Monitoring and health evaluation of stormwater runoff processes: A case study of Handan metropolis, North China

M T Pei¹², Y Y Zhou², Q H Luan¹³⁵, W H Xiao² and F Q Wang⁴

¹School of Water Conservancy and Hydroelectric Power, Hebei University of Engineering, Handan, 056038, China
²State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
³Research Centre for Water Ecological Civilization & Social Governance of Hebei Province, Handan, 056038, China
⁴Department of Water Conservancy Engineering, North China University of Water Conservancy and Electric Power, Zhengzhou 450011, P. R. China

E-mail: carol97011202@163.com

Abstract. Metropolitan areas are facing increasing environmental risks of urban flooding under changing climate and intensified human activities. Therefore, it is of vital importance to evaluate the health of processes of stormwater runoff in changing environment. In this paper, the health evaluation was conducted using an indices system integrating the Analytic Hierarchy Processes (AHP) and Key Performance Indices (KPI) methods. This system consists of four dimensions, i.e. rainfall, runoff generation, runoff routing and river retention, and 12 indicating indices, considering the impacts of urban development on water cycling processes. Case study was conducted in Handan metropolis, North China. Particularly, an extreme stormwater runoff event, i.e. “2017.06.21 Stormwater Event”, one of the most severe and typical urban stormwater events recently, was analysed. Results showed that the processes of stormwater runoff in this study rest in a sub-health state. The production processes is the most critical link in the urban water cycling health assessment. This result maps out the problem of poor infrastructure construction in Handan metropolis. Methods and results of this study could help better understanding of urban stormwater management and could serve as a reference for health evaluation of urban flooding in other metropolitan areas.

1. Introduction

Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity [1]. Based on this conception, some scholars extended "Health" for evaluating the social water cycle processes [2,3], which means the social water cycle processes could follow the natural principle, i.e. rational and scientific use of water resources, and appropriate wastewater treatment, disposal and reuse. Many researches related to the water health evaluation. Setu et al evaluated the impact of natural disasters on the water cycle in Bangladesh [4]. Amrita et al. analyzed the source, producing, route, health effects and attenuation processes of new organic matter in drinking water production [5] based on the principle of urban water cycle. Zhang et al proposed a method for health evaluation of regional water cycle and established a hierarchical evaluation model based on comprehensive indices and fuzzy mathematics theory, according to the theory of Natural-Social Dualistic Water Cycle [6]. In most of the related researches, the Analytic Hierarchy Processes...
[7] and the Synthetical Indices Method [6] were selected. Recently, it has been reported that increasing number of heavy rainfall events are observed, especially in urban areas [3]. Coupled with the rapid changes in the underlying surface of the urban area, environment risks occur frequently, and the regional stormwater water cycle has undergone significant variation. However, previous studies are mostly concentrated on the annual scale [6,8], few of them look at the urban water cycle health status for even-based stormwater flooding. Therefore, how to evaluate the impact of a heavy rain on various links of the urban water cycle, how to properly solve the respective challenges brought by waterlogging in urban areas, how to establish a healthy water circulation system become major challenge of urban monitoring and management.

The concept of Health Assessment of Water Cycle in the processes of stormwater runoff is proposed in this paper. Through analyzing and evaluating of the health status of each layer and indicating index, the health degree of the whole water cycling processes can be finally obtained. In order to accurately locate the health degree of the water cycle, appropriate and scientific methods should be used for computational analysis. The water cycle health of stormwater runoff processes in June 21th to June 22th (hereinafter referred to as “6.21”) in Handan metropolis was evaluated through integrated method of AHP and KPI in this study. The research can provide technologic support to water quality improvement of catchment river system and local urban waterlogging management.

2. Study area and data collection

2.1. Study area
Handan metropolis (114°03’-114°40’E, 36°20’-36°44’N), which belongs to the Haihe River Basin, is located in the south of Hebei Province, North China. The total area of the metropolis is 12073.8 km². Handan metropolis is a typical warm temperate semi-humid continental monsoon climate, the annual average temperature is 14°C, and the annual average precipitation is 589 mm. The study area is from flood diversion sluice in Zhangzhuangqiao (ZZQ) to the North Lake (NL), with a length of 16km and a study area of 8280 km². There are 3 rivers, i.e. the Fuyang River (FYR), Qin River (QR) and Shuyuan River (SYR) and 2 artificial lakes, i.e. North Lake (NL) and South Lake (SL) in the study area (figure 1).

![Figure 1. Location of the study area.](image-url)
2.2. Data collection

The monitoring of the stormwater runoff processes in the study area mainly includes two aspects: river water quality monitoring and waterlogging survey. The rainfall runoff processes on June 21 is selected to study and the assessment is carried out as follows. According to the China Weather Network, the daily weather data of Handan is used to plot the rainfall histogram with a rainfall of more than 1 mm in the rainy season in Handan metropolis in 2017 (figure 2). The total precipitation of the study area from June to August 2017 was 181.4 mm. It can be clearly seen from figure 2 that “6.21” is the first torrential rain in 2017 and the only stormwater exceeding 40mm, so it is much of representation to be evaluated the water cycle processes. According to the 5-minute rainfall data of 2017.06.21 provided by the Handan Municipal Hydrographic Bureau, the “6.21” Rainfall Processes Line Graph is as follows (figure 3). It can be seen from figure 3 that the ”6.21” rainfall has a short duration, the rainfall is concentrated, and the flood peak is on the front of the whole processes. 2017.06.21 stormwater event caused a serious test for urban drainage network.

Figure 2. Statistics of typical rainfall daily rainfall in the rainy season in 2017.  
Figure 3. “6.21” rainfall processes line graph.

2.2.1. Monitoring of stormwater runoff processes. On the basis of field investigations and studies on the water system in the study area, 5 monitoring sections (figure 4) were selected for water sampling. Taking into account changes in river water quality, under the stormwater, water sampling is performed before, during, and after each rainfall.

The water samples are tested by Urban Water Supply Quality Testing Network Monitoring Station. The test items mainly include pH, Permanganate Indices, Total Phosphorus (in terms of P), Total Nitrogen (lake, reservoir, in N), Dissolved Oxygen, and Five-day Bod. According to the China Water Resources Bulletin (Water Quality Section) Water Quality Nutrition Status Indices Grading Method (Supplementary Schedule 2), Through the measured pre- and post-rain data of the river water quality in the study area, the Pollutant Yield Modulus (Nutritional status) is calculated from the inflow monitoring section (ZZQ) to the outflow monitoring section (NL). Calculate the average number of water quality scores before, during, and after rain in five monitoring sections, and obtain evolution river water quality indices. According to the water quality scores during the raining processes to obtain the river water quality indices loss factor \((R)\) to reflect the regional water environment capacity [9]. See the supplementary material for the \(R\) calculation method.

Table 1. “6.21” ZZQ and LHK hydrological station flow information.

| Flow(m³/s)       | 2017.06.20 | 2017.06.21 | 2017.06.22 |
|------------------|------------|------------|------------|
| ZZQ hydrological station | 4.73       | 4.43       | 6.40       |
| LHK hydrological station   | 8.99       | 14.5       | 23.0       |

Chemical indicator of rainfall is analyzed by the detected pH of rainwater. Through the flow data (table 1) provided by the ZZQ hydrological station and the Lianhuakou (LHK) hydrological station
(distribution map shown in figure 4), calculate the amount of water generated by the entire rainfall in the river channel of the study area. The ZZQ hydrological station mainly controls the inflow of the inlet of the study area, and the LHK hydrological station controls the outflow of the outlet. Further, the pollutant yield modulus can be obtained.

Figure 4. Distribution of monitoring sections and inundation points survey points in the study area.

2.2.2. Reconnaissance of waterlogging and inundation points in study area. According to the information provided by the relevant departments of Handan metropolis, combined with field visits to determine the inundation points in the metropolis (figure 4). The main content of the survey is to measure the distribution of inundation points, the depth of inundation and the drainage time, the data is shown in schedule 5 of the supplementary materials. According to the stormwater water cycle health assessment indices threshold table (Schedule 1 of the supplementary materials), the inundation drainage time and inundation points distribution scores are calculated.

2.2.3. Other information. The construction of the indicator also involves rain intensity, rain pattern, ecological slope protection ratio, channel flood control capacity and longitudinal connectivity of river-lake water system. Among them, the rain intensity and rain pattern are based on the 5-minute rainfall data provided by the hydrological station. Channel flood control capacity is calculated according to the flood control standards of the Handan (20 years frequency). Ecological slope protection ratio is obtained according to the survey along the FYR and QR. Longitudinal connectivity of river-lake water system (DCI) is calculated based on the number of obstacles such as dams (there are two obstacles in FYR and QR in Handan metropolis,) obtained from actual surveys [10].

3. Methods

3.1. Interpret of water cycle health of urban stormwater runoff processes
The urban water cycle processes are typical "natural-social" dualistic processes [8]. With the coupling
of the water cycle in the natural unit and the social unit, rainfall runoff generation, runoff routing and river retention connects and consist each other and a role in stormwater water cycling processes, and cycle structure and path are shown in figure 5. Rainfall is one of the sources of the water cycle processes. Through the runoff generation in land surface and confluence in urban pipeline system, water flows into the river network. Water volume remits to the next link after regulating in river network. It can be seen that the determinants of water cycle depend on the source and processes in rainstorm runoff processes.

![Figure 5. Stormwater runoff processes water cycling processes structure and path.](image_url)

3.2. Health indicator system construction

3.2.1. Indices system construction. Based on the above interpret of water cycle health and the natural and social properties of the stormwater processes, the water-cycle health evaluation system of urban stormwater runoff processes was constructed in this study. The indices and weight of the system was calculated by the concept of AHP and the SMART principle of KPI (Specific, Measurable, Attainable, Relevant, Time-based) [11]. In the construction of indices, it is necessary to follow the connotation of circular health, but also to consider the data collection, accessibility and practical operability, and consider the independence of indicators [12]. Finally, the evaluation system concludes four dimensions and 12 indicating indices in this paper (figure 6).

- The rainfall factor is the source of natural water circling processes, which mainly has three indicators to reflect the contents. Rain intensity is an important indicator of the characteristics of stormwater and the determining of runoff. As the concept of describing the rainstorm processes, the rain pattern represents the distribution processes of rain intensity on the time scale [13]. Rainfall quality has a certain impact in the processes.
- The runoff generation reflects the structural characteristics of regional land use and real-time change of runoff processes. The water production modulus refers to the amount of water generated per square kilometer from the basin. The pollutant yield modulus is mainly the amount of pollutants generated per kilometer of rainfall in the river channel. Regional water environment capacity refers to the ability of rivers to absorb external pollutants.
- Runoff routing is the reflection of real-time situation of water cycle and the capacity of regional urban pipe network construction. The ability of the drainage system can be indicated by inundation drainage time. The distribution of inundation points represents the balance of urban modernization development. The evolution of river water quality reflects the evolution of water quality during the runoff routing and the situation of urban sewage discharge.
- The flood control capacity and ecological functions of metropolitan rivers is embodied by capacity of flood storage processes. Ecological slope protection reduces the damage of the artificial channelization of the river to the natural environment, and reflects the coordination between urban construction and ecological environment. The level of urban channels can be
reflected by channel flood control capacity. The longitudinal connectivity of river-lake water system characterizes the integrity of urban river ecosystems and the ability of urban river networks to regulate floods [14]. The longitudinal connectivity of river-lake water system (DCI) is calculated according to the number of obstacles such as dams in the river (calculation processes is shown in the supplementary materials).

Figure 6. Water cycle health assessment system for storm flood production and runoff routing.

3.2.2. Quota measurement and evaluation standard. Make the basic data been dimensionless. According to the evaluation method selected in this paper, the four dimensions and 12 indicators are graded by the method of grade description [15]. The threshold of each indicator is determined according to a series of standards and norms [14,16,17] in China and related literature [18,19]. Details could be found in the Schedule 1 of the supplementary materials.

3.2.3. Determination of indicator weight. The weight of the indicator is the importance of each indicator to the upper element that governs it [20]. Through the comparison of the importance of the two indicators under the same dimension layer, paired comparison method and the evaluation criteria of 1~9 and its reciprocal (Supplementary Materials Schedule 3) describes the relative importance relationship among the elements [21], and establish judgment matrix:

$$A = \left( a_{ij} \right)_{n \times n}$$ (1)

First, calculate the weight 4 elements of the dimension layer through the AHP model, and followed by the 3×4 indicators in the indicator layer. Finally, the weight of the indices layer to the evaluation layer is obtained by the Weighted Average Method. Calculate the consistency ratio (CR) of the above weights from the highest level to the lowest level:

$$CR = CI / RI$$ (2)

when $CR<0.1$, the consistency of the judgment matrix is acceptable. The mean random consistency (RI) is shown in Supplementary Material Schedule 4.
\[ CI = \frac{(\lambda_{\text{max}} - n)}{(n-1)} \]  

(3)

where, \( \lambda_{\text{max}} \) is the maximum eigenvalue of the judgment matrix [10].

The CR of the weight of the indices evaluation system of the stormwater water cycle is 0.0077, which satisfies the consistency condition. The weight results are shown in Table 2.

| Dimensions        | Serial number | Indices code | Indices weight | Dimensions weight |
|-------------------|---------------|--------------|----------------|-------------------|
| Rainfall          | (1)           | \( a_1 \)    | 0.0588         | 0.1089            |
|                   | (2)           | \( a_2 \)    | 0.0324         |                   |
|                   | (3)           | \( a_3 \)    | 0.0178         |                   |
| Runoff generation | (4)           | \( b_1 \)    | 0.1505         | 0.3512            |
|                   | (5)           | \( b_2 \)    | 0.1505         |                   |
|                   | (6)           | \( b_3 \)    | 0.0502         |                   |
| Runoff routing    | (7)           | \( c_1 \)    | 0.0878         | 0.3512            |
|                   | (8)           | \( c_2 \)    | 0.0878         |                   |
|                   | (9)           | \( c_3 \)    | 0.1756         |                   |
| River retention   | (10)          | \( d_1 \)    | 0.0308         | 0.1887            |
|                   | (11)          | \( d_2 \)    | 0.1018         |                   |
|                   | (12)          | \( d_3 \)    | 0.0560         |                   |

3.3. **Health evaluation of dimension layer and indicator layer**

According to the threshold range of the indicators in Schedule 1 of supplementary materials, though the calculating the data of each indicator collected through monitoring and investigating, the scores of each indicator can be obtained, and then the health status of each indicator can be obtained. By multiplying the health scores of each index of different dimensions by their corresponding weights (Table 2) and summing, the health of different dimension layers is obtained to reflect the health status of each key link of the urban water cycle under the processes of stormwater production and convergence.

The total evaluation results can be obtained by weighting all the indicator scores. The formula is as follows:

\[
H = \sum_{i=1}^{n} h_i \times w_i \quad (i = 1, 2, \cdots, n)
\]  

(4)

where, \( H \) is the total score for evaluation, \( h_i \) is the health score for individual indicators, \( w_i \) is the weight of each indicator [22].

4. **Results**

From the section of 3.2, the scores of 12 evaluation indicating indices of the “6.21” stormwater runoff processes were calculated. According to the weighted average method in Chapter 2, the health scores of each dimension and the comprehensive processes were obtained. The results are shown in Table 3.

| Indices name | Indices score | Dimensions layer score | Synthesis results |
|--------------|--------------|------------------------|-------------------|
| \( a_1 \)    | 2.78         | 2.78                   | 3.08              |
| \( a_2 \)    | 2.11         |                        |                   |
| \( a_3 \)    | 5            |                        |                   |
| \( b_1 \)    | 3.35         | 3.42                   |                   |
| \( b_2 \)    | 3.42         |                        |                   |
### 3.1 Single indicator evaluation result

For the convenience of display, the results of each indicator are made into columnar section, as shown in figure 7. It can be seen from the figure that the evaluation scores are as follows: a3 evaluation score is the highest, which is in an extra healthy state, followed by d2, which is in a healthy state, indicating that the River channel design standard in Handan can meet the flood control standard. Indices b1, b2, b3, c2, and d3 are sub-healthy states, indicating that the infrastructure construction capacity and the integrity level of the ecological environment in the metropolis areas ought to be improved. The other indicators are all in morbidity status. a1 and a2 indicate that the “6.21” has great rainfall and the time of flood peak appeared is in front. It is a relatively large test for urban flood control and flood removal system. The morbidity status of c1 reflects the unbalanced development of urbanization level, especially in the southwest direction of the urban area. The maximum inundation area exceeds 2000 m² where seriously affects the normal travel of residents. c3 reflects the changes in the water quality of the FYR under the stormwater. The quality of river water in the rain is best, and the quality before the rain is worse. The morbidity result shown in d1 reflects the inconsistency between the construction of the metropolis and the development of ecological civilization.

| Index | Evaluation Score |
|-------|------------------|
| a1    | 3.18             |
| a2    | 2.73             |
| b1    | 3.31             |
| b2    | 2.19             |
| b3    | 2.66             |
| c1    | 3.31             |
| c2    | 2.73             |
| c3    | 2.19             |
| d1    | 4                |
| d2    | 3.52             |
| d3    | 3.31             |

4.1. **Single indicator evaluation result**

The convenience of display, the results of each indicator are made into columnar section, as shown in figure 7. It can be seen from the figure that the evaluation score of a3 is the highest, which is in extra healthy state, followed by d2, which is in a healthy state, indicating that the River channel design standard in Handan can meet the flood control standard. Indices b1, b2, b3, c2, and d3 are sub-healthy states, indicating that the infrastructure construction capacity and the integrity level of the ecological environment in the metropolis areas ought to be improved. The other indicators are all in morbidity status. a1 and a2 indicate that the “6.21” has great rainfall and the time of flood peak appeared is in front. It is a relatively large test for urban flood control and flood removal system. The morbidity status of c1 reflects the unbalanced development of urbanization level, especially in the southwest direction of the urban area. The maximum inundation area exceeds 2000 m² where seriously affects the normal travel of residents. c3 reflects the changes in the water quality of the FYR under the stormwater. The quality of river water in the rain is best, and the quality before the rain is worse. The morbidity result shown in d1 reflects the inconsistency between the construction of the metropolis and the development of ecological civilization.

![Figure 7. Urban water cycle health assessment indices score.](image7)

![Figure 8. Urban water cycle health assessment dimensional layer score.](image8)

### 4.2 Dimensional layer health assessment results

The health evaluation results in dimensional layer are shown in figure 8. Capacity of flood storage has the highest score, reaching 3.5, which belongs to the sub-health state. It reflects the better ecological flood control and sustainable development level. The dimension of the processes of runoff generation is 3.35, which also in a sub-health level, and indicators in it are all in sub-health status. The consequence reflects that the response of each element of the runoff generation is equivalent. The rainfall dimension is 2.94, which is in morbid level. The evaluation score of the runoff routing is at least 2.60, indicating that the construction capacity of the drainage facilities in the region is poor.

### 4.3 Comprehensive evaluation result

The comprehensive evaluation score of "6.21" is 3.08 in Handan metropolis, which means a sub-health status. Thus it is necessary to conduct some measures for improving the health level of water cycle in Handan metropolis.
5. Conclusions and suggestions

Health evaluation of stormwater runoff events was conducted in this study, based on the concept of social water cycle in metropolitan areas. A health evaluation indices system of event-based stormwater runoff processes was established by integrating the AHP and KPI methods. The Handan metropolis, North China, was selected as a case study. Research showed that the evaluation of stormwater runoff processes in study shows a sub-health status. Among the four dimensions of the evaluation, the weakest is the runoff generation, followed by the rainfall. Thus, it is shown that the processes of production are the most critical link in the health evaluation of stormwater runoff processes in metropolitan areas. This result maps out the problem of poor infrastructure construction in Handan metropolis. Possible solutions for better stormwater management could be:

- In terms of reducing the ecological risk: improve the effective utilization of rainfall by increasing the area of non-hardened ground in metropolitan areas. Pollution control of the FYR water system should be increased and river's ability of absorbing pollutants must be improved.
- In functions of urban channel: improve the flood control standard for river construction by constructing ecological slope protection, and obstacles in rivers should be reduced to improve river connectivity.
- In metropolis waterlogging management: ensure that residents in heavy rains are not affected by inundation by improving the construction capacity of the drainage system and increasing the efforts of the municipal departments.

Acknowledgments

The researchers would like to extend their thanks to the National Key Research and Development Program of China (No. 2016YFC0401401-6) and the Natural Science Foundation of Hebei Water Authority, China (No. 201757).

References

[1] World Health Organization 2006 Constitution of the World Health Organization - Basic Documents
[2] Zhang J and Ding G G 2002 China's water environment engineering restoration engineering strategy Eng. Sci. 4 44-9
[3] Zhang S, Fan W and Yi Y J 2017 Evaluation method for regional water cycle health based on nature-society water cycle theory J. Hydrol. 22 352-64
[4] Amrita P, Yiliang H and Martin J 2014 Emerging contaminants of public health significance as water quality indicator compounds in the urban water cycle Environ. Int. 71 46-62
[5] Setu N N, Hossain S and Saha R 2014 Natural disasters impact on the water cycle, resource, quality and human health ICCESD 25 1-10
[6] Zhang S, Fan W and Yi Y J 2017 Evaluation method for regional water cycle health based on nature-society water cycle theory J. Hydrol. 22 352-64
[7] Wei R W and Zeng T M 2005 Calculating of proportion based on analytic hierarchy process in basin water allocation J. Tongji Univ. (Nat. Sci.) 33 1133-66
[8] Luan Q H, Zhang H X and Liu J H 2015 KPI-based health assessment for water cycle of Handan Water Resour. Hydr. Eng. 10 26-30
[9] Cai J N, Pan W B and Cao Y G 2010 Impact of river morphology on urban river self-purification capacity in Guangzhou Water Resour. Prot. 05 16-9
[10] Deng X and Li J M 2012 Research on computation methods of AHP wight vector and its applications Math. Pract. Theory 7 93-100
[11] Khalifa N B, Tyteca D and Marianela C 2012 Structural features of the KPI domain control APP dimerization, trafficking, and processing FASEB J. 26 855-67
[12] Zhou L F, Xu S J and Sun W G 2008 Healthy water circulation assessment of Zhalong wetland based on PSR model Adv. Water Sci. 2 205-13
[13] Hou J M and Guo K H 2017 Numerical simulation of design storm pattern effects on urban flood inundation *Adv. Water Sci.* 6 820-8
[14] Wang J H and Hu P 2013 Studies on evaluation system of water ecological civilization *Chin. Water Resour.* 15 39-42
[15] Naouel B K, Donatienne T and Claudia M 2012 Structural features of the extracellular and juxta/transmembrane domains controlling APP dimerization, trafficking and processing *Alzheimer's & Dementia* 8 730
[16] Code for design of outdoor wastewater engineering GB 50014-2006 CPP
[17] Urban interior control design standards GB51222-2017 2017 CPP
[18] Cai J N 2008 Relationship between urban river form and river self-purification ability *SCUT* 1-67
[19] Luo X and Xu Y P 2012 Study on impacts from water conservancy projects on river network connectivity-a case of Xizhaoxi River Sub-catchment of Taihu Lake Basin *Water Resour. Hydr. Eng.* 09 004
[20] Wang W R and Tu M C 2005 Calculating of proportion based on analytic hierarchy process in basin water allocation *J. Tongji Univ. (Nat. Sci.)* 33 1133-6
[21] Jin J L, Wei Y M and Fu Q 2002 Application of analytic hierarchy process based on genetic algorithm to water environment systems engineering *Adv. Water Sci.* 04 013
[22] Luan Q H, Zhang H X Chu J Y 2012 Health assessment of water cycle in Tianjin metropolis based on KPI *Int. J. Hydroelectric Energy* 5 38-41