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Non-stationary Hydrological Frequency and Uncertainty Analysis of Extreme Tide Levels in the Huangpu River under Changing Environments

Zhihui Liu[1], Shuguang Liu[1,2], Guihui Zhong[1,2]
Department of Hydraulic Engineering, Tongji University, Shanghai 200092, China[1]
E-mail: liuzzh@tongji.edu.cn (Z.L.)
Key Laboratory of Yangtze River Water Environment, Ministry of Education, Tongji University, Shanghai 200092, China[2]
E-mail: liusgliu@tongji.edu.cn (S.L.), 04098@tongji.edu.cn (G.Z.)

ABSTRACT

Increasingly frequent and intense floods driven by climate change and human activities have challenged the assumption of hydrological stationarity. As a result, non-stationary hydrological frequency analysis (NHFA) has become essential for more reliable design estimation of tide levels in tidal rivers under changing conditions. This study focuses on the Huangpu River in China, a tidal river influenced by both upstream inflows from the Taihu Basin and tidal propagation from the Yangtze River Estuary. Using long-term annual maximum tide level records from Wusong Station, trends and abrupt changes were detected through the Mann–Kendall test, Sen's slope estimation, and multiple change-point tests, including the Pettitt and Lee-Heghinian methods. Based on the identified non-stationary characteristics, a conditional probability distribution-based NHFA model was established and compared with traditional stationary and decomposition–composition approaches. Furthermore, a non-stationary Bootstrap uncertainty estimation framework was developed to quantify the parametric and model uncertainties of hydrological design values. Results reveal that both stations exhibit significant non-stationarity, with increased design tide levels and widening confidence intervals as return periods extend. The traditional stationary model fails to capture the uncertainty ranges produced by non-stationary analysis, underscoring the necessity of incorporating non-stationarity into flood design standards. This study provides a scientific basis for resilient flood control planning and adaptive water level management in tidal river systems such as the Huangpu River.

KEYWORDS: Changing environment, Huangpu River, Non-stationary hydrological frequency analysis, Uncertainty analysis, Conditional probability distribution

1 INTRODUCTION

Hydrological frequency analysis is a crucial step in the design and safety assessment of water conservancy and flood control infrastructure. Traditional approaches are established on the assumption of stationarity, which presumes that the statistical characteristics of hydrological processes remain constant over time. In recent years, climate change and human activities have disrupted hydrological systems, leading to more frequent and intense extreme events such as torrential rains, storm surges, and compound floods(IPCC, 2023). This has further resulted in hydrological sequences exhibiting non-stationary characteristics, a phenomenon particularly pronounced in Shanghai, China(Milly, 2008). Incorporating non-stationarity into frequency analysis has become a growing research focus, yet it also introduces more complex sources of uncertainty into design value estimation.

Non-stationary hydrological frequency analysis (NHFA) has evolved from traditional sample reconstruction-based approaches to direct modeling of non-stationary characteristics, including time-varying models, mixture distribution-based approaches, and conditional probability distribution models

(CPDM) (Lu, 2023; Yan et al., 2023). Time-varying models can effectively describe the evolution of hydrological behaviour over time (Anzolin, 2024; Han, 2022; Strupczewski, 2001). However, under the influence of human activities, hydrological series frequently show abrupt changes rather than continuous trends, in which case mixture distributions and conditional probability approaches are more suitable (Liang et al., 2018). Despite differing in their theoretical assumptions, both approaches employ similar computational schemes and have demonstrated robust performance in modeling non-stationary series with abrupt change. The conditional probability distribution model, originally proposed by Singh et al. (2005), assumes that extreme hydrological sequences across different seasons follow distinct distributions and are mutually independent, employing the product rule of probability to conduct frequency analysis on non-stationary hydrological series. Building on this concept, Song et al. (2012) developed a CPDM that explicitly accounts for abrupt changes, and Li et al. (2016) successfully applied it to annual runoff series, obtaining reliable frequency estimates.

As the complexity of NHFA models increases, the sources of uncertainty in hydrological design values also become more diverse. Beyond traditional factors such as sample representativeness, curve selection, and parameter estimation, the model's own handling of non-consistency introduces new uncertainties. Previous research has extended uncertainty analysis to time-varying models through various methodologies. For instance, Hu et al. (2023) combined Bayesian theory with ensemble strategies to quantify parameter uncertainty in NHFA models, and Du Tao et al.(2018) employed a residual Bootstrap method to infer the uncertainty in sample length when calculating design floods using the Generalised Additive Model. Ankush et al. (2024) employed a Bootstrap method based on Markov Chain Monte Carlo algorithms to examine variations in parameter uncertainty within NHFA models under different covariates. Subsequently, they utilised Bayesian theory to explore the uncertainty in covariate selection and assessed the relative importance of covariate uncertainty compared to parameter uncertainty. By contrast, only a handful of scholars have engaged in discussions regarding uncertainty analysis within mixture distribution and conditional probability distribution models. Sen et al.(2020) proposed incorporating particle filtering into mixture distribution models to optimise the estimation of distribution parameters and their uncertainties. Yan et al. (2019) employed the Bootstrap method to analyse parameter uncertainties in mixture distribution models. Regarding conditional probability distribution models, research into parameter uncertainties arising from non-stationary treatments, such as variant point identification, remains a crucial issue that warrants further in-depth exploration.

To address these issues, this study investigates the non-stationary characteristics and associated uncertainty of annual maximum tide levels in the Huangpu River, focusing on the representative hydrological station Wusong. Using tide level records from 1950 to 2024, we first identify the key non-stationary variations in the time series. A conditional probability distribution model is then employed to conduct hydrological frequency analysis under non-stationary conditions. Furthermore, a Bootstrap-based uncertainty quantification framework is proposed to evaluate parameter and model uncertainty under non-stationary conditions. This study provides a methodological basis for improving the reliability of hydrological design values and contributes to the development of adaptive flood control standards in the Yangtze River Delta region.

2 STUDY AREA AND DATA

The Huangpu River, the largest river in Shanghai, is the last major tributary of the Yangtze River before it enters the East China Sea. Originating from Dianshan Lake in the Taihu Basin, the river flows northward through the Shanghai metropolis and joins the Yangtze River at Wusong. It has a total length of about 113 km, with a width ranging from 300 to 770 m and a drainage area of 24,000 km². Although it occupies only 6.6% of Shanghai's river–lake system by area, it stores nearly 28% of the total channel volume, underscoring its strategic importance for urban flood regulation and inland navigation.

As a typical tidal river, the Huangpu River is jointly affected by upstream runoff from the Taihu Basin and downstream tidal forcing from the Yangtze Estuary, producing a distinctive bidirectional flow regime. During the flood season, the combined impacts of wind, precipitation, and storm surges further intensify hydrodynamic interactions, generating compound flood risks for Shanghai's flood-defence system. Among the hydrological stations along the river, the Wusong Station, located near the estuary, directly reflects tidal–fluvial interactions.

This study focuses on the annual maximum tide levels recorded at these two stations, based on the Hydrological Yearbooks of the People's Republic of China from 1950 to 2024. The dataset provides a continuous and reliable 75-year time series. All water levels are referenced to the Wusong Datum and have been corrected for land subsidence according to data published by the Shanghai Municipal Surveying and Mapping Department.

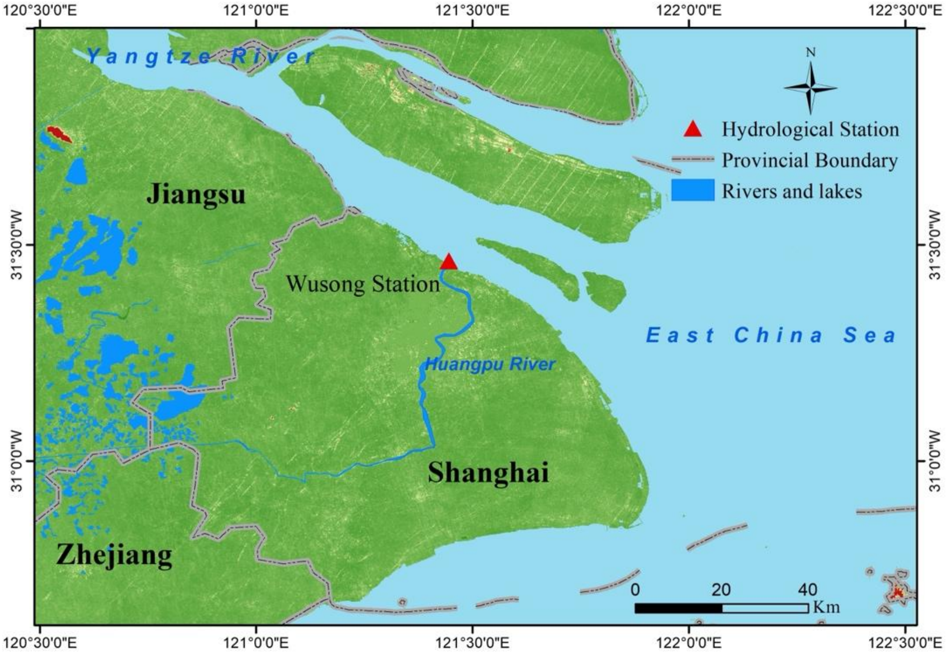

Figure 1: Location of the Huangpu River basin and the distribution of two hydrological stations.

3 METHODOLOGY

The conditional probability approach divides a hydrological sequence with a capacity of N into some periods based on the variance diagnostics. It is generally recommended to divide the sequence into two subsequences $X_1 = \{x_1, x_2, x_3, \ldots, x_\tau\}$, $n_1 = \tau$ and $X_2 = \{x_{\tau+1}, x_{\tau+2}, x_{\tau+3}, \ldots, x_n\}$, $n_2 = N - \tau$ by the mutation point τ, and it is assumed that each subsequence X_i is independent of each other and has its own distribution, then the frequency distribution $F(x)$ of non-sationary distributed hydrological sequences with mutation variances can be expressed as:

$$F(x) = P(X_1)P(x \mid X_1) + P(X_2)P(x \mid X_2) \tag{1}$$

Where $P(X_1) = n_1/N$, $P(X_2) = n_2/N$, n_1 and n_2 are the lengths of the two respective subsequences X_1, X_2, respectively, and N is the sample capacity of the full sequence. $P(x|X_i)$ is in fact the probability of occurrence of the event B in the sequence, which is fitted to determine the corresponding parameter by choosing the appropriate distributional line shape, and then obtaining the frequency distribution of the hydrological text under the conditional probability model. The study adopts P-III type distribution to characterise the distribution of each sub-sequence, and the frequency distribution of the whole sequence is obtained as:

$$F(x) = \frac{n_1}{N}(1 - \frac{\beta_1^{\alpha_1}}{\Gamma(\alpha_1)}\int_{a_{01}}^{x}(t - a_{01})^{\alpha_1 - 1}e^{\beta_1(t - a_{01})}dt) + \frac{n_2}{N}(1 - \frac{\beta_2^{\alpha_2}}{\Gamma(\alpha_2)}\int_{a_{02}}^{x}(t - a_{02})^{\alpha_2 - 1}e^{\beta_2(t - a_{02})}dt) \tag{2}$$

where α_i, β_i, and a_{0i} represent the shape, scale, and location parameters of the P-III distribution, respectively, relating to the mean $\bar{x}$, coefficient of variation C_v, and skewness coefficient C_s as follows: $\bar{x} = (\alpha/\beta) + a_0$, $Cv = \sqrt{\alpha}/(\alpha + \beta a_0)$ 和 $Cs = 2/\sqrt{\alpha}\ x$.

Based on the conditional probability distribution model, the specific procedure for calculating the design tide level uncertainty by the non-consistent Bootstrap method is as follows:

i. Derive the design value H_p of the non-stationary annual maximum tide level series under a certain return period according to Eqs. (2);

ii. Sample the X_1 and X_2 with putback using the Bootstrap method to obtain two new sample sequences X_1* and X_2* of the same length as the corresponding subsequence, respectively;

iii. Based on the new sample sequences X_1* and X_2*, the conditional probabilities $p(x|X_1^*)$, $p(x|X_2^*)$ of each subsequence are calculated, respectively, and the respective distributions of the two sequences before and after the mutation can be obtained. Given the design frequency P, Newton's iterative method is applied to obtain the calculated value of the k+1st iteration of the design value at the corresponding frequency, and finally, the design value H_p^* under the corresponding reproduction period $T=1/P$ is obtained;

iv. Repeat (ii) and (iii) N times, i.e., repeat sampling N times to obtain N sampling design values $H_{p,i}^*$, $i=1,2,\ldots, N$;

v. Based on the N sampling design values determined in the above steps, with N ordered from smallest to largest, solve for the confidence interval of H_p at a certain confidence level α.

4 RESULTS AND DISCUSSION

4.1 Detection of non-stationarity

A preliminary diagnosis of the non-stationarity in the observed annual maximum tide level series (H_{max}) at Wusong Station was conducted using the moving average method and cumulative curve slope difference analysis. As illustrated in Figure 2, the five-year moving average and cumulative average of H_{max} at Wusong Station have exhibited an overall trend of fluctuating decline-rise-decline-fluctuating rise since 1950, with distinct inflection points indicating potential non-stationary changes in the sequence. According to the inflection point locations, potential abrupt change points were preliminarily identified as occurring in 1981, 1989, and 2005. Concurrently, the Hurst coefficient method was applied to diagnose the variability of annual maximum tide levels at Wusong Station, with the Hurst coefficient determined to be 0.73, indicating moderate variability in the H_{max}.

Based on the interannual variations and preliminary test results, the trend variation of H_{max} at Wusong Station was examined in detail using the linear trend method, the Mann-Kendall test combined with the Sen slope estimator(Sen+MK), and the Spearman rank test. Using the Pettitt test, the sliding t-test, Lee-Heghinian method, and Mann-Kendall (MK) mutation test, the mutation characteristics of the station are analyzed. The results, as shown in Table 1, indicated that at a significance level of α=5%, the H_{max} at Wusong Station exhibited a significant upward trend and significant mutations. By assigning a score of “1” to the more credible mutation points and accumulating these scores, the years with the highest combined weights for the mutation point of H_{max} at Wusong Station were identified as 1987, indicating that this year was the most probable mutation point for the respective tide level series.

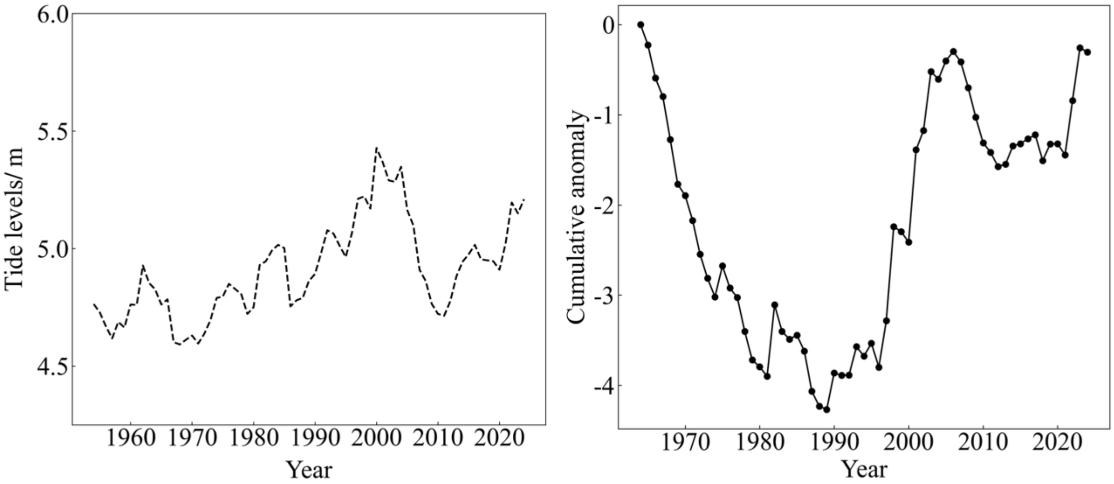

Figure 2: The 5-year sliding average curve and cumulative anomaly of H_{max} at Wusong stations.

Table 1 Detailed hydrological variation analysis of annual maximum tide levels at Stations

Trend test				**Mutation test**			
Diagnostic method	**Statistic**	**Confidence interval threshold**	**Result**	**Diagnostic method**	**Statistic**	**Mutation year**	**Score**
Linear trend	0.0061	> 0	increase	sliding t-test	2.18	2003	1
Sen+MK trend test	β=0.0057, Z=3.99	> 0, 1.960	significant increase	Pettitt	1.24e-4	1987	1
				MK mutation test	-	1987	2
Spearman's rank test	4.44	2.014	significant	Buishand U test	0.1476	1987	3
				Lee-Heghinian	30996.55	1981	1

In view of the fact that both trend and mutation of the tide series at Wusong Station showed significant variations, the study introduced an efficiency coefficient (R^2) to evaluate the degree of fit of the annual maximum tide series to the mutation component and the trend component. The results showed that the efficiency coefficient of the mutability component at this station is greater than that of the trend component, indicating non-stationary changes in the annual maximum tide level series of Wusong Station, with significant variability in mutability. Since the 1970s, Shanghai has implemented integrated management of hydraulic infrastructure, with a particular emphasis on systematic planning and construction around 1987. Gradually, a comprehensive flood control system has been established, dominated by reservoirs, flood detention and retention areas, and major river channels. According to official statistics, by 2019, the total net gate width of sluices along the Huangpu River in Shanghai had reached 826.8 m, and the total installed pumping capacity amounted to 386.82 m³/s. Notably, since 1987, newly constructed sluices along the main stem of the Huangpu River have contributed approximately 518.3 m of net gate width, while pumping stations added an installed capacity of about 382.82 m³/s, accounting for 63% and 99% of the total construction scale from 1967 to 2019, respectively. These substantial hydraulic interventions provide a reasonable and reliable explanation for the statistically identified abrupt change in the annual maximum tide level series at the Wusong station in 1987.

4.2 Parameter calculation and performance evaluation

Based on a comprehensive diagnosis of variability, the annual maximum tide levels at Wusong Station exhibited pronounced non-stationarity, rendering the stationary assumption underlying traditional frequency analysis invalid. Accordingly, this study applied a conditional probability distribution approach (Model 1) to perform non-stationary frequency analysis at Wusong Station and compared the results with those obtained from a time-series decomposition–recomposition method (Model 2) and the traditional stationary hydrological frequency analysis(Model 3).

Table 2 Parameter estimation results for the probability distribution of H_{max} at Wusong Station.

Model	Series	$p(X_i)$	α	ξ	β	S_{AB}	S_{OL}	S_{WL}
Model3	W_0	-	1.210	4.910	0.331	2.151	0.128	0.015
Model2	W'_0	-	1.209	5.060	0.294	2.174	0.171	0.025
Model1	W_1	38	1.326	4.764	0.254	1.236	0.122	0.047
	W_2	37	1.531	5.060	0.352	1.227	0.083	0.020

According to the detected change point, the annual maximum tide level series at Wusong Station ($n = 75$) was divided into two sub-sequences: W_1 (1950-1987, $n_1 = 38$) and W_2 (1988-2024, $n_2 = 37$). Subsequent mutation testing revealed no significant variability, confirming that each sub-series can be regarded as stationary. Using the mutation point of Wusong Station as the boundary, the probability weight $p(X_i)$ of each sub-distribution was determined from the ratio of the sample size of each sub-series to that of the entire dataset. These weights were then incorporated into Eqs. (1) - (2) to derive the non-stationary conditional probability distribution. Under the decomposition–recomposition approach, the mean values of the tide-level series before and after the mutation point were denoted as $\overline{y}_{i1}$ and $\overline{y}_{i2}$, respectively. The deterministic mutation component under current conditions was calculated from the difference between the two means, $\overline{y}_{i2} - \overline{y}_{i1}$. The corrected stochastic component S_t was subsequently obtained by subtracting the mutation component from the original annual maximum tide levels. Accordingly, the corrected sequence S_{t1} for Wusong Station, using the post-mutation state as the baseline, can be written as:

$$S_{t1} = \begin{cases} X_t + 0.378, & 1950 \le t \le 1987 \\ X_t, & 1988 < t \le 2024 \end{cases} \tag{3}$$

The Pettitt test was then reapplied to the corrected series, confirming that no significant mutation remained. This indicated that the corrected series satisfied the stationary assumption required for traditional hydrological frequency analysis. Finally, the maximum likelihood method was used to estimate the parameters of the P-III distribution for the conditional probability model, the decomposition-corrected series (W'_0), and the uncorrected measured series (W_0) at Wusong Station. As uncorrected observation sequences do not satisfy the stationarity assumption, they are theoretically unsuitable for traditional frequency analysis, with results serving only as comparative tests. As shown in Table 2, we calculated the absolute error sum (S_{AB}), squared error sum (S_{OL}), and weighted squared error sum(S_{WL}) for each model. Results indicated that the conditional probability distribution model yields lower fitting index values than both traditional methods and decomposition-synthesis approaches. Consequently, Model 1 delivers the optimal overall performance for non-stationary frequency analysis at Wusong Station.

4.3 Uncertainty analysis under non-stationary conditions

According to the optimal distribution results of the tide level series, a non-stationary Bootstrap method based on conditional probability was employed to analyse the uncertainty of the distribution results of H_{max} at the Wusong Station. After several rounds of debugging, the number of bootstrap iterations was set to $N = 5000$, with the resampling sizes n_1 and n_2 taken from the sequence length of H_{max}. For each bootstrap sample, the parameters of the P-III distribution were estimated using the maximum likelihood method, and the iterative trajectories of the parameter estimates were recorded to derive their sample means and standard deviations. The results showed that when the number of bootstrap samples exceeds approximately 2000, both the mean and standard deviation of the estimated parameters converge to stable values, indicating satisfactory convergence of the resampling process and adequate coverage of the parameter space. To further assess the reliability and uncertainty structure of the estimated distribution parameters, quantile plots and kernel density estimates were constructed, as shown in the Figure. 3. Among them, except for the shape parameters of the pre-mutation series, which show a bimodal distribution, the distribution of each parameter shows a central distribution. The kernel density plot curve is smooth, and the line shape remains good, indicating that the estimated value accuracy of the parameter distribution is good.

Applying the estimated parameters to the conditional probability distribution, the design tide levels and their corresponding 95% confidence intervals were derived for different design frequencies based on *N* sets of parameter samples. Table 3 summarizes the design tide levels, 95% confidence intervals, and the length of the confidence intervals for Wusong Station under both stationary and non-stationary assumptions. The results indicated that, at all frequencies, the design tide levels obtained under non-stationary conditions are consistently higher than those derived assuming stationarity, and the magnitude of change increases with increasing frequency. Influenced by climate change and intensified human activities, the non-stationary evolution of tide levels at the river estuary leads to elevated hydrological design values. This trend imposes more stringent requirements on flood-protection standards for water conservancy projects in the estuarine region, highlighting the necessity of enhancing flood-defense capacity to mitigate flooding and related hazards.

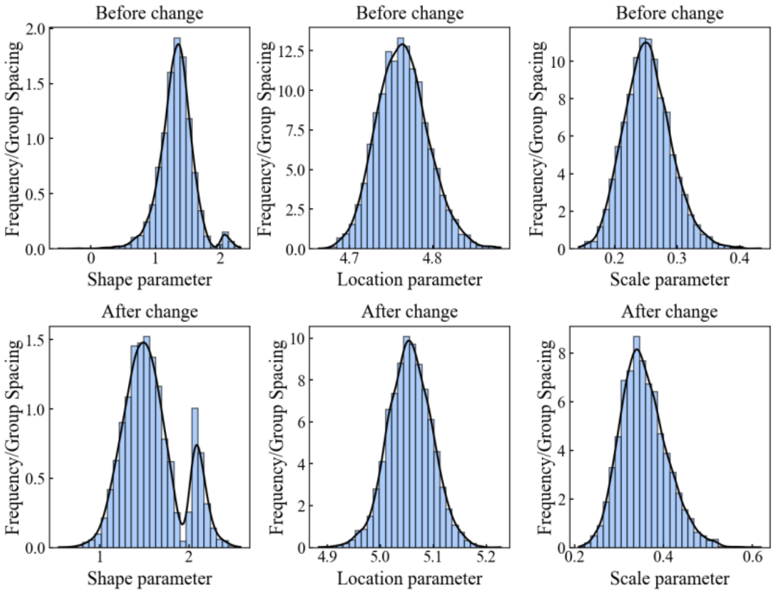

Figure 3: Distribution histogram of the P-III distribution parameters of H_{max} at Wusong Station

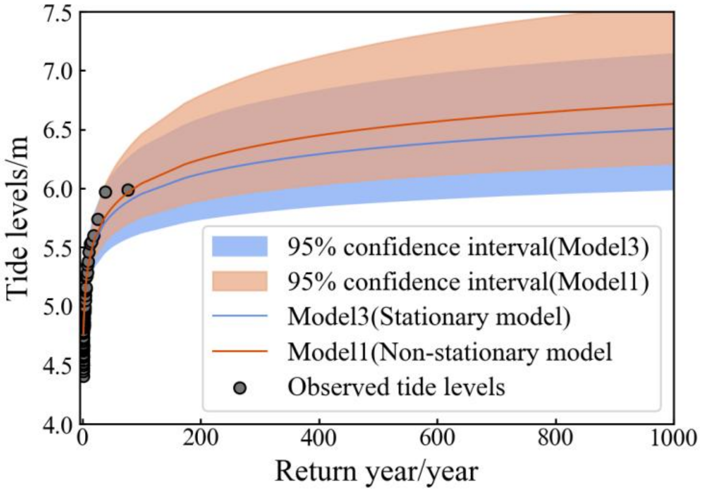

Figure 4: Conditional probability distribution frequency curve (P-Ⅲ) of H_{max} at Wusong Station

Table 3 Represents the design tide level at Wusong Station under different probabilities.

Frequency	**Traditional hydrological frequency calculation (Model 3)**			**Conditional probability distribution method (Model 1)**		
	Design tide level /m	**95% confidence interval estimation /m**	**Interval**	**Design tide level /m**	**95% confidence interval estimation /m**	**Interval**
$P = 0.1\%$	6.51	[5.99,7.14]	1.15	6.72	[6.21,7.56]	1.35
$P = 0.2\%$	6.34	[5.89,6.91]	1.02	6.51	[6.08,7.23]	1.15
$P = 0.5\%$	6.12	[5.74,6.59]	0.85	6.25	[5.90,6.79]	0.89
$P = 1\%$	5.95	[5.62,6.35]	0.72	6.04	[5.76,6.46]	0.70
$P = 2\%$	5.78	[5.50,6.10]	0.60	5.84	[5.61,6.14]	0.53

The theoretical frequency distribution curves and uncertainty intervals of H_{max} at Wusong Station were presented in Figure 4. The lengths of the uncertainty intervals for the design tide levels, under both stationary and non-stationary conditions, increased with increasing return period. This behavior occurred because longer return periods were associated with fewer effective samples, resulting in larger estimation errors for extreme values. Moreover, introducing additional variables or distributions, given the limited availability of observed data, often heightens the instability and uncertainty of the model.

However, as shown in Figure 4 and Table 3, the widths of the 95% confidence intervals derived from the non-stationary conditional model were not markedly different from those obtained under the stationary assumption, with only slight increases observed at high return periods (i.e., greater than 100 years). The difference between the two models became more evident as the return period increased. For example, at Wusong Station, the uncertainty intervals for the 500-year and 1000-year return periods increased by 0.13 m and 0.20 m, respectively, compared with those estimated without considering non-stationarity. Under lower return periods, the degree of interval dispersion in uncertain intervals decreases, effectively controlling the uncertainty caused by non-stationarity. This indicates that the non-stationary P-III conditional probability distribution in this study did not significantly increase the uncertainty of the reproducibility level estimation results due to the complexity of model parameters, and effectively reduced the uncertainty interval in the low recurrence period range.

5 CONCLUSION

To address the issue of increasing uncertainty in hydrological frequency analysis caused by non-consistent changes in hydrological series, this paper introduces a non-consistent Bootstrap uncertainty calculation method based on the theory of conditional probability distribution for frequency analysis of variable hydrological series with mutations. Using Wuaong Station as an example, we examine the annual maximum tide level variations at representative hydrological stations in the Huangpu River and further analyze the impact of non-consistency on the uncertainty in design tide level calculations, leading to the following conclusions:

(1) From 1950 to 2024, the annual maximum tide level series at Wusong Station in the Huangpu River exhibited a distinct non-stationary mutation, with the detected change point occurring in 1987.

(2) Under non-stationary conditions, directly estimating the hydrological frequency of annual maximum tide levels using a conditional probability model proved to be more effective than the time-series decomposition–recomposition method. The resulting design tide levels increased across different return periods, indicating that flood control standards should be further enhanced to improve the actual flood defense capacity of the estuarine region.

(3) The proposed non-stationary Bootstrap uncertainty analysis method based on the conditional probability model was well-suited for uncertainty estimation of design tide levels at stations along the Huangpu River. In low return periods (less than 100 years), hydrological non-stationarity increases the uncertainty of design values.

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