Vulnerability Assessment and Empirical Study of Urban Drainage Network Based on Coupling Analysis

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Abstract. The implementation of vulnerability assessment of urban drainage network is of great significance to improve the efficiency of urban waterlogging control. Based on the coupling perspective, the vulnerability assessment index system of urban drainage network is constructed from three dimensions of "exposure-sensitivity-adaptability". Taking Tianjin as an example, the vulnerability of urban drainage network is empirically analyzed. The results show that reducing the exposure index and improving the sensitivity index and strain capacity of urban drainage network can effectively reduce the vulnerability of urban drainage network; According to the vulnerability of urban drainage networks, targeted prevention and control measures are taken.

Keywords: Urban drainage pipe network; Coupling analysis; Vulnerability assessment.

1. Introduction
With the acceleration of urbanization, urban waterlogging in China has a sharp increasing trend, which shows that the urban impervious ground rate increases from 20% to 80%, and 90% of the whole urban drainage network is responsible for it. If the urban drainage network can't resist the rainstorm at this time, that is, the urban drainage network is fragile, and waterlogging disaster will easily occur in the city once it encounters rainstorm. Therefore, under the background of frequent urban waterlogging, it is necessary to diagnose the vulnerability of urban drainage network, find out the vulnerability of urban drainage network and take corresponding emergency measures to reduce the occurrence of urban waterlogging.

From the existing achievements, scholars at home and abroad have carried out multi-level and multi-faceted research on urban vulnerability in many fields, and have achieved fruitful results in theory and method. However, most of the results are too general, the operability is not strong, the accuracy of spatial pattern recognition and positioning is not accurate enough, and the policies tend to be macro-scale. Therefore, some scholars have narrowed their research scale and turned their research direction to infrastructure, which is the material basis for ensuring the normal operation and healthy development of cities. Song collected the factors affecting subway vulnerability through expert interviews and literature research, and used ISM and MICMAC to construct the hierarchical relationship and dependence quadrant diagram of embrittlement factors respectively. The research results show that subway embrittlement factors can be divided into three types: independence, linkage and dependence; Wang constructed a power grid vulnerability assessment model by comprehensively considering factors such
as power grid topology characteristics, voltage stability, and system power flow distribution, and based on this, comprehensively assessed the vulnerability of the system by using hesitant fuzzy decision-making method; Yu constructed the topology of high-speed railway network based on complex network theory, and analyzed the performance of high-speed railway under random attack and deliberate attack by calculating the maximum connectivity subgraph and network efficiency. Through literature research, it is found that most of the researches on the vulnerability of infrastructure focus on the power grid and road network, while the related researches on the drainage system as the disaster-bearing body are rare.

Therefore, in this study, deductive reasoning method and literature analysis method are used to construct an index system for vulnerability evaluation of urban drainage network according to drainage design specifications. In order to verify the hierarchical structure and rationality of the index system, the questionnaire method and SPSS statistical software are used to carry out item analysis on the survey data, screen out inappropriate indicators, and then determine the final evaluation index system. Through literature research, this paper sorts out the vulnerability assessment methods commonly used by researchers at present, such as BP neural network method, set pair analysis method, data envelopment analysis, ecological footprint analysis method, comprehensive index method, vulnerability assessment method based on coupling degree, compares and analyzes the basic connotation, basic principles, advantages and disadvantages, application fields and other aspects of the above commonly used vulnerability assessment methods, and determines the vulnerability assessment methods adopted in this study and constructs specific models of vulnerability assessment according to the selection principles of vulnerability assessment methods for urban drainage networks. On this basis, the waterlogged area of a certain district in Tianjin is selected to verify the scientificity, effectiveness and rationality of the vulnerability evaluation index and method of urban drainage network.

2. Research area and Data resources

2.1. Study area

Tianjin is located in the northeast of North China Plain and the lower reaches of Haihe River Basin, which has a continental climate. Rainfall is mainly concentrated in summer, with an average annual
rainfall of about 550 ~ 700 mm. The rainfall from June to July accounts for about 80% of the total annual rainfall. In this example, the drainage pipe network of a certain district in Tianjin is selected as the evaluation object. The total area of the district is 570km², and the resident population is about 700,000. The terrain is low and flat, with the highest in the northwest, lower in the southeast and the lowest in the middle. There are 3 first-class rivers, 10 second-class rivers, and a district-level medium-sized reservoir with a capacity of 30 million cubic meters. It governs 2 streets and 7 towns with an average annual rainfall of 585mm the total length of drainage pipe network involved in this community is 15km, with 475 inspection wells and 792 road drainage grates, with a building area of about 120,000 km² and 1,350 households. There are some problems in this community, such as low management level, low construction standard, low gradient coefficient of drainage pipe network, drainage pipe diameter less than 600mm, and blockage of drainage pipe network caused by domestic sewage poured into drainage pipe network by residents. Some physical drawings are shown in Figure 1.

2.2. Data resources
The basic data and materials involved in the research were collected with the support of Tianjin Municipal Design Institute, Tianjin Drainage Management Office, Tianjin Water Affairs Bureau, Tianjin Statistics Bureau and other relevant departments. The missing data in individual years were obtained by trend extrapolation and other methods.

3. Vulnerability Evaluation Model of Urban Drainage Network

3.1. Rating Index System of Urban Drainage Network
By consulting relevant data and visiting relevant governments for investigation, the vulnerability evaluation index of urban drainage system is constructed from three aspects: exposure, sensitivity and resilience of urban drainage system, as shown in Table 1.

| Criterion Layer                  | Indicators                                   | Properties of | Data standard |
|----------------------------------|----------------------------------------------|---------------|---------------|
| Exposure of urban drainage system| Roughness of ground                          | +             | 0.454         |
|                                  | Terrain                                      | +             | 0.552         |
|                                  | Soil permeability coefficient                 | -             | 0.631         |
|                                  | Urban permeable ground rate                   | -             | 0.542         |
|                                  | Green coverage rate                           | -             | 0.601         |
|                                  | The rate of water                             | -             | 0.412         |
|                                  | Rainstorm intensity                           | +             | 0.687         |
|                                  | Duration of rainfall                          | +             | 0.436         |
|                                  | Population density                           | +             | 0.556         |
|                                  | Citizen's quality and education level         | -             | 0.625         |
|                                  | Urban environmental sanitation                | -             | 0.633         |
| Sensitivity of urban drainage system | Discharge capacity of rainwater inlet         | -             | 0.698         |
|                                  | Pipe diameter                                 | -             | 0.586         |
|                                  | Pipeline slope                                | -             | 0.662         |
|                                  | Roughness coefficient of pipeline             | +             | 0.453         |
|                                  | Pipeline age                                  | +             | 0.775         |
|                                  | Pipeline section                              | -             | 0.595         |
|                                  | Setting height of water outlet                | -             | 0.756         |
|                                  | Density of drainage pipe network              | -             | 0.758         |
|                                  | Pipe network laying rate                      | -             | 0.794         |
| Coping ability of urban drainage system | Financial investment ratio of                 | -             | 0.886         |
|                                  | Management level of drainage                  | -             | 0.894         |
|                                  | Rainstorm recurrence period                   | -             | 0.561         |
|                                  | The regulatory capacity of that               | -             | 0.743         |
|                                  | Number of rainwater pumping                   | -             | 0.612         |
3.2. Data standardization

The range standardization method is used to normalize the original data, and according to the different attributes (+,-) of the evaluation index, the formula (1) and formula (2) are used to calculate, so that the standard value of the index is distributed in the interval \([0, 1]\).

\[
L_i = \frac{x_i - \min(x_j)}{\max(x_j) - \min(x_j)}, \quad 1 \leq j \leq n
\]  
(1)

\[
L_i = \frac{\max(x_j) - x_i}{\max(x_j) - \min(x_j)}, \quad 1 \leq j \leq n
\]  
(2)

\(L_i\) is the standardized value of index i; \(X_i\) is the actual value of index i; \(\max\{X_j\}\) and \(\min\{X_j\}\) are the maximum and minimum values of index i in the study period.

3.3. Determination of index weight

The weight determined by entropy method. The entropy value and weight are calculated by using formula (3) and formula (4) below.

\[
H_i = -\frac{\sum_{i=1}^{n} f_i \ln(f_i)}{\ln(n)}
\]  
(3)

\[
f_i = \frac{L_i}{\sum_{i=1}^{n} L_i}, \quad n \text{ is the total number of indicators, and } L_i \text{ is the standard value of indicators.}
\]

\[
Q_i = \frac{(1 - H_i)}{\sum_{i=1}^{n}(1 - H_i)}
\]  
(4)

\(H_i\) is the entropy value of index i. Determine the final index weight. Use formula (5) to calculate the final index weight, as shown in table 2.

\[
W_i = \frac{(1 - H_i)}{\sum_{i=1}^{n}(1 - H_i)}
\]  
(5)

| Table 2. Weight value of each evaluation index |
|-----------------------------------------------|
| **Criterion Layer**                           | **Indicators**                        | **AHP weight** | **Entropy method weight** | **Final weight** |
| Exposure of urban drainage system             | Roughness of ground                   | 0.0335         | 0.0329                    | 0.0332          |
|                                                | Terrain                               | 0.0221         | 0.0220                    | 0.0221          |
|                                                | Soil permeability coefficient         | 0.0558         | 0.0547                    | 0.0553          |
|                                                | Urban permeable ground rate           | 0.0595         | 0.0594                    | 0.0595          |
|                                                | Green coverage rate                   | 0.0536         | 0.0539                    | 0.0538          |
|                                                | The rate of water                     | 0.0421         | 0.0422                    | 0.0422          |
|                                                | Rainstorm intensity                   | 0.0501         | 0.0498                    | 0.0500          |
|                                                | Duration of rainfall                  | 0.0582         | 0.0577                    | 0.0580          |
|                                                | Population density                    | 0.0301         | 0.0312                    | 0.0307          |
|                                                | Citizen's quality and education level | 0.0115         | 0.0113                    | 0.0114          |
|                                                | Urban environmental sanitation level   | 0.0281         | 0.0275                    | 0.0278          |
| Sensitivity of urban drainage system          | Discharge capacity of rainwater inlet | 0.0392         | 0.0401                    | 0.0397          |
|                                                | Pipe diameter                         | 0.0405         | 0.0396                    | 0.0401          |
|                                                | Pipeline slope                        | 0.0522         | 0.0526                    | 0.0524          |
|                                                | Roughness coefficient of pipeline     | 0.0296         | 0.0288                    | 0.0292          |
|                                                | Pipeline age                          | 0.0465         | 0.0455                    | 0.0460          |
|                                                | Pipeline section                      | 0.0374         | 0.0358                    | 0.0366          |
|                                                | Setting height of water outlet        | 0.0238         | 0.0230                    | 0.0234          |
|                                                | Density of drainage pipe network      | 0.0629         | 0.0635                    | 0.0632          |
|                                                | Pipe network laying rate              | 0.0622         | 0.0641                    | 0.0632          |
| Coping ability of urban drainage system       | Financial investment ratio of infrastructure | 0.0311         | 0.0302                    | 0.0307          |
|                                                | Management level of drainage system   | 0.0413         | 0.0389                    | 0.0401          |
|                                                | Rainstorm recurrence period           | 0.0352         | 0.0327                    | 0.0340          |
|                                                | Regulatory capacity of that storage construct | 0.0213         | 0.0206                    | 0.0210          |
|                                                | Number of rainwater pumping stations  | 0.0322         | 0.0337                    | 0.0330          |
3.4. Calculation of comprehensive vulnerability index
Formula (6) is used to calculate the vulnerability comprehensive index of urban drainage network.
\[ V = \sum_{i=1}^{n} L_i W_i \]  
(6)

\( L_i \) is the standard value of index i, and \( W_i \) is the weight value of index i.

3.5. Classification of vulnerability of urban drainage network
In order to compare the vulnerability of urban drainage networks, the vulnerability of urban drainage networks is divided into five grades with reference to existing research, as shown in Table 3.

| \( V \) classification | Vulnerability degree |
|-------------------------|----------------------|
| 0.85 ≤ \( V \) < 1.00 | I no                 |
| 0.65 ≤ \( V \) < 0.85 | II minor             |
| 0.45 ≤ \( V \) < 0.65 | III moderate         |
| 0.25 ≤ \( V \) < 0.45 | IV serious           |
| 0 ≤ \( V \) < 0.25    | V ultra-severe       |

4. Results and policy recommendations

4.1. Results

4.1.1. Exposure analysis. In the process of urban development and construction in Tianjin, the construction concept of "sponge city" has been integrated into it. The permeable ground rate has gradually increased from 25% to nearly 40%, and the green coverage rate has now increased to 38%. The addition of the concept of "sponge city" has increased the flexibility of the city to a certain extent, making Tianjin's ability to cope with severe rainstorms constantly enhanced; In addition, the average rainfall in Tianjin during the flood season is about 700 mm. In the face of more rainfall, Tianjin has adopted the "source control" strategy, such as: parking lots, residential roads, etc. are paved with permeable ground according to specific conditions; Set up grass planting ditch on the premise of allowing on both sides of the road; When the old city is reconstructed, the workload of the original drainage pipe network shall not be increased, and the concept of low-impact development shall be adhered to. The construction of "Sponge City" has achieved initial success, and the exposure variable weight index is generally on the rise. In the dimension of exposure, rain intensity and rainfall are difficult to be controlled artificially. Therefore, the emphasis should be placed on permeable ground rate and green coverage rate, which have great influence on the exposure. However, the topography of different regions in Tianjin is not the same, so we should pay attention to local conditions and make up for the blind area of urban drainage network function.

4.1.2. Sensitivity analysis. According to Tianjin Drainage Special Plan (2008~2020), Tianjin is divided into the main city, Binhai New Area and other districts and counties. According to various indicators such as topography and vegetation coverage, different target values of pipe network penetration rate are set, which are 95%, 90% and 85% respectively. In the last round of drainage planning, only the downtown area of Tianjin was included in the planning scope. After the successful implementation of the last round of planning, by 2007, the penetration rate of drainage network in downtown area of Tianjin had reached 70.06%. From 2008 to 2017, Tianjin carried out rain and sewage diversion transformation in the old city based on urban construction, and upgraded and expanded the existing drainage pipe network at the same time. Until 2016, the drainage pipe network penetration rate in the central city of Tianjin reached 80.4%. The improvement of drainage pipe network penetration rate greatly improved the sensitivity variable weight index, and its variable weight index generally showed an upward trend. In 2013 and 2016, the sensitivity was increased. On the other hand, the construction and renovation of urban drainage network is restricted by the municipal finance, so the sensitivity variable weight index
fluctuates in individual years. There is still a big gap between the penetration rate of urban drainage network in Tianjin and the target set in the planning. There are some problems in the old urban drainage network, such as long service time and low standard of pipeline construction, which hinder the upgrading and reconstruction of the old urban drainage network. The planning and construction of urban drainage networks should focus on the modernization of drainage networks in new districts and the upgrading and transformation of drainage networks in old districts.

4.1.3. Coping ability analysis. From 2008 to 2017, the length of rainwater pipes in downtown Tianjin increased from 1190km in 2008 to 1338km in 2017, and the number of rainwater pumping stations increased from 98 in 2008 to 120 in 2017; The construction of drainage network in new urban areas and the reconstruction of drainage network in some old urban areas have improved the drainage capacity of Tianjin drainage network from 671m³/s in 2008 to 1940.3m³/s in 2017. With the great improvement of drainage capacity, the drainage network's ability to cope with unfavorable factors such as heavy rainfall weather has been continuously improved. In addition, the relevant government departments in Tianjin pay close attention to the frequent urban waterlogging problems. The municipal capital investment for the construction and renovation of urban drainage network is also increasing, but we should pay more attention to the effective use of the investment funds, continuously improve the related basic supporting facilities of urban drainage network, and accelerate the overall level of urban drainage network.

4.1.4. Comprehensive analysis. According to the above formula and data, the comprehensive evaluation index of urban drainage network in the research target district is 0.6265, and the drainage network in the research area is moderately fragile according to the classification table of urban drainage vulnerability. It shows that the drainage network in the study area still can not meet the drainage demand, the drainage speed is slow, the phenomenon of water accumulation often occurs in rainy season, and the drainage facilities lag behind the urban development speed. In view of the drainage network in this community, on the one hand, it is necessary to upgrade and transform the existing drainage facilities to speed up the development of the drainage network itself and reduce the physical sensitivity and structural sensitivity of the drainage network itself; On the other hand, we should improve the utilization rate of financial allocation and the internal and external coping ability of urban drainage network. At the same time, we should pay attention to local conditions in the process of "sponge city" construction, and focus on the permeable ground rate and green coverage rate which have a great impact on exposure, so as to improve urban flexibility and make up for the blind area of urban drainage network function.

4.2. Policy recommendations
According to the vulnerability assessment and analysis results of drainage network in a certain district of Tianjin, in order to effectively prevent the occurrence of urban waterlogging disasters and strengthen the management of urban drainage network, the following measures can be taken.

(1) Drainage pipe access shall be standardized and unified. The municipal department shall carry out unified planning, unified design, unified construction and unified acceptance of the drainage pipeline access points of residential areas, restaurants and other drainage users, and prohibit individuals from reforming without permission.

(2) Fine management. Formulate regular cleaning plans for residential areas, markets and downtown areas with large population density, and prohibit all catering and other industries from dumping domestic sewage into drainage pipelines; Relevant government departments need to increase capital investment, focus on supervising the whereabouts and utilization efficiency of funds, increase the number of drainage outlets on both sides of main roads, improve the drainage capacity, and ensure that each road discharges water by itself to avoid water accumulation in low-lying areas.

(3) Constructing GIS database of drainage pipe network. At present, many cities at home and abroad have established the GIS database of drainage pipe network. Combining with the Internet of Things technology, the GIS database is connected with the sensors on the drainage pipe network, collecting,
storing and analyzing the relevant data of drainage pipe network in time, and constructing a standard data database to realize the functions of early finding problems and accurate positioning.

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