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Risk assessment of water supply system safety based on WHO Water Safety Plan; Case study: Ardabil, Iran

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ABSTRACT

WHO has recommended a document for an assessment of water supply systems being titled as water safety plan (WSP). This research was conducted to assess and identify the vulnerable points in Ardabil water supply system based on WSP in 2014. Initial investigations were performed using WSP quality assurance (QA) tool. At first, WSP checklists were prepared and filled up by experts and data analysis using WSP QA tool. Then, system hazards were listed and prioritized according to WHO matrix by team member's scientific view and then risk analyses were prepared. Results showed that "System Description" and "Management Procedure" phases scored the highest and the lowest grades, respectively. Discharge of wastewater by communities in catchment area, trihalomethanes generation in finished water, old infrastructures, old pipes, and consequently pressure drop in point of use were identified as the most important hazardous events. With regard to the low level of overall implementation in WSP steps and lack of enough attention to water supply system in some phases, current control approach has no sufficient efficiency to provide safe drinking water. Collaboration and support of health authorities can lead to better performance and improvement of water safety in water supply system.

Keywords: Water safety plan; Ardabil city; Risk assessment

1. Introduction

Water supply system should receive considerable attention since water has vital and important role in human health and ecosystem. Poor water quality can pose a major threat to human health [1–3]. Based on official data "more than one billion people have no access to any kind of improved and safe water source" and "every year there are more than 2 million diarrheal deaths related to unsafe water consumption, sanitation, and hygiene" mainly among children under 5 years old, especially in developing countries [4,5]. In the study conducted by Gunnarsdottier et al. [6] revealed that preventive approach can decrease diarrhea through improved water quality.

Since water supply systems are often constructed and operated in open environment, inadequate management of

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water supply systems can affect either water quality or water quantity which can led to prevalence of illness in both developed and developing countries and threat potable water safety during delivery to consumers [3,7,8]. To assess the reliability of water supply systems for safe water delivery to consumers, risk assessments have been recognized as a useful tool to identify and determine risks of, threats, critical and vulnerable points in systems and this will lead to selection of corrective actions [3]. There are so many methods and concepts for risk assessment of water supply throughout the world [8,9]. One of these is water safety plan (WSP). This approach is proposed and described by guidelines of World Health Organization (2011) which has been implemented in some countries and is being developed in many other countries. This plan is the "most appropriate method for ensuring continuous provision of safe potable water that employs a general risk assessment on transferring clean and safe water to consumers" [10,11]. This plan has created a global shift in how water supplies should be managed [12]. It is important to know that risk management can cover the whole system from water catchment to consumer (Fig. 1).

A general water supply system consists of four main components as below:

- water sources or catchments (rivers, reservoirs, and wells);
- raw water transmission pipes;
- water treatment plants; and
- water distribution networks.

In each abovementioned parts, vulnerable and high risk points may exist in water supply system, which require a better monitoring and close supervision. In a study carried out in Iceland, old distribution pipes were renewed in some areas, where often they had high bacterial count in water samples, also, some limitations were observed in waterworks due to inadequate external and internal auditing [14].

In most countries, water supply organizations only pay attention to end point testing, so there is a lack of attention on risk assessment and management in whole system. Ardabil city being located in north-western part of Iran (latitude: 48°16′ longitude: 38°15′) was selected as case study. In Ardabil, surface water accounts for more than 70% of the available water source. The purpose of this study is to assess and identify the vulnerable points with high risk in Ardabil water supply system based on WSP in 2014. Detection and

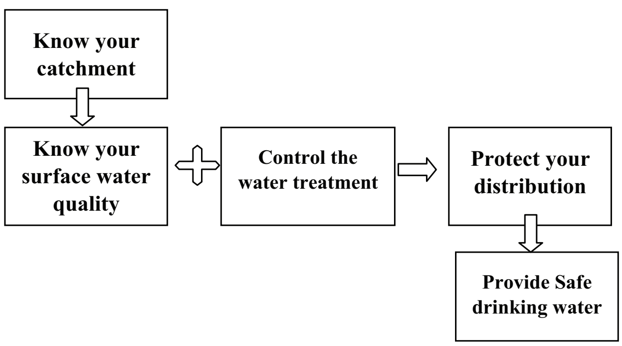

Fig. 1. Catchment to consumer's approach to risk management of drinking water safety [13].

anticipation of weak points in management of Ardabil drinking water supply system will guide us to identify those areas that need improvements. By control of these points safe drinking water can be delivered to consumers.

2. Materials and methods

Surface water and groundwater are the two water supply systems in Ardabil city, which surface water provides more than 70% of drinking water in the community. Therefore, just surface water was considered in this study. The study area and its location are shown in Fig. 2. Component of Ardabil water supply system (catchment to consumer) are represented in this figure.

Guidelines of WSP were used for risk assessment of Ardabil water supply system. At first, possible hazards in Ardabil water supply system were identified. Research was conducted in two parts as follows.

2.1. First section: water safety plan quality assurance tool (WSP QA tool)

Survey of current water supply condition and WSP QA tool was used as baseline in our study with the help of WHO WSP. WSP tool is the MS Excel-based tool that can be used by WSP team composed of water supply organizations and also external assessors.

This tool has four sections including menu, description of the tool, assessment of data entry, and assessment of results. The assessment of data entry section is divided into two parts: qualitative and quantitative questions being presented in 12 tables as follows:

Table 1 – general information on the water supplier;
Table 2 – general information on each water supply system;
Table 3 – WSP team;
Table 4 – system description;
Table 5 – hazard identification and risk assessment;
Table 6 – control measures and validation (including reassessment and prioritization of risks);
Table 7 – improvement plan;
Table 8 – operational monitoring;
Table 9 – verification;
Table 10 – management procedures;
Table 11 – supporting programs; and
Table 12 – review of the WSP (including periodic reviews and following incidents).

Each table includes a series of questions where each question includes some guidance on how to answer. Further guidance may also be available in the WSP manual: step-by-step risk management of drinking-water suppliers ("WSP Manual") and other references as well.

Since WSP is not implemented in Ardabil and evaluation of some phases in this plan is not possible without implementation, there is not any result related to them in that table.

For this purpose, all of the questions in the WSP tools translated to Persian and were answered through interview by the team members. After entering this question to tool, results extracted in form of charts and graphs.

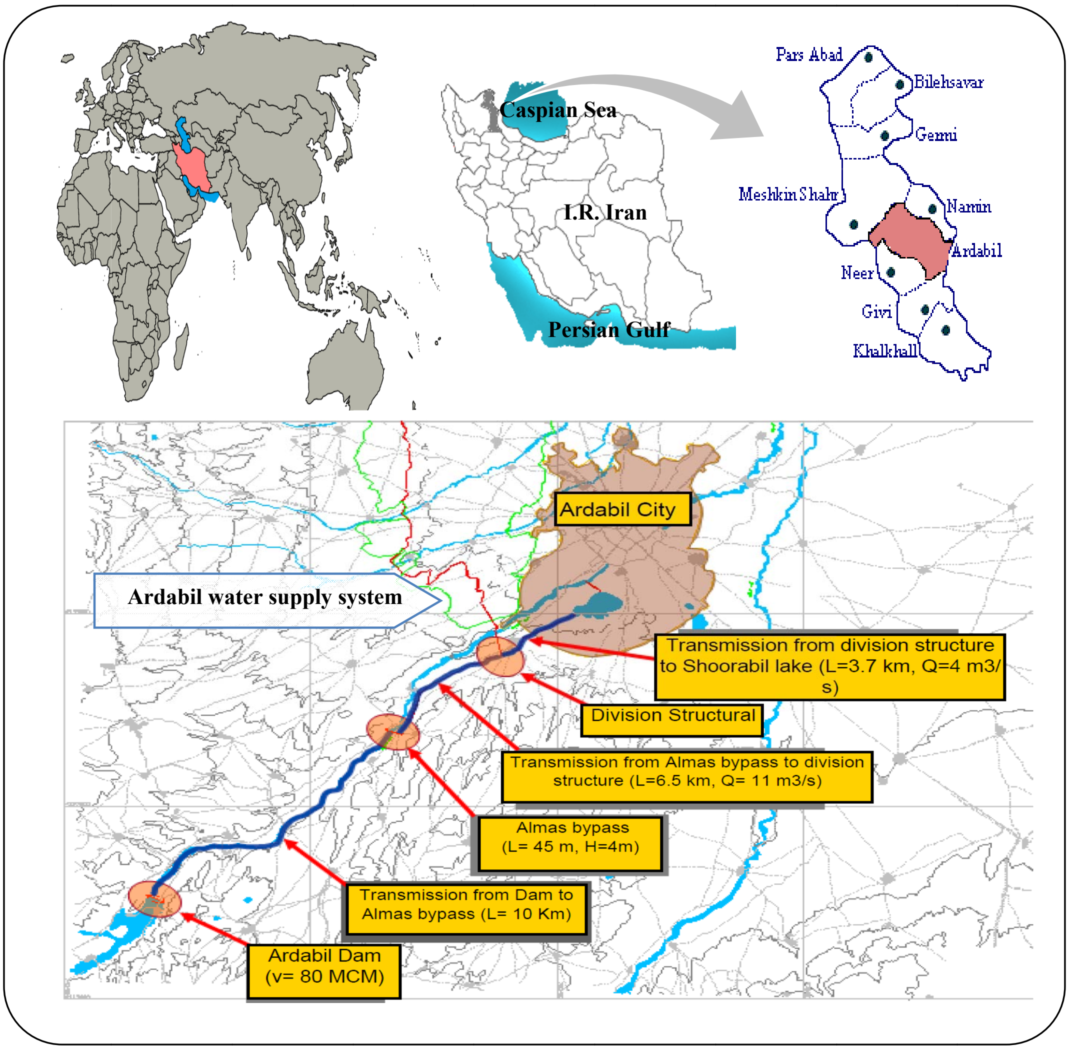

Fig. 2. Component of Ardabil water supply system and location of Ardabil city in Iran.

2.2. Second section: risk assessment

Risk assessment of Ardabil WSP performed by consulting with experts in Ardabil Water and Wastewater Company and Regional Water Company. These selected experts should be aware and familiar with any hazards or risks that may affect the safety of water in different components of the system, from catchment to consumer. This group must be able to propose methods to prevent and control the identified risks. The purpose of the prioritization matrix is to rank hazardous events to provide a focus on the most significant hazards [15].

Next, most of the common hazards in all four main component of Ardabil water supply system were identified and listed. Then, identified risks were prioritized based on risk assessment matrix in WSP. The objective of this matrix is to emphasize the risks and hazardous events that have the greatest importance in the water supply system. After risk assessment, hazard analysis tables were prepared and finally corrective actions were proposed to control and reduce the identified risks. All common identified hazard events in each component are listed as follows:

- Watershed and catchment: 10 hazards;
- Water treatment plant: 12 hazards;
- Distribution network: 12 hazards; and
- Point of use (premises consumer): 9 hazards.

After 3 weeks, section 2 was repeated in the same way to measure the reliability of answers presented by the teams. R statistical software was used to obtain Cronbach's alpha coefficient (by using intraclass correlation [ICC]). Cronbach's alpha is one of the most common measures of internal consistency ("reliability"). To calculate it, the following equation was used (Eq. (1)):

$$r_{\infty} = \frac{j}{(j-1)}\left[1 - \frac{\Sigma s_j^2}{s^2}\right] \quad (1)$$

where j is the number of questions; S^2_j is the variance of scores on each question; and S^2 is the total variance of overall scores on the entire test.

Team members developed a risk for each identified hazard: ranking matrix to address both likelihood and severity, using semi-quantitative ranking system by allocating numbers to different levels of likelihood and different levels of severity. A risk score is then calculated by multiplying two quantities together:

$$\text{Risk} = \text{Likelihood} \times \text{Severity} \quad (2)$$

Table 1 shows examples on definitions of likelihood and severity categories for risk scoring.

3. Results

Since in Ardabil water supply system, only a few staffs were familiar with WSP approach, implementation of some phases of WSP was obtained briefly. It is worth to add that there was no formal process and plan for preventive risk assessment. After entering the gathered data on to WSP tool in Microsoft Excel, results were obtained as follows (Tables 2 and 3).

In this research, four main components of water supply system were analyzed (Table 4). The result of reliability test was performed using R statistical software (ICC) which is presented in Table 5. In addition, prioritization and risk assessment of most important hazardous events in Ardabil water supply system are shown in Table 6. The coordinated implementation of WSP in four components of Ardabil water supply system during 2014 is represented in Fig. 3.

Results of percentage of coordinated implementation of WSP phases in main components of system are shown in Figs. 4(A)–(D).

4. Discussion

In a water supply system natural threats (such as flood, earthquake, etc.) and anthropogenic and operational hazards can cause serious damages to some parts of water supply system and sometimes can have irreversible effects on drinking water quality. Hence, this study was conducted to investigate and identify vulnerable areas of drinking

Table 1
Examples of definitions of likelihood and severity categories for risk scoring used in risk scoring (hazard prioritizations)

Likelihood category	Definition	Weight
Almost certain	Once per day	5
Likely	Once per week	4
Moderately likely	Once per month	3
Unlikely	Once per year	2
Rare	Once every 5 years	1
Severity categories	**Description**	**Weight**
Catastrophic	Potentially lethal to large population	5
Major	Potentially lethal to small population	4
Moderate	Potentially harmful to large population	3
Minor	Potentially harmful to small population	2
Insignificant	No impact or not detectable (insignificant)	1

Table 2
General water supplier information

Total population covered	490,366
Number of water supply system	2
Population obtaining water from supplier	99.9%
Number of incidents that have occurred within the past year	7,173
Water loss in the distribution system within the past year	27%
Number of water treatment plant	1
Population obtaining water as surface water	>70%
Population obtaining water as groundwater	<30%

Table 3
Result of general assessment of WSP steps using WSP AQ tool for Ardabil water supply system in 2014

Step	Total question	Total possible score	Acquired score (%)
WSP team	5	20	40
System description	2	8	62.5
Hazard identification and risk assessment	7	100	32
Control measure and validation	5	68	17.65
Improvement plan	3	48	–[a]
Operation monitoring	4	64	0.25
Verification	8	32	50
Management procedures	3	36	11.11
Supporting programs	2	8	–[a]
Review of the WSP	5	56	–[a]
Total	44	440	21.14

[a]Assessment of these phases require full implementation of the WSP.

Table 4
Acquired score by main component of water supply system

Component	Number of questions	Total possible score	Acquire score
Catchment	23	88	14.88 (16%)
Treatment	23	88	25.88 (25%)
Distribution	23	88	16.88 (18%)
Point of use	23	88	6.88 (7%)

Table 5
Result of reliability test (C = catchment, T = treatment, D = distribution, P = point of use) by R statistical software (ICC: intraclass correlation)

	Code	Alpha	Standard error (SE)	Lower	Upper
1	C11	0.974576	0.014364	0.946423	1.00273
2	C21	0.964912	0.021042	0.923669	1.006155
3	C31	1	0	1	1
4	C41	0.954955	0.033556	0.889184	1.020726
5	**C51**	**–0.875**	**1.379963**	**–3.57973**	**1.829727**
6	C61	0.978903	0.015112	0.949284	1.008522
7	C71	0.979424	0.01304	0.953865	1.004983
8	C81	0.970332	0.022398	0.926431	1.014232
9	C91	0.688525	0.235047	0.227833	1.149216
10	C101	0.857143	0.107129	0.647169	1.067116
11	T11	0.883642	0.035571	0.813922	0.953363
12	T21	0.967136	0.017107	0.933607	1.000666
13	T31	0.885246	0.063803	0.760192	1.0103
14	T41	0.632588	0.267919	0.107467	1.157709
15	T51	0.75	0.188471	0.380597	1.119403
16	T61	1	0	1	1
17	T71	0.677249	0.243458	0.200071	1.154426
18	T81	0.975309	0.018301	0.939438	1.011179
19	T91	0.604167	0.278666	0.057981	1.150352
20	T101	0.950943	0.037078	0.878271	1.023616
21	T111	0.907895	0.068819	0.77301	1.04278
22	T121	0.96732	0.024558	0.919187	1.015454
23	D11	0.980695	0.013444	0.954346	1.007044
24	D21	0.939759	0.038329	0.864635	1.014883
25	D31	0.987406	0.006396	0.974869	0.999942
26	D41	0.943478	0.029545	0.885569	1.001387
27	D51	0.921348	0.059455	0.804816	1.03788
28	D61	0.972527	0.012116	0.94878	0.996275
29	D71	0.934579	0.049273	0.838004	1.031155
30	D81	0.909091	0.040861	0.829004	0.989178
31	D91	0.957346	0.028896	0.900709	1.013983
32	D101	0.968215	0.020704	0.927635	1.008795
33	D111	0.978632	0.011737	0.955628	1.001637
34	D121	0.938776	0.046281	0.848064	1.029487
35	P11	0.779661	0.135952	0.513195	1.046127
36	**P21**	**0.407767**	**0.442526**	**–0.45958**	**1.275118**
37	P31	0.9625	0.021651	0.920065	1.004935
38	P41	0.72	0.149999	0.426003	1.013997
39	P51	0.825	0.129361	0.571452	1.078548
40	P61	0.902655	0.069192	0.767038	1.038272
41	P71	0.980892	0.014197	0.953066	1.008718
42	P81	0.805755	0.131805	0.547418	1.064093
43	**P91**	**0.057143**	**0.403946**	**–0.73459**	**0.848876**

Note: The bold cases are those which did not meet are aims as a matter of having higher Cronbach' alpha coefficient than 0.6, so they were left aside of this study. This is a method to measure the stability of the questionnaires. In this regard 3 of them were omitted.

water supply system with high risk in Ardabil city based on WSP in 2014.

This plan presents systematic approach in order to ensure the quality of distributed water to consumers and it is based on comprehensive assessment of risk factors that may affect the quality of drinking water. Although in water supply organization of Ardabil some staffs were familiar with WSP, some phases of this program were implemented briefly in some

Table 6
Prioritization and risk assessment of most important hazardous event in Ardabil water supply system

Corrective action	Component	Risk	Severity	Likelihood	Hazardous events
Sewage and waste discharges to water sources or catchment by villagers and local communities	5	4	20	Catchment (source)	– Wastewater collection and treatment systems in some rural and urban areas around the river and surface waters – Preventing dumping of waste in upstream via development of waste management system – Promoting awareness in the community living in that area who can affect water quality – Regular inspection for effective actions – Control of human activities in catchment boundaries
Contamination of water due to raw water storage (algae bloom and stratification)	4	4	16	Catchment (source)	– Use microstrain, copper sulfate, sand spray, etc. – Reservoir mixing (aerated under layers using aeration devices, submersible pumps, etc.)
Older pipes and aging water infrastructure	5	3	15	Distribution system	– Investment on replacing and renewing of old pipes in distribution system
Inadequate residual chlorine in storage tanks and distribution network	3	4	12	Distribution system	– Essential chlorination in output of reservoirs – Booster dosing – Super chlorination in related pipes or reservoirs – Operator education for proper chlorination
Lack of organic pollutant remove during process and THM formation	4	3	12	Treatment	– Use of enhanced coagulation process for removing total organic matter and color – Optimizing disinfectant dose and contact time – Adding disinfectant at the end of the treatment process – Use the alternative disinfectant (ozone, chloramines, etc.)
Problems associated with disinfection and filtration performance	3	3	9	Treatment	– Regulate the filter backwashing cycle and its reuse (troubleshooting possible) – Proper design and operation of filtration – Online monitoring of turbidity and reducing filtration rate by decreasing the current input in high turbidity times – Proper operation of pretreatment processes, coagulation, flocculation
Problem of water pressure drop in houses	3	3	9	Point of use	– Combined use of water resources for pressure supply (e.g., wells, etc.) – Use less water during peak hours
Any uncontrolled risk for any reason that has not decreased in distribution network	2	4	8	Point of use	– Appropriate measures to eliminate the uncontrolled risk with regard to type and nature (boiling, filtration, etc.) – Secondary treatment in homes (household treatment)

parts of the system, although there were no principles for preventive risk management. The input of some steps was zero because of lack of complete implementation of the plan in Ardabil water supply system.

There were a total of 440 scores in the case that all phases of WSP to be implemented [12]. In this study, 328 total scores were related to the investigated phases. Result of "WSP quality assurance Tool" showed from 328 total scores, only 93 scores were obtained and just 21% compliance was observed using WSP. "System Description" and "Management Procedure" phases obtained the highest and the lowest scores of performance with 62.5% and 11.11%, respectively.

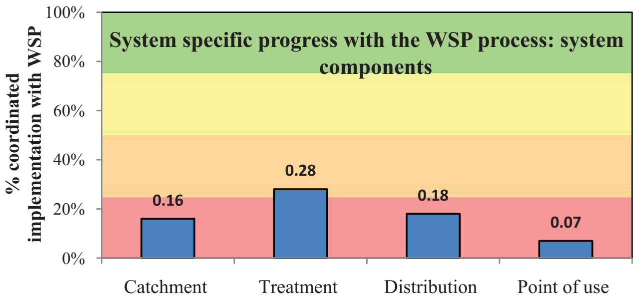

Fig. 3. Coordinated implementation of water safety plan in four components.

The hazard identification phase was determined as a key factor in WSP in investigations of developments. This has been obtained in Japan using WSP in 2009 [16]. In our study, this phase received 32 scores out of 100 total possible score.

The highest attention was related to the water treatment plan and distribution network and the lowest to the point of use and catchment by water supply organization. In this study, some factors such as "Review" and "improvement plan" cannot be assessed due to lack of complete implementation of WSP in Ardabil and their scores are shown by dashes in Table 3.

Totally, it is clear that these results distinguished the areas and points which need to be improved and also determined the insufficiency of current approach (according to end point testing). Another major defect of current approach in Ardabil drinking water management is concentration on "Verification" and "System Description" and neglecting other stages by authorities. This study appeared that management of major components of water supply system was not considered appropriately that may affect the quality of delivered water to consumers. So, the investigated system was not completely safe and it needs to be upgraded and improved. Nevertheless, high scores that are given to some phases like verification, system description, and operation monitoring, increase the system flexibility to change current quality management to WSP.

After system assessment by team members, hazards with the most risk were identified in the system and some corrective actions were proposed. Direct discharge of wastewater and solid waste disposal by communities in the vicinity of water catchment area, stratification in dam reservoir and algal bloom were recognized as the most important among 10 identified hazards in water catchment.

Since, approximately 70% of Ardabil drinking water consumption is supplied by surface water, it is necessary to pay great attention to water source protection. Because of continuous discharge of municipal wastewater of Nir city around Balikhlou River, this risk is identified as the main hazard. In this regard, the following measures are essential:

- Construction of wastewater treatment plants for surrounding river catchment.
- Solid waste management in boarder areas.
- Promoting the awareness of communities in these areas which affect water quality.
- Controlling the industrial effluents quality.
- Periodic control of water catchment.

When the results of this study are compared with other studies including in Melbourne [17] and Germany [18], it is clear that protection of water source is the first and main barrier in preventing contaminants from entering into system and causing decrease in water quality. The next significant measures are to identify, control, and reduce risks in water treatment plant and distribution process. According to studies various methods such as microfilter, sand spray, and coal application were proposed to eliminate the unpleasant odor and algae [19,20]. It seems using microfilter is recognized as better method due to well function, low cost, and time. Aeration in under water layers also can be useful.

Lack of complete removal of organic pollutants and due to this, Trihalomethanes (THMs) generation and malfunction of filters are the two other factors that affected water quality safety.

In addition to the control of organic compounds and materials in surface waters, improving water treatment techniques is another solution for impressive removal of TOC and organic compounds. These techniques are: optimization of flocculation process using powder activated carbon which increase the removal efficiency of organic materials, advanced coagulation and electrocoagulation [21], nanofiltration [22], ultrasonic process [23], adsorption by MWCNT [24], agrowastes [25,26], and change of chlorination areas to reduce the contact time.

Risks associated with filter can be reduced by regulating the backwash cycle or by removing its possible defects, online monitoring and decreasing filtration rate in cases of high raw water turbidity. According to conducted studies [27], greatest weight percentage was assigned to filtration and chlorination in treatment plants, so necessary measures should be taken to increase reliability in those units. In risk assessment of Urmia urban water supply system, old water treatment plant identified as the main component in increasing the risks in system [8].

In distribution system, lack of water distribution system development along with the urbanization growth, failure to comply with the technical principles in network development plan, development of small diameter distribution systems, pumping groundwater directly into the network are the important causes and the main failures in distribution system in different cities of Ardabil province.

Based on expert's opinion, at present, the main risk is related to the old infrastructures and pipes (causing 27% water loss) and subsequently insufficient residual chlorine in distribution network. Also, US EPA has introduced the corrosion of pipes as one of the main concerns in distribution system [28]. Since, huge money investments are needed for network modernization, and prioritizing is required for areas with high exposure to risk, high potential of chlorine consumption and high bacteria counts, should be repaired, and replaced at first.

There was pressure drop and insufficient residual chlorine problems which this pressure drop in point of use of water caused consumer dissatisfaction. In a study carried out in Iceland, old distribution pipes were renewed in some areas that often had high bacteria count in water samples, some limitation also observed in waterworks due to inadequate external and internal auditing [14].

Same as the developed in Iceland framework for water supply system safety [29], development of a national

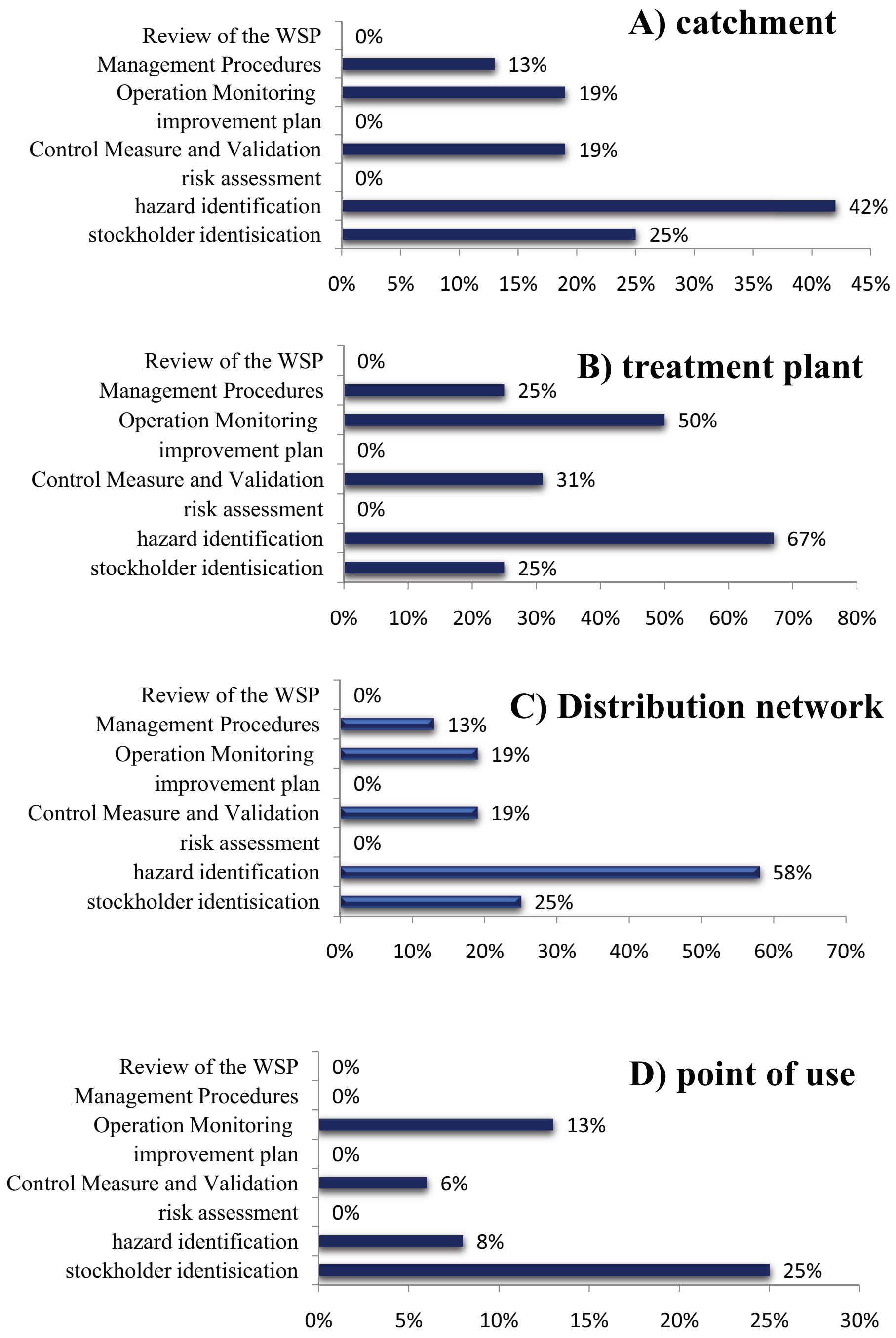

Fig. 4. Results of coordinated implementation of WSP phases in main component of system: (A) catchment, (B) treatment plant, (C) distribution system and (D) point of use.

framework that includes legal requirements for protection and surveillance of drinking water quality and its safety is recommended for Ardabil water supply system.

5. Conclusions

The high points of some phases such as verification, system description, and operational monitoring, make the system flexible to change current quality management approach to WSP. To achieve desired and high drinking water quality, the control of pollutants discharge in the upstream of catchment, coordinating existing treatment processes, and water quality protection in the distribution system is needed. Regular inspections also recommend in all components of the system. In this way, collaboration and support by health authorities can lead to good performance and improvement of water quality and safety.

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