Analysis about the impacts of changing basin underlying surface on design floods for design units of water diversion projects

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Abstract: After the water diversion project has been put into operation for many years, due to the long distance, complex hydro-meteorological conditions, and rapid development of social economy, the underlying surface conditions of corresponding natural basins in the design units of water diversion project have changed to some extent compared with the beginning of the project design, especially the underlying surface situation of rivers in the northern region has changed greatly. Based on ArcGIS to extract basin characteristic values of the design unit of water diversion project, such as basin area, river length and slope, this paper analyzes the changes of current basin characteristic values of design unit compared with the design period. For the design unit with significant changes in the basin characteristics, the original design flood calculation method is used to calculate the flood of the same design rainstorm under current conditions, and the impacts of changing basin underlying surface on design floods are analyzed.

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1. Introduction

Design flood calculation is the core technology of water related project planning and design [1], flood control and disaster reduction planning. It determines the scale of water related engineering buildings, and is an important basis to ensure the safety of engineering and flood protection objects. At the initial stage of design, the design flood calculation should be carried out in strict accordance with the relevant regulations and technical requirements, and according to the landform, hydrological and climatic characteristics and data conditions of the cross river basin. However, as the project has been put into operation for many years, climate change and human activities continue to affect the hydrological consistency, the acceleration of land development and utilization, urbanization process and the change of local topography and geomorphology have led to great changes in the underlying surface characteristics of the basin [2-4], the change of runoff generation and concentration mechanism. So under the primary designed standard of rainstorm, the change of underlying surface conditions in the flow concentration region, the drainage channel in the right bank is dissatisfied the designed demand, the flood discharge condition in the upper and lower reaches changes, and the actual flow capacity of the discharge structure is reduced compared with the designed conditions, all can cause risk event of the
rising of designed flood level in the left bank and will cause local flood risk, and also affects the safety of the water transfer project and the water supply guarantee of the water receiving area, and cause corresponding economic losses and social impacts [5]. Therefore, it is urgent to study the impact of basin underlying surface changes on the design flood of water diversion project design unit, and improve the design flood calculation method according to the new environment.

At present, the research on runoff change caused by underlying surface change mainly focuses on cities with higher construction level. Zhao Gang and others [6] analyzed the response of surface runoff by using SWMM model of rainstorm and flood management based on the characteristics of impermeable area increase and river network structure change caused by urbanization. Many scholars combined prototype observation experiments and hydrological models to study underlying surface changes and runoff characteristics. Based on rainfall observation experiments and urban hydrological models, Liu Huijuan [7] and Xia Jun [8] discussed the impact of land use / Cover Change on Runoff in urban areas. The research focuses on the change of underlying surface characteristics of urban construction land area. In terms of the impact of underlying surface on design flood, Gu Weiqi [9] established Xin'anjiang-Haihe model by using the measured rainstorm flood data from 1967 to 2011, calibrated the model parameters of large, medium and small floods around 1980, and statistically analyzed the impact of underlying surface changes on different flood magnitudes. For the water diversion project as the research object, there are few studies on directly extracting multiple underlying surface features through geographic information systems (GIS).

This paper takes the water diversion project as the research object, aiming at the cross building design unit, through the geospatial information technology, extracts the basin characteristic parameters, land use parameters and vegetation type data of the water diversion project. The original design flood calculation method is used to calculate the flood process of the same design rainstorm under the condition of the existing underlying surface for the design unit with obvious change of watershed eigenvalue. According to the selection principle of the unit with larger change of underlying surface (that is, the unit with more than 20% increase of watershed area and more than 10% decrease of river length), the relevant design unit is selected to analyze the impact of the change of underlying surface on the design flood. So that the relevant departments can adjust the flood control countermeasures and project layout accordingly.

2. Analysis about the impacts of changing basin underlying surface on design floods for design units of water diversion projects

The underlying surface of a watershed is a complex of many factors that affect the runoff generation and confluence. The underlying surface features mainly include topography, land use, soil physical properties and so on. The change of watershed area and river length can significantly affect the runoff generation and confluence conditions. At the same time, the change of land use type is the main form of human activities, especially the change of construction land area. Therefore, the catchment area, river length and average gradient above the cross section of the water diversion project design unit are used to characterize the landform characteristics of the watershed, and the data of land use and vegetation type are used to characterize the construction land in the watershed.

2.1. Data Sources

Based on 1:50000 DEM and ArcGIS 10.1 platform, the Hydrology of Spatial Analyst Tools is used to obtain the basin characteristic parameter information such as basin area, river length and slope of each design unit of water diversion project above the cross section by the method of automatic extraction and manual correction, and then compare with the original design value. By comparing the land use and vegetation type data of 2.5-meter resolution remote sensing images in the initial design stage and more than ten years after the completion and operation of main channel, the change of the proportion of construction land in the basin is analyzed. For the design units with significant changes in basin characteristic, the original design flood calculation method is used to calculate the flood of same design
rainstorm under current conditions, and the impacts of changing basin underlying surface on design floods are analyzed.

2.2. Method

According to the design flood calculation standard [10], the design flood of the cross section in design unit of water diversion project is calculated by the design rainstorm [11]. Basin runoff is calculated by design rainstorm through the rainfall-runoff relationship recommended in the 《Hydrological Atlas》 of the region where design unit is located, if the rainfall-runoff relationship in some areas has been tested and adjusted, the adjusted rainfall-runoff relationship shall be used for calculated. According to the basin size and characteristics of rainfall and flood, the rainstorm period and flood volume period are determined for different basins. For rivers with large basin area and long duration of rainstorm flood, 3-day design rainstorm can be used to calculate basin runoff; for those with small basin area and duration of rainstorm flood within 1-day and less, 24 hours designed rainstorm is used to calculate basin runoff. For the design flood process and flood peak discharge, according to the basin area, topographic and geomorphic characteristics, and production confluence above the cross section, different design units of water diversion projects use different methods to calculate based on region's confluence characteristics [12]. Among them, the integrated unit line method was used to calculate the design flood process for cross rivers with basin area over 200 km$^2$, instantaneous unit line method is adopted to calculate the design flood process for cross rivers with basin area over 100 km$^2$, cross rivers with basin area of less than 200 km$^2$ and less than 100 km$^2$, and mountain rivers in Beijing, the design flood peak discharge at different frequencies is calculated by using reasoning formula method, and then the design flood process line is calculated by generalized process line method.

The calculation formula of design flood volume and design flood peak is as follows:

①Design flood volume:

The basin runoff is calculated by the design rainstorm through the rainfall-runoff relationship recommended in Rainstorm and flood Atlas. Taking 24-hour design flood volume as an example, 24-hour design flood volume at various frequencies of each river cross section is calculated by the following formula:

$$W_{24h}=1000R_{24h}F$$ (1)

where:

$W_{24h}$: 24-hour design flood volume, m$^3$;

$R_{24h}$: net rainfall after infiltration is deducted from 24-hour design rainstorm, mm;

$F$: basin area, km$^2$.

②Design peak discharge:

Rivers with basin area less than 200km$^2$ above the cross section without measured discharge data and rivers without measured discharge data to the west of Beijing-Guangzhou railway of Tianjin trunk line, the design peak discharge is calculated by the reasoning formula method. The formula used is:

$$Q_m = 0.278\psi \frac{S}{\tau^n} F$$ (2)

$$\psi = 1 - \frac{\mu}{3}\tau^n$$ (3)

$$\tau = 0.278 \frac{L}{m \frac{1}{3} Q_m \frac{1}{5}}$$ (4)

where:

$Q_m$: design peak discharge (m$^3$ / s);

$\psi$: peak runoff coefficient;

$\tau$: flood peak confluence duration (h);

$F$: basin area (km$^2$);

$h_{x}$: the maximum net rain corresponding to $\tau$ period in case of comprehensive confluence and the net rain of single flood peak in case of partial confluence;

$L$: length of main channel, the longest distance from outlet section to watershed (km);
\( J \): average slope along main channel \( L \), in decimal; 
\( S \): design maximum 1-hour average rainfall intensity, i.e. design frequency 1-hour rainfall, (mm / h); 
\( n \): design rainstorm decline index, and take the value according to the corresponding confluence duration, when \( \tau < 1 \) h, plug in \( n_1 \); when \( \tau = 1 \sim 6 \) h, plug in \( n_2 \); when \( \tau = 6 \sim 24 \) h, plug in \( n_3 \). 
\( \mu \): average infiltration rate, calculated in mm / h, the value of which is obtained from the \( \mu \) partition table. 
\( m \): confluence parameter, which are found from the \( \theta \sim m \) correlation line in the rainstorm map set or calculated according to the empirical formula of \( m \sim \theta \):

\[
m = 0.7 \theta^{0.137} 
\]

\[
\theta = \frac{L}{T^{3/5}} 
\]

| Hydrological regionalization | I   | II  | IV  | III | V   | VI  |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| \( \mu \) (mm/h)            | 2-3 | 3-5 | 4-6 | 5-8 |     |     |

③Flood hydrograph
Due to the lack of measured flood data in small watershed, it is difficult to deduce the design flood hydrograph. At present, the design flood of small watershed mainly depends on the empirical generalization method [13], that is, to select the measured flood hydrograph from the flood data, to analyze the relationship between flood peak volume, flood rising time, peak appearing time, flood duration, and the flood flow time history distribution process at the generalization place.

3. Application example-Analysis about the impact of changing underlying surface on design floods for design units in a management office of water diversion project

3.1. Characteristics of rainstorm and flood in Xinzheng Management office
The Xinzheng Management Office is located in the southern part of the North China Plain, which belongs to the temperate monsoon climate zone. The rainfall is unevenly distributed throughout the year, and the interannual variation is large. In summer, it is affected by the southeast monsoon, with concentrated and heavy rainfall. From the census data of torrential rains, the weather systems that produce torrential rains in this area mainly have typhoons, typhoon inverted troughs, east-west shear lines at 700 mb altitude, and the ground weather systems are mainly cold fronts, cyclonic waves and low-pressure troughs. Rainstorm mainly occur from July to August, especially from late July to early August.

The flood occurred at the same time as the torrential rain. Most of the floods occurred in late July and early August, but some were delayed in mid-August and early September. Floods and torrential rains vary greatly from year to year. The measured maximum and minimum floods at some hydrological stations can differ by more than tens of times. The characteristics of flood peaks and quantities are related to the basin characteristics and the characteristics of the rainstorm. For some small and medium-sized rivers on the slope in front of the mountain, because of the small basin area, the peak discharge is affected by the change of rainstorm intensity in a short period of time, and the flood rises and falls steeply, with the characteristics of small peak height, small volume and thin peak type. The peak shape of the river in the plain area is gentle, and the period of recession is long.

3.2. Analysis of the impacts of the changing underlying surface on the design flood
Table 2 shows the changes of basin area, river length and construction land area ratio of each design unit in a management office before and after the completion of main canal project.
Table 2. Change of evaluation indexes in a management office

| Number | Name of evaluation units       | Change degree of basin area | Change degree of river length | Change degree of construction land area proportion in the river basin |
|--------|--------------------------------|----------------------------|-----------------------------|------------------------------------------------------------------|
| 1      | Huangshui River                | -7.37%                     | 69.83%                      | 2.76%                                                            |
| 2      | Qishui River                   | 0.34%                      | 4.07%                       | -3.12%                                                           |
| 3      | Shuangzi River Tributary       | -2.17%                     | 14.20%                      | -3.07%                                                           |
| 4      | Mei River                      | 1.02%                      | -4.36%                      | 0.91%                                                            |
| 5      | Shuangzi River                 | -3.34%                     | 13.77%                      | -1.13%                                                           |
| 6      | Wanglao Village Ditch          | -0.65%                     | 0.29%                       | 0.72%                                                            |
| 7      | Lou Village Ditch              | 13.49%                     | -7.72%                      | -0.35%                                                           |
| 8      | Qiaohu Ditch                   | 13.10%                     | 0.34%                       | -6.34%                                                           |
| 9      | Yingli Village Ditch           | 12.78%                     | -4.81%                      | -2.49%                                                           |
| 10     | Xiaozhu Village Ditch          | 6.51%                      | -2.82%                      | -6.21%                                                           |
| 11     | Tian Village Ditch             | -6.67%                     | 16.13%                      | 9.67%                                                            |
| 12     | Shilipu Ditch                  | 0.21%                      | 0.41%                       | 3.63%                                                            |
| 13     | Feng Village Ditch             | -5.28%                     | 8.08%                       | -8.08%                                                           |
| 14     | Liyuan South Ditch             | 8.74%                      | 13.54%                      | -20.52%                                                          |
| 15     | Wuchen Ditch                   | -14.34%                    | -31.09%                     | -1.45%                                                           |
| 16     | Nuanquan River                 | -0.49%                     | 4.53%                       | 0.33%                                                            |
| 17     | Gao Village Ditch              | 6.76%                      | 30.97%                      | -2.41%                                                           |
| 18     | Miaohoutang Ditch              | -7.24%                     | -29.22%                     | -5.94%                                                           |
| 19     | Mei River Tributary Ditch      | -12.87%                    | 26.74%                      | -5.16%                                                           |
| 20     | Mengjia Ditch                  | -0.10%                     | 30.64%                      | -2.49%                                                           |
| 21     | Miaohouli Ditch                | 4.99%                      | -6.17%                      | 5.61%                                                            |

Among them, for the unit with large underlying surface change, that is, the unit with more than 20% increase in basin area and more than 10% decrease in river length, the impact of wuchengou drainage inverted siphon underlying surface change on the basin design flood is analyzed. Table 3 and table 4 show the comparison between the current watershed characteristic values and the design period of the cross section of Xinzhou management office.

Table 3. Basic information of current cross section of Xinzhou management office

| Name of management office | Name of unit                     | Design basin area (km²) | Selection basis                          |
|---------------------------|----------------------------------|-------------------------|------------------------------------------|
| Xinzhou                   | Wuchen Ditch drainage inverted siphon | 2.9                    | The river length is greatly reduced compared with the design value |

Table 4. Comparison between the current basin characteristic and design period of Xinzhou management office

| Name of unit          | Parameter comparison | Basin Area F(km²) | River Length L(km) | Slope J (%) | \( \theta = \frac{L}{J^{1/3}F^{1/4}} \) | Confluence parameter m |
|-----------------------|----------------------|------------------|-------------------|-------------|---------------------------------|-------------------|
| Wuchen Ditch          | Original parameter   | 2.9              | 4.6               | 9           | 22.11                           | 1.07              |
|                       | Current parameter    | 2.48             | 3.17              | 9.8         | 14.81                           | 1.01              |
On the basis of design flood calculation method introduced in section 2, the impact of changing underlying surface of Xinzheng management office on the design flood is analyzed and calculated, and the results are as follows:

| Number | Name of unit  | Peak Discharge (m³/s) |
|--------|---------------|-----------------------|
|        |               | Original design       | Current situation |
|        |               | 20% 5% 2% 0.5% 20% 5%| 2% 0.5%           |
| 1      | Wuchen Ditch  | 23 45 59 84 21.60 51.42| 71.17 101.32      |

By comparing the results, it is found that under the current situation, the peak discharge of 5-year return period flood is lower than the original design value, and the peak discharge of 20-year return period flood, 50 year return period flood and 100 year return period flood is higher than the original design value. The results show that due to the change of underlying surface conditions in the basin, under the same rainfall conditions, the current high frequency flood has a significant growth trend compared with the design conditions, which increases the risk of crossing buildings in flood season, and also brings challenges to the work of relevant flood control departments.

4. Conclusion
This paper analyzes the change of the current basin characteristic for design units of water diversion projects compared with the design period, and use the original calculation method to analyze the impact of changing underlying surface on design floods of the three-level unit with significant changes in basin characteristic (increased basin area, decreased river length and increased construction land area which compared to the design value). For the design unit that the changing underlying surface has a great impact on the design flood, it is suggested to open the drainage channel upstream. At the same time, it is suggested to carry out special demonstration and research on the units with obvious changes in hydrological parameters such as basin area, river length and underlying surface conditions before and after the construction of main canal.

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