Journal of Water and Health | 13.2 | 2015

Risk assessment and water safety plan: case study in Beijing, China

Bixiong Ye, Yuansheng Chen, Yonghua Li, Hairong Li, Linsheng Yang and Wuyi Wang

ABSTRACT

Two typical rural water utilities in Beijing, China were chosen to describe the principles and applications of water safety plans (WSP), to provide a methodological guide for the actual application and improve the quality of rural drinking water quality, and to establish an appropriate method for WSP applied in rural water supply. Hazards and hazardous events were identified and risk assessment was conducted for rural water supply systems. A total of 13 and 12 operational limits were defined for two utilities, respectively. The main risk factors that affect the water safety were identified in water sources, water processes, water disinfection systems and water utility management. The main control measures were strengthening the water source protection, monitoring the water treatment processes, establishing emergency mechanisms, improving chemical input and operating system management. WSP can be feasibly applied to the management of a rural water supply.

Key words | risk assessment, rural areas, water safety plans, water utilities

Bixiong Ye
Institute of Environmental Health and Related Product Safety,
China CDC,
Beijing 100021,
China

Bixiong Ye
Yuansheng Chen (corresponding author)
Yonghua Li
Hairong Li
Linsheng Yang
Wuyi Wang
Key Laboratory of Land Surface Pattern and Simulation,
Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences,
Beijing 100101,
China
E-mail: *chenyuansheng@igsnrr.ac.cn*

INTRODUCTION

A high quality and reliable supply of safe drinking water is the foundation of a healthy society and its economic development. Strengthening the management of water utilities is an important safeguard to ensure continued provision of safe drinking water for people (UNEP 2005). Hazard analysis critical control point (HACCP), qualitative microbial risk assessment (QMRA), and water safety plans (WSP) are effective measures to safeguard water supply safety. The HACCP, a quality management system applied in the food industry and established by the US National Aeronautics and Space Administration (NASA) in the 1960s, involves hazard analysis of food and critical control point monitoring (Kumagai *et al.* 1997). QMRA is the process for estimating risk from exposure to microorganisms by combining dose-response information for the infectious agent with information on the distribution of exposures (Haas 1999). WSP, as promoted by the World Health Organization (WHO) in the third and fourth editions of 'Guidelines for Drinking Water Quality' (WHO 2004, 2011), are tools that allow for proactive measures to ensure safety of drinking water supply using risk assessment and risk management approaches. The WSP is based on an established HACCP concept with special focus on water. QMRA can be used in the WSP system assessment to determine whether treatment is meeting health-based targets with the required level of certainty. The primary objective of a WSP is to minimize contamination of water sources, and prevent or remove contamination during treatment, storage, and distribution of water supplies (Vieira 2011). These objectives are equally applicable to large water supply systems, smaller community-managed water supply systems, and individual household water supplies as well.

The application of the WSP approach for drinking water supplies has often been reported in European countries, Australia, and New Zealand (Dewettinck *et al.* 2001; Nokes & Taylor 2003; Dominguez-Chicas & Scrimshaw 2010). Since

doi: 10.2166/wh.2014.101

publication of the WHO drinking water quality guidelines, global application of WSP has been gathering momentum (Rand 2007; Mahmud et al. 2007; Kunikane 2007; Gunnarsdóttir & Gissurarson 2008; Vieira 2011; Gunnarsdóttir et al. 2012b; Mouchtouri et al. 2012). In China, some studies have been conducted on application of a WSP approach to water supply plants (Ren 2006; Zhang et al. 2008). However, the detail on how to generate a WSP is lacking (Summerill et al. 2010b), and there is limited evidence available demonstrating the effectiveness of WSP on water quality and health (Gunnarsdóttir et al. 2012a). Furthermore, in developing countries, WSP are often applied in urban water supplies but there are only few applications in water supplies of rural areas (Howard et al. 2005). The objective of this paper is to describe the principles and applications of WSP, to provide a methodological guide for actual application, and to demonstrate the effectiveness of WSP on improving the quality of rural drinking water supplies.

MATERIALS AND METHODS

Study area

The access to safe tap water in Beijing rural areas is a top priority in China. Investigating drinking water safety in rural Beijing provides a perfect model for investigating rural drinking water safety in other areas of China. Thus, two typical water utilities in rural Beijing were selected to study the application of WSP management tools. Figure 1 shows the location and Table 1 the information for selected water utilities. Both utilities have complete water treatment processes, complete water utility monitoring and maintenance information and are operated by professional technical and management staff. The staffs of both utilities are aware of health and safety risks associated with plant operation and management.

Methods

The WSP for this study was developed following the WHO guidelines (Bartram et al. 2009) and in collaboration with Beijing Municipal Bureau of Health and Beijing Water Group Company. Figure 2 presents the main methodological steps applied in the WSP study (Mouchtouri et al. 2012). System assessment, operational monitoring, and management plans are the three key components of the WSP.

Establishing the team

Appropriate implementation of WSP offers an important opportunity to engage in and promote preventative risk management within water utilities. To ensure success, the whole organization, especially organizational culture and leadership in water safety plan implementation, needs to be the advocate (Summerill et al. 2010a). Thus, establishing the team and team role are very important. The WSP study team consists of the leading group, development group, operating group, and expert group. The leading group plans and organizes the coordination of WSP activities. The development group develops the WSP including system description, risk identification, development of control measures, and impact assessment. The expert group assesses risk of water utilities and makes recommendations for control measures. The operating group carries out control measures, operates monitoring, and conducts the validation and verification of the WSP. The WSP team members for this study consisted of the management and technical staff of Beijing Municipal Bureau of Health, Beijing Water Group Company, and water utility staff.

System description

Description of water systems was carried out by the examination of basic materials and on-site inspection. Basic materials included the frame chart for water utility management, components of water treatment systems (intake information, water treatment process, storage tanks, and water distribution networks, etc.), the rule and regulation of water utilities, emergency reserve, staff training, power and water process device management, user complaints and customer satisfaction surveys. On-site inspection included item-by-item audits of the water supply system.

System assessment

A number of hazards and hazardous events may occur at any step in the water supply system. Hazards are defined

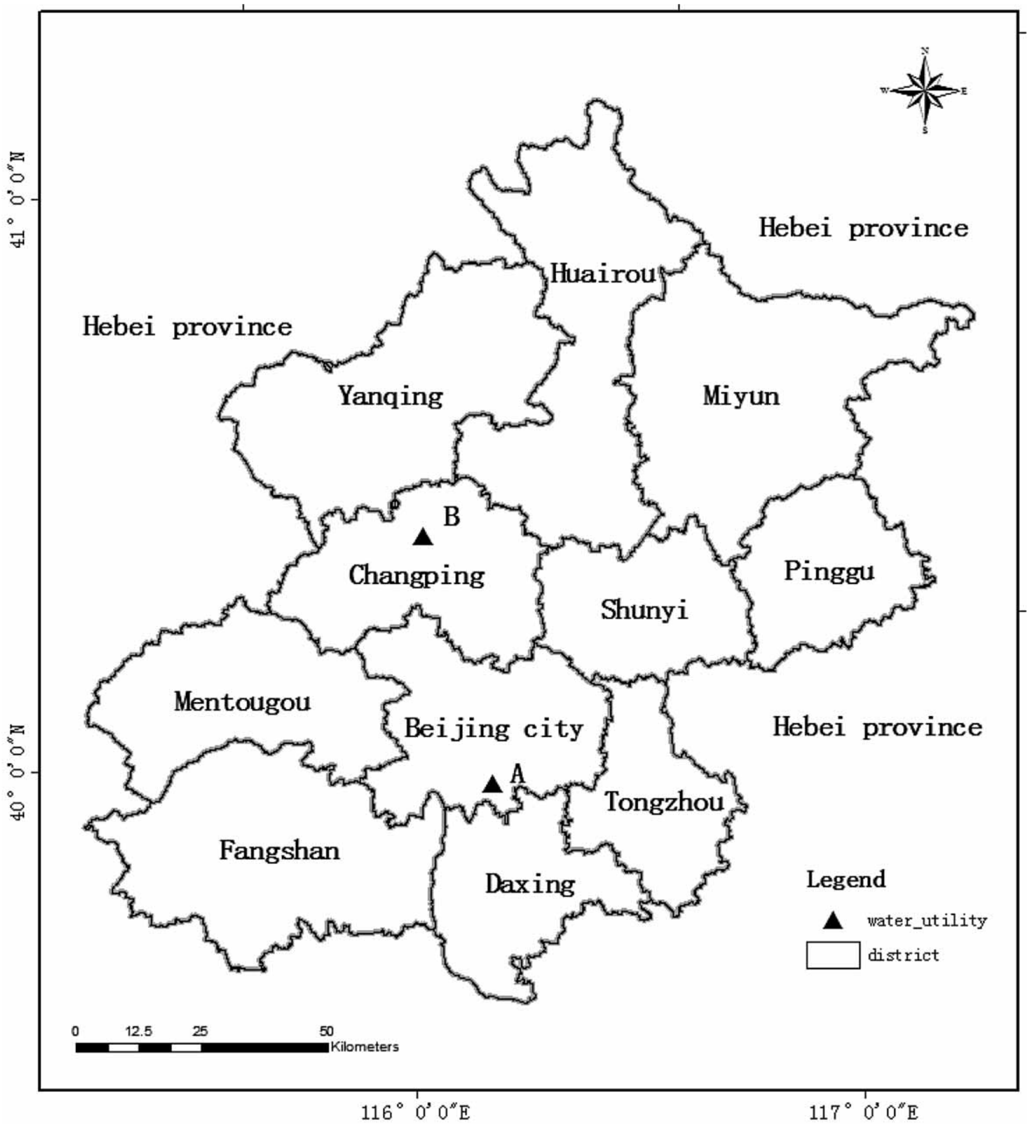

Figure 1 | The location of two selected water utilities in rural areas of Beijing, China.

Table 1 | Water supplier information for two selected water utilities

	Plant A	Plant B
Region	South of Beijing	North of Beijing
Latitude and longitude	116°06′ 24″, 39°48′ 28″	116°8′21″,40°8′16″
Ownership	Public	Public
Water source	Groundwater	Groundwater
No. consumers	45,000	10,000
Water treatment process	Aeration, filtration, and chlorination	Aeration, filtration, and chlorination

as physical, biological, chemical, or radiological agents that can cause harm to public health (Bartram *et al.* 2009). A hazardous event is defined as an event that introduces hazards to, or fails to remove them from, the water supply (Bartram *et al.* 2009). The process diagram of the water treatment is shown in Figure 3. Risk factors were identified according to the WHO water safety plan guidelines (Bartram *et al.* 2009) and the evaluation form of the risk factors of the water supply facilities in rural areas (Chinese Ministry of Health 2011). Risk factors for this study included water sources, water treatment processes, water distribution

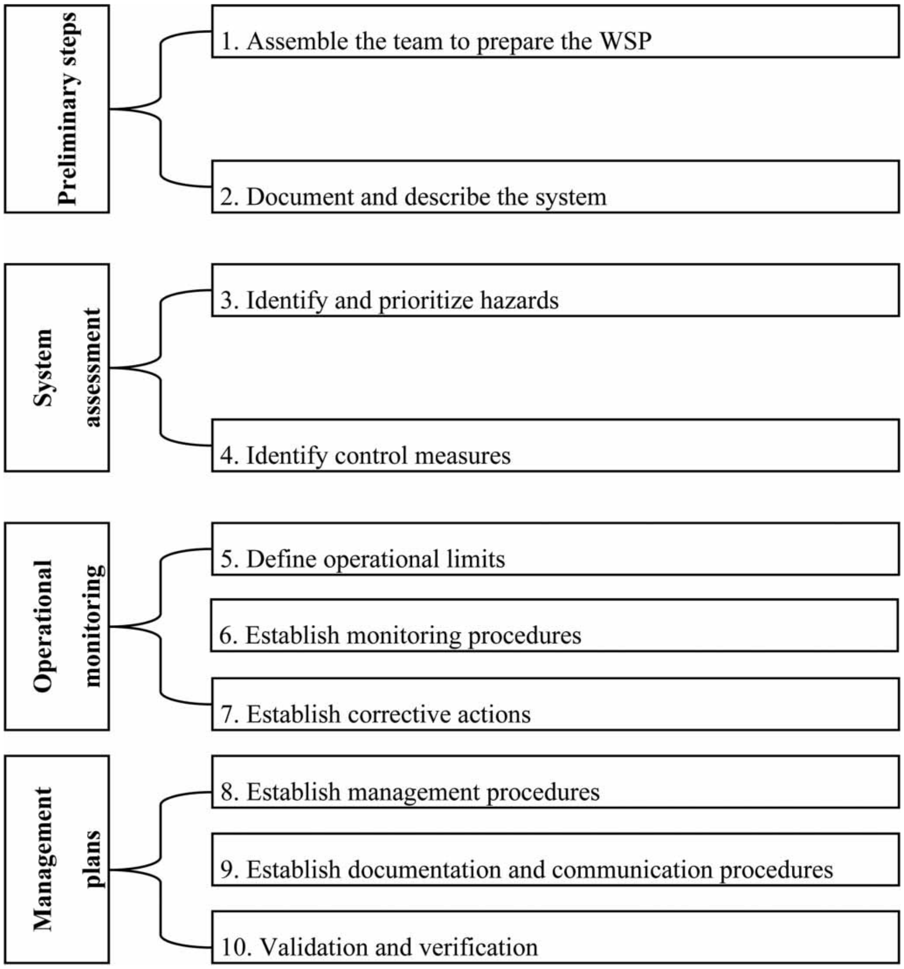

Figure 2 | Methodological steps for developing WSP for water utilities in rural areas of Beijing (Mouchtouri *et al*. 2012).

networks, water consumers, and other relevant supporting elements.

A semi-quantitative risk matrix approach (Deere *et al.* 2001; Bartram *et al.* 2009) was used to conduct the water supply system risk assessment (Table 2). The risk levels were divided into: very high (>15), high (10–15), medium (6–9), low (<6). All risks should be documented in the WSP and be subject to regular review even when the likelihood is rare and the risk rating is low.

Based on the water safety plan manual requirements (Bartram *et al*. 2009), all potential hazards were considered and those that constituted a significant risk to drinking water quality were established. How each of these risks was controlled and whether the controls were adequate were considered too. The existing control measures, risk assessment, and risk optimization were recorded and re-assessed for their effectiveness.

Operational monitoring

Operational monitoring includes defining and validating the monitoring of control measures and establishing procedures to demonstrate that the controls continue to work (WHO 2004; Davison *et al.* 2005). These actions should be documented in the management procedures. Defining the monitoring of the control measures also requires inclusion of the corrective actions necessary when operational targets are not perfect. Monitoring includes online monitoring, non-online monitoring, and evaluation of monitoring results. Online monitoring is in strict accordance with the

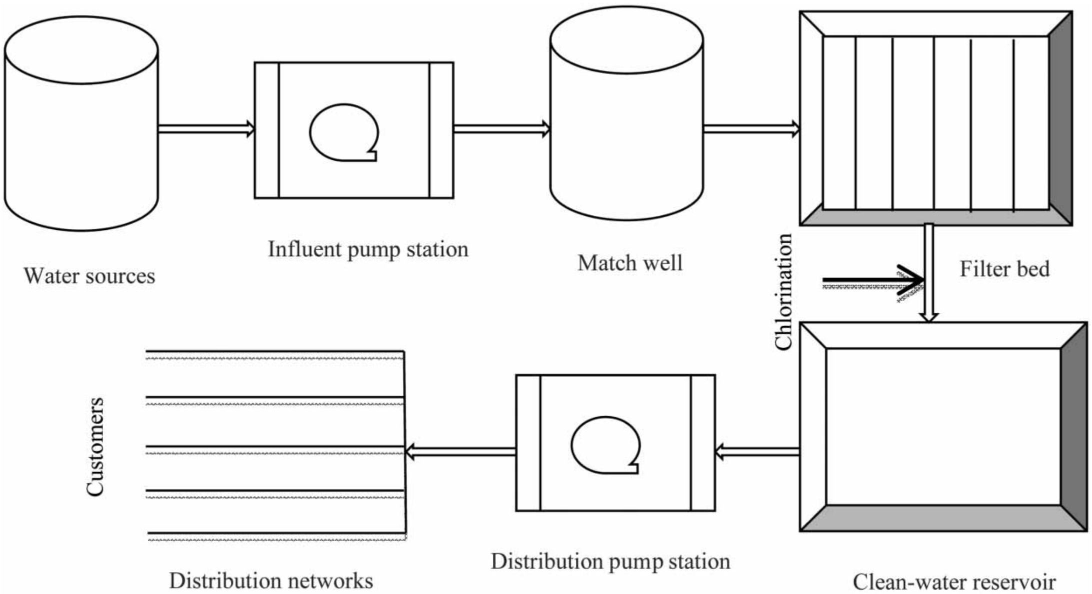

Figure 3 | Process diagram of water treatment.

Table 2 | Semi-quantitative risk matrix approach (Deere *et al.* 2001; Bartram *et al.* 2009)

		Severity or consequence				
		Insignificant or no impact – Rating: 1	**Minor compliance impact – Rating: 2**	**Moderate esthetic impact – Rating: 3**	**Major regulatory impact – Rating: 4**	**Catastrophic public health impact – Rating: 5**
Likelihood or frequency	Almost certain/Once a day – Rating: 5	5	10	15	20	25
	Likely/Once a week – Rating: 4	4	8	12	16	20
	Moderate/Once a month – Rating: 3	3	6	9	12	15
	Unlikely/Once a year – Rating: 2	2	4	6	8	10
	Rare/Once every 5 years – Rating: 1	1	2	3	4	5
	Risk score	< 6	6–9	10–15	> 15	
	Risk rating	Low	Medium	High	Very high	

requirements for water quality monitoring and is organized by the members of the working group. Non-online monitoring is in accordance with the provisions for other risks to complete the rectification work. Monitoring and evaluation of results provide monitoring for the results reporting system.

Checking if the controls are working correctly is very important in operational monitoring. Daily or weekly checks were carried out to make sure that the operator was following the operating procedures. These checks are the most important as they ensure that the main line of defense is secure in providing safe drinking water.

Table 3 shows several water quality indices monitoring results before the WSP. Compliance percentages of certain parameters will change by operational monitoring measures.

Table 3 | Water quality of Plant A and Plant B for 2 years before WSP

	Treated water of Plant A				Treated water of Plant B			
Content	Number	Mean	Std	Compliance percentages	Number	Mean	Std	Compliance percentages
Color	181	2.69	2.70	99.45	180	2.96	1.33	99.44
Turbidity	184	0.46	1.32	95.10	180	0.44	0.48	94.44
Fe (mg/kg)	180	0.027	0.042	99.44	180	0.057	0.071	99.44
Mn (mg/kg)	181	0.015	0.022	99.45	180	0.029	0.024	99.44
NO_2^- (mg/kg)	82	0.0021	0.0036	100.00	87	0.0025	0.0041	100.00
NO_3^- (mg/kg)	85	3.92	5.36	88.24	85	5.33	4.93	89.41
Total bacterial count (cfu/mL)	82	39	164	91.46	89	51	816	89.89
Total coliform (cfu/100 mL)	82	0.50	2.58	93.90	82	1.64	23.18	95.12
Free chlorine (mg/kg)	82	0.03	2.88	89.02	80	0.05	2.19	91.25

cfu: colony-forming unit.

Management procedures

Management plans describe actions to be taken during normal operation or extreme and incident conditions. The emergency plan is a very important part of the WSP. The emergency plans were developed and improved for each water utility. Water emergencies include water pollution, emergency power outages, and sudden damage of water supply pipes. Development of the emergency plan improves the ability for water utilities to respond to emergencies.

Documentation and training

Records of regular monitoring and verification were maintained in both electronic format and hard copies. Record forms were developed for incident investigations, water utility water safety staff, monitoring of checking the controls, repair and maintenance, and verification. Staff training is an important part of the management plan. The staffs of water utilities were trained on site. The training program included knowledge of laws and regulations, and knowledge of water treatment processes and pollution detection methods. After training, participating staff were tested on their theoretical knowledge of the water system. In addition, to ensure the accuracy of the drinking water monitoring results, technical training content of the water quality laboratory technicians was strengthened. Although utility water safety staff were trained and examined according to the above-mentioned theoretical knowledge, in addition, they received training in the Beijing Center for Diseases Control and Prevention for operational skills.

Verification

Laboratory sampling and analysis were conducted to verify controls were working accurately. These included microbiological and chemical sampling and quality assurance and quality control analysis. The water quality laboratory plays an important role in the WSP and monitors the water quality of all aspects of the production processes.

RESULTS

Water system assessment

The water system assessment for two water utilities (Plant A and Plant B) in Beijing rural areas are listed in Tables 4 and 5. The results revealed high risk in the water source, treatment process, water quality, disinfection, and water utility management. For risk assessment, 13 and 12 hazards or hazardous events were considered for Plant A and Plant B, respectively. For Plant A, two parameters, which were agricultural fertilization surrounding the water source and not checking the exhaust value of the water source well, were characterized as medium risks. For Plant B, three

Table 4 | Matrix risk assessment of the WSP in Plant A

	Hazard and hazardous event	Hazardous types	Likelihood or frequency	Severity or consequence	Risk score	Risk rating
Water source	Agricultural fertilization surrounding water source	Chemical	2	4	8	Medium
	Livestock defecation around water source	Microbiological and chemical	4	4	16	Very high
	The exhaust value of water source well was not checked	Water supply	2	3	6	Medium
Water process	The staff could not control the amount of disinfectant dosing	Microbiological	5	2	10	High
	The monitoring system has not got safeguard provisions	Water supply	5	2	10	High
Water quality	The check method of chlorine dioxide was wrong	Microbiological	5	2	10	High
	No water quality testing after cleaning or maintenance of tank and pipes	Microbiological or chemical	2	5	10	High
Disinfection equipment and materials	No effective management methods for disinfectant materials	Chemical and safety	2	5	10	High
	No safety measures on storage disinfectant	Chemical and safety	5	2	10	High
Management	No emergency plan Staff responsibilities and job procedures were not perfect Staff training was not perfect Customer health education public awareness was not perfect	Water supply	2	5	10	High

parameters, which were agricultural fertilization surrounding the water source, lack of data for water sources, treated water, and pipe water, and no health permit for disinfection of equipment, were characterized as medium risks. The risk of livestock defecation around the water source for Plant A and the laboratory analysis of contaminants for Plant B were characterized as very high risk. The risks of other hazards or hazardous events were high for both plants.

Operational monitoring

Operational monitoring and control measures for Plant A and Plant B are listed in Tables 6 and 7, respectively. Results show improvement in monitoring procedures, including signing an agreement with the village committee, increasing the warning signboard around water sources, improving health of water sources, and re-installing and commissioning of disinfection equipment that did not run properly. In addition, some monitoring methods were improved: selecting monitoring parameters, establishing the value of operational limits and thresholds, and the monitoring of control measures.

Verification results

As shown in Table 3, nine water quality indicators were selected for verification. Total (bacterial) coliform counts, the microbiological indicator parameter, were checked weekly. Chemical indicator parameters – color, turbidity, iron, manganese, and free chlorine – were checked daily. Nitrate nitrogen and nitrite nitrogen, toxicological parameters, were checked weekly. The changes of water quality after WSP in Plant A and Plant B are listed in Table 8. Compared to the water quality before WSP, compliance percentages of total bacterial counts and total coliform counts were improved by protection of water source and strengthening of water disinfection. Nitrite nitrogen compliance percentage was improved by

Table 5 | Matrix risk assessment of the WSP in Plant B

	Hazard and hazardous event	Hazardous types	Likelihood or frequency	Severity or consequence	Risk score	Risk rating
Water source	No fence and warning signboard	Microbiological and chemical	5	2	10	High
	Agricultural fertilization surrounding water source	Chemical	2	4	8	Medium
Water process	Disinfection machine did not work	Microbiological	5	2	10	High
Water quality	The laboratory did not run	Microbiological or chemical	5	4	20	Very high
	No water quality testing after cleaning or maintenance of tank and pipes	Microbiological or chemical	2	5	10	High
	Lack of data of water sources, treated water and pipe water	Water safety	3	2	6	Medium
Disinfection equipment and materials	Disinfection equipment did not have a health permit	Microbiological and chemical	2	4	8	Medium
	No effective management for disinfection materials	Chemical and safety	5	2	10	High
Management	No emergency plan Staff responsibilities and job procedures were not perfect Staff training was not perfect Customer health education public awareness was not perfect	Water supply	2	5	10	High

controlling the chemical contamination by agriculture. Compliance rate of free chlorine was improved by running disinfection equipment. Compliance rates of color and turbidity were improved by water source protection and water treatment methods. These results show improved water quality after WSP was implemented. The application of the WSP approach in European countries, Australia, and New Zealand also found water quality improvements (Dewettinck *et al.* 2001; Nokes & Taylor 2003; Dominguez-Chicas & Scrimshaw 2010). Customer satisfaction surveys were also carried out to verify the effect of WSP. The results show that customer satisfaction for water supply pressure, water quality, and the overall satisfaction were very high (Table 9). The overall satisfaction for both Plant A and Plant B was 100%.

DISCUSSION

System assessment involves assessing the capability of the drinking-water supply chain (from water source to the point of consumption) to deliver water of a quality that meets the identified targets, and assessing design criteria for new systems (Vieira 2011). Hazards or hazardous events can be due to a number of causes, including pollution of water source or system failure. This study revealed main risks in the water source, treatment process, water quality, disinfection, and water utility management. Of the 25 parameters evaluated, five parameters were assessed as medium risk, 18 parameters as high risk, and two parameters that the laboratory did not run as very high risk. In water utilities of rural areas, microbiological, chemical, and water supply hazards were ranked as high risk, and they differed from the high-risk groups (pesticides, organic, disinfection by-products, and microbial) in urban areas, so these indicated that the scoring system provided by the WHO guidelines should be regarded only for guidance and not used prescriptively (Gunnarsdóttir *et al.* 2012a).

Monitoring parameter selection will enable understanding of the effectiveness of control measures and to initiate timely and appropriate response measures when something is not working. For each control measure, a proper

Table 6 | Operating monitoring and control measures of Plant A

	Hazard and hazardous event	Control measures	Who does that?	Who checks it is done?
Water source	Agricultural fertilization surrounding water source	Sign an agreement with the village committee for not permitting agricultural fertilization surrounding water source; Strengthen the monitoring of relevant indicators of the source water	Village committee; Water utilities	Company of Beijing water group
	Livestock defecation around water source	Warning signboards; Improving health of water source surrounding	Water utilities	Beijing Municipal Bureau of Health
	The exhaust value of water source well was not checked	Ask to submit supplement inspections provisions and additional inspection records	Water utilities	Beijing Municipal Bureau of Health
Water process	The staff could not control the amount of disinfectant dosing	Establish the disinfection instructions and correct operation method	Water utilities	Beijing Municipal Bureau of Health
	The monitoring system has not got safeguard provisions	Establish the maintenance requirement of monitoring system	Water utilities	Beijing Municipal Bureau of Health
Water quality	The check method of chlorine dioxide was wrong	Establish systems of chlorine dioxide monitoring methods and establish procedures of staff training	Water utilities	Beijing Municipal Bureau of Health
	No water quality testing after cleaning or maintenance of tank and pipes	Establish a system to provide testing records and reports	Water utilities	Beijing Municipal Bureau of Health
Disinfection equipment and materials	No effective management methods for disinfectant materials	Establish management system and standardization	Water utilities	Beijing Municipal Bureau of Health
	No safety measures on storage disinfectant	Develop provisions of the security measures	Water utilities	Beijing Municipal Bureau of Health
Management	No emergency plan	Establish contingency plans	Water utilities	
	Staff responsibilities and job procedures were not perfect	Establish waterworks profile, organizational charts, process diagrams, pipe network diagram (on the wall) and improve the various accusations and procedures to regulate a variety of records	Water utilities; Company of Beijing water group	Beijing Municipal Bureau of Health
	Staff training was not perfect	Staff training, inspection personnel training (content: the written and practical operation of blind assessment)	Water utilities; Company of Beijing water group	Beijing Municipal Bureau of Health
	Customer health education public awareness was not perfect	Conducting health education	Water utilities; Company of Beijing water group	Beijing Municipal Bureau of Health

Table 7 | Operating monitoring and control measures of Plant B

	Hazard and hazardous event	Control measures	Who does that?	Who checks it is done?
Water source	No fence and warning signboard	Fencing and add the warning signboard	Village committee; Water utilities	Company of Beijing water group
	Agricultural fertilization surrounding water source	Sign an agreement with the village committee for not permitting agricultural fertilization surrounding water source. Strengthen the monitoring of relevant indicators of the source water	Water utilities	Beijing Municipal Bureau of Health
Water process	Disinfection machine did not work	Run disinfection equipment and establish operating procedures and personnel training	Water utilities	Beijing Municipal Bureau of Health
Water quality	The laboratory did not run	Establish operating procedures and personnel training for laboratory technology	Water utilities	Beijing Municipal Bureau of Health
	No water quality testing after cleaning or maintenance of tank and pipes	Establish system to provide testing records and reports	Water utilities	Beijing Municipal Bureau of Health
	Lack of data of water sources, finished water and pipe water	Create a file managed system and data submitted system		
Disinfection equipment and materials	Disinfection equipment did not have a health permit	Apply for and collect health permit for disinfection equipment	Water utilities	Beijing Municipal Bureau of Health
	No effective management for disinfection materials	Establish a management system and standardize the treasury	Water utilities	Beijing Municipal Bureau of Health
Management	No emergency plan	Establish contingency plans	Water utilities	
	Staff responsibilities and job procedures were not perfect	Establish waterworks profile, organizational charts, process diagrams, pipe network diagram (on the wall) and improve the various accusations and procedures to regulate a variety of records	Water utilities; Company of Beijing water group	Beijing Municipal Bureau of Health
	Staff training was not perfect	Staff training, inspection personnel training (content: the written and practical operation of blind assessment)	Water utilities; Company of Beijing water group	Beijing Municipal Bureau of Health
	The customer's health education public awareness was not perfect	Conduct health education	Water utilities; Company of Beijing water group	Beijing Municipal Bureau of Health

operational monitoring method should be provided, so as to get effective monitoring. An operational limit value is provided for each control measure. If monitoring results indicate that one limit has been exceeded, scheduled corrective measures need to be taken. To maintain the performance and safety of the water supply, implementation of the

Table 8 | Changes in water quality one month after WSP

Content	Number	Treated water of Plant A		Treated water of Plant B	
		Mean	Compliance percentages	Mean	Compliance percentages
Color	30	5	100.00	0	100.00
Turbidity	30	0	100.00	0	100.00
Fe (mg/kg)	30	0.11	100.00	0.17	100.00
Mn (mg/kg)	30	0.06	100.00	0.013	100.00
NO_2^- (mg/kg)	5	0.018	100.00	0.021	100.00
NO_3^- (mg/kg)	5	2.05	100.00	1.41	100.00
Total bacterial count (cfu/mL)	5	2	100.00	2	100.00
Total coliform (cfu/100 mL)	5	0	100.00	0	100.00
Free chlorine (mg/kg)	30	0.35	100.00	0.4	100.00

cfu: colony-forming unit.

deviations discovered and corrective measures should be implemented within a certain time. Determining the monitoring of control measures includes what is monitored, how to monitor, and who is responsible for monitoring.

Timely corrective measures should be considered when a change in water quality is observed. Changes in water quality can be used to evaluate the effect of the WSP. The verification results show significant benefit from WSP implementation in the form of strengthened and standardized operational monitoring of water utilities, improved water supply, water quality, treatment process, management level of water utilities, and reduced disease risk. This indicates that there are measurable benefits from implementing WSP in water utilities of rural areas.

CONCLUSIONS

Two typical rural water utilities in Beijing were selected in order to establish an appropriate method for WSP applied in a rural water supply. The method developed following the WHO guidelines and in collaboration with the actual status of rural water utilities was an effective and appropriate method.

Based on the system description and risk assessment, hazard or hazardous events that affected water quality were found in each rural water utility. Fourteen and 13 parameters were taken into consideration for risk assessment of Plant A and Plant B, respectively. Of the 27 parameters evaluated, five parameters were assessed as medium risk, 18 parameters high risk, and two parameters that the laboratory did not run as very high risk. According to the results of the risk assessment, the appropriate control measures and management system were developed.

The verification result shows that water quality after the WSP was better than that before WSP and high customer satisfaction also increased when WSP was implemented. Compliance percentages of certain parameters such as microbiological indicator parameters, nitrite nitrogen, free chlorine, etc. were effectively improved by the improvement in monitoring procedures and methods. Results show that a WSP can be an important instrument in improving water quality, reducing the occurrence of waterborne illnesses, and improving public health.

Table 9 | The result of customer satisfaction surveys of two rural water utilities

		Total population	Excellent		Good		Bad	
			Population	%	Population	%	Population	%
Plant A	The water supply pressure	120	110	91.7	8	6.7	2	1.6
	The water quality	120	103	85.9	16	13.3	1	0.8
	The overall satisfaction	120	115	95.8	5	4.2	0	0.0
Plant B	The water supply pressure	53	10	18.8	40	75.5	3	5.7
	The water quality	53	13	24.5	39	73.6	1	1.9
	The overall satisfaction	53	42	79.2	11	20.8	0	0.0

ACKNOWLEDGMENTS

Funding and support for this project was provided by NSFC (grant no. 41171085) and the National Key Scientific Program of China (grant no. 2012CB955503). The authors also thank the Beijing Center for Disease Control and Prevention for providing field and laboratory technical support.

REFERENCES

Bartram, J., Corrales, I., Davison, A., Deere, D., Drury, D., Gordon, B., Howard, G., Rinehold, A. & Stevens, M. 2009 *Water Safety Plan Environmental Science & Technology Manual: Step-by-Step Risk Management for Drinking-water Suppliers*. World Health Organization, Geneva.

Chinese Ministry of Health 2011 *Rural Drinking Water Hygiene Monitoring Technology Program of 2011 Year*. Chinese Ministry of Health, Beijing.

Davison, A., Howard, G., Steven, M., Callan, P., Fewtrell, L., Deere, D. & Bartram, J. 2005 *Water Safety Plans: Managing Drinking-water Quality from Catchment to Consumer*. World Health Organization, Geneva.

Deere, D., Stevens, M., Davison, A., Helm, G. & Dufour, A. 2001 Management Strategies. In: *Water Quality: Guidelines, Standards and Health – Assessment of Risk and Risk Management for Water-related Infectious Disease* (J. Bartram & L. Fewtrell, eds). IWA Publishing, London, pp. 257–288.

Dewettinck, T., Van Houtte, E., Geenens, D., Van Hege, K. & Verstraete, W. 2001 Hazard analysis and critical control point (HACCP) to guarantee microbial safe water reuse and drinking water production: a case study. *Water Sci. Technol.* **43** (12), 31–38.

Dominguez-Chicas, A. & Scrimshaw, M. 2010 Hazard and risk assessment for indirect potable reuse schemes: an approach for use in developing water safety plans. *Water Res.* **44**, 6115–6123.

Gunnarsdóttir, M. J. & Gissurarson, L. R. 2008 HACCP and water safety plans in Icelandic water supply: preliminary evaluation of experience. *J. Water Health* **6** (3), 377–382.

Gunnarsdóttir, M. J., Gardarsson, S. M., Elliott, M., Sigmundsdottir, G. & Bartram, J. 2012a Benefits of water safety plans: microbiology, compliance and public health. *Environ. Sci. Technol.* **46** (14), 7782–7789.

Gunnarsdóttir, M. J., Gardarsson, S. M. & Bartram, J. 2012b Icelandic experience with water safety plans. *Water Sci. Technol.* **65** (2), 277–288.

Haas, C. 1999 *Quantitative Microbial Risk Assessment*. Wiley, New York.

Howard, G., Godfrey, S., Tibatemwa, S. & Niwagaba, C. 2005 Water safety plans for piped urban supplies in developing countries: a case study from Kampala, Uganda. *Urban Water J.* **2** (3), 161–170.

Kumagai, S., Konuma, H., Kokubo, K., Fujiwara, S. & Takezawa, T. 1997 *HACCP*. Chuohoki Publishers, Tokyo, Japan.

Kunikane, S. 2007 Application of 'Water Safety Plan' to drinking water quality management in Japan. In *Memorias de Governmental Conference*, Okinawa, Enero.

Mahmud, S. G., Shamsuddin, A. J. & Feroze, M. 2007 Development and implementation of water safety plans for small water supplies in Bangladesh: benefits and lessons learned. *J. Water Health* **5** (4), 585–597.

Mouchtouri, V. A., Bartlett, C. L. R., Diskin, A. & Hadjichristodoulou, C. 2012 Water Safety Plan on cruise ships: a promising tool to prevent waterborne diseases. *Sci. Total Environ.* **429**, 199–205.

Nokes, C. & Taylor, M. 2003 *Towards public health risk management plan implementation in New Zealand*. In: *Water Safety Conference Abstracts* (O. Schmoll & I. Chorus, eds). 28–30 April 2003, Berlin, Umweltbundesamt. Text 74/03, Berlin.

Rand Water 2007 *Water Safety Plan Case Study*. Rand Water, Glenvista, South Africa.

Ren, X. W. 2006 *Water Safety Management in China through Water Safety Plan*. World Water Congress, Beijing, China, September, IWA.

Summerill, C., Pollard, S. J. T. & Smith, J. A. 2010a The role of organizational culture and leadership in water safety plan implementation for improved risk management. *Sci. Total Environ.* **408**, 4319–4327.

Summerill, C., Smith, J., Webster, J. & Pollard, S. 2010b An international review of the challenges associated with securing 'buy-in' for water safety plans within providers of drinking water supplies. *J. Water Health* **8** (2), 387–398.

UNEP GEMS/Water Programme 2005 *United Nations Environment Programme Global Environment Monitoring System/Water Programme*. Ontario, Canada.

Vieira, J. 2011 A strategic approach for water safety plans implementation in Portugal. *J. Water Health* **9** (1), 107–115.

WHO 2004 *Guidelines for Drinking Water Quality*. 3rd edn, World Health Organization, Geneva.

WHO 2011 *Guidelines for Drinking-Water Quality*. 4th edn, World Health Organization, Geneva.

Zhang, R., Yong, T. & Li, H. X. 2008 *Water Safety Plan Application in China Rural Centralized Water Supply Facilities*. Memorias Water Safety Plans: Global *Experiences* and *Future Trends*. ASPEB, IWA, OMS, Mayo, Lisbon, Portugal.

First received 14 March 2014; accepted in revised form 8 August 2014. Available online 9 September 2014