Health evaluation of urban water supply pipe network using the Bayesian method based on triangular fuzzy number optimization

Xiangyi Ding1,3, Siran Liu1, Xiaolin Shi2 , Junying Chu1 and Xinlei Guo1

1 China Institute of Water Resources and Hydropower Research (IWHR), Beijing, 100038, China;  
2 Zhengzhou University, Zhengzhou, 450001, China

3 Email: dingxiangyi840318@163.com

Abstract. With the rapid increase of urbanization level in China, the accidents related to urban water supply pipe network occurred frequently due to the impacts of pipeline aging, environmental change and human factors, thus the health evaluation of urban water supply network has become one of the hot topics in recent years. Related researches mostly refer to qualitative and static analysis, some quantitative studies consider the influence of only one aspect on the status of water supply pipe network such as hydraulic, water quality and static structure, and cannot objectively reflect the health status of pipe network due to neglecting or simplifying the influence of internal hydraulic condition on the health of the pipe network. Comprehensively considering the influencing factors and the hydraulic mechanism during the operation process of pipe network, this study constructs a health evaluation index system for the water supply pipe network, and introduces the triangular fuzzy number theory into the traditional Bayesian water supply network health status evaluation model taking the uncertainty of model structure and data into account. Through applying the method to Yunhe county of Zhejiang Province China, some suggestions for the optimization and transformation of the regional water supply network are proposed, which can provide a basis for ensuring the safety of regional water supply and scientifically determining the renewal sequence of the pipe network.

1. Introduction

Water supply pipe network is an important part of urban infrastructure, as well as a necessary foundation for ensuring normal life and production development. Due to the pipe aging and the change of pipeline environment as well as the influence of human factors, water supply pipe network accidents have frequently occurred in recent years, which not only waste precious fresh water resources, but also have great influence on human life and social and economic development. Therefore, the health evaluation and related technologies of urban water supply pipe network have emerged, and have become one of the hot topics among worldwide scholars. Whether based on the needs of urban water supply safety and public safety, or for social and economic development and construction, it is of great practical application value and theoretical significance to evaluate the health status of urban water supply pipe network. However, a set of effective evaluation system and methods for the health evaluation of water supply pipe network has not been formed at present. Related researches mostly refer to qualitative and static analysis, some quantitative studies often consider
influence of only one aspect on the status of pipe network such as hydraulic, water quality and static structure, and cannot objectively reflect the health status of pipe network due to neglecting or simplifying the influence of internal hydraulic condition on the health of the pipe network system [1-10]. Thus it is difficult to provide technical support for leakage reduction as well as maintenance and updating of pipe network.

The operation of urban water supply pipe network is a complex dynamic process. The status of water supply pipe network under various working conditions changes constantly and is full of uncertainty. The factors affecting the health status of water supply pipe network are numerous and interrelated. It is necessary to consider the influence of different factors such as the inside of the pipeline, the pipeline itself, and the outside of the pipeline during the health assessment. This study proposes a mechanism-oriented dynamic evaluation method of water supply pipe network health status, and applies the method to Yunhe County of Zhejiang Province of China.

2. General outline
Based on Bayesian theory and triangular fuzzy number theory, the dynamic evaluation model of water supply pipe network health status is firstly constructed. The prior probability of evaluation index is determined according to the layering idea. The concept of geometric distance is used to determine the conditional probability. The weight of evaluation index is determined using the variation coefficient method. The health status grade of pipe network is finally determined according to the principle of maximum membership degree. In addition to conventional statistical indexes, some hydraulic and water quality indexes are obtained using the micro-model of water supply pipe network based on EPANET software. The general outline of this study is shown in Figure 1 as below.

![Figure 1. General outline of the study](image)

3. Establishment of evaluation index system

3.1. Principle of evaluation index selection
There are four principles selecting evaluation indexes. Firstly, representative. There are many factors affecting the health status of water supply pipe network. When selecting the evaluation indexes, it is necessary to select representative and sensitive indicators while ensuring that important features and factors are not ignored including hydraulic characteristics, water quality, as well as factors affecting the structural safety of the water supply network itself. Secondly, completeness. The selected evaluation indexes should be able to fully reflect the true health status and changing trend of the pipe network under specific working conditions. Thirdly, relative independence. The selected evaluation indexes should be able to reflect a certain aspect of the health status of the pipe network relatively independently. It is necessary to reduce the correlation between the evaluation indexes as much as
possible ensuring the objectivity and accuracy of the evaluation results. Finally, operability. The data of the selected indexes should be easy to collect, taking spatiotemporal distribution and technical feasibility into account.

3.2. Evaluation index system
Based on the existing research results, according to the principles of representativeness, completeness, relative independence and data availability, 23 indicators were initially selected. Through probabilistic statistics and ignoring the indicators with low frequency of use and less impact on the health status of the pipe network, the evaluation index system is finally established considering the actual situation of water supply pipe network in China. The evaluation index system includes 12 indicators, of which 8 static structure indicators, i.e., pipe diameter, pipe age, pipe material, soil thickness, interface form, ground load, inner and outer lining, and the impact degree; 2 hydraulic indicators, namely node water pressure / minimum service water pressure, node flow / total flow; 2 water quality indicators, residual chlorine and water age. The evaluation index system can be adjusted according to the specific situation.

It should be noted that since the geographic information system of the urban water supply network has not been established in China, it is difficult to effectively obtain the dynamic hydraulic and water quality data of the pipeline network. Therefore, it is necessary to establish a dynamic hydraulic model to simulate the operation conditions of the pipeline network. The simulation is carried out to obtain the hydraulic and water quality evaluation index data such as node pressure, node flow, residual chlorine and water age under various working conditions, and the simulated data is used instead of the measured data to evaluate the health status of the water supply pipe network.

In this study, the EPANET software package developed by US Environmental Protection Agency is used as the dynamic hydraulic model. EPANET is a computer program primarily used for time-delay simulation of hydraulic and water quality characteristics of pressurized network systems. EPANET has complete functions and friendly interface. It has facilitated the scientific research of water supply pipe network system and improved the operation and management level of water supply enterprises, and has been widely used in recent years.

EPANET uses the hybrid node-ring method to solve the flow continuity and head loss equations for the hydraulic state of a pipe at a given time, and the global gradient method is used during the solution process. The friction head loss can be calculated using the Chezy-Manning formula, the Hazen-Williams formula, and the Darcy-Weisbach formula considering water demand requirements at different nodes [11]. EPANET can be used to simulate the movement of chemical substances in the entire pipe network with time such as the attenuation of residual chlorine and the growth of disinfection by-products, and calculate the change of residence time of water in the pipeline. Thus it is possible to simulate the operation of water supply pipe network under different conditions using EPANET.

4. Health evaluation method of water supply pipe network
The urban water supply pipe network is a complex system with randomness and uncertainty. Its health evaluation indexes include both quantitative and qualitative indexes. At present, the monitoring data of water supply pipe network in China is generally less, and the data accuracy is not enough. In order to reflect the health status of the pipe network more objectively and reasonably, the Bayesian model based on triangular fuzzy number optimization is used to evaluate the health status of the pipe network.

4.1. Traditional Bayesian model
Traditional Bayesian model uses the following formula to calculate the posterior probability of each level of the evaluation index, which can be used to further evaluate the health status of water supply pipe network.

\[
P(y_j|x_j) = \frac{P(y_j)P(x_j|y_j)}{\sum_{i}P(y_i)P(x_j|y_i)}
\] (1)
where \( i \) is the grade of the pipeline, \( s \) is the total number of grades, \( j \) is the evaluation index, \( x_j \) is the observation of index \( j \), \( y_{ij} \) is the event of index \( j \) at grade \( i \), \( P(y_{ij}) \) is the prior probability of indicator \( j \) at grade \( i \), \( P(x_j | y_{ij}) \) is the conditional probability, which refers to the probability of state \( x_j \) when the grade of index \( j \) is \( i \), \( P(y_{ij} | x_j) \) is the posterior probability, which refers to the probability of grade \( i \) when the state of index \( j \) is \( x_j \).

### 4.2. Bayesian model based on triangular fuzzy number optimization

The triangular fuzzy number can reflect the variation range of the index value under a certain level of confidence, and can be used to process and express fuzzy information as well as characterize random information under the condition of less data or low data accuracy, and thus has good practicability [12].

In the process of evaluating the health status of water supply pipe network, assuming the real numbers \( a, b, c \) are the minimum, median, and maximum possible values of the evaluation indexes respectively, \( (a, b, c) \) forms a triangular fuzzy number \( \tilde{A} = (a, b, c) \). It is known that the data \( m_1, m_2, m_3, ..., m_n \) is a set of measured data of an evaluation index, \( \bar{m} \) is the average value of the evaluation index, and \( \sigma \) is the standard deviation, then \( a = \bar{m} - 2\sigma \), \( b = \bar{m} \), \( c = \bar{m} + 2\sigma \), i.e., \( \tilde{A} = (\bar{m} - 2\sigma, \bar{m}, \bar{m} + 2\sigma) \).

Equation 1 can be rewritten as follow:

\[
P^a(y_{ij} | \tilde{x}_j^a) = \frac{P(y_{ij}) P^a(\tilde{x}_j^a | y_{ij})}{\sum_{i=1}^{s} P(y_{ij}) P^a(\tilde{x}_j^a | y_{ij})}
\]

where \( P^a(\tilde{x}_j^a | y_{ij}) \) is the fuzzy conditional probability of state \( x_j \) when the grade of index \( j \) is \( i \), \( P^a(y_{ij} | \tilde{x}_j^a) \) is the fuzzy posterior probability of grade \( i \) when the state of index \( j \) is \( x_j \).

### 4.3. Determination of prior probability

The prior probability of each evaluation index can be calculated according to the layering idea using the following formula.

\[
P(y_{ij}) = \frac{K_{i, j, u} - K_{i, j, l}}{K_{w, j, u} - K_{i, j, l}}
\]

Where \( K_{i, j, u} \) is the upper limit of index \( j \) at grade \( i \), \( K_{i, j, l} \) is the lower limit of index \( j \) at grade \( i \), \( K_{w, j, u} \) is the upper limit of index \( j \) at grade IV, \( K_{i, j, u} \) is the upper limit of index \( j \) at grade I.

### Table 1. Prior probability of evaluation index for each grade

| Grade | Pipe diameter (mm) | Pipe year (y) | Pipe material | Soil thickness (m) | Interface form | Ground load |
|-------|-------------------|---------------|---------------|-------------------|----------------|-------------|
| I     | 0.38              | 0.13          | 0.22          | 0.33              | 0.22           | 0.33        |
| II    | 0.25              | 0.25          | 0.22          | 0.20              | 0.33           | 0.22        |
| III   | 0.19              | 0.25          | 0.44          | 0.13              | 0.22           | 0.22        |
| IV    | 0.17              | 0.38          | 0.11          | 0.33              | 0.22           | 0.22        |

| Grade | Lining | Impact degree | Node water pressure minimum water pressure | Node flow total flow | Residual chlorine (mg/L) | Water age (h) |
|-------|--------|---------------|-----------------------------------------------|---------------------|--------------------------|---------------|
| I     | 0.33   | 0.22          | 0.29                                          | 0.20                | 0.20                     | 0.22          |
| II    | 0.22   | 0.33          | 0.14                                          | 0.40                | 0.30                     | 0.22          |
| III   | 0.33   | 0.33          | 0.29                                          | 0.20                | 0.30                     | 0.33          |
| IV    | 0.11   | 0.22          | 0.29                                          | 0.20                | 0.20                     | 0.22          |
The calculation results of prior probability for 12 indexes are shown in Table 1. For 8 quantitative indexes, the grade limits are determined according to relevant standards, existing research results as well as experience values of typical cities. For 4 qualitative indexes including pipe, interface form, ground load, inner and outer lining, the value range and boundary can be obtained by expert scoring method.

It should be noted that, in combination with existing research results and related standards, each evaluation index is graded to 4 levels, which is consist with the health grades of pipe network described in Section 4.6. Due to space limitations, the specific classification criteria are not listed here, and details can be referred in [13].

4.4. Determination of conditional probability
The conditional probability of each evaluation index can be calculated using the distance method, and the formula is as follows.

\[ \tilde{p}^a(x_j^a | y_{ij}) = \frac{1}{\sum_{i=1}^{4} 1/L_{ij}^a} \]

\[ L_{ij}^a = |x_j^a - y_{ij}| \]  

where \( L_{ij}^a \) is the distance between the actual value \( x_j \) and the standard value \( y_{ij} \) of index \( j \). The farther the distance is, the smaller the probability that the grade is \( i \), and the reciprocal thereof can represent the probability that \( x_j \) belongs to grade \( i \).

4.5. Determination of index weight
The initial weight of each evaluation index can be calculated using the variation coefficient method, and can be adjusted in combination with the characteristics of local pipe network or expert scoring during specific application process.

\[ W_j = \frac{D_j / K_i}{\sum D_j / K_i} \]

\[ D_j = \sqrt{\frac{\sum (K_{ij} - \bar{K}_{ij})^2}{n}} \]  

where \( W_j \) is the weight of index \( j \), \( D_j \) is the standard deviation of each grade value of index \( j \), \( K_{ij} \) is the standard value of grade \( i \) of index \( j \), \( \bar{K}_{ij} \) is the average of each grade value of index \( j \), \( n \) is the number of assessment index.

4.6. Determination of pipe network health status grade
The comprehensive posterior probability of the pipeline health status can be calculated based on the posterior probability that each index belongs to each grade considering the weight of each index, and the final health status grade of water supply pipe network can be determined according to the principle of maximum membership degree.

\[ \tilde{P}_i^a = \sum_{j=1}^{n} W_j \times \tilde{p}^a(y_{ij} | x_j^a) \]

\[ \tilde{P}_i^a = \max \tilde{P}_i^a \]
where \( P^{a}_i \) is the comprehensive posterior probability that grade is \( i \), \( P^{a}_i \left( y_j \mid x_j \right) \) is the fuzzy posterior probability of grade \( i \) when the observation value of index \( j \) is \( x_j \), \( W_j \) is the weight of index \( j \), \( i \) is the number of grade, \( n \) is the number of index, \( B^{a} \) is the health status grade.

Pipe network health status grade can be divided into 4 grades based on the existing research results, i.e., I, II, III and IV, from good to bad, refers to the status of "good condition", "periodic inspection", "plan to maintain" and "update immediately", respectively.

5. Case study

5.1. Overview of study area

Yunhe County is located in the mountainous area in the southwest of Zhejiang Province, China, with a total area of 984 km². It has a subtropical climate. The annual average temperature is 17.6 °C, the annual average precipitation is 1610.4 mm, the annual average evaporation is 1335.5 mm. The surface morphology is dominated by mountainous hills, and the terrain is high in the southwest and low in the northeast. Water resources in the county are mainly formed by precipitation, with a total annual average runoff of 1.02 billion m³, and the per capita possession of water resources is 9100 m³. In general, water resources in the county are abundant and water quality is good.

5.2. Application of EPANET

The real water supply pipe network is a complex and huge system. Considering the data availability and the efficiency of model calculation, this study has carried out a certain degree of generalization of the pipe network in the study area, ignoring the pipelines that have less influence on hydraulic and water quality conditions, and only retains the main trunks above DN100. The generalized pipe network has a water plant, 68 nodes and 94 pipe segments. The total length of the main pipeline is about 37.5km.

This study selects Nodes 12, 40 and 58 located at Zhongshan East Road, Chengnan Road and Xinjian Road to monitor the pressure and flow for continuously 48 hours. Comparison of the measured pressure and simulation is shown in Table 2. It can be seen that the model simulation results are in good agreement with the actual situation, and the average error is controlled within 5%. Therefore, the model is considered to have certain practicability and can be applied to actual pipe network health evaluation.

The hydraulic and water quality simulation data of each node can be obtained through EPANET. The health status of the pipe segment should be reflected by the average of the nodes at both ends of the pipe segment rather than the two nodes themselves. In this study, the average value of the upstream and downstream nodes of the pipe section is taken as the evaluation index value.

6. Results and discussion

The above method is applied to evaluate the health status of water supply network in Yunhe County. The evaluation results and distribution of pipe network health grade are shown in Table 3 and Figure 2.

It can be seen from Table 3 and Figure 2 that:

(1) The health status of 47 pipelines is Grade I, which accounts for 50% of total pipe sections. These pipelines are in good condition, and no maintenance and update measures are required. It is recommended to re-evaluate in the next 3 to 5 years.

(2) The health status of 44 pipelines is Grade II, which accounts for 47% of total pipe sections. These pipelines can basically complete the task of water supply and distribution. They should be regularly monitored, and their operation status should be strengthened to prevent pipe network accidents.

(3) The health status of 3 pipelines is Grade III, which accounts for 3% of total pipe sections. The three pipelines are pipeline 53, pipeline 55 and pipeline 71. The hydraulic and water quality indexes of these pipe sections are relatively good, but the pipe diameter is small and the buried depth is shallow. Additionally, the traffic volume on the road is relatively large, and the anti-corrosion layers of the...
pipelines have a certain degree of damage. Taking the pipeline 71 as an example, the pipe material is concrete which should be eliminated, and the pipe age has been nearly 20 years, thus there is a great safety hazard. These pipe sections are currently in an inefficient operation state, and there is a high possibility of water supply accidents. The maintenance and update should be planned according to the actual operation conditions.

**Table 2.** Relative error comparison at monitoring points.

| Monitoring time | Node 12 | Node 40 | Node 58 |
|-----------------|---------|---------|---------|
| 2017-10-20 8:00| 5.79%   | -1.49%  | 5.84%   |
| 2017-10-20 12:00| 7.60%   | 7.78%   | 4.70%   |
| 2017-10-20 16:00| 7.29%   | -2.94%  | -0.31%  |
| 2017-10-20 20:00| 4.43%   | 4.66%   | 4.70%   |
| 2017-10-21 0:00 | -1.73%  | 0.11%   | 5.08%   |
| 2017-10-21 4:00 | 0.80%   | -0.92%  | 5.38%   |
| 2017-10-21 8:00 | -1.74%  | 3.32%   | 4.70%   |
| 2017-10-21 12:00| 6.62%   | 4.20%   | -0.56%  |
| 2017-10-21 16:00| 7.92%   | 5.99%   | 4.50%   |
| 2017-10-21 20:00| 5.35%   | -3.22%  | 7.11%   |
| 2017-10-22 0:00 | 3.36%   | 4.21%   | 3.20%   |
| 2017-10-22 4:00 | 1.98%   | -2.25%  | 9.24%   |
| 2017-10-22 8:00 | 0.24%   | 5.73%   | -1.08%  |
| **Average**     | 3.69%   | 1.94%   | 4.04%   |

**Table 3.** Assessment results of pipe network health grade.

| Grade           | Pipe Number | Percentage |
|-----------------|-------------|------------|
| I    Good condition | 47          | 50%        |
| II   Periodic inspection | 44          | 47%        |
| III  Plan to maintain   | 3           | 3%         |
| IV   Update immediately | 0           | 0%         |

**Figure 2.** Distribution map of pipeline health grade.
(4) There is no grade IV pipe segment in the evaluation results, that is, there is no pipeline that needs to be updated immediately.

In fact, water supply pipe network in the county has been updated and reorganized in several stages since 2006, and regular inspections have been carried out. Therefore, the evaluation result is in line with the actual situation.

7. Conclusions

This study proposes a mechanism-oriented dynamic evaluation method of water supply pipe network health status, and applies the method to Yunhe County of Zhejiang Province of China. Comprehensively considering the influencing factors and hydraulic mechanism during the operation process of pipe network, this study constructs a health evaluation system for water supply pipe network, which improves the scientific and comprehensive level of the indexes. Taking the uncertainty of model structure and data into account, this study introduces triangular fuzzy number theory into traditional Bayesian water supply network health status evaluation model, thus improves the objectivity and rationality of evaluation. Through the case study in Yunhe county, the proposed method is proved to be feasible and practical. Combined with the evaluation results, some suggestions for the layout optimization and transformation of pipelines are proposed, which can provide a basis for ensuring the safety of regional water supply and scientifically determining the renewal sequence of the pipe network.

Although some preliminary research results were obtained, due to the late start time of relevant study and the lack or inaccuracy of actual history and monitoring data of the pipe network, many researches need to be further improved, such as the determination of the weight, model validation, and the grading standards of indexes. In addition, the contribution of different influencing factors to the health status of the pipe network should be further studied.

Acknowledgment

This research is supported by the Chinese National Key Research and Development Project (2016YFC0400605) and Chinese National Natural Science Foundation (No. 51522907, No. 51279208).

References

[1] Yang Q 1985 China Water & Wastewater 1 1-6
[2] Bate J, Gregory A 1994 Process of AWWA Computer Conference, Denver, USA
[3] Wu X W, Zhao H B 1998 Journal of Harbin University of Civil Engineering and Architecture 2 57-62
[4] Tao J K 1999 China Water & Wastewater 4 12-14
[5] Tesfamariam S, Rajani B, Sadiq R 2006 Canadian Journal of Civil Engineering 33 1050-1064
[6] Wu X H 2007 Dissertation, Xi’an University of Architecture and Technology, Xi’an, China
[7] Wang J L 2008 Dissertation, Qingdao Technological University, Qingdao, Shandong, China
[8] Yin Y 2012 Dissertation, Tianjin University, Tianjin, China
[9] Tian C 2014 Dissertation, Tianjin University, Tianjin, China
[10] Chang T, Liu S, Wang M, Li M, Wu X 2016 Water & Wastewater Engineering 6 138-141
[11] Liu B C, Lin L, Lin J Q 2010 Water & Wastewater Engineering 46(51) 416-419
[12] Yu X, Liang J, Zeng G M 2013 Acta Scientiae Circumstantiae 33(3) 904-909
[13] Liu S R 2018 Dissertation, Liaoning Normal University, Dalian, China