_c=\frac{\sum_{i=1}^{n}\phi(i)(Z_i-\overline{Z})}{\sum_{i=1}^{n}Z_i} \tag{7}$$

$$\phi(i)=\begin{cases}0, Z_i<\overline{Z}\\1, Z_i\geq\overline{Z}\end{cases} \tag{8}$$

GI has been widely used to analyze spatial-temporal variabilities in hydrological process (Jawitz and Mitchell, 2011; Shi et al., 2013; Masaki et al., 2014; Cai et al., 2018). Here, it is used to characterize the intra-annual water level distribution. The Lorentz curve is drawn by taking the cumulative percentage of days as the independent variable and the cumulative percentage of daily water levels as the dependent variable. *GI* is expressed as:

$$GI=\frac{S_B}{S_A+S_B} \tag{9}$$

where S_A and S_B are the areas of sections A and B (Fig. 2), respectively.

<Figure 2>

2.2 Comprehensive detection for hydrological variability

The deterministic components in the water level series are first detected by using statistical methods. After subtracting the deterministic components of the mean from original series, we square each value in the residual series. Then, the same detection process is applied to the squared residual series (Vinnikov and Robock, 2002) to detect the deterministic components of the variance. The detection/decomposition process is presented as follows.

An initial judgment about the stationarity/nonstationarity of the series is made by the ranked version of the von Neumann's ratio (*RVN*) test (Bartels, 1982) at the significance level of α (Machiwal and Jha, 2012). The *RVN* formula is given below:

$$RVN = \frac{\sum_{i=1}^{n-1}(R_i - R_{i+1})^2}{\sum_{i=1}^{n}(R_i - \overline{R})^2} \tag{10}$$

where, $\overline{R} = \frac{1}{n}\sum_{i=1}^{n} R_i$, R_i is the rank of the i^{th} observation, and *n* is the length of the samples.

If the series shows nonstationarity, its trend is detected by using the nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1955) and is described using a linear equation:

$$y_{trend} = a + bt \tag{11}$$

where parameters *a* and *b* can be estimated using the least squares fitting method.

After that, the Moving T test (Afifi and Azen, 1972), Brown-Forsythe test (Brown and Forsythe, 1974) and Lee-Heghinian (Lee and Heghinian, 1977) method are used to detect abrupt changes. Since the detected change-points are sometimes rather different due to the methods used (Li et al., 2016; Xie et al., 2018), the results of the three methods need to be considered comprehensively. If two (or all) of the three methods obtain the same change-point, this change point is confirmed. If the change-points obtained by the three methods are completely different, then a comprehensive judgment should be made based on investigated physical causes. The detected abrupt change is expressed as:

$$y_{abrupt} = \begin{cases} 0, t = 1, 2, ..., n_1 \\ \overline{x_{tn2}} - \overline{x_{tn1}}, t = n_1 + 1, n_2 + 2, ..., n \end{cases} \tag{12}$$

where n_1 and n_2 are the lengths of sub-series before and after the change-point, respectively, $\overline{x_{tn1}}$ and $\overline{x_{tn2}}$ are the means of the sub-series before and after the change-point, respectively.

The significant trend or abrupt change should be subtracted from the original series. When both forms show significance, the R-squared value is introduced to determine the major form of variability, which is given as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \overline{Q}_{obs})^2} \tag{13}$$

where $Q_{obs,i}$ is the observed hydrological series with the length n, $\overline{Q}_{obs}$ is the mean of the observed hydrological series, and $Q_{sim,i}$ is the sum of the assumed deterministic component and the stochastic component. The trend or the abrupt change with the larger R^2 should be removed from the series in priority.

Then, the *RVN* test is applied to the residual series. When the residual is nonstationary, then the test is continued to check if the series contains another trend or abrupt change. After all the trends and abrupt changes are subtracted, the Fourier series (Bras and Rodriguez-Iturbe, 1993) is used to detect the periodic component (Machiwal and Jha, 2012) if the remainder still shows nonstationarity.

$$y_{periodicity} = A_0 + \sum_{k=1}^{l} [A_k \sin(\frac{2\pi kt}{T}) + B_k \cos(\frac{2\pi kt}{T})] \tag{14}$$

where A_0 is the population mean, l is the total number of harmonics ($l=T/2$ for even T and $l=(T+1)/2$ for odd T), T is the base period or period of the function, A_k and B_k are the sine and cosine Fourier coefficients, respectively.

2.3 Composing stationary water level series

The deterministic components y_t (including y_{trend}, y_{abrupt} and $y_{periodicity}$) of each water level time series are identified by the methods described above. Then, the stochastic component s_t can be obtained as:

$$s_t = x_t - y_t = \frac{x_t - a_t}{b_t} \tag{15}$$

where x_t is the original series, a_t and b_t are the deterministic components of the mean and standard deviation, respectively.

The composed water level series x_{t,t_0} is a combination of the stochastic component s_t and deterministic component y_{t_0} under the environment of year t_0. The composition formula is shown as follows:

$$x_{t,t_0} = a_{t_0} + b_{t_0} s_t = a_{t_0} + \frac{b_{t_0}}{b_t}(x_t - a_t) \tag{16}$$

where x_{t,t_0} is the composed water level series under the environment of year t_0, constants a_{t_0} and b_{t_0} are deterministic components of the mean and standard deviation under the environment of year t_0, respectively. Based on the reconstructed series, Pearson-III frequency curves are used to estimate annual 3-, 10-, 15-, 30-, 60-, 90-, 120-, 150-, 180-, 240-, 300-day minimum water levels and annual average water level for a given exceedance probability.

2.4 Design of intra-annual water level hydrograph and LNWLs

First, the change-points of both inter- and intra-annual variabilities are used to split the whole time period. The changing environment is therefore divided into several relatively stable stages, because the water level condition in each sub-period is relatively stable. It should be noted that there is no need to split the time period if no abrupt change is identified.

Second, typical years in different sub-periods/environments are selected. Abnormal hydrological years should be excluded before this selection, because the water level process of the selected typical year should fully reflect the water level condition of the corresponding environment. During this selection, the worst water level situation for shipping is considered to ensure safe and continuous navigations. Specifically, the following principles are followed to obtain reasonable typical years and benchmark water level hydrographs: (1) The annual 3-, 10-, 15-, 30-, 60-, 90-, 120-, 150-, 180-, 240-, 300-day minimum water level values of the typical year should be close to the corresponding designed water levels; (2) the duration for which the water levels are below the multi-year average water level should be long; and (3) when the chosen years follow the first two principles, the year with a relatively large C_n is preferentially chosen.

The third step is to design the intra-annual water level process for assumed environment by scaling the benchmark water level hydrograph of the typical year. Different amplifiers are calculated by Eq. (17). This equation is sourced from a method for designing flood processes and ensures the water level values at different time scales in the designed water level process have the same exceedance probability.

$$K_j = \begin{cases} \dfrac{Z_{d,j}}{Z_{t,j}}, & j = 1 \\ \dfrac{Z_{d,j} - Z_{d,j-1}}{Z_{t,j} - Z_{t,j-1}}, & j \geq 2 \end{cases} \tag{17}$$

where K_j is the amplifier for the j^{th} time scale, $Z_{d,j}$ and $Z_{d,j\text{-}1}$ are the designed water levels for the j^{th} and $(j\text{-}1)^{\text{th}}$ time scales, respectively, $Z_{t,j}$ and $Z_{t,j\text{-}1}$ are the actual water levels of the typical year for the j^{th} and $(j\text{-}1)^{\text{th}}$ time scales, respectively.

<Figure 3>

In the fourth step, daily average water levels in the designed water level hydrograph are sorted from large to small, and then they are subdivided according to the percentages of time during which specific water levels are equaled or exceeded. After that, the relationship between the percentage of time (i.e., guaranteed rate) and water level is drawn as the water level duration curve. Finally, the designed LNWL can be obtained from the duration curve according to the annual navigable guaranteed rate.

3. Study area and data

The North River is the second largest tributary river in the Pearl River system in South China (Figure 4). It is a main waterway connecting the southern and northern parts of Guangdong Province and has a great significance in transportation and trading (Luo et al., 2008; Li et al., 2019). However, various navigation standards for the river, including the LNWL, need to be redesigned. One reason is that the waterway is planned to upgrade from grade VI to grade III to satisfy the increasing demand of waterway capacity of the North River. Another reason is that human activities have changed the streamflow characteristics in the North River (Du et al., 2020). For example, the construction and operation of the Feilaixia hydroelectric project (see Figure 4) have caused the upstream area to be affected by the backwater since March 1999 (Wu et al., 2014), and the navigation condition in the upper river has improved significantly. The water level in the downstream area also changed due to dam closure and reservoir regulations. Additionally, Lu et al. (2007) have measured annual channel cross-sections at Sanshui hydrological station in the lower North River, and pointed out that extensive sand mining in the lower North River has caused rapid channel incision and water level reduction. Dai et al. (2008) analyzed temporal variations in sediment load at Shijiao station in the North River and found that the sediment flux of the station has reduced. The reduction of sediment load is due to effective soil and water conservation projects, dam constructions and regular channel dredging in upstream areas, and such human activities are likely to contributed to bed downcutting to some extent as well (Lu et al., 2007). Overall, the LNWL used in the past cannot satisfy the current conditions anymore.

<Figure 4>

In this study, the observed daily average water level series at Gaodao station from 1955 to 2016 and at Shijiao station from 1952 to 2017 are used to illustrate the proposed framework. The two stations comply with the highest hydrological monitoring standards in China, and are located in the middle and low reaches of the North River, respectively. Although the distance between the two stations is not far (xx km), the water level variations of the two stations are quite different. It should be noted that the disruptions of navigation in the area are caused by low water levels. The navigation disruptions caused by ice formation do not exist in this study area, due to its subtropical warm climate conditions.

4. Results

4.1 Inter- and intra-annual variability in the water level

Hydrological year in this region starts from April 1st and lasts until March 31st of the following year. The annual minimum water levels at multiple scales and different indicators are calculated under the hydrological year. Then, the annual 3-, 10-, 15-, 30-, 60-, 90-, 120-, 150-, 180-, 240-, 300-day minimum water level time series and annual average water level time series are detected, and the results are shown in Table 1 (More details can be found in Appendix A).

<Table 1>

<Figure 5>

<Figure 6>

On the whole, the water level variations at different time scales are roughly similar, but some change-points and the degrees of variations are different. In terms of the variability in the first-order moments, all the water level series at Gaodao station have abrupt upward changes, and the change-points in extremely low (the 3-, 10- and 15-day minimum) water level series occur in 1999. While all the water level series at Shijiao station have abrupt downward changes, and the change-points in the low water level series occur in 2006. With regard to the variability in the second-order moments, only the 3-, 10-, and 15-day minimum water level series at Gaodao station contain change-points. The change-point of 3-day minimum water level series occurs in 1999, and the change-points of 10- and 15-day minimum water level series both occur in 2002. At Shijiao station, almost all the water level series have two change-points in their second-order moments, occurring in 2003 (abrupt upward changes) and 2007 (abrupt downward changes). Among the series, the 3-, 15-, 120-day minimum water level series and annual average water level series are taken as examples (Figs. 5-6) to intuitively display the inter-annual water-level variabilities at Gaodao and Shijiao stations.

For Gaodao station, the construction and operation of the Feilaixia water conservancy project on the main stream of the North River are regarded as the main causes of variabilities. The river closure work was started in 1998 and the whole Feilaixia project was completed in 1999, and these two time-nodes are consistent with most of the change-points above. In addition, the abrupt upward changes of various water level series are consistent with the fact that the river water level at Gaodao station sharply increased due to the retaining effect of the dam. Moreover, the relationship between low water levels and low flows has become complicated and irregular, which corresponds to the abrupt upward changes in the variances of low water level series. In terms of Shijiao station, the water level was affected by regulations of upstream Feilaixia reservoir, high flows in downstream confluence stream, and local excessive sand mining. These factors made the water-level variability complicated. Caused by excessive sand mining, the annual average water level and low water levels of Shijiao station continually dropped significantly from 2003 to 2010, which was similar to the detection results.

To detect the variability in intra-annual water level distribution, annual C_d, C_n, C_c and GI are calculated and their series are used for detection. The detection results of intra-annual variability are shown in Table 2.

<Table 2>

The intra-annual water level variabilities at Gaodao and Shijiao stations differ greatly due to their different positions in the North River basin. All the indicators of Gaodao station have abrupt changes (C_d↓, C_n↓, C_c↓ and GI↑) in 1998. It means that the intra-annual water level process became more homogeneous (Fig. 7(a)) after 1998, which is in accordance with the retaining effect of dam after 1998. The series of C_n (↑), C_c (↑) and GI (↓)at Shijiao station have abrupt changes in 2007, and the change-point in the series of C_d (↑) is 2006. Accordingly, the intra-annual water level hydrograph at Shijiao station is more uneven than that in the past (Fig. 7(b)). According to the investigation, the water level in the flood season could be lifted more obviously by backwater flooding because of the riverbed downcutting at Shijiao station, resulting in sharper and multi-peak water level processes.

<Figure 7>

4.2 Design of the LNWLs

There are three types of change-points related to the intra-annual variability, to the inter-annual variability in the mean and to the inter-annual variability in the variance, respectively. After excluding recurring change-points, all the change-points that appear at Gaodao station occur in 1998, 1999, and 2002. However, since 1998 and 1999 are rather close, they should be merged into one point when splitting the time series. Here we choose 1998 when the Feilaixia project started as the merged change-point. As a consequence, three sub-periods, i.e., 1955 to 1998, 1999 to 2002 and 2003 to 2016 are obtained. The first sub-period represents the past environment in which there is no human-induced water level variation; the transition period from 1999 to 2002 contains a variety of water level variations due to external impacts; and the post-impact period from 2003 to 2016 stands for the current environment where all kinds of water level variations have already happened. At Shijiao station, the change-points occur in 2003, 2005, 2006 and 2007. Similarly to the sub-periods created for Gaodao station, the entire time period at Shijiao station is also divided into three parts: the pre-impact period from 1953 to 2003, the transition period from 2004 to 2007 and the post-impact period from 2008 to 2017.

Then, water level series are reconstructed for the pre- and post-impact periods, and the water levels $Z_{d,j}$ are estimated based on reconstructed series by using Pearson-III frequency curves. The estimated parameters are shown in Table 3, and the fitting efficiency of each water level series is higher than 95%.

<Table 3>

<Table 4>

Since the North River is a grade-III waterway, the return period for the disruption of shipping should be 4 years or 5 years according to the national navigation standard (GB50139-2014) of inland waterways in China (Table 4). Here, the return period is assumed to be 5 years (i.e., exceedance probability is 80%). Therefore, the 3-, 10-, 15-, 30-, 60-, 90-, 120-, 150-, 180-, 240-, 300-day minimum water levels and annual average water levels designed at the exceedance probability of 80% (Table 5) are used for the subsequent design.

<Table 5>

Next, some years are selected as candidate for typical years (Appendix B) according to the principles mentioned in Section 2.4. Considering them comprehensively, 1983 and 2004 are selected as typical years of Gaodao station, and their water level hydrographs represent the benchmark water level processes of pre- and post-impact periods, respectively. The years 1987 and 2013 are selected as typical years for the pre- and post-impact periods at Shijiao station, respectively. Then the designed intra-annual water level processes for both periods (Figs. 8(a) and (b)) are obtained by scaling the corresponding benchmark hydrographs (Table 5). Based on the designed water level processes, water level duration curves of the pre- and post-impact periods (Figs. 8(c) and (d)) are drawn. Finally, the LNWLs at the annual navigable guaranteed rates of 95% and 98% are obtained from the duration curves. The recommended LNWLs at Gaodao station for the current environment are 22.32 m for 95% guaranteed rate and 21.84 m for 98% guaranteed rate; LNWLs at Shijiao station for the current environment are 0.27 m for 95% guaranteed rate and 0.15 m for 98% guaranteed rate.

The designed water level hydrograph of Gaodao station for the post-impact period (i.e., current environment) is more uniform than the hydrograph for the pre-impact period (i.e., past environment). Compared to the past, the designed water level hydrograph of Shijiao station for the current environment contains more obvious seasonal changes. Both conclusions are consistent with the detected results of intra-annual variabilities. It can also be seen in Fig. 8(c) that the tail of the duration curve of the post-impact period has a larger slope than that of the pre-impact period, implying that the intra-annual fluctuation of low water levels in the current environment is more intense than that in the past environment at

Gaodao station. However, at Shijiao station, the intra-annual fluctuation of low water levels in the current environment is similar to that in the past, because the tails of the two duration curves are approximately parallel (Fig. 8(d)). Besides, the differences in the LNWL for the same guaranteed rate between the past and current environments are 2.48 m (for 95% guaranteed rate) and 2.05 m (for 98% guaranteed rate) at Gaodao station, -4.14 m (for 95% guaranteed rate) and -4.21 m (for 98% guaranteed rate) at Shijiao station, respectively. These differences indicate the necessity of considering nonstationarity when designing the LNWL.

<Figure 8>

5. Discussion

5.1 Impact of variance variability on estimating LNWLs

The LNWLs estimated by the proposed framework without considering the variability in variance are used for comparison, and the differences between the LNWLs estimated under different considerations are used to evaluate the impact of variance variability on LNWLs. The LNWLs estimated under different considerations are shown in Table 6.

For Gaodao station, differences in the LNWLs caused by considering and not considering the variance variability are 0.03 m (for 95% guaranteed rate) and 0.02 m (for 98% guaranteed rate) in the past environment. In the current environment, the differences are 0.11 m when the guaranteed rate is 95% and 0.48 m when the guaranteed rate is 98%, accounting for approximately 6%~30% of the ship draft of standard ships in the North River. If the variance variability is not considered, the designed value will be overestimated. A higher LNWL means a smaller capacity of the waterway. In that case, the LNWL supposed to have

95% guaranteed rate actually has 93% guaranteed rate due to the impact of variance variability, and the LNWL supposed to have 98% guaranteed rate actually has 95% guaranteed rate. Therefore, the guaranteed rate for navigation at Gaodao station will be artificially reduced, the waterway will not be fully exploited and the shipping benefits will be reduced.

For Shijiao station, differences between the LNWLs estimated with and without consideration of the variability in variance are -0.17 m (for 95% guaranteed rate) and -0.19 m (for 98% guaranteed rate) in the past environment. Differences in the LNWLs of the current environment are 0.04 m when the guaranteed rate is 95% and 0.03 m when the guaranteed rate is 98%, accounting for 14.8% and 20% of the corresponding recommended LNWLs, respectively. At Shijiao station, if the variance variability is not considered, the designed value will be underestimated. To prevent ships from bottoming out, there should be a certain under keel clearance (UKC) in the channel. Therefore, there will have a greater risk of ship grounding. The underestimation seems not significant in the current environment, however, since the water level itself at Shijiao station is relatively low, a few centimeters of estimation error equals to 15%~20% of the design result. In that case, the increased shipping risk should not be ignored.

<Table 6>

<Figure 9>

As shown in Fig. 9, there are obvious differences between the reconstructed low water level series (the 3-, 10-, and 15-day minimum water level series) with and without consideration of the variance variability. These differences can affect the designed water levels $\overline{Z_{d,j}}$ and the amplifiers for the design of water level processes, so as to influence the estimation of the LNWL. At Gaodao station, the designed 3-, 10-, and 15-day minimum water levels in the current environment are 21.52, 21.79 and 21.82 m (Table 5). When the variance variability is not considered, the corresponding designed values change to 21.89, 22.25 and 22.32 m. At Shijiao station, the designed 3-, 10-, and 15-day minimum water levels in the current environment are 0.13, 0.24 and 0.32 m (Table 5). The corresponding designed values are 0.17, 0.28 and 0.34 m when the variance variability is not considered. Obviously, at Shijiao station, the differences of the designed water levels with different considerations are relatively small, which explains why the impact of variance variability on LNWLs at Shijiao station is not significant.

For further analysis, the tails (guaranteed rate is larger than 80%) of water level duration curves under different considerations are compared using Tukey-boxplots (Sheskin, 2011). The minimum values and lower quartiles of low water levels from two duration curves have clear differences in Figs. 10(b) and (c), and the differences between the LNWLs in both cases are also significant. Whereas in Figs. 10(a) and (d), the minima (including the outliers denoted in red points) and lower quartiles under the two considerations are relatively close, and in the past environment of Gaodao station and the current environment of Shijiao station, the differences between the LNWLs are not very significant either. Therefore, the influence of variance variability on LNWLs basically depends on its influence on low water levels when reconstructing the series.

<Figure 10>

For Gaodao station, the pre-impact period is 30 years longer than post-impact period. When the variance variability is considered in the reconstruction of the series for the past environment, a relatively small number of low water levels are corrected. When the series before the change-point is modified to the current environment, a relatively large number of water level values become lower due to the variance variability, and therefore the low water level part of the whole series becomes lower. However, for Shijiao station, although the pre-impact period is 41 years longer than the post-impact period, when reconstructing the series for the past environment, many low water level values in the transition and post-impact periods which far away from the mean are corrected, resulting in a big impact on the low water level part of the whole series. Conversely, in the current environment, whether the variance variability is considered or not has less influence on the low water level part.

5.2 Comparison with the NSDC method

In this section, the proposed design framework for LNWLs considering both the inter- and intra-annual variabilities in water levels is compared with the NSDC method mentioned above. In the NSDC method, the annual average water level is used to represent the overall water level condition each year. Thus, only the annual average water level series is reconstructed for the past and current environments. Because the form and extent of the variability on each day of the year are regarded as the same, stationary daily water level series for each year are obtained by multiplying the observed daily water level series with the corresponding annual scaling ratio. Finally, all the daily water level values are combined to plot a multi-year synthetic duration curve (Figs.11 (a) and (b)), and the LNWL is estimated according to the multi-year guaranteed rate.

<Figure 11>

<Table 7>

As shown in Table 7, LNWLs of the current environment at Gaodao station estimated by the NSDC method are 22.25 m for the guaranteed rate of 95% and 22.08 m for the guaranteed rate of 98%. The differences in the LNWLs between two methods at Gaodao station are -0.07 m (95% guaranteed rate) and 0.24 m (98% guaranteed rate). LNWL of Shijiao station estimated by the NSDC method under the current environment is 0.59 m for the guaranteed rate of 95%, which is 0.32 m (accounting for 118.5%) difference from the LNWL estimated by the proposed framework. When the guaranteed rate is 98%, the LNWL obtained using the NSDC method is 0.16 m at Shijiao station, which is close to the LNWL designed by our framework. The differences of the values are resulted from the ways to consider the guaranteed rate and the steps of designing. In practical hydrological design, it is contradictory that there are different LNWLs in the same river section. Therefore, it is necessary to identify the advantages and limitations of each method, and select the suitable method for practical design.

The NSDC method is simple in calculation, but it does not consider whether the water level process of the current is more uniform/uneven than that of the past. In theory, this lack of consideration would make the LNWLs estimated by the NSDC method inaccurate. According to the design principles, the variance variabilities in low water level series (the 3-, 10- and 15-day minimum water level series) of Gaodao station are overlooked, since the annual average water level series does not contain the variability of variance. Meanwhile, the abrupt changes of water levels at different time scales are unreasonably regarded as the same at both stations.

To compare the water level duration curves designed by the two methods, the violin plots are used to display their distributions. For Gaodao station, the shapes of the distributions in the past and current are very similar (Fig.11(c)) in NSDC method, indicating that the uniformity of water level process hardly changes over time. However, by using our comprehensive framework, the water level distribution of the past environment has a longer upper tail (Fig. 11 (d)), indicating that the past water level process has a number of high water levels far from the average. In other words, the water level process in the past is more uneven than that in the current. Therefore, only the duration curves designed by comprehensive framework are match with the detection results of intra-annual variability. For Shijiao station, because the distribution of the past has both long upper and lower tails, the synthetic duration curve designed by NSDC method for the past environment is more uneven than that of the current environment (Fig. 11 (e)). This indication is contrary to the detection results. However, the duration curves designed by our comprehensive framework show that the water level process in the current is more uneven (Fig. 11 (f)), which is match with the detection results.

To sum up, in NSDC method, the variabilities in the annual water level process are generalized by the variability of annual average water level. When the annual average water level series has variance variability, it is easy to cause some water levels (especially high water levels and low water levels) to be over enlarged or reduced when reconstructing the series, resulting in unreasonable duration curves for estimations. However, if the water level variabilities are consistent across the timescales and the intra-annual variability is not significant, the NSDC method is more convenient than the developed framework, and the design results are similar. In our comprehensive framework, the variabilities are considered comprehensively, therefore, the estimated LNWLs are more reliable when the waterway is faced with complex multi-scale variabilities and prominent intra-annual variability. As for the future LNWLs, according to the expressions of deterministic components and the formulas for "decomposition and composition", the framework can compose the "stationary" series under any year t_0 of the future. Then, the LNWLs can be estimated according to the original steps. Since the forms of variabilities in the case study are all abrupt changes, the LNWLs in the current environment can be taken as the LNWLs of the future. However, with the extension of water level series, the deterministic components are variable. Therefore, the LNWLs estimated in this way only have the significance when the external environment remains relatively stable (e.g., the operating mode of the reservoir remains unchanged, the riverbed has no obvious undercutting).

6. Conclusion

In this paper, we proposed a comprehensive framework for designing LNWLs by considering the intra- and inter-annual variabilities in water levels, as well as the shipping risks during the annual and multi-annual periods. Since the hydrological variability has extended to higher-order moments, the variability in variance is also described when decomposing the observed series and is eliminated when composing the new series.

The proposed framework was illustrated by case studies of Gaodao and Shijiao monitoring stations in the North River basin, South China. The results showed that water levels at multiple timescales at Gaodao and Shijiao stations had different degrees of abrupt changes in their means and variances. Meanwhile, the abrupt changes in C_d, C_n, C_c and GI indicated that the shape of annual water level process changed with time. By taking the inter- and intra-annual variability into consideration, the LNWLs of Gaodao station were recommended as 22.32 m (for 95% guaranteed rate) and 21.84 m (for 98% guaranteed rate), and the LNWLs of Shijiao station were recommended as 0.27 m (for 95% guaranteed rate) and 0.15 m (for 98% guaranteed rate).

To evaluate the impact of variance variability on the LNWL, the LNWLs estimated by the proposed framework without considering any variability in variance were used for comparison. Results indicated that the variability in variance had impact on the estimation of LNWLs, so this variability should not be ignored. Additionally, the magnitude of the impacts mainly depended on the extent of variance variability and the difference between the water level values of the two reconstructed series at assumed exceedance probability.

To understand the differences in the estimated LNWLs caused by different design methods, LNWLs designed by the NSDC method (adding the consideration of variance variability) were compared with the recommended LNWLs of the proposed framework. The differences in the LNWLs between the two methods at Gaodao station were -0.07 m (95% guaranteed rate) and 0.24 m (98% guaranteed rate); at Shijiao station, the differences in the

LNWLs were 0.32 m (95% guaranteed rate) and 0.01 m (98% guaranteed rate). In theory, some daily water levels (especially high- and low-water levels) could be over enlarged or reduced when reconstructing the pre- and post-impact series, resulting in unreasonable duration curves for estimations. Evidence also showed that the reconstructed series as well as the duration curves calculated by the NSDC method did not match the detected intra-annual variabilities.

In summary, our comprehensive framework is suitable for waterways faced with complicated water level variabilities, especially where the variabilities of water levels at different time scales are different or where the historical data contain various kinds of variations. In future research, this framework can be applied in more sites, and the uncertainty of estimated LNWLs caused by the selection of typical years can be further studied.

Declarations

Funding

This study was financially supported by the National Natural Science Foundation of China (No. 51579181, 91547205, and 41971040); the Research Council of Norway (No. 274310), and the Youth Innovation Promotion Association CAS (No. 2017074).

Conflicts of interest

Authors have no conflicts of interest to disclose.

Availability of data and material

The authors gratefully acknowledged the valuable hydrological data and information provided by the Hydrology Bureau of Guangdong Province, China. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

The code is available from the corresponding author upon reasonable request.

Authors' contributions

Ping Xie developed the main ideas. Lu Wang implemented the algorithms of the methods. Ping Xie collected the data used in the case study. Ping Xie, Chong-Yu Xu and Yan-Fang Sang provided funding for this study. Lu Wang wrote the original draft of the manuscript. Chong-Yu Xu, Yan-Fang Sang and Jie Chen supervised this study, reviewed and edited the original draft. Tao Yu validated the results of this study.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere. All authors have read and approved the manuscript being submitted and agree to its publication in this journal.

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Six Tables submitted

Table 1 Detection results of inter-annual variability

Gaodao station		3-day	10-day	15-day	30-day	60-day	90-day
Mean	Form of variability	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change
Mean	Position of change points	1999↑	1999↑	1999↑	1998↑	1998↑	1998↑
Variance	Form of variability	Abrupt change	Abrupt change	Abrupt change	-	-	-
Variance	Position of change points	1999↑	2002↑	2002↑	-	-	-
Gaodao station		120-day	150-day	180-day	240-day	300-day	Annual average
Mean	Form of variability	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change
Mean	Position of change points	1998↑	1998↑	1998↑	1998↑	1998↑	1998↑
Variance	Form of variability	-	-	-	-	-	-
Variance	Position of change points	-	-	-	-	-	-
Shijiao station		3-day	10-day	15-day	30-day	60-day	90-day
Mean	Form of variability	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change
Mean	Position of change points	2006↓	2006↓	2006↓	2006↓	2005↓	2005↓
Variance	Form of variability	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change
Variance	Position of change points	2003↑; 2007↓	2003↑; 2007↓	2003↑; 2007↓	2003↑; 2007↓	2003↑; 2007↓	2003↑; 2007↓
Shijiao station		120-day	150-day	180-day	240-day	300-day	Annual average
Mean	Form of variability	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change
Mean	Position of change points	2005↓	2005↓	2005↓	2005↓	2007↓	2007↓
Variance	Form of variability	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change	Abrupt change
Variance	Position of change points	2003↑;	2003↑;	2003↑;	2003↑	2003↑;	2003↑;

		2007↓	2007↓	2007↓		2007↓	2007↓

Note: The test is taken under the significance level of α = 0.05; "-" means there is no significant variability; "↑" or "↓" means that the abrupt change is upward or downward.

Table 2 Detection results of intra-annual variability

Station	Indicator	C_d	C_n	C_c	GI
Gaodao	Form of variability	Abrupt change	Abrupt change	Abrupt change	Abrupt change
	Position of change points	1998↓	1998↓	1998↓	1998↑
Shijiao	Form of variability	Abrupt change	Abrupt change	Abrupt change	Abrupt change
	Position of change points	2006↑	2007↑	2007↑	2007↓

Note: The test is taken under the significance level of α = 0.05; "↑" represents the abrupt change is upward, " ↓ " represents the abrupt change is downward.

Table 3 Estimated parameters for pre- and post-impact periods

	Gaodao station	3-day	10-day	15-day	30-day	60-day	90-day
EX/m	Pre-impact	19.98	20.04	20.05	20.08	20.15	20.22
	Post-impact	22.23	22.55	22.59	22.88	23.19	23.33
C_v	Pre-impact	0.011	0.011	0.011	0.013	0.011	0.012
	Post-impact	0.037	0.040	0.040	0.013	0.011	0.011
C_s	Pre-impact	0.392	0.065	0.265	0.652	0.620	0.519
	Post-impact	0.392	0.065	0.265	0.652	0.620	0.519
	Gaodao station	120-day	150-day	180-day	240-day	300-day	Annual average
EX/m	Pre-impact	20.28	20.34	20.42	20.65	20.96	21.20
	Post-impact	23.38	23.43	23.47	23.53	23.59	23.63
C_v	Pre-impact	0.012	0.012	0.012	0.013	0.014	0.013
	Post-impact	0.011	0.011	0.011	0.012	0.012	0.012
C_s	Pre-impact	0.625	0.454	0.317	0.097	0.401	0.364
	Post-impact	0.625	0.454	0.317	0.097	0.401	0.364
	Shijiao station	3-day	10-day	15-day	30-day	60-day	90-day
EX/m	Pre-impact	4.48	4.55	4.58	4.65	4.75	4.84
	Post-impact	0.66	0.76	0.832	0.89	1.16	1.22
C_v	Pre-impact	0.058	0.059	0.060	0.065	0.059	0.064
	Post-impact	0.941	0.803	0.718	0.723	0.613	0.596
C_s	Pre-impact	0.164	0.229	0.389	0.385	0.708	0.772
	Post-impact	0.184	0.246	0.389	0.385	0.708	0.772
	Shijiao station	120-day	150-day	180-day	240-day	300-day	Annual average
EX/m	Pre-impact	4.93	5.02	5.12	5.44	5.77	6.03
	Post-impact	1.32	1.40	1.49	1.79	2.15	2.42
C_v	Pre-impact	0.066	0.068	0.068	0.066	0.066	0.062
	Post-impact	0.556	0.540	0.534	0.638	0.442	0.382
C_s	Pre-impact	0.638	0.658	0.538	0.546	0.820	0.770
	Post-impact	0.638	0.658	0.538	0.546	0.820	0.770

Note: the statistical parameter EX represents the mean value, C_V represents the non-uniformity coefficient, and C_S represents the coefficient of skewness.

Table 4 Standards of designing LNWLs

Grade of channel	I~II	III~IV	V~VII
Annual guaranteed rate/%	99~98	98~95	95~90
Return period/year	10~5	5~4	4~2
Allowable carrying weight of a vessel/tons	2000	1000~500	300~50

Table 5 Designed water levels (in average) and amplifiers for scaling benchmark hydrographs

Water levels		Pre-impact period			Post-impact period		
		$\overline{Z_{d,j}}$ /m	$\overline{Z_{t,j}}$ /m	Amplifier	$\overline{Z_{d,j}}$ /m	$\overline{Z_{t,j}}$ /m	Amplifier
Gaodao station	Annual average	20.96	21.01	0.992	23.38	23.41	0.992
	3-day min	19.79	19.84	0.997	21.52	21.79	0.987
	10-day min	19.85	19.93	0.996	21.79	21.89	0.999
	15-day min	19.86	19.96	0.992	21.82	22.03	0.981
	30-day min	19.87	19.96	0.996	22.63	22.61	1.010
	60-day min	19.96	20.01	0.999	22.97	22.89	1.006
	90-day min	20.01	20.04	1.001	23.11	23.13	0.990
	120-day min	20.07	20.12	0.995	23.16	23.17	1.002
	150-day min	20.13	20.18	0.996	23.20	23.25	0.991
	180-day min	20.21	20.28	0.994	23.24	23.27	1.003
	240-day min	20.43	20.43	1.010	23.30	23.28	1.007
	300-day min	20.71	20.73	0.994	23.34	23.34	0.997
Shijiao station	Annual average	5.71	5.73	1.027	1.63	1.38	1.161
	3-day min	4.26	4.25	1.004	0.13	0.05	2.822
	10-day min	4.33	4.32	1.000	0.24	0.20	1.052
	15-day min	4.35	4.35	0.998	0.32	0.26	1.305
	30-day min	4.39	4.37	1.008	0.34	0.26	1.376
	60-day min	4.51	4.46	1.018	0.55	0.26	2.915
	90-day min	4.58	4.52	1.014	0.60	0.32	1.567
	120-day min	4.65	4.60	1.011	0.69	0.50	0.924
	150-day min	4.73	4.69	0.997	0.75	0.52	1.661
	180-day min	4.82	4.71	1.094	0.81	0.54	1.778
	240-day min	5.13	5.04	1.005	0.81	0.71	0.669
	300-day min	5.45	5.52	0.902	1.33	1.12	1.239

Table 6 Designed LNWLs under different considerations

Station	Considered variability	Annual guaranteed rate /%	Designed LNWLs/m	
			Past	Current
Gaodao	Mean and variance	95	19.84	22.32
		98	19.79	21.84
	Mean only	95	19.87	22.43
		98	19.81	22.32
	Difference between the two considerations	95	0.03	0.11
		98	0.02	0.48
Shijiao	Mean and variance	95	4.41	0.27
		98	4.36	0.15
	Mean only	95	4.24	0.31
		98	4.17	0.18
	Difference between the two considerations	95	-0.17	0.04
		98	-0.19	0.03

Table 7 Designed LNWLs by NSDC method

Methods		Considered variabilities	Guaranteed rate /%	Designed LNWLs/m	
				Past	Current
Gaodao	NSDC	Inter-annual variability (mean and variance)	95	19.99	22.25
			98	19.83	22.08
	Proposed framework	Inter-annual variability (mean and variance) and intra-annual variability	95	19.84	22.32
			98	19.79	21.84
	Differences between two methods/m		95	0.15	-0.07
			98	0.04	0.24
Shijiao	NSDC	Inter-annual variability (mean and variance)	95	3.04	0.59
			98	1.63	0.16
	Proposed framework	Inter-annual variability (mean and variance) and intra-annual variability	95	4.41	0.27
			98	4.36	0.15
	Differences between two methods/m		95	-1.37	0.32
			98	-2.73	0.01

Figure captions

Fig. 1 Framework for designing the LNWL

Fig. 2 The schematic diagram of Lorentz curve, section A and section B

Fig. 3 Different time scales of intra-annual water level process

Fig. 4 The North River basin in Guangdong Province, China

Fig. 5 (a) Variabilities in annual 3-, 15-, 120-day minimum water level series and annual average water level series at Gaodao station (mean); **(b)** Variabilities in annual 3-, 15-, 120-day minimum water level series and annual average water level series at Shijiao station (mean).

Fig. 6 (a) Variabilities in annual 3-, 15-, 120-day minimum water level series and annual average water level series at Gaodao station (variance); **(b)** Variabilities in annual 3-, 15-, 120-day minimum water level series and annual average water level series at Shijiao station (variance).

Fig. 7 (a) Monthly average water levels at Gaodao station; **(b)** Monthly average water levels at Shijiao station.

Fig. 8 (a) Designed intra-annual water level processes at Gaodao station; **(b)** Designed intra-annual water level processes at Shijiao station; **(c)** Water level duration curves at Gaodao station; **(d)** Water level duration curves at Shijiao station.

Fig. 9 Reconstructed annual 3-, 10- and 15-day minimum water level series: **(a)** Under the past environment at Gaodao station; **(b)** Under the current environment at Gaodao station; **(c)** Under the past environment at Shijiao station; **(d)** Under the current environment at Shijiao station.

Fig. 10 Comparisons of low water levels estimated under different considerations: **(a)** Under the past environment at Gaodao station; **(b)** Under the current environment at Gaodao station; **(c)** Under the past environment at Shijiao station; **(d)** Under the current environment at Shijiao station.

Fig. 11 **(a)** Duration curves at Gaodao station (by NSDC method); **(b)** Duration curves at Shijiao station (by NSDC method); **(c)** Violin plots of duration curves at Gaodao station (by NSDC method); **(d)** Violin plots of duration curves at Gaodao station (by proposed framework); **(e)** Violin plots of duration curves at Shijiao station (by NSDC method); **(f)** Violin plots of duration curves at Shijiao station (by proposed framework).