Research on the Vulnerability Assessment Model of Urban Water Supply Systems

LU Ren-qiang, NIU Zhi-guang*, ZHANG Hong-wei
School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China

Abstract: **In this paper, the vulnerability of urban water supply systems was analyzed to protect the safety of water supply effectively, and a new vulnerability assessment model for urban water supply systems was proposed. Firstly, According to the characteristics of systems, the concept of vulnerability in urban water supply systems was proposed based on the definitions of vulnerability in the other areas. Secondly, the interaction of natural, social, economic and environmental factors was considered comprehensively. Then the physical exposure level and inherent respond sensitivity of water supply systems to resist the threat were analyzed, and the disaster respond capacity of human which accompanied with the water supply systems was also analyzed. On this basis, the vulnerability assessment indicators of urban water supply systems were proposed. Thirdly, according to the cascade characteristics and collaborative mechanism of different subsystems, the transmission mechanism of vulnerability in urban water supply systems was analyzed. Then, the vulnerability assessment model for urban water supply systems was established. Finally, the model was used to analyze and assessment the vulnerability of KGWL processing zone's water supply systems in North China. The results show that the assessment model which proposed in this paper is simple, practical, and could be used to provide decision basis for the security upgrade of urban water supply systems.**

Keywords: urban water supply systems; vulnerability; assessment model

I INTRODUCTION

Urban water supply systems is the critical infrastructure of urban construction. It is also the essential material basis for economic development, and has an extremely important position to protect the people's normal life. So, the urban water supply systems is known as the "lifeline project". However, because of the complexity and openness characteristics, the urban water supply systems is vulnerable to the natural disasters, vandalism and other threats. If the urban water supply systems was damaged and impacted by the threats above, the economic development will be affected greatly, and the safety and health of people's lives will be threaten also. E.g., the pollution incident of Song-hua river made nearly 400 million residents of Harbin city without water lasted for 4 days in 2005. The urban water supply systems of disaster areas was devastated by the "5.12" earthquake in 2008. The main water pipe of Chong-qing city was burst three times in 10 days for the subway construction and about 10 million people's water supply was cut off. From the water supply accidents above, we found that the security issue has been involved in the source water systems, water distribution systems, etc, which exposed the major risks of urban water supply systems when to counter a emergencies in China. However, the foreign countries pay more attention to analyze the impact of terrorist attacks to protect the security of urban water supply. After the "9.11" accident of America, many terrorist attacks which attempted to destroy the urban water supply systems have been reported in abroad. So, the foreign countries began to consider the safety problems of operation and management of urban water supply systems to adapt the escalating risks [1-2]. Therefore, the security of water supply has become an important component of urban safety and disaster prevention plan, and the risk assessment study of urban water systems is very important. However, the vulnerability analysis of urban water supply systems is the basis of risk assessment. It is also able to identify the weaknesses of urban water supply systems effectively, which could provide decision basis for security update of urban water supply systems. In response to these problems above, the interaction of natural, social, economic and environmental factors was considered comprehensively, and a new vulnerability assessment model for urban water supply systems was proposed.

II COMPONENTS OF URBAN WATER SUPPLY SYSTEMS AND ITS POSSIBLE THREATS

As a service systems, the ultimate aim of urban water supply systems is to meet the users' normal requirements of water quantity, water quality and

* Corresponding author: lrq150@163.com
The Project is currently sponsored by the Tianjin Municipal Science and Technology Commission through the Contracts # 09ZCGYSF00600 and the National Science and Technology Major Project of Water Pollution Control and Treatment through the Contracts # 2008ZX07314-005

978-1-4244-4713-8/10/$25.00 ©2010 IEEE

pressure with a given operating conditions. The urban water supply systems is composed of many different subsystems, which are source water systems, water purification systems, water distribution systems, electrical systems, etc. The safety and effectively of water supply was determined by the coordinate relation and function mechanism of subsystems above, and the function of any subsystems become invalid will lead to the not normal water supply of urban water supply systems. Thus, before the study of vulnerability assessment, it must to analyze the respective role of subsystems which played to make the entire water supply systems to complete the purpose of water supply. Only the coordinate relation and function mechanism of these subsystems were considered comprehensively, the vulnerability of entire urban water supply systems can be analyzed and assessed. In addition, the vulnerability of urban water supply systems is linked to the threat. Before the vulnerability assessment of urban water supply systems, we also have to identify the types and sources of threats. Because of the complexity and openness characteristics, the possible threats of urban water supply systems are great uncertainty. According to the source of external threats, the possible threats of urban water supply systems can be divided into natural and man-made threats. Natural threats are mainly include floods, earthquake, drought, landslides, water-borne diseases, etc. Man-made threats are mainly include terrorist attacks, deliberately poisoning by criminals, etc.

III VULNERABILITY ASSESSMENT MODEL OF URBAN WATER SUPPLY SYSTEMS

A. Concept of vulnerability in urban water supply systems

The term of vulnerability has been widely used in environmental, ecological, disaster science and other fields. It was used to describe the level of destruction when the systems and its component elements affected by external threats. It was also used to describe the ability of systems itself to resist the interference and restore the initial state. Despite the term of vulnerability was proposed for a long time, but it has no a uniform definition in academia so far. According to the characteristics of different fields, the concepts of vulnerability of hazard bearing body, ecosystem, groundwater resources were proposed by H. L. Liu [3], X. D. Wang [4] and national research council [5] respectively. Although the term of vulnerability has different definitions and explanations in these fields above, all of the definitions contain the same meaning as follows. Firstly, vulnerability is the inherent properties of systems itself. Secondly, vulnerability is the susceptibility of systems itself to resist the potential threats. Thirdly, the vulnerability of systems is determined by natural, social, economic and environmental factors. Based on the definitions of vulnerability above, taking into account the characteristics of urban water supply systems, the concept of vulnerability in urban water supply systems was proposed in this paper. The vulnerability of urban water supply systems is the inherent properties of the systems itself which was determined by the natural, social, economic and environmental factors. It was used to describe the physical exposure level, inherent respond sensitivity of water supply systems to resist a specific threat, and the disaster respond capacity of human or society which accompanied with the water supply systems.

B. Vulnerability assessment indicators of urban water supply systems

1) Assessment indicators of physical exposure level

The physical exposure level is defined as the exposure intensity when the urban water supply systems faced a specific threat. It was determined by the strength of threat, and often used to describe the possible loss of total urban water supply systems. The physical exposure level of urban water supply systems can be introduced and expressed as follows [6]:

$$V_e = F(H, N). \qquad (1)$$

Where V_e is the physical exposure level of urban water supply systems, H is the strength of threat, and N is the total of urban water supply systems.

At presently, the physical exposure level is mainly expressed by quantitative indicators. For urban water supply systems, the pumping station and clean water tank are usually expressed by number. The reservoir-type water source is usually expressed by area, and the water distribution pipes are usually expressed by length.

2) Assessment indicators of inherent respond sensitivity

The inherent respond sensitivity is defined as the extent of losses when the urban water supply systems affected by a specific threat. It was determined by the structural characteristics of urban water supply systems, and was used to describe the ability of systems itself to resist the damage of threats. Therefore, the inherent respond sensitivity is the dynamics of urban water supply systems itself. Moreover, the physical destruction process of urban water supply systems is also determined by the type and strength of threat. For example, when we analyze the inherent respond sensitivity of urban water supply systems affected by earthquake, the structure and materials of buildings, and the materials and time of water distribution pipes are the important indicators.

3) Assessment indicators of disaster response ability

The disaster response ability is defined as the strength of measures which the water sector used to protect the urban water supply systems from the threats. Therefore, the disaster response ability is reflects the initiative of water sector which is a part of urban water supply systems. It can be divided into foundation disaster response ability and special disaster response ability. For urban water supply systems, the management number and reserve material quality can be used as the indicators of foundation disaster response ability. The special disaster response ability can be expressed by the forecasting capabilities of natural threats, intelligence gathering capacity of terrorist attacks or the special disaster response projects to protect the safety of water supply.

C. Vulnerability assessment model of urban water supply systems

According to the vulnerability assessment indicators above, the vulnerability of urban water supply systems can be calculated and assessed. Firstly, based on the characteristics of different subsystems, the minimum assessment unit was determined, and let $i = 1,2,\cdots,n$ denoted the subsystems. Secondly, the physical exposure index, inherent respond sensitivity index and disaster response ability missing index of subsystems were computed, which were denoted by V_e, V_s, $1-V_d$ respectively. Then, the vulnerability index V_{hi} of subsystems can be computed as follows:

$$V_{hi} = V_{ei} \times V_{si} \times (1 - V_{di}) \qquad (2)$$

According to the coordinate relation and function mechanism of subsystems which illustrated in Fig.1, the urban water supply systems can be seen as a cascade systems. Based on the function characteristics of cascade systems, the problem of any subsystems will be cause the function failure of the entire systems. Therefore, the vulnerability index V_h of entire urban water supply systems can be computed as follows:

$$V_h = 1 - \prod_{i=1}^{n} (1 - V_{hi}) \qquad (3)$$

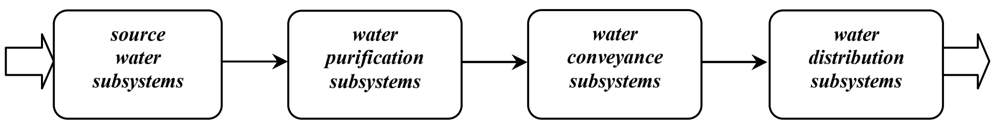

Figure 1. Coordinate relation and function mechanism of subsystems

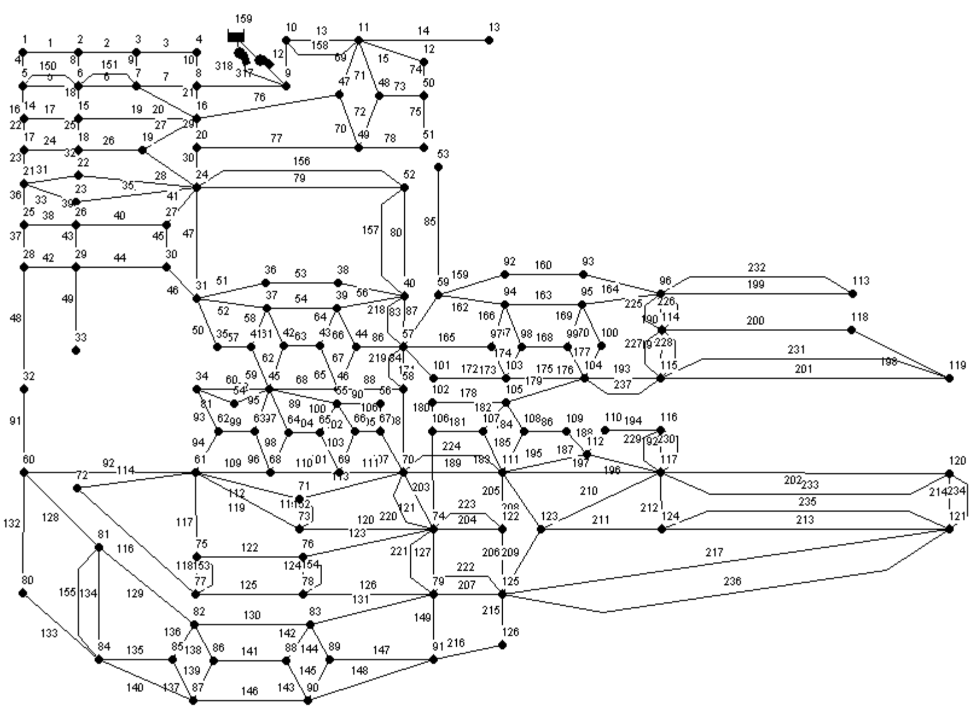

Figure 2. Topology of KGWL processing zone's water supply systems

IV CASE STUDY

A. Introduction of study object

In this paper, the water supply systems of KGWL processing zone in North China was taking as an example, and its topology diagram was illustrated in Fig.2. The water supply systems is consists of 126 nodes, 237 pipes and a pumping station [7]. At presently, the water of KGWL processing zones was supplied by the WG road pipeline with the 50000 m^3/d of transportation capacity. According to the incomplete statistics of historical data, to the early 90s in 20th century, about 1009 devastating earthquakes were occurred in china. The north region of china is affected by the circum-pacific seismic belt, so its frequency of earthquakes even higher than the other zones. Taking into account the frequency and destructive capacity, the earthquake was taking as a specific threat to analyze the vulnerability of water supply systems in this paper. Simultaneously, the water supply systems of KGWL processing zones was designed and constructed based on 8 degrees earthquake. Therefore, the strength of earthquake was fixed at 8 degrees when we analyze the vulnerability of water supply systems. According to the actual situation, the vulnerability of five subsystems were analyzed and assessed, which were the main water pipeline, clean water tank, pumping station, power systems and water distribution network.

B. Results of vulnerability assessment

1) Physical exposure assessment of urban water supply systems

According to the strength and disaster records data of earthquake which occurred in Yun-nan province, the damage area was 8176 km^2 when the strength and seismic intensity of earthquake were 7.7 and VII respectively. However, the areas of KGWL processing zone's water supply systems occupied only has 23.9 km^2. So, all of the water supply systems was exposed, and the V_e of each subsystems can be determined as 1.

2) Inherent respond sensitivity assessment of urban water supply systems

The damage extents of different subsystems are not the same when the urban water supply systems destroyed by the earthquake. So, based on the historical records data of earthquakes, the classification method of hazard bearing body was used to compute the inherent respond sensitivity index V_s of subsystems in this paper. According to the research results of C. G. Liu [8], the overall leakage level was 17.90% when the water distribution network destroyed by 8 degrees earthquake. So, the V_s of water distribution network and the main water pipeline can be determined as 0.179. According to the research results of X. C. Wang [9], the buildings which designed and constructed based on 8 degrees earthquake can be remained intact when it destroyed by 8 degrees earthquake. So, the V_s of clean water tank and pumping station can be determined as 0. According to the research results of L. F. Yin [10], the V_s of power systems can be determined as 0.24.

3) Disaster response ability assessment of urban water supply systems

So far, it was difficult to forecast the earthquake, and there is no special disaster response project for KGWL processing zone's water supply systems to resist the earthquake. So the special disaster response ability can be considered as 0. Through the field research of KGWL processing zone's water supply systems, the main water pipeline is long and has no reserve to resist earthquake, so its foundation disaster response ability can be considered as 0. The clean water tank is buried and has no reserve, but there is a certain number of staff, so its foundation disaster response ability can be determined as 0.5 by the expert scoring method. The pumping station has many excess pumps to resist emergency, its foundation disaster response ability can be computed as 0.6. Although there are many management staff to protect the water distribution network, its foundation disaster response ability can be considered as 0 still for the large distribution areas. The power systems of KGWL processing zone's water supply systems is buried and has no other standby power, but it has a high proportion of staff, so its foundation disaster response ability can be determined as 0.7 by the expert scoring method. Then the $1-V_d$ of each subsystems could be computed.

4) Results of vulnerability assessment

According to the analyze results of vulnerability above, the vulnerability index of each subsystems could be computed based on the Equation (2), and the results were illustrated in Table.1. Then, the vulnerability index of the entire water supply systems could be computed based on the Equation (3) and Table.1, and the value of V_h was 0.4311.

V CONCLUSION

In this paper, through the analysis of vulnerability's definition in other areas, the concept of vulnerability in urban water supply systems was proposed based on its characteristics and functions. Then, the interaction of natural, social, economic and environmental factors was considered comprehensively, and the vulnerability assessment indicators of urban water supply systems was proposed from the three aspects as follows, which were physical exposure level, inherent respond sensitivity of systems itself to resist a specific threat, and the disaster respond capacity of human or society which accompanied with the systems. Afterwards, according to the cascade characteristics and collaborative mechanism of different subsystems in urban water supply systems, the vulnerability assessment model of urban water supply systems was established based on the transmission mechanism of vulnerability in urban water supply systems. Finally, the model was used to analyze and assessment the vulnerability of KGWL processing zone's water supply systems in North China. The results show that the vulnerabilities of KGWL processing zone's urban water supply systems was identified effectively, and can be used to provide decision basis for the security upgrade of urban water supply systems.

TABLE 1. RESULTS OF VULNERABILITY INDEX OF EACH SUBSYSTEMS

subsystems	V_e	V_s	$1-V_d$	V_h
main water pipeline	1	0.179	1	0.179
clean water tank	1	0	0.75	0
pumping station	1	0	0.7	0
water distribution network	1	0.179	1	0.179
power systems	1	0.240	0.65	0.156

REFERENCES

[1] P. H. Gilbert, G. B. Isenberg and L. T. Papay, et al, "Infrastructure issues for citys-countering terrorist threat," Journal of Infrastructure Systems, vol. 9(1), 2003, pp. 44-54.

[2] S. B. Peter, "Threats on tap: understanging the terrorist threat to water," Journal of Water Resources Planning and Management, vol. 128(3), 2005, pp. 163-167.

[3] H. L. Liu, Q. S. Ge and J. C. Xi, "Disaster risks assessment of regional tourism resources: a case study of inner mongolia keshiketeng banner," Resources Science, vol. 29(1), 2007, pp. 118-125.

[4] X. D. Wang and X. H. Zhong, "Approaches to concept of vulnerability of ecology and environment," Journal of Mountain Science, vol. 21, 2003, pp. 21-25.

[5] National Research Council, "Groundwater vulnerability assessment: predicting relative contamination potential under conditions of uncertainty," Washington: National Academy Press, 1993, pp: 204-206.

[6] Q. S. Ge, M. Zhou and J. Y. Zheng, "Integrated assessment of natural disaster risks in china," Beijing: Science Press, 2008.

[7] T. Y. Pei, "Security and optimization of water supply network in planned area," Tianjin: Tianjin University, 2008.

[8] C. G. Liu and A. Y. Zhang, "Seismic performance analysis on water supply network," Engineering Mechanics, vol. 24(3), 2007, pp. 142-146.

[9] X. C. Wang, B. Wang and G. Q. Zhou , et al, "Research on earthquake damage to multistory brick buildings and reinforced concrete frame from dayao magnitude 6.1 earthquake in Yunnan," Journal of Catastrophology, vol. 19(3), 2004, pp. 45-50.

[10] L. F. Yin, L. H. Tang and J. Xue, et al, "Earthquake disaster prediction of lifeline engineerings in shihezi, xinjiang-power system," Inland Earthquake, vol. 17(1), 2003, pp. 47-53.