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Importance Assessment of Water Supply Networks Considering Multi-Features

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Abstract

With the increasing expansion of cities, the water supply pipeline network is becoming increasingly complex. How to scientifically and effectively evaluate the water supply networks will be of great significance to the maintenance of the urban water supply network. Based on the analysis of the spatial characteristics of water supply network data, this paper builds a multi-feature evaluation model considering network characteristics, year, and pipe diameter. The experimental results show that the proposed method realizes the importance evaluation of complex water supply networks, and can provide support for the scientific management of urban water supply networks.

Keywords

Water Supply Pipeline; Multi-Features; Betweenness Centrality; Importance Evaluation.

1. Introduction

City underground pipelines are an important infrastructure, known as the city lifeline [1]. With the rapid expansion of cities, the spatial distribution of underground pipelines becomes wider and the network structure becomes more complex. Due to the lack of a scientific and effective evaluation of the underground pipeline network as well as a regulatory mechanism, a variety of safety accidents are common, causing significant losses to the city's economy and society. As far as urban water supply networks are concerned, pipe bursts occur almost daily in major cities. In addition to construction excavation, the lack of necessary maintenance of critical pipe networks and the lack of supervision of key pipe sections are important reasons [2]. Traditionally, the importance of water supply networks is often judged by the diameter or year of the network, ignoring the overall spatial structure of the network. Some pipe segments in a complex network, are not specific in their explicit properties but are critical to the overall network location, carrying an important role as 'bridge'. So, this paper focuses on the water supply network and discusses the importance of evaluating the importance of each pipe segment in the urban underground pipeline network from spatial, semantic, and other perspectives.

2. Characteristics Analysis of Water Supply Network

The water supply network is an important type of urban underground pipeline. Water is piped from the source to the consumer, forming a complex urban water supply network. The main features are described below:

(1) Attribute information is abundant. Pipelines contain a variety of information such as pipe diameter, date, etc.

(2) Significant characteristics are evident. Traditionally, the pipe diameter is used as an indicator of the importance of the pipe network, and the pipe diameter of the main network is much larger than that of the branch network.

(3) The spatial structure is complex. As urban water supply networks are built and renewed, the complexity of the network composition gradually increases.

It consists of two basic structures: ring and tree. The backbone pipe network is interconnected to form several closed-loop structures and carry the main load functions of the entire pipe network. The structure of the tree-like pipe network is relatively simple, usually occurring at the bottom or end of the network, with the diameter of the pipe decreasing as the number of users decreases. The comprehensive evaluation of the urban water supply network needs to consider its semantic information and its implied spatial structure. Therefore, this paper integrates the properties and spatial characteristics of the water supply network and selects network structure, year, and pipe diameter as the indicators for evaluation.

3. Methodology

3.1. 'Stroke' Data Model Construction of Water Supply Network

A large amount of data in the water supply network, in which a large number of adjacent pipe sections are of the same material and diameter, results in data redundancy. First of all, we use 'stroke' to reduce the complexity of the network. The method is widely used in research on road network synthesis, pattern recognition, etc [3,4]. According to the 'Gestal' cognitive principle, sections of road that satisfy the 'good Continuation' can be connected to form a chain of roads, called 'Stroke' [5]. It is smoother and more coherent than fragmented pipe sections. Stroke is computed as the smallest unit, which will greatly reduce the complexity of the overall calculation. Take the pipeline Stroke as the basic unit of the pipeline hierarchy, the specific steps are shown in Figure 1. Stroke is defined as a continuous collection of pipe segments of the same material and diameter, determined by constraints and connection strategies. (1) Sections of pipe of the same diameter and material are joined together to form a single Stroke. (2) When multiple pipe segments are connected, the every-best-fit policy (Calculate the offset Angle between two pairs and choose the smallest group) is applied.

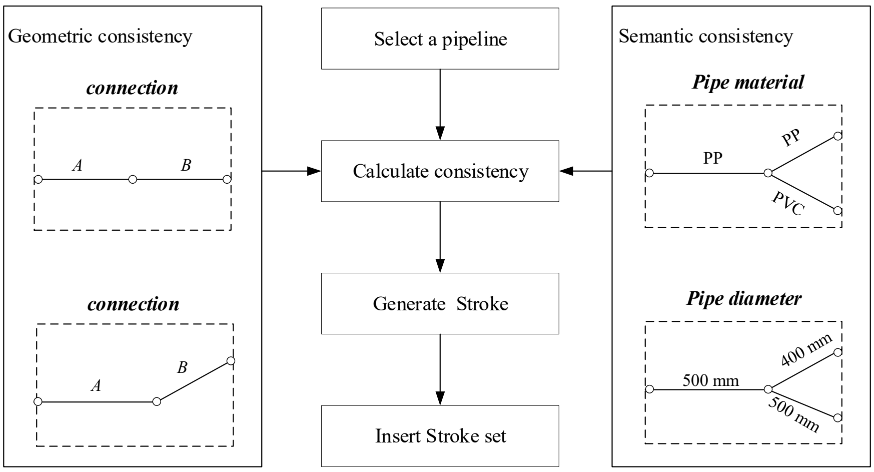

Figure 1: Generate Pipe Network Stroke Set

3.2. Calculation of Network Characteristic

Numerical attributes such as years and pipe diameter are normalized to participate in the index calculation. But the index to pipe network structure should be from an analysis of network characteristics. In related research of complex networks, centrality can be used to describe the importance of nodes in the network [7]. Centrality calculation mainly includes degree centrality, close centrality, and betweenness centrality. Betweenness centrality (BC) denotes the probability that a node is located in the middle of other points in the network [8]. We chose BC as the network structure indicator:

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$$BC_i = \sum_{j,k \in N} \frac{n_{jk}(i)}{n_{jk}} \tag{1}$$

where n_{jk} is the number of lines of the shortest path between node j and k,$n_{jk}(i)$ represents the number of lines passing through the node i. The value of BC is in [0,1]. 0 means that the pathway between the other pipe segments does not pass through the segment, 1 signals that the pathway between all other pipe segments passes through the segment. It can be seen that the betweenness centrality is a global indicator, and the higher the intermediary center is, it means that the pipe segment acts as a 'bridge' in the network, which is more important for maintaining the connectivity of the graph.

3.3. Importance Evaluation Model

Analytic Hierarchy Process(AHP) breaks down the elements related to decision making into levels such as goals, guidelines, and programs. It greatly simplifies the complexity of the human empowerment process and makes the analysis process and results more concise and easy to understand, so it is widely used in dealing with complex decision problems. We take years(T), pipe diameter (D), and network structure as indicators, and use AHP to calculate weights. Firstly, the importance evaluation factors are represented hierarchically, as shown in Figure 2.

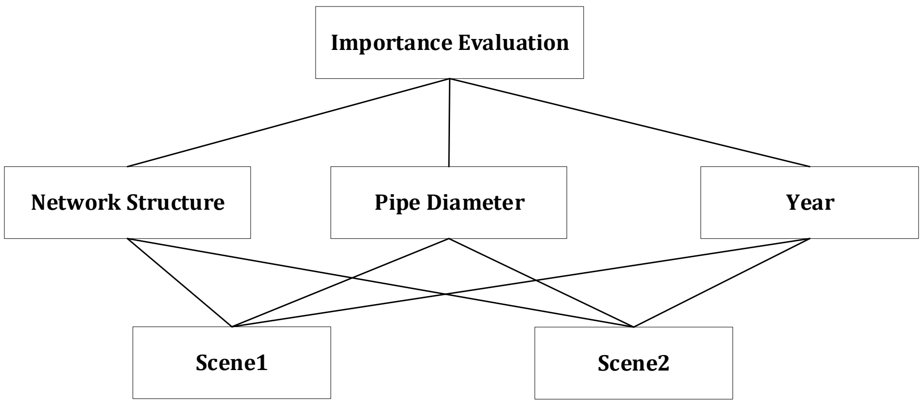

Figure 2: the hierarchical importance evaluation model

Then, the factors are compared in the hierarchical Importance evaluation model, divided into 1-9 levels, to construct an importance discrimination matrix. The meaning of the judgment scale is as follows:

Table 1: Scale of the hierarchical model

Scale	Description
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very Strong importance
9	Absolution importance
2, 4, 6, 8	Indicates the middle value of the above neighboring judgments

Calculate the maximum eigenvalue λmax of the judgment matrix and the corresponding eigenvector ω. Define consistency metrics as:

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

The larger the CI, the greater the inconsistency. For the consistency test, the proportion of consistency was calculated using CI and the random consistency index RI as follows:

$$x = \frac{CI}{RI} \tag{3}$$

The RI values for the number of indicators n ranging from 1 to 9 are shown in Table 2. When CR < 0.1, the inconsistency is within tolerable limits and the test is passed.

Table 2: RI value

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

In summary, the steps of importance evaluation are as follows:

(1) Pre-process the pipeline data and generate the Stroke data set for the pipeline;

(2) Perform calculations of spatial structure indicators in pipeline Stroke.

(3) Discriminate the importance between network structure, years, and diameter of the pipeline Stroke, construct a discriminant matrix and calculate the weights of each indicator.

(4) Calculate the importance of each pipe segment, and extract the corresponding hierarchy.

4. Results and Discussion

A part of the water supply network in Nanjing City is selected for zoning experiments, covering an area of about 6 km2. The pipe network data consists of 12,772 pipe segments with a total length of 100.52 km, and after simplification, more than 5800 pipe network Strokes are generated, as shown in Figure 1 (a).

(a) (b)

Figure 3: Study area and experimental results

According to the AHP, the importance index of each pipeline is calculated to form a comprehensive level of importance, with parameters as shown in Table 3. The value of CR is 0.05. It indicates that the consistency check is passed and the weight is acceptable.

Table 3: Index judgment matrix

Index	Matrix	Weights
betweenness centrality	$\begin{bmatrix} 1 & 2 & 4 \\ 1/2 & 1 & 4 \\ 1/4 & 1/4 & 1 \end{bmatrix}$	0.54
pipe diameter		0.35
years		0.11

Finally, the importance of each pipe segment is quantified. Selecting 10%, 20%, and 70% to divide the pipe network into three parts, correspondingly extract the backbone network, branch network, and terminal network of the pipe network, in Figure 3 (b). The experimental results show that different from selecting a single index such as pipe diameter or length, the method in this paper highlights neighboring pipe segments with the same properties that have higher network mediation.

5. Conclusion

This paper focuses on the important evaluation of urban water supply pipeline networks and extracts a Multi-Features evaluation model that takes into account the network characteristics, years, and diameter of the pipeline network. Different from the traditional single index, the proposed method integrates both semantic and spatial dimensions, calculates relatively scientific index weights using a hierarchical analysis model, and selects actual data of Nanjing city for validation. The experimental results show that this method can provide technical support for the scientific management of urban water supply pipeline networks.

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