Analysis of the Impact of the Temporal and Spatial Variation of the High Water Level of the Pearl River Estuary on Urban Sluice Discharge

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Abstract. According to the tide level data of 8 main tide level stations at the Pearl River Estuary from 2001 to 2015, the long-term sequence of annual maximum tide level changes were analyzed through the Mann-Kendall trend analysis method, and its influence on the design tide level was explored, with a view to provide certain scientific references for the department of water conservancy project and management to formulate regional flood control planning and management. The results show that the annual highest tide level at the mouth of the Pearl River Estuary went upward from 2001 to 2015. The significance level of Dongsikoumen was lower than that of Xisikoumen, and the annual highest tide level of the Koumen site was constantly refreshed, leading to the increase of the design tide level, which will affect the flow capacity of the nearby sluices.

1. Introduction
The Pearl River is one of the seven major rivers in my country, which is composed of the Xijiang River, Beijiang River, Dongjiang River and the internal river network of the Pearl River Delta. It flows into the South China Sea through Humen, Jiaomen, Hongqimen, Hengmen, Modaomen, Jikoumen, Hutiaomen, Ya’men sluices. In recent years, frequent typhoon disasters in the Pearl River Delta, such as "Nida", "Hato", and "Mangkhut" have occurred one after another, causing floods and affecting social and economic development [1]. The tidal characteristics of the Pearl River Delta have attracted more and more attention from related scholars. Liang Guangcheng took the year-by-year measured extreme tide level of Lantern Mountain Station from 1959 to 2017 as the research object, and concluded that the annual highest tide level at Modaomen Lantern Mountain Station showed a significant upward trend as a whole [2]. Liu Junyong and others analyzed the changes in the annual highest and lowest tide levels of the Lingdingyang River Estuary since the 1970s using measured data, and concluded that the rise of high tide level is related to the increase of tidal volume, due to large-scale excavation of the port and channel construction and large-scale sand mining [3]. According to the characteristics of the Pearl River Delta network area, Lu Jianzhen and others collected the water level and flow data of several major floods in the Pearl River Delta such as "94.6", "98.6", "05.6", and "08.6" and the annual series of high tide data of each tide level station, and analyzed the water level changes in the Pearl River Delta in the past 20 years [4].

The river network area of the Pearl River Delta is not only affected by the floods of Beijiang, Xijiang, Dongjiang, and Liuxi River, but also by the tidal action of the Lingding Ocean. Under the influence of
upstream runoff, estuary tidal current and storm surge, the dynamic characteristics of the network river area are complex and changeable, with frequent increase of extreme water levels. In order to cope with the frequent floods in the Pearl River Delta, from the founding of the People's Republic of China to the establishment of the Pearl River Delta Office of the Guangdong Provincial Hydropower Department in 1974, the Pearl River Delta has carried out large-scale joint construction of sluices. Meanwhile, large-scale management work has been carried out on the entrance area represented by Modaomen, Jiaomen and Hengmen since the 1980s. So far, the net river area of the Pearl River Delta has formed a flood control system with the enclosed area and its attached sluices as the dominant part. In view of this, this article is based on the hydrological data of major tidal level stations in the Pearl River Estuary from 2001 to 2015, and uses the Mann-Kendall method to analyze the characteristics of tidal level changes, in order to provide a certain scientific reference for the water conservancy project management department to formulate regional flood control planning and management. According to the tide level data at the Pearl River Estuary from 2001 to 2015, the tide level changes were analyzed through the Mann-Kendall trend analysis method, with a view to provide certain scientific references for the department of water conservancy project and management to formulate regional flood control planning and management.

2. Temporal and Spatial Changes of High Water Level at the Mouth Station of the Pearl River Estuary

2.1. Research Data

In order to study the long-term temporal and spatial changes of the tide level at the mouth of the Pearl River Estuary, their monthly peak tide level of eight stations (Dahu, Nansha, Wanqingshaxi, Hengmen, Lantern Mountain, Gold, West Fort, and Guanchong) of the Pearl River Estuary eight stations were selected from 2001 to 2015 (Figure 1). According to these data, the trend change characteristics of the station high tide level are analyzed via the Mann-Kendall trend test method. Figure 2 shows the monthly maximum tide level process curve of each station. It can be seen from the figure that the tide level process at these stations has a higher consistency regardless of inter-annual changes or inter-month changes. The tide level in the flood season shows a clear extreme value than that in the dry season.
2.2. Nonparametric Mann-Kendall Trend Test

The Mann-Kendall trend test method, as a non-parametric statistical method recommended by the World Meteorological Organization (WMO) [5], can effectively distinguish whether a natural process is in natural fluctuations or a definite change trend. It is one of the time series trend analysis methods. In recent years, it has been used by many scholars to analyze the change trend of the time series of runoff, temperature, precipitation and water quality [6]. In this method, the null hypothesis $H_0$ is a stable and independent sequence data related to time $(X_1, X_2, \ldots, X_n)$, and its probability distribution is equivalent. The formula for constructing a test sequence [7][8] is:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)$$ (1)

$$\text{sgn}(\theta) = \begin{cases} 
1 & \theta > 0 \\
0 & \theta = 0 \\
-1 & \theta < 0
\end{cases}$$ (2)

Among them, the approximation $S$ obeys the normal distribution, and the mean value $E(S) = 0$ and variance \( \text{var}(S) = n(n-1)(2n+5)/18 \) of the median data of the data series are not considered in the process. When $n > 10$, the calculation formula of the standard normal distribution statistical variable $Z_{MK}$ is:

$$Z_{MK} = \begin{cases} 
(S-1)/\sqrt{\text{var}(S)} & S > 0 \\
0 & S = 0 \\
(S+1)/\sqrt{\text{var}(S)} & S < 0
\end{cases}$$ (3)

Considering that the time series of the monthly average high tide level of the site may have two trends, rising or falling, the bilateral test $\alpha = 0.05$ is used under the significance level of this article. When $|Z_{MK}| > Z_{0.05} = 1.96$, the data series $X_a = (x^1, x^2, \ldots, x^n)$ is considered to have passed the significance test of confidence. When $Z_{MK} > 0$, it means the data series shows an increasing trend, while $Z_{MK} < 0$, it means that the data sequence shows a decreasing trend, otherwise $X_a$ has no trend [9].

2.3. Trend Analysis

From 2001 to 2015, the range of the annual highest tide level at the 8 stations in the Koumen District was 0.731-2.980m (Table 1). The results of Mann-Kendall non-parametric trend test are shown in Table 2 below. For stations in the Koumen area, their $Z_{MK}$ are all larger than 0, indicating that the annual highest water level at the mouth of the Pearl River Estuary showed an upward trend from 2001 to 2015.

Figure 2 the Highest Water Level at the Entrance of the Pearl River Estuary from 2001 to 2015

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On the whole, the Dongsikoumen did not reach the critical value when the significance level is 0.05, which shows that although the annual maximum tide level of these 4 stations is increasing during the study period, the performance is not significant. All the Xisikoume stations are larger than the significant value of 0.05 except for Lantern Mountain Station, which indicates that the annual maximum water level of Xisikoumen basically increased obviously during the study period.

| Name       | DAHU   | NANSHA | WANQINGSHAXI | HENGMEN | DENGLONGSHAN | HUANGJIN | XIPAO | TAI | GUANCHONG |
|------------|--------|--------|--------------|---------|--------------|---------|------|----|----------|
| MAX        | 2.669  | 2.697  | 2.692        | 2.721   | 2.752        | 2.98    | 2.947| 2.841 |
| MIN        | 1.069  | 1.097  | 1.093        | 1.061   | 0.731        | 1.332   | 1.01 | 0.98 |

Table 2 Mann-Kendall non-parametric trend test results

| Name       | Z_{MK} | | | Trend |
|------------|--------|--------|---|------|
| DAHU       | 0.07   | 0.07   | ↑ |
| NANSHA     | 0.21   | 0.21   | ↑ |
| WANQINGSHAXI | 0.14   | 0.14   | ↑ |
| HENGMEN    | 0.55   | 0.55   | ↑ |
| DENGLONGSHAN | 1.03   | 1.03   | ↑ |
| HUANGJIN   | 1.99   | 1.99   | ↑ |
| XIPAO      | 2.74   | 2.74   | ↑ |
| GUANCHONG  | 3.57   | 3.57   | ↑ |

3. The influence of the Annual Maximum Water Level at the Entrance Site on the Design Tide Level

3.1. Tide Level Data and Current Design Tide Level

It is selected 7 stations (Nansha, Wanqingshaxi, Hengmen, Lantern Mountain, Gold, West Fort, Guanchong) among the eight major entrances of the Pearl River Estuary as the stations for the analysis of the influence of the annual maximum tide level change on the design tide level. Based on previous design tide level data, the extension of the design tide level during the 2001-2015 are carried out, and compare it with the design tide level after review of each site in 2011 (sequence to 2008). The design tide level of each site in 2011 (sequence to 2008) can be seen in Table 3 for review design values.

| Recurrence Interval | 0.5% | 1% | 2% | 5% | 10% | 20% |
|---------------------|------|----|----|----|-----|-----|
| NANSHA              | 2.90 | 2.75 | 2.61 | 2.40 | 2.25 | 2.08 |
| WANQINGSHAXI        | 2.84 | 2.71 | 2.58 | 2.39 | 2.25 | 2.09 |
| HENGMEN             | 2.83 | 2.69 | 2.55 | 2.35 | 2.20 | 2.03 |
| DENGLONGSHAN        | 2.88 | 2.70 | 2.51 | 2.26 | 2.07 | 1.87 |
| HUANGJIN            | 2.98 | 2.79 | 2.58 | 2.31 | 2.10 | 1.88 |
| XIPAO              | 2.94 | 2.78 | 2.61 | 2.38 | 2.20 | 2.01 |
| GUANCHONG           | 2.94 | 2.78 | 2.61 | 2.38 | 2.20 | 2.01 |

3.2. Design Tide Level Analysis

The tides at the Pearl River Estuary are irregular half-day mixed tides, with “two ups and two downs” during the day. The estuary is not only controlled by the tidal power of the open sea, but also affected
by upstream runoff. The tide level frequency analysis during the design return period adopts the Pearson III distribution curve for extension calculation:

$$h_p = k_p \cdot \bar{h}$$

(4)

where, $h_p$ is the tide level value corresponding to the annual frequency $P$. According to the above formula, the sum of the empirical frequency points $C_v$ and the theoretical frequency curve $C_s$ of each station is calculated, and the high tide level of each station's different frequency design is shown in Table 4.

| Recurrence Interval | Name         | $C_v$ | $C_s$ | 0.5% | 1%  | 2%  | 5%  | 10% | 20% |
|---------------------|--------------|-------|-------|------|-----|-----|-----|-----|-----|
|                     | NANSHA       | 0.14  | 8     | 3.46 | 3.24| 3.00| 2.69| 2.44| 2.18|
|                     | WANQINGSHAXI | 0.14  | 8     | 3.49 | 3.27| 3.05| 2.74| 2.51| 2.26|
|                     | HENGMEM      | 0.13  | 6     | 3.40 | 3.17| 2.94| 2.63| 2.40| 2.15|
|                     | DENGLONGSHAN | 0.19  | 8     | 3.33 | 3.08| 2.82| 2.54| 2.21| 1.95|
|                     | HUANGJIN     | 0.20  | 8     | 3.24 | 3.02| 2.80| 2.51| 2.28| 2.04|
|                     | XIPAOTAI     | 0.17  | 8     | 3.14 | 2.94| 2.74| 2.47| 2.26| 2.04|
|                     | GUANCHONG    | 0.18  | 6     | 3.05 | 2.87| 2.68| 2.43| 2.23| 2.03|

3.3. Design Tide Changes

Figure 3 and Table 5 show the comparison between the results of this extended review of the above-mentioned sites and the results of the design tide level review in 2011. From the table, we can see that the tide levels of 0.5%, 1%, 2%, 5%, 10%, and 20% of the design frequencies are all rising, where the rise extreme value of the 0.5% and 1% design frequency tide level is 0.65 m.

Table 5 Comparison table of the difference between this extended review of each site and the design tide level in 2011

| Recurrence Interval | Name         | 0.5%  | 1%  | 2%  | 5%  | 10% | 20% |
|---------------------|--------------|-------|-----|-----|-----|-----|-----|
|                     | NANSHA       | 0.56  | 0.49| 0.39| 0.29| 0.19| 0.10|
|                     | WANQINGSHAXI | 0.65  | 0.56| 0.47| 0.35| 0.26| 0.17|
|                     | HENGMEM      | 0.57  | 0.48| 0.39| 0.28| 0.20| 0.12|
|                     | DENGLONGSHAN | 0.45  | 0.38| 0.31| 0.22| 0.14| 0.08|
|                     | HUANGJIN     | 0.26  | 0.23| 0.22| 0.20| 0.18| 0.16|
|                     | XIPAOTAI     | 0.20  | 0.16| 0.13| 0.09| 0.06| 0.03|
|                     | GUANCHONG    | 0.11  | 0.09| 0.07| 0.05| 0.03| 0.02|

3.4. Preliminary Analysis of the Reasons for design Tide Level Changes

According to data, since the 1950s, the tide levels at the eight major entrances of the Pearl River Estuary have shown an upward trend year by year. Combined with the Mann-Kendall trend analysis results in this article, the highest tide level at the entrances has maintained its upward trend since this century. Analyzing the reasons, there are mainly the following three points:

The first reason is estuary reclamation. From 1978 to 2000, the total reclamation area of the Pearl River Estuary was 45,000 hm² and the reclamation rate was about 2,000 hm²/a. The total reclamation from 2000 to 2018 was 13,100 hm², of which 6,000 hm² was constructed from 2000 to 2006, with the reclamation rate was about 1,000 hm²/a. From 2006 till now, 7,100 hm² was constructed, with reclamation rate at 600 hm²/a. The extension of reclamation has caused the opening of the sea to narrow and the tide level continues to rise.
The second reason is frequent storm surges and short-term heavy rains. In recent years, extreme weather such as typhoon surges and short-term heavy rains have occurred frequently. The storm surges of "Typhoon Hato" in 2017 and "Typhoon Mangkhut" in 2018 successively set the historical record of the highest tide level at eight major control stations. The storm surge and the waterlogging drainage in the urban areas led to the increase of design tide level continuously, and passive decrease of the original dyke fence dam prevention standard.

The third reason is the increase of sea level and estuary tidal power, which has also caused the continuous rise of the tide level of the estuary.

Figure 3 The comparison chart between the original design tide level of each station and this extended review tide level.

4. Urban Drainage in the Estuary Area
Under the background that the design tide level of the entire Pearl River Estuary continues to rise, coupled with the intensified influence of global warming and urbanization development on urban rainstorms [10], the pressure of urban drainage in the estuary area is increasing. According to the statistics of flood disasters in the urban area of Guangzhou, the most serious flood disasters occurred in June 1955, May 1957, June 1959, May 1985, August 1988, May 1989, August 1999, and 2005. June, June 2008,
March 2009, May 2010 and May 2020. Taking the “5.22” flooding in Guangzhou in 2020 as an example, only the Guanhu River area has a submerged depth of 0.8-3m in the flooded area, and the flood mark height of the storm flood near Guanhu Metro Station is about 1.35m.

At present, flood drainage in the major enclosures of the Pearl River estuary basically follows the principle of “self-draining first, drainage as supplementary”. For heavy rainstorms, pre-drainage is basically adopted to reduce the water level of the enclosed river. Even so, under extreme rainstorm conditions, the urban water collection rate in the Pearl River estuary enclosure is still relatively fast. Therefore, the drainage situation should be considered when the enclosed area sluice is fully opened and the flood is encountered.

4.1. Sluice Case Overview

The Guangchang sluice near the Lantern Mountain Station of Modaomen was built in 1966. The distance between the initial sluice and the exit of Guangchang River is 1.1km. It was rebuilt in 1997 at the lower reaches of the original site according to the 50-year Flood standard. After the renovation and expansion project, the total net width of the sluice after the renovation and expansion is 48 m, the bottom elevation of the sluice is -3.586 m, and the top elevation of the sluice is 5.014 m. The flood drainage standard of the Zhongzhu United Encirclement is that a 24h rainstorm will not cause disaster once in 20 years. According to the analysis of flood encounters, a 20-year flood \( (Q = 267m^3/s) \) within the enclosure was used when the 20% frequency water level of Lantern Mountain Station of Waijiang was at its maximum.

A two-dimensional mathematical model is used to analyze the sensitivity of the Guangchang sluice flow under the condition of frequency and water level changes, \( f_1 \) is the tide level process with the maximum value of the water level (20%, 1.87m) and of the original design frequency water level (20%, 1.87m) of the Lantern Mountain Station of Waijiang River when the 20-year flood occurred in the reclamation \( (Q = 267m^3/s) \). \( f_2 \) is the tidal level process where the water level (20%, 1.95m) at the maximum value of the design frequency water level \( (Q = 267m^3/s) \) of the rechecked design frequency of the Lantern Mountain Station of Waijiang River occurred within the reclamation.

![Figure 4 Case Model of Guangchang Sluice](image)
4.2. Simulation Result Analysis

In order to correspond to the flood drainage standard of the reclamation area where the Guangchang Sluice is located, according to the calculation results, the peak value of the gate flow in the interval and the change of the gate time under the original flow of the gate are counted. Under f1 condition, the peak flow rate of Guangchang sluice section is 289.6 m$^3$/s, and under f2 condition, the peak flow rate of Guangchang sluice section is 285.8 m$^3$/s, which is about 1.3% lower than that of f1 condition, correspondingly, the overcurrent time increased by 0.6%, and the risk of waterlogging in the upstream showed an increasing trend.

5. Conclusion

This paper uses the data of the annual highest tide level at the Badakoumen Station in the Pearl River Estuary from 2001 to 2015, and applies the Mann-Kendall trend analysis method to analyze the law and trend of the annual highest tide level change in the Pearl River Estuary. The sluice near the station is selected, and the change of the flood draining and passing flow of the sluice under the condition of the design tide level change is simulated by numerical simulation method, and the conclusions are as follows:

Firstly, the tide level process at the eight major entrance sites (Dahu, Nansha, Wanqingshaxi, Hengmen, Lantern Mountain, Gold, West Fort, Guanchong) at the Pearl River Estuary has a high consistency regardless of inter-annual or monthly changes. The seasonal tide level amid flood season presents an obvious extreme value phenomenon than the dry season.

Secondly, from 2001 to 2015, the annual highest tide level at the mouth of the Pearl River Estuary showed an upward trend. On the whole, the significance level of Dongsikoumen was lower than that of Westsikoumen, indicating that although the annual maximum tide level of Dongsikoumen was increasing, the performance is not significant, and the annual highest tide level of Xisikoumen basically shows a significant increase trend.

Thirdly, the annual maximum tide level of the entrance site is constantly refreshed, resulting in an increase in its design tide level. This paper takes the Guangchang Sluice near the Lantern Mountain Station (the design tide level increased by 0.08m) as a case. After analyzing the design tide level change, the flow capacity of the sluice decreases by about 1.3%, and the corresponding flow time increases by 0.6%. At the Wanqingshaxi Station at the mouth of the Pearl River Estuary, the 20% frequency water level rises to 0.17m, which has a greater impact on the overcurrent of the nearby sluices.

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