Evaluation Method Of Important Nodes Of Water Supply Network Under Terrorist Attack

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Abstract: Aiming at the problem of urban water supply network protection under terrorist attack, a new comprehensive value evaluation method for important nodes of water supply network is proposed. Combined with the characteristics of terrorist attacks, Epanet and Aloha were used to simulate the changes in the efficiency of the water supply network and the consequences of secondary disasters after the node was destroyed, and a comprehensive value evaluation model based on the node's own value, system value and indirect value was constructed. Taking an urban water supply network in Hubei Province as an example, the results can get the following conclusions: ① Compared with the buried water pipeline, the water supply plant as the source of the urban water supply network is the key target of terrorists; ② the calculation results show the comprehensive value of different water plants The gap is huge, and the comprehensive value of water plant 3 is nearly 5 times that of water plant 4; ③ the greater the comprehensive value of the water plant, the greater the terrorist attack revenue and the higher the probability of attack. Therefore, when responding to terrorist attacks, the comprehensive value should be High water plants provide more protection resources.

1. Introduction
The urban water supply network is one of the most important infrastructures in the urban lifeline system [1]. As the foundation of modern city operation and development, urban water supply system is closely related to people's lives. If it is subjected to a terrorist attack, it will seriously affect urban residents' water and industrial water, and affect the economy and people's livelihood [2]. In recent years, terrorist activities have become more and more rampant, and many studies have also pointed out that terrorism throughout the end of the 20th century to the beginning of the 21st century has become one of the most important issues in the world [3]. On December 1, 2016, terrorists in the Mosul recovery war destroyed the urban water supply network, causing 40% of the local population to face the dilemma of water cuts, and nearly 650,000 people were greatly affected [4]. The urban water supply network is likely to become an important target for terrorists in the future, and its importance cannot be ignored.

So far, there are few studies on the performance evaluation of urban water supply networks after terrorist attacks. Quite a lot of research has also focused on the performance evaluation of urban water supply networks and restoration of water supply under earthquake disasters. Wang Yong and others evaluated and analyzed the damage to the water supply pipeline network in 12 cities and towns under the 2008 Wenchuan earthquake [5]; Lu Jinsuo and others conducted risk analysis on the urban water
supply system after the earthquake and water supply after the earthquake [6]; Yin Yin is investigating the pipeline network. Based on the operating status, a comprehensive evaluation model for the performance of the water supply network is established [7]. The above studies have provided theoretical basis for the performance evaluation of urban water supply network, but failed to consider the performance analysis of water supply network in the context of terrorist attacks.

Unlike natural disasters, the destruction of urban water supply networks by terrorist attacks is subjectively deliberate to a large extent [8]. For example, the probability and extent of damage to the water supply network caused by natural disasters such as earthquakes are random. Terrorists will evaluate the damage benefits of targets from many aspects and carry out precise strikes on targets with the greatest gains. At the same time, the two methods of attack also have huge differences in destroying targets. Most natural disasters damage the buried and widely distributed water pipelines. Terrorist attacks will select targets that have larger targets and play an important role in the water supply network, such as water supply plants. The water supply plant filters and disinfects the raw water transported from the water source, and feeds the treated water into the urban water supply network through a pressure pump [9]. If the water supply plant is destroyed, it will have a huge impact on the city's water supply and surrounding safety. This article will take the water supply network of a certain city in Hubei Province as a case, through the quantitative analysis of the water plant's own value, system value and indirect value, obtain the comprehensive value evaluation model of the water plant. The water plant with the largest comprehensive value is the target most threatened by terrorist attacks and provides a basis for the protection of urban water supply networks.

2. Comprehensive valuation model

The urban water supply network consists of water plants, water pipelines, pump units and gate valves. Without affecting the characteristics of the network, appropriate abstractions are made to simplify the water supply network to a pipe network model consisting of only two types of elements: pipelines and nodes. Because most of the water pipelines are buried underground and are widely distributed. For terrorists, the sensation caused by the attack on the water plant is huge, and it is usually the preferred target. Therefore, the important node of the urban water supply network is the water supply plant. The comprehensive value evaluation of the water supply plant mainly includes three aspects of the water plant's own value, system value and indirect value, and then the weight coefficients of different values are determined by the entropy weight method. The establishment of a comprehensive value evaluation model is shown in Figure 1.

![Figure 1. Water plant comprehensive value evaluation model](image_url)
2.1. Self-valuation method

This paper chooses the analytic hierarchy process to evaluate the value of important nodes in the urban water supply network. Analytic Hierarchy Process (AHP) [10] is a qualitative and quantitative, systematic and hierarchical system analysis method proposed by Saaty, an American operations researcher, in the early 1970s. This method uses less The mathematicalization of the thinking process of decision-making, thereby simplifying complex decision-making problems. It has been widely used in non-quantitative weight determination problems.

To determine the weight of important nodes in the water supply network, the analytic hierarchy process first needs to determine the judgment matrix. When determining the weights of various factors, it is not easy to obtain consensus if the results are only qualitative. Therefore, the Analytic Hierarchy Process proposes the consistent matrix method, which determines the appropriate scale through the pairwise comparison of each element, and realizes the conversion from qualitative to quantitative by combining expert scores. Let \( a_{ij} \) be the comparison result of the importance of factor \( i \) and factor \( j \), and establish a judgment matrix based on the comparison result. among them

\[
a_{ij} = \frac{1}{a_{ji}}
\]  

Taking the Saaty scale as the benchmark, the specific scale and meaning are shown in Table 1

| Factor i vs. factor j          | Scale value | Factor i vs. factor j          | Scale value |
|-------------------------------|-------------|-------------------------------|-------------|
| Extremely important           | 9           | Extremely unimportant          | 1/9         |
| Strongly important            | 7           | Strong unimportant             | 1/7         |
| Stronger important            | 5           | Obviously unimportant         | 1/5         |
| Slightly important            | 3           | Slightly unimportant           | 1/3         |
| Equally important             | 1           |                                |             |

In order to avoid logical errors when constructing the judgment matrix, it is necessary to check the consistency of the judgment matrix. Define the consistency index \( CI \) as

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1}
\]  

Where \( n \) represents the order of the judgment matrix, and \( \lambda_{\text{max}} \) is the maximum eigenvalue of the judgment matrix. When \( CI=0 \), the matrix has complete consistency; \( CI \) is close to 0, and there is satisfactory consistency; the larger the \( CI \), the more serious the data inconsistency. In order to measure the size of \( CI \), the random consistency index \( RI \) is introduced. The \( RI \) value is related to the order of the judgment matrix. Generally speaking, the larger the order \( n \), the greater the probability of random deviation from consistency. The corresponding relationship is shown in Table 2.

| Order n | 1.2 | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11  |
|---------|-----|----|----|----|----|----|----|----|----|-----|
| RI      | 0   | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 |

For the first-order and second-order judgment matrices, they are always the same. When the order is greater than 2, in order to avoid the error of consistency caused by random reasons, the random consistency ratio \( CR \) is introduced to test whether the judgment matrix has satisfactory consistency. Define the random consensus ratio \( CR \) as
When CR<0.1, the judgment matrix is considered to have satisfactory consistency, otherwise the consistency is not satisfied. The weight coefficient $V_E$ calculated by the judgment matrix is the value of water plant $i$.

### 2.2. System Valuation Method

The performance of the water supply network indicates the ability of the network to provide water for residents. When the water supply network is operating normally, all residents can use water, and the network performance is the total water consumption of residents. When the water supply network is damaged, the most obvious feature of network performance degradation is insufficient water pressure at the water demand point. According to the design requirements in China's "Urban Water Supply Project Planning Code": the water supply pressure of the urban water supply network should meet the requirement of 28 meters at the water demand point [11]. Therefore, this article assumes that if the water pressure at the water demand point is lower than 28 meters, it means that the point cannot supply water. We use the total network water supply $P$ to represent the performance of the water plant. As shown in formula (4):

$$P_i = \sum_{j=0}^{m} D_j \alpha_j = \sum_{j=0}^{n} p_j$$

$$\alpha_j = \begin{cases} 
1 & M_j < 28 \\
0 & M_j > 28 
\end{cases}$$

Where $L_j$ represents the water demand of water demand point $j$; $p_i$ is the water supply performance of water plant $i$; $M_j$ represents the water pressure value at water demand point $j$; $\alpha_j$ is a parameter about 0 and 1, when water demand point $j$ is normally supplying water is 1; $n$ is the total number of water plants; $m$ is the total number of water demand points.

When the water supply network is operating normally, the normal water supply of all water plants can meet the water consumption of all water demand points. At this time, $\alpha_j$ is equal to 1, and the initial performance of the water supply network is $P_0$, which is expressed as:

$$P_0 = \sum_{j=0}^{w} L_j$$

When the water plant $i$ is attacked and destroyed, the water pressure of each water demand point of the water supply network drops, and the water consumption of some water demand points cannot be guaranteed. The performance change of the water supply network can be expressed as:

$$\Delta P_i = P_0 - P_i$$

Among them, $\Delta P_i$ is the decrease in network water supply performance caused by the destruction of water plant $i$; $P_0$ is the initial performance of the water supply network; $P_i$ refers to the performance of the water supply network after water plant $i$ is destroyed. When the water plant $i$ is destroyed, the greater the $\Delta P_i$, the greater the performance degradation of the water supply network, the greater the impact on the water supply network, and the higher its system value.

According to formula (7), the data is normalized, and the system value $V_{Si}$ of water plant $i$ is obtained as:
2.3. Indirect valuation method

The water plant is the source of the urban water supply network and an important link in the conversion of raw water into domestic water. At present, the water plants in many cities in China still use the chlorination disinfection method and are equipped with a large amount of chlorine. Chlorine is a yellow gas with a pungent odor, which is very irritating to the human body. Therefore, the diffusion of chlorine will cause serious poisoning and casualties. The indirect value mainly reflects the impact of casualties caused by the diffusion of chlorine gas after the water plant is destroyed. According to the degree of personnel poisoning, we divide it into three situations: death, serious injury and minor injury. In order to facilitate the calculation, the degree coefficient $\phi$ is defined in this article, and $\phi$ represents the severity of the three poisoning states. The values can be defined by different regions. Therefore, the consequences of casualties $D_i$ can be expressed as:

$$D_i = (S_{i1}\phi_1 + S_{i2}\phi_2 + S_{i3}\phi_3) \times \rho_i$$  \hspace{1cm} (9)

Among them, $S_{i1}$, $S_{i2}$ and $S_{i3}$ respectively represent the area of deaths, serious injuries and minor injuries caused by the diffusion of chlorine after the destruction of the $i$-th water plant; represent the population density around the $i$-th water plant; $\phi_1$, $\phi_2$ and $\phi_3$ represent deaths, serious injuries and minor injuries respectively Degree coefficients, according to relevant literature, this article sets the degree coefficients as 2:1:0.035 [12].

According to formula (9), the data is normalized, and the indirect value $V_{Di}$ of water plant $i$ can be expressed as:

$$V_{Di} = D_i \sum_{i=1}^{n} D_i$$  \hspace{1cm} (10)

2.4. Comprehensive Value Evaluation of Nodes

This paper chooses the entropy method to determine the weight coefficients of different values of nodes, and comprehensively evaluate the importance of nodes. The steps of entropy method to determine the weight coefficient are as follows:

Step 1: Establish the index data matrix: For $n$ groups of data and $m$ indexes, record the value of the $j$-th index of the $i$ group of data as, and establish the index data matrix as

$$R_{m,n} = (x_{ij}) = \begin{bmatrix} x_{i1} & \cdots & x_{in} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}_{m\times n}$$ \hspace{1cm} (11)

Step 2: Data standardization processing.

$$X_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$ \hspace{1cm} (12)

Step 3: Calculate the index proportion of the $i$-th group of data under the $j$-th index:

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}$$ \hspace{1cm} (13)
Step 4: Calculate the entropy value of the j-th index:

\[ e_j = \frac{1}{\ln(n)} \sum_{i=1}^{n} P_{ij} \ln(P_{ij}) \]  

(14)

Step 5: Calculate information entropy redundancy:

\[ d_j = 1 - e_j \]  

(15)

Step 6: Calculate the weight of each indicator:

\[ \omega_j = \frac{d_j}{\sum_{j=1}^{m} b_j} \]  

(16)

The weights of various indicators are calculated by the entropy method. Based on the value \( V_{Ei} \), system value \( V_{Si} \), and indirect value \( V_{Di} \) of important nodes in the urban water supply network, the comprehensive \( V_i \) of important node i can be calculated, as shown in equation (17):

\[ V_i = \omega_1 V_{Ei} + \omega_2 V_{Si} + \omega_3 V_{Di} \]  

(17)

Among them, \( \omega_1 \) is the weight of the node's own value, \( \omega_2 \) is the weight of the node system value, and \( \omega_3 \) is the weight of the node's indirect value.

3. case study

According to the above comprehensive value evaluation method of important nodes in the urban water supply network, this section selects a city water supply network in Hubei Province as an example. In this water supply network, there are 5 water plants, 332 water demand points and 577 pipelines. Each water demand point provides water for residents in the area. The water plant can be regarded as the water source of the urban water supply network. Water supply plays a vital role, and it is also the target of terrorists' heavy attacks. For the sake of confidentiality and safety, this article omits the specific geographic information of the city, and appropriately simplifies the water supply network for analysis. The topological structure diagram of the case urban water supply network is shown in Figure 2, and the relevant information of the five water plants in the water supply network is shown in Table 3.

![Figure 2. Topology of urban water supply network](image)

Table 3. Relevant information of water plants

| plants | Elevation | project cost | Chlorine | Average |
|--------|-----------|--------------|----------|---------|


3.1. Self-value calculation

In this case, the number of water plants is 5, which are defined as W₁, W₂, W₃, W₄ and W₅. Through expert scoring, a pairwise comparison matrix is constructed as shown in Table 4.

|   | W₁ | W₂ | W₃ | W₄ | W₅ |
|---|----|----|----|----|----|
| W₁ | 1  | 1/5| 1/4| 2  | 4  |
| W₂ | 5  | 1  | 1/2| 4  | 7  |
| W₃ | 4  | 2  | 1  | 7  | 9  |
| W₄ | 1/2| 1/4| 1/7| 1  | 3  |
| W₅ | 1/4| 1/7| 1/9| 1/3| 1  |

From this calculation of the comparison matrix, the weight coefficients are 0.1120, 0.3190, 0.4596, 0.0737, 0.0357. The maximum eigenvalue of the comparison matrix is λ_{max}=5.1837, and the consistency index of the solution according to formula 2 is CI=0.046. From Table 2, the average random consistency index RI is 1.12, and CR=0.041<0.1 is solved according to formula 3. Therefore, the judgment matrix has satisfactory consistency. The value of the water plant is V₁=0.1120, V₂=0.3190, V₃=0.4596, V₄=0.0737, V₅=0.0357.

3.2. System value calculation

At present, the international development of water supply network analysis is relatively mature. Among them, EPANET, as a water supply pipe network hydraulic and water quality simulation software, has been widely used in teaching, scientific research and engineering design all over the world since its birth, and has received wide acclaim in all aspects [13]. Therefore, this article chooses EPANET as the hydraulic analysis simulation software.

EPANET hydraulic analysis is to use the pipe network adjustment principle to solve the node-ring equations through repeated iterations. In the solving process, the Todini-Pilati gradient iteration is used as the basic algorithm [14]. In determining the total water head, pump flow and head, and reservoir elevation, Under constraint conditions such as node water demand, the continuity equation, pressure drop equation and energy equation are solved simultaneously to finally determine the pipe section flow, flow direction, node water pressure and other data. Through EPANET simulation calculation, we can get the pressure change of each node after different water plants are hit, and then get the performance change ΔPᵢ of the water supply network after each water plant is destroyed. Figure 3 shows the water supply pressure at each demand node in the city after the first water plant was destroyed.

Through the EPANET simulation calculation, we can obtain the water demand points in the network that cannot supply water after each water plant is destroyed, and then obtain the network water supply performance change ΔPᵢ. By calculating the water supply performance Pᵢ of each water plant before the attack, the initial water supply performance Pₒ of the water supply network can be calculated, and the total water supply volume of the water demand point after the water plant is attacked is calculated to obtain the network performance Pᵢ after the water plant i is attacked. Thus, the network performance change ΔPᵢ and the system value Vᵢ of each water plant are calculated, as shown in Table 5.
3.3. Indirect value calculation
This article chooses ALOHA software as the simulation tool for chlorine diffusion. The software was jointly developed by the US Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) Response and Recovery Office. It can be used to analyze the toxic gas diffusion, flashover, pool fire, fireball and other models after the leakage of hazardous chemicals. [15]. According to the most unfavorable principle, we focused on analyzing that after the water plant was attacked, the liquid chlorine storage tank was completely ruptured, and the chlorine gas diffused into the atmosphere in an instant.

Assuming that the chlorine in the water plant is stored in liquid chlorine cylinders, the cylinders are standard for refilling, and the pressure is 2.0 Mpa. The water plants are located in an urban environment with buildings or forests around. Assuming that the terrorist attack occurred on a sunny summer day, the specific meteorological parameters are listed in Table 6.

| Weather: | sunny |
| Wind speed: | 2.4 m/s (10 meters above the ground) |
| Ground environment: | city |
| Wind direction: | southeast |
| Air temperature: | 36.5°C |
| Humidity: | 65% |
| Release type: | Instant release |

The diffusion of chlorine gas can cause poisoning of personnel, and the severity of poisoning depends on the concentration of chlorine gas and the exposure time of personnel. This article selects the widely used internationally used acute exposure guideline level (AEGL: Acute Exposure Guideline Levels). The specific values are listed in Table 5.
Level) to determine the hazard degree of the toxic gas concentration. According to Aloha simulation, the damage range of chlorine diffusion after each water plant is destroyed. Figure 4 and Figure 5 show the network simulation analysis of the secondary disaster effect of chlorine gas in the third water plant:

![Simulation diagram of the damage effect of chlorine diffusion in water plant 3](image1)

![Real-world simulation diagram of the damage effect of chlorine diffusion in water plant 3](image2)

According to the simulation results, we can calculate the damage range of chlorine gas diffusion within two hours. By calculating the coverage area of different damage levels and combining the local population density, we can get the casualties of chlorine gas diffusion $D_i$, and get the indirect value of each water plant through standardized data. As shown in Table 7, the greater the scope of chlorine diffusion, the more dense the personnel, the more serious the casualties, and the greater the indirect value of the water plant.

| Plants | Degree          | Hazardous Area ($m^2$) | Number of People | Casualties Consequences $D_i$ | Indirect Value $V_{Di}$ |
|--------|-----------------|------------------------|------------------|-------------------------------|-------------------------|
| 1      | death           | 367566                 | 331              |                               |                         |
|        | Seriously injured | 1045333               | 941             | 1677                         | 0.150                   |
|        | Minor injuries  | 2371900               | 2135            |                               |                         |
| 2      | death           | 574518                 | 689             |                               |                         |
|        | Seriously injured | 1551176               | 1861            | 3352                         | 0.299                   |
|        | Minor injuries  | 2654644               | 3186            |                               |                         |
| 3      | death           | 710816                 | 782             |                               |                         |
|        | Seriously injured | 1818164               | 2000            | 3681                         | 0.329                   |
|        | Minor injuries  | 3047342               | 3352            |                               |                         |
| 4      | death           | 201030                 | 141             |                               |                         |
|        | Seriously injured | 545883                | 382             | 705                          | 0.063                   |
|        | Minor injuries  | 1680751               | 1177            |                               |                         |
| 5      | death           | 479564                 | 384             |                               |                         |
|        | Seriously injured | 1173792               | 939             | 1777                         | 0.159                   |
|        | Minor injuries  | 2528980               | 2023            |                               |                         |
3.4. Comprehensive value of node
Weight analysis of different values based on entropy weight method, the weight coefficients of each value are obtained as $\omega_1=0.62$, $\omega_2=0.13$, $\omega_2=0.25$. According to the calculation results of the water plant's own value, system value and indirect value, the importance $VI$ of the water plant is calculated according to formula 17. As shown in Table 8, the results quantitatively analyze the importance of water plants, clarify the key position of each water plant in the water supply network, and provide the basis for the protection of urban water supply network.

| plant | Self value $V_{Ei}$ | System value $V_{Si}$ | Indirect value $V_{Di}$ | Comprehensive value $V_i$ |
|-------|---------------------|----------------------|------------------------|-------------------------|
| 1     | 0.112               | 0.227                | 0.150                  | 0.136                   |
| 2     | 0.319               | 0.239                | 0.299                  | 0.304                   |
| 3     | 0.460               | 0.294                | 0.329                  | 0.406                   |
| 4     | 0.074               | 0.090                | 0.063                  | 0.073                   |
| 5     | 0.036               | 0.150                | 0.159                  | 0.081                   |

Figure 6. Comprehensive value of water plants

4. Conclusion
The urban water supply network that has been attacked by terrorists is vital to residents and economic development. Most of the current research focus on the performance loss and recovery of urban water supply networks under natural disasters, and have not considered highly targeted terrorist attacks. This paper proposes a water supply network performance evaluation model based on the destruction of important nodes, which fully considers the functional characteristics of the water supply network and simulates the damage state of the water supply network after different important nodes are attacked. Taking the water supply network of a certain city in Hubei Province as a case, the comprehensive value of water plants in the network was evaluated with the mentioned model. The results showed:

1) The urban water supply network is mainly composed of water plants and water supply pipelines. Compared with water supply pipelines, which are mostly buried underground and widely distributed, terrorists usually choose water plants as their targets. Therefore, the comprehensive value evaluation of important nodes in the water supply network is also a comprehensive value evaluation of water plants.

2) Traditional water supply network performance evaluation is based on natural disasters, and does not consider the particularity of terrorist attacks. Therefore, this article analyzes the three aspects that terrorists care most about, and establishes a comprehensive target value evaluation model that includes its own value, system value and indirect value. The higher the comprehensive value of the target, the greater the proceeds of terrorist attacks and the greater the probability of being attacked.
3) It can be seen from the target comprehensive value evaluation result that the comprehensive value of different water plants varies greatly. Targets with higher comprehensive value should invest more protection resources, further strengthen the urban water supply network, and prepare emergency measures for protection and repair in case of attack in advance to provide a basis for urban water supply network protection.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (51708554) and Natural Science Foundation of Jiangsu Province (BK20181336).

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