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Research on Water Source Security Evaluation of Dahuofang Reservoir Based on Pressure-State-Response Model, China

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ABSTRACT

In accordance with the characteristics of water source, this study analysed its influencing factors. Pressure-state-response (PSR) model for drinking water source security was proposed. The security evaluation system with three levels was established based on the model; the indicator weights were determined by analytic hierarchy process. The five-grade assessment standard was adopted, and according to the choice principle of the indicator, 14 indicators were selected. Each grade range of every indicator was determined, and fuzzy comprehensive evaluation method applied to evaluate the security grade of criterion layer and the whole system. The evaluation results indicated that drinking water source security grade of Dahuofang reservoir was "high" level, but very close to the "medium" level. The corresponding protective measures for water source were put forward.

INTRODUCTION

Water security, as an important part of national security, is the same with food security and energy security. Water security has become a serious problem to the development process of economy and society of our nation, even affecting the survival, health, social harmony and stability. Once threatened, it will lead to some secure, economical and social problems inevitably (Zhu et al. 2010). At present, there are three main aspects of threats to the drinking water sources. Firstly, the water pollution. Most of our rivers and lakes are contaminated seriously, the varieties of diseases caused by water pollution have been increasing, which pose a threat to the living environment of human life and health. Secondly, water shortage. The shortage of freshwater has become a common phenomenon and will affect the regional economic development seriously. Thirdly, poor monitoring and management mechanism. When emergency situation occurs, effective measures ca not be taken timely. Central first document about the decision to accelerate development of water conservancy reformation (Central Committee and State Council of Communist Party of China 2011), explicitly requested to improve the security of drinking water and put forward the target for all water sources in towns to meet the water quality standards. In order to ensure the security of drinking water source, the document (notice on the construction of security guarantees of major drinking water sources to meet the standards in China) was issued by ministry of water resources, that drinking water source security construction would be carried out throughout the nation. Dahuofang reservoir was listed in the first batch of national main drinking water sources list. The scientific and reasonable evaluation on the drinking water source is the basis for related protective and corrective actions. The relevant department will implement according to the standard requirements, "adequate amount of water, qualified water; comprehensive monitoring system; sound institution".

At present, connotation and evaluation of the security of drinking water sources are rarely seen at home and abroad. The research about water source areas mainly focused on water quality assessment (Chen et al. 2010, Hurley et al. 2012), water supply (Liu et al. 2012), ecological compensation (Zhang et al. 2013, Wang et al. 2015), and for water security evaluation. The research was also focused on some regions (Hu 2013), cities (Shi et al. 2010) or river basins (Jin et al. 2008, Wu et al. 2009). The overall security evaluation of drinking water source was very rare. In this study, based on the definition and connotation of drinking water source security, pressure-state-response model of water source was proposed. Indictor system of water source security was established based on the model, to evaluate security situation of Dahuofang reservoir source area.

MATERIALS AND METHODS

Study area: Dahuofang reservoir is situated in east longitude of 123°04'28" to 124°27'46", north latitude 42°21'103" to 42°04'01", at the eastern part of Fushun city, Liaoning

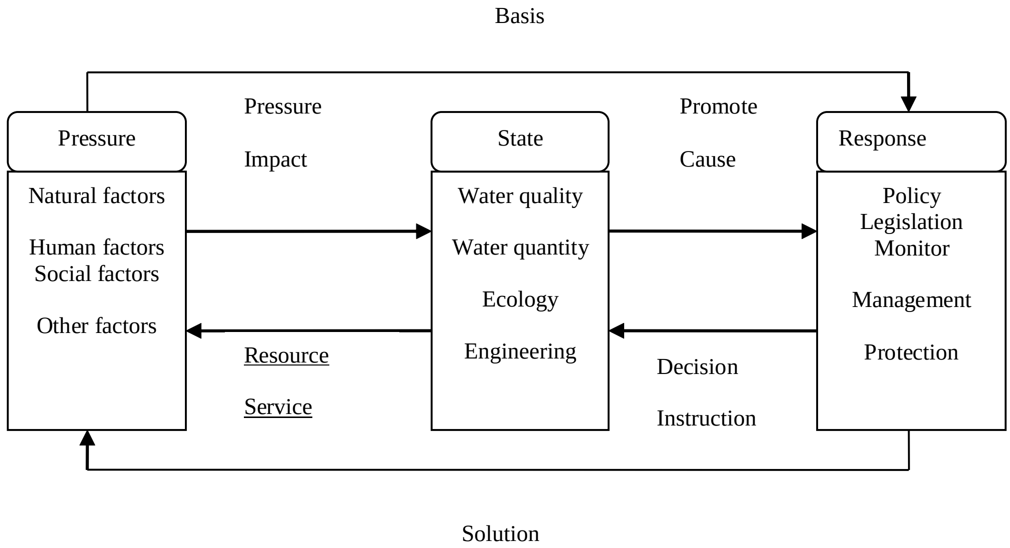

Fig. 1: Pressure-state-response model analysis framework.

province, middle and upper area of Hun river. Dahuofang reservoir is a typical valley type reservoir for flood prevention, irrigation, industrial and domestic water. With the completion of the water conveyance project of Dahuofang reservoir, it has become a drinking water source for population of 23 million in 7 cities of Liaoning province, and is one of the nine major water sources in China. The reservoir was completed and put into use in 1958, all basins are distributed in three countries, which are Qingyuan, Xinbin and Fushun in Fushun city. The reservoir controls a total area of 5437 km^2 of all basins. The maximum capacity is 2.268 billion m^3. Dahuofang reservoir accepts the surface water from Hun River, She River and Suzi River. Hun River originates in Qingyuan country, and flows from east to west throughout the whole Fushun city. Hun River is 169 km long above the dam site, the river slope is 2.8 ‰, and flows into Dahuofang Reservoir in Beizamu. Suzi River originates in the Xinbin country, river length is 132 km, the river slope is 2.3 ‰, and flows into Dahuofang Reservoir in Gulou. She River originates in Fushun county and is 46 km long, the river slope is 7 ‰, and flows into the reservoir in Taigou.

Data collection: Data information of Dahuofang reservoir of 2012 was selected as an evaluation object. Water quality grade adopts the evaluation results of BP neural network method by the author Ma et al. (2014). Other data come from Fushun statistical yearbook, hydrological information network of Liaoning province, national economy and society developed statistical bulletin of Liaoning province, standards construction of security assurance of Dahuofang reservoir source area and government affairs public network.

PSR model: The PSR model was proposed by Canadian academicians Ropport and Friend (1979), which was applied in studies of the environmental framework by United Nations Environment Program (UNEP) and the Organization for Economic Cooperation and Development (OECD) in 90s and the applicability and effectiveness of the model were evaluated, which promoted the application of the model. Press indicators describe the load from human activities to the system to be evaluated. State indicators reflect the state of evaluation object. Response indicators are measures and methods taken by people. At present, PSR model is widely applied to the environmental assessment (Munier 2011), ecosystem assessment (Santibáñez-Andrade et al. 2015, Wang et al. 2010, Guo et al. 2008, Qiu et al. 2008), water resources carrying capacity assessment (Jiang et al. 2011), healthy water circulation assessment of wetland (Zhou et al. 2008) and animal husbandry evaluation (Bockstaller 2014).

The PSR model is applied to security evaluation of reservoir source area in this study. Guided by the concept of PSR model, drinking water source PSR security evaluation model was establish as shown in Fig. 1. The model shows that natural factors, human factors and social factors exert pressure on the source area and then state of the source changes under the pressure. Corresponding management and monitoring strategies are taken to make the water source to the safe direction.

RESULTS AND DISCUSSION

Security evaluation indicator system of reservoir source area: Indicators were selected following the principle of

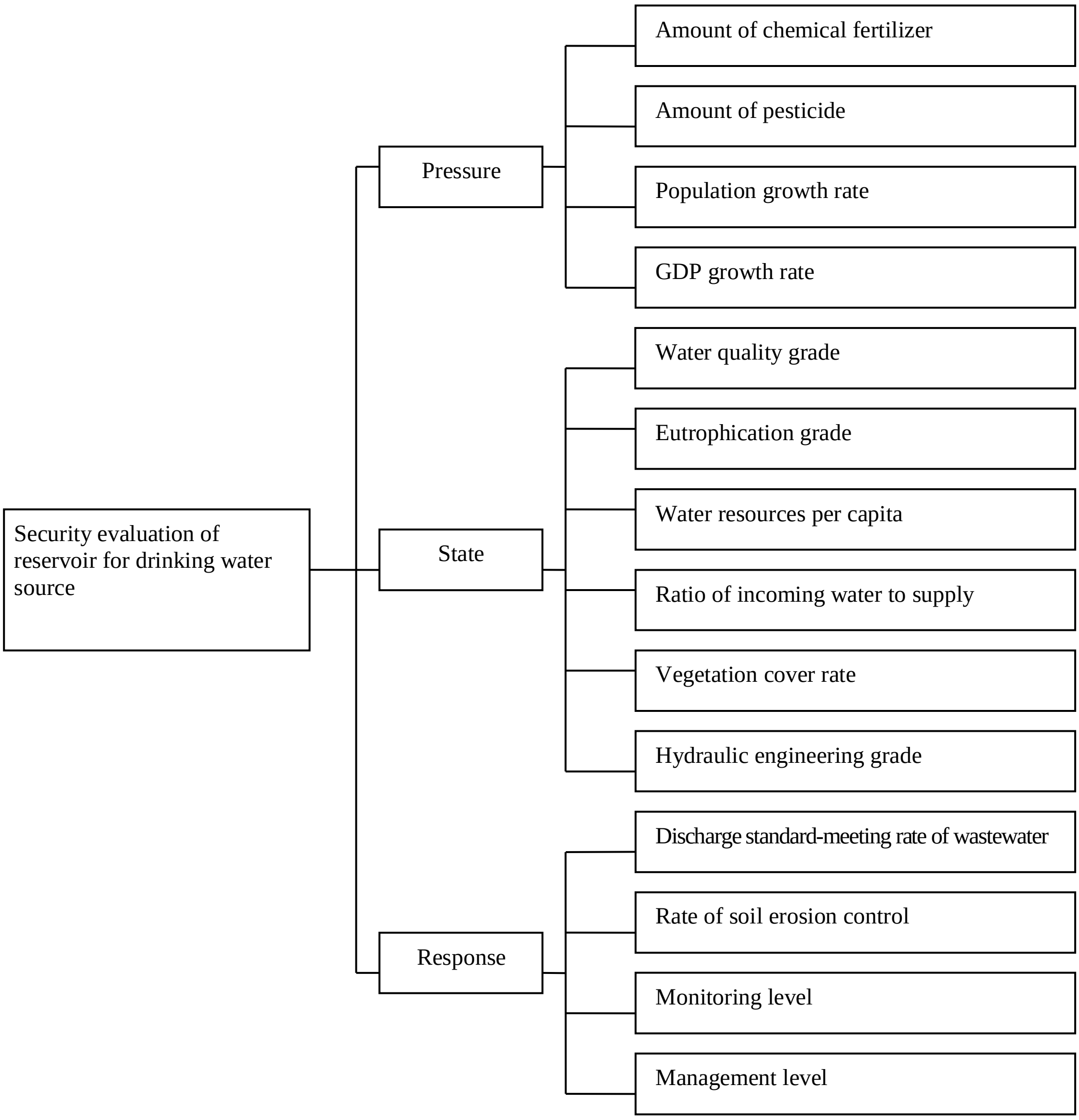

Fig. 2: Security evaluation indicator system of reservoir for drinking water source.

science, representation, hierarchy, operability, integrity and systematization. Considering the actual situation of reservoir for drinking water source, the indicator system was set up as shown in Fig. 2.

***Pressure indicators*:** Pressure on reservoir for drinking water source mainly comes from the development of social economy, as part from natural factors. The pressure on water and land resources increases under the social development, so the amount of chemical fertilizers and pesticides were selected as evaluation indicators. The more of their application, the more serious is pollution of the environment. The GDP growth rate represents regional economic development level; high rate of growth indicates a good economic development. Relevant departments have strong investment capacity to the source area construction and the regional economy security can be better safeguarded. Pressure on water supply will increase under the population growth. Under the condition of gross water resources remaining constant, the more quickly the population grows, the less per capita water resources will be.

***State indicators*:** They reflect the state during the reservoir operation. According to the definition of drinking water source security, the secure source area should be in a safe state on six basic aspects, that is water quality security, water quantity security, ecological security, engineering security, monitoring system security and management system security. Water quality security can be reflected by water quality grade and eutrophication grade. The higher the level is, the better water quality will be. Per capita water resources and ratio of incoming water to supply are selected to represent water quantity security. Per capita water resources reflect regional water situation of abundance or deficiency. The higher the ratio of incoming water to supply is, the more secure the water source area will be. Ecological security can be reflected by vegetation coverage. Good vegetation can conserve water resources, adjust surface runoff, protect and strengthen water conservancy projects, and reduce the sediment deposition resulting from soil erosion, non-point source pollution and flood pressure. Hydraulic engineering security grade is applied to represent engineering security. The fundamental task of conservancy project is flood control, which provides security and protection for people's life and property. The higher the security grade is, the greater the protection efforts will be.

***Response indicators*:** These pertain to response of related departments to the pressure and state in order to make safe operation of source area. Quantifiable indicators selected are discharge standard-meeting rate of wastewater and rate of soil erosion control. Most of the response indicators are management measures belonging to qualitative indicators and are hard to quantify. Following aspects are considered: whether they have related drinking water area protection regulations and measures being approved for implementation, automatic online monitoring facilities and feasible monitoring system, and the ability of capital management, technology management and organization management.

Set up multi-level fuzzy comprehensive evaluation model: Without clear hierarchy boundaries on the drinking water area security, it has a certain amount of ambiguity. The fuzzy comprehensive evaluation is a method to evaluate the object or phenomenon affected by variety of fuzzy factors and is a powerful tool to research multiple attributes. Considering the effect of the membership at all levels to evaluation results, the evaluation based on the model is hierarchical. So in this study, two-class fuzzy comprehensive evaluation method was applied (Li 2004). Fuzzy complex index method will be used to determine the final grade, formula 1.

$$FCL = B \cdot S = (b_1, b_2, \ldots, b_m) \cdot \begin{bmatrix} 1 \\ 2 \\ \vdots \\ n \end{bmatrix} \qquad ...(1)$$

Where, FCL is fuzzy comprehensive index, B is fuzzy comprehensive evaluation results, S is evaluation standard vector.

Indicator weights are decided by the method of analytic hierarchy process, which was put forward by operational research expert T. L. Saaty (Saaty 1977) of the University of Pittsburgh in the 1970s. AHP is an effective multi-target decision method combining qualitative analysis with quantitative analysis (Wu & Li 2013). The basic principle of analytic hierarchy process is to establish different layers of indicators in the evaluated system according to the affiliations, the indicators of each layer are served as criteria for next layer. Compare two indicators, judge and calculate the weight, and order in single hierarchy and then the whole system. Then the importance weights of each indicator to the system are obtained. Specific steps are as follows: 1. Set up analytic hierarchy structure model: Dividing decision targets (target layer), considering factors (criterion layer), decision objects (indicator layer) into different layers according to the relationship between them. 2. Construct the judgment matrices: Using nine-scale demarcation method (Wang & Xu 1990), the elements in the judgment matrix are weights. 3. Single order of hierarchy and matrix consistency inspection. 4. The whole system ordering and matrix consistency inspection.

The indicator evaluation standard: The evaluation results will be influenced by the rationality of the evaluation standards. The locations of the basin, water conservancy project types, the population of water supply, all correspond to different evaluation standards on the evaluation of reservoir for drinking water source.

Security level of drinking water source area is divided into five grades, which are I (very high), II (high), III (middle), IV (low), V (very low). Security grade achieving III is considered secure. Meantime, secure state of each indicator is divided into five grades corresponding to the source area security level. Establish standards of each indicator are given in Table 1.

Due to Fushun city being a mountain city, vegetation coverage is replaced by forest coverage. Water quality is in accordance with environmental quality standards for surface water in China. The eutrophication level is calculated by comprehensive nutrition state index, denoted by a series of consecutive numbers 0-100. National standard, flood control standard (GB50201-94), and industry standard, and the hydraulic structure engineering of reservoir flood control standard (SL252-2000) are referenced to evaluate hydraulic engineering grade. Document issued by ministry of water, i.e., notice on the construction of security guarantees of major drinking water sources to meet the standards in

Table 1: Classification standard of evaluation indicator of Dahuofang reservoir for drinking water source.

	I	II	III	IV	V
Amount of chemical fertilizer (t/hm^2)	[0,1]	(1,2]	(2,3]	(3,4]	(4,∞)
Amount of pesticide (t/hm^2)	[0,0.01]	(0.01,0.025]	(0.025,0.035]	(0.035,0.045]	(0.045,∞)
Population growth rate (‰)	(-∞,2]	(2-4]	(4-6]	(6-10]	(10, ∞)
GDP growth rate (%)	(10, ∞)	(8,10]	(6,8]	(4,6]	(-∞,4]
Water quality grade	I	II	III	IV	V
Eutrophication grade	(0,30]	(30,50]	(50,60]	(60,70]	(70,100]
Water resources per capita (m^3/per)	(10000, ∞]	(1670,10000]	(1000,1670]	(500,1000]	(0,500]
Ratio of incoming water to supply (%)	(120, ∞)	(100,120]	(80,100]	(60,80]	(0,60]
Forest coverage (%)	[70,100)	[50,70]	[30,50]	[10,30]	[0,10)
Hydraulic engineering grade	I	II	III	IV	V
Discharge standard-meeting rate of wastewater (%)	(97.5,100]	(92.5,97.5]	(85,92.5]	(80,85]	(0,80]
Rate of soil erosion control (%)	[0.9,1]	[0.8,0.9)	[0.7,0.8)	[0.6-0.7)	(0,0.6)
Completion rate of monitoring construction (%)	(80,100]	(60,80]	(40,60]	(20,40]	(0,20]
Completion rate of management construction (%)	(80,100]	(60,80]	(40,60]	(20,40]	(0,20]

Table 2: Weight and membership degree summarization of indicator layer based on the security evaluation of Dahuofang reservoir source area.

Index layer	Weight	Membership degree				
		I	II	III	IV	V
Amount of chemical fertilizer	0.0625				1	
Amount of pesticide	0.0259				1	
Population growth rate	0.0459	1				
GDP growth rate	0.0291		1			
Water quality grade	0.2144		0.7143	0.2857		
Eutrophication grade	0.1275	1				
Water resources per capita	0.0808				1	
Ratio of incoming water to supplied	0.0536			1		
Forest coverage	0.0341		1			
Hydraulic engineering grade	0.0292	1				
Discharge standard-meeting rate of wastewater	0.1160		1			
Rate of soil erosion control	0.0259					1
Completion rate of monitoring construction	0.0676			1		
Completion rate of management construction	0.0875			1		

China, is referenced to evaluate monitoring and management level, which is represented by completion rate of monitoring construction and management construction. Monitoring system should reach the level of all-direction monitor, the perfect monitoring mechanism and emergency monitoring ability. Management system should have dedicated management staff, relevant laws and regulations approved for implementation, online mechanism of relevant departments and have emergency contingency plans and emergency response capabilities. Qualitative analysis combined with expert evaluation, monitoring and management level are classified into five grades according to the completion rate. Other indicator standards are determined based on features of Dahuofang reservoir source area and combined with research of other scholars (Wolfslehner & Vacik 2008, Van Gerven et al. 2007).

EVALUATION RESULTS AND DISCUSSION

The membership degree of each indicator corresponding to the security grade is concluded by the investigated and statistics data corresponding to each evaluation standard. The membership degree of water quality to certain evaluation grades is the rate of number of sections belonging to this evaluation grade to number of sections. Weight of indicator is taken by analytic hierarchy process as given in Table 2. The normalized membership degrees and weights of each criterion layer are calculated by Table 2. Fuzzy composite index is calculated by formula (1), the evaluation grades are obtained of the criterion layers and target layers as given in Table 3.

Security grade of pressure indicators is III (middle). After observation of pressure indicators, it is found that the

Table 3: Weight and membership degree summarization of criterion layer based on the security evaluation of Dahuofang reservoir source area.

	Weight	Membership degree					Composite index	Evaluation results
		I	II	III	IV	V		
Pressure	0.1634	0.2809	0.1781	0	0.5410	0	2.8011	III (middle)
State	0.5396	0.2904	0.3470	0.2128	0.1498	0	2.2220	II (high)
Response	0.2970	0	0.3906	0.5222	0	0.0872	2.7838	III (middle)
Whole		0.2026	0.3324	0.2699	0.1692	0.0259	2.4834	II (high)

security grade of population growth rate is very high. The population growth rate of the seven cities fed by Dahuofang Reservoir is negative in 2012, which is bound to reduce the requirement of water quantity. Per capita GDP of Funshun city belongs to II. It explains that economic development level is quite high. But the whole security level of pressure indicators is III. It is due to that Dahuofang reservoir basin is located in the three countries which are traditional agricultural areas. They have large farm areas and main crops are corn, rice and soybean. Chemical fertilizers are often excessively applied to increase production and revenue. Weeding and insecticides are not accomplished by manual work, but by spraying pesticides and insecticides. Amount of straw returning is very little, most of them are used for animal feed or heating source in the countryside. Untreated water flows directly into the rivers after the rice irrigation, which cause nitrogen and phosphorus nutrient elements run into rivers.

In the state indicators, water quality of Dahuofang reservoir 2012 was evaluated based on BP neural network and concludes that in the seven sections, water quality of two sections is determined as III and the remaining five is determined as II. The membership degree to grade II is 0.7143 and to grade III is 0.2857. Based on water function and standard classification of surface water quality standard (GB3838-2002), the quality in the reservoir should reach grade II, but the content of nitrogen has been excessive for a long time with the reason of non-point source pollution. Eutrophication level is judged as grade I, so water has poor nutrition, which concludes that though nitrogen content is high, water eutrophication has not been caused. Relevant departments should be reminded that protecting water quality is a task which brooks no delay. Dahuofang reservoir engineering level is grade I, installed capacity is 32 thousand kilowatts, irrigated area designed is 1.29 million mu. The reservoir is designed as a thousand year frequency flood and checked as 10 thousand year frequency flood. Flood control safety level is grade I. Forest coverage in the basin is grade II, forest coverage rate of Fushun city is the highest in Liaoning province and is triple as high as the national average. It has been started to implement green hills engineering in 2011 and forest coverage rate would be expected to reach 70% in this year. Ratio of incoming water to supply is 95%, belonging to grade III. Only water resources of per capita is low, water of per capita of the seven cities fed by Dahuofang Reservoir is 925 m^3, water resources of per capita of the whole Liaoning province is only 806 m^3, is 40% of the whole nation and 10% of the whole world. The low water consumption of per capita is a common phenomenon in China.

In the response indicators, discharge standard-meeting rate of wastewater reaches 95% and security grade is high. The total area of Funshun city is 11271.47 km^2, the area of soil erosion has been 2655.12 km^2 by the end of 2010, account for around 23.56% of the whole area (Liu 2011). Firstly, the volume of rainfall is quite unevenly distributed in Fushun, serious and frequent floods are caused easily. Secondly, the terrain features of high mountains and steep slopes are the natural factors prone to soil erosion. Thirdly, Fushun city has rich mineral resources, a large number of blind mining are the main human factors of soil erosion. It is concluded that the cumulative amount of controlled soil and water loss area of small watershed accomplished is 800,000 mu by checking Fushun yearbook, rate of soil erosion control is only 0.2. The security grade is very low. The completion rate of monitoring and management construction are middle level, automatic online monitoring facilities are not established by relevant administrative departments of Dahuofang reservoir, security management information system of water quality and quantity and the mechanism of monitoring and management are all not perfect and complete yet.

Comprehensive security index of Dahuofang reservoir source area is 2.4834, between 2 and 3, and is closer to 2. So, it is determined that the whole security grade is high, but it is sound close to middle.

Dahuofang reservoir is an important drinking water source in China. According to the analysis results, firstly, relevant departments should take effective measures to control the application amount of fertilizers, pesticides and other pollution sources, adjust agricultural structure, and reduce non-point source pollution. In the grade 1 water source protective areas, all pollutant discharges should be forbidden. No security grade of indicators belonging to water quantity security are satisfactory, which indicates that water quantity security of the source area is poor. Though the water shortage problem has been resolved through water conveyance project of Dahuofang reservoir, effective measures should be taken to improve water resources utilization in the source area itself. Self producing water resources in the basin should be utilized fully, more reasonable scheduling solution must be formulated to determine the water transfer time and reduce the water loss. Secondly, relevant departments should step up efforts to control soil and water loss, through the measures of conversion of land to forestry, changing the firewood to stove and increase the compensation, which are feasible, scientific and reasonable measures to control soil and water loss. For the potential regional soil and water loss, protection and management should be taken simultaneously. For the monitoring and management level, relevant departments should build linkage mechanism, establish related institutions and clear the responsibility. Comprehensive monitoring system should be constructed in drinking water source area, which is the most effective way to preserve water source.

CONCLUSIONS

1. The whole security evaluation on the water source area is rare, this study defines the connotation of water source security, confirms the factors influencing the security condition of reservoir source area. Based on the pressure-state-response model, the security evaluation indicator system of reservoir source area was designed. It is interpreted that what is the pressure of water source area, what happened under the pressure, and what measures should be taken, which provides theoretical basis for planning and management of water source areas.
2. With the security condition 2012 of drinking water source area of Dahuofang reservoir as the case, the security level is classified into five grades, I (very high), II (high), III (middle), IV (low), V (very low), all indicators are correspondingly classified to five grades, too. The indicator weights are determined by analytic hierarchy process. The security grades of criterion layer and the whole are obtained by fuzzy comprehensive index method, the whole security grade is high, but very close to middle.
3. The major threats to the water source security are non-point source pollution, large areas of soil erosion in the basin, and the negligence of monitoring and management. Therefore, relevant departments should take their efforts to control the application of chemical fertilizers and pesticides, make more scientific scheduling scheme, control soil and water loss, and establish a sound and scientific monitoring management system.
4. Secure drinking water has important significance for human life, economic development and national security. This study applies pressure-state-response model to water source security evaluation for the first time and establishes the evaluation indicator system. But the connotation and evaluation of water source area are developing theory and needed to be studied deeply.

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