Research Paper

Study of Risks in Rural Water Supply Systems of Khorramshahr City, Iran, Based on Water Safety Plan

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ABSTRACT

Background: Water safety planning is a comprehensive risk assessment and management approach encompassing all steps in a drinking-water supply chain, from catchment to consumer. A Water Safety Plan (WSP) ensures drinking water safety through this approach. In this study, risk factors are initially identified and evaluated. Then control and corrective measures are determined to reduce or eliminate health and environmental hazards of rural water supply systems in Khorramshahr City, Iran, according to the guidelines of the WSP provided by the World Health Organization.

Methods: This research is a descriptive cross-sectional study in which rural water supply systems in Khorramshahr were studied using the Failure Mode and Effects Analysis (FMEA) risk systematic method. The Risk Priority Number (RPN) was calculated to determine the risk level after identifying 14 risk factors using experts' opinions. Then, control and corrective measures were considered for medium, high, and very high-level risk factors.

Results: The evaluation results of 14 risk factors identified in the distribution network and point of consumption indicated that 71.5% of them were at the medium risk level and 28.5% at the high (critical) risk level. After determining control and corrective measures, 92.9% of risk factors reached the medium (manageable) level and 7.1% the critical level.

Conclusion: This result indicates that water safety guidelines can replace traditional methods of inspection and process control, and significant improvements can be achieved with the help of risk assessment by the FMEA method and step-by-step implementation of the WSP as an essential evolutionary solution for preventive measures and reducing the level of existing risks.

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1. Introduction

Water resources have always been exposed to pollution and loss of quality due to exploitation, misuse, and the occurrence of various natural, unnatural and functional threats. Water pollution can have devastating effects on public health. Therefore, providing adequate and good quality drinking water has always been one of the most critical challenges for managers and decision-makers in urban and rural water [1-6]. Installation of water supply system in the environment and next to pollution sources, due to the vast potential of water pollution, requires special attention and the establishment of a robust monitoring system from the point of production to the point of consumption [7-11].

Delivery of safe water goes beyond achieving the final quality of treated water because water supply systems may provide this goal. However, in case of hidden defects in design and operation, various accidents can happen [2, 12]. To ensure the safety of the drinking water supply, performance accuracy parameters of control criteria should also be considered in addition to quality monitoring of the final product. Thus, the World Health Organization has presented a new approach to achieving the goal of implementing the Water Safety Program (WSP) [13]. The execution of WSP provides a systematic approach to ensure the quality and safety of distributed water and covers all stages of water supply from the reservoir to the point of consumption [14]. WSP comprises a comprehensive approach to water delivery risk assessment and management, recommended in 2004 internationally. WSP consists of 5 execution steps followed by evaluation [15].

The purpose of the WSP is to ensure the quality of drinking water based on risk management, which focuses on preventing contamination of the drinking water sources, treating water to reduce or eliminate contamination to meet standards, and preventing re-contamination of water during storage, distribution, and consumption. Objectives of Section 7 of the WSP Summit Statement to Ensure Quality and Sustainability of Drinking Water Supply Systems in the Eastern Mediterranean Region of the World Health Organization in 2009 introduces the health ministries of the countries in the region as responsible for the development and facilitation of inter-sectoral coordination between organizations and influential decision-makers in drinking water quality management. [2, 16]. Many countries in Africa and Asia have launched and implemented water safety programs [13, 17]. Hong Kong also developed the plan in 2005 for its drinking water supply systems and implemented it in 2007 [18]. Ten Latin American countries (2007) emphasized WSP execution, followed by Pan American Health Organization (PAHO).

PAHO and the United States Environmental Protection Agency (EPA) implemented a water safety plan in Jamaica [19]. Subsequently, different countries such as New Zealand, Germany, and Italy used this plan for the urban water supply system [20]. Also, this plan was implemented in Iran in the cities of Isfahan and Ahvaz. The results of Howard et al.'s study on the use of WSP in Kampala showed some design and operational problems in the Kampala water supply system so that the level of hazards identified in water storage tanks was reported to be high risk. This issue was attributed to unprotected or uncovered valves, corrosion inside the tanks, and non-compliance with safety principles in the storage of water tanks [21].

The results of the WSP execution in a small number of water supply systems in Portugal have also demonstrated that the most important constraints for the development of this process at the national level are the lack of binding laws and policies, as well as the need for appropriate regulatory tools [22]. Different treatment processes in Germany also showed that the risks affecting water quality, continuity, and water supply capacity from irrigation basin to treatment and distribution could be identified with a systematic approach, and appropriate control measures have been defined [23]. The WSP proposal for Mortara in Italy was also very useful not only as a risk reduction method but also as a cost-effective tool for water suppliers. In addition, WSP reduces public health risk, ensures better compliance with water quality parameters with regulatory requirements, increases consumer and municipal confidence, and improves resource management due to intervention planning. The WPS team in this study also used new control measures [24].

A study was conducted based on a WSP and HACCP (Hazard Analysis of Critical Control Points) environmental management system in 5 villages in Indonesia. The result of the assessment on quality-type risk shows 12 risk factors belonging to a very high category, 14 to medium, and 31 to a low category, while there is a high risk in quantity type in Sawangan village, 1 very high risk in continuity type in Sawangan village, and no risk in accessibility type [25].

In an evaluation of the implementation of WSPs in two council areas versus non-WSP implementing communities, the following activities were conducted: 120 household surveys, water sample testing at water sources, and focus group discussions with key informants and water facility staff. Results showed that the water sources in both councils are producing relatively clean water; water management practices at the source were relatively safe with few risky practices in a few communities; households were involved in risky practices that led to contamination from transported through to stored water, and water facility caretakers were aware of their responsibilities [26].

There are different methods and techniques for assessing the risk of processes and ranking them. These are Preliminary Hazard Analysis (PHA), Sub-System Hazard Analysis (SSHA), System Hazard Analysis (SHA), Hazard and Operability study (HAZOP), Failure Mode and Criticality Effect Analysis (FM & CEA), Frank & Morgan, Failure Mode and Effects Analysis (FMEA) and William fine method. In this study, according to the recommendation of the World Health Organization, the FMEA technique was used.

The water supply for 64% of the villages in Khorramshahr is provided by the Karun and Karkheh rivers, and water treatment facilities in these villages often do not have the necessary security and safety. This issue has led to many environmental concerns about the lack of access to safe and secure water for these communities. The fields of interest in this research have been primarily used in studies related to urban water supply systems, and such research has not been implemented in small rural communities, especially in Iran, and its implementation abroad is very limited and few so far.

This study is intended to identify, evaluate, and prioritize existing and potential risks in rural water supply systems of Khorramshahr City using risk assessment and prioritization methods.

2. Materials and Methods

This study was performed on rural water supply systems in Khorramshahr City, Monikh village, and some villages in the west of Karun (in 2020-2021). Khorramshahr City is located next to the border Arvand river with 48 degrees and 10 minutes east longitude to 36 degrees and 26 minutes north latitude on marshy lowlands. The distance from Monikh village to Khorramshahr is 5 km, and the distance from the villages west of Karun to Khorramshahr is 75 km.

In this study, the statistical population consisted of 21 water supply systems with a population of 16652 people and 5349 households. The water supply source is 6 villages away from Haffar-e Sharqi water supply facilities and 8 villages away from Shohada West Karun water supply facilities, and 7 villages away from Shahid Mansouri water supply facilities.

The research study method is descriptive cross-sectional based on its nature and purpose. A field inspection checklist was designed to inspect and describe the system using supportive protocols. Initially, all potential risks were listed, and water supply systems were inspected based on this checklist. Field visit areas of the river route were designated from Omm ol Khareyn area (Karun river entrance to Kofeysheh) up to Soveychti-ye Do Terminal and Mared Canal (Karun River entrance to the Haffar-e Sharqi) as the drainage basin of Karun River. After performing the system description steps based on the checklist results in the field visits, identification, evaluation, and prioritization of existing risks and potential risks in water supply systems were performed based on the WSP water safety plan and through FMEA.

WSP by World Health Organization (WHO) (2009) and the International Water Association (IWA) presented a manual for developing and implementing a practical water safety plan that includes 11 consecutive execution modules based on risk management and assessment that encompasses all steps in water supply from catchment to consumer [27, 28].

The risk assessment table uses the FMEA method to evaluate and prioritize existing and potential risks in water supply systems. In the table, all the main activities or processes were listed, and the type of risks and the causes of their occurrence and the amount of risk were calculated in the continuation of the work.

Failure Modes and Effects Analysis (FMEA)

FMEA is an analytical method in risk assessment that tries to identify and score as much as possible the potential risks in the area where the risk assessment is performed and also the related causes and effects. The method is based on obtaining the Risk Priority Number (RPN). The number results from multiplying the occurrence probability of a risk by the risk detection probability at the risk severity. In this process, an event that is likely to occur once a week has a different score than one that occurs once every 5 years. Risk scores are graded based on the low, medium, and high (critical) levels [29-31]. The process of risk description and assessment by the FMEA method is presented in Figure 1 [28, 32].

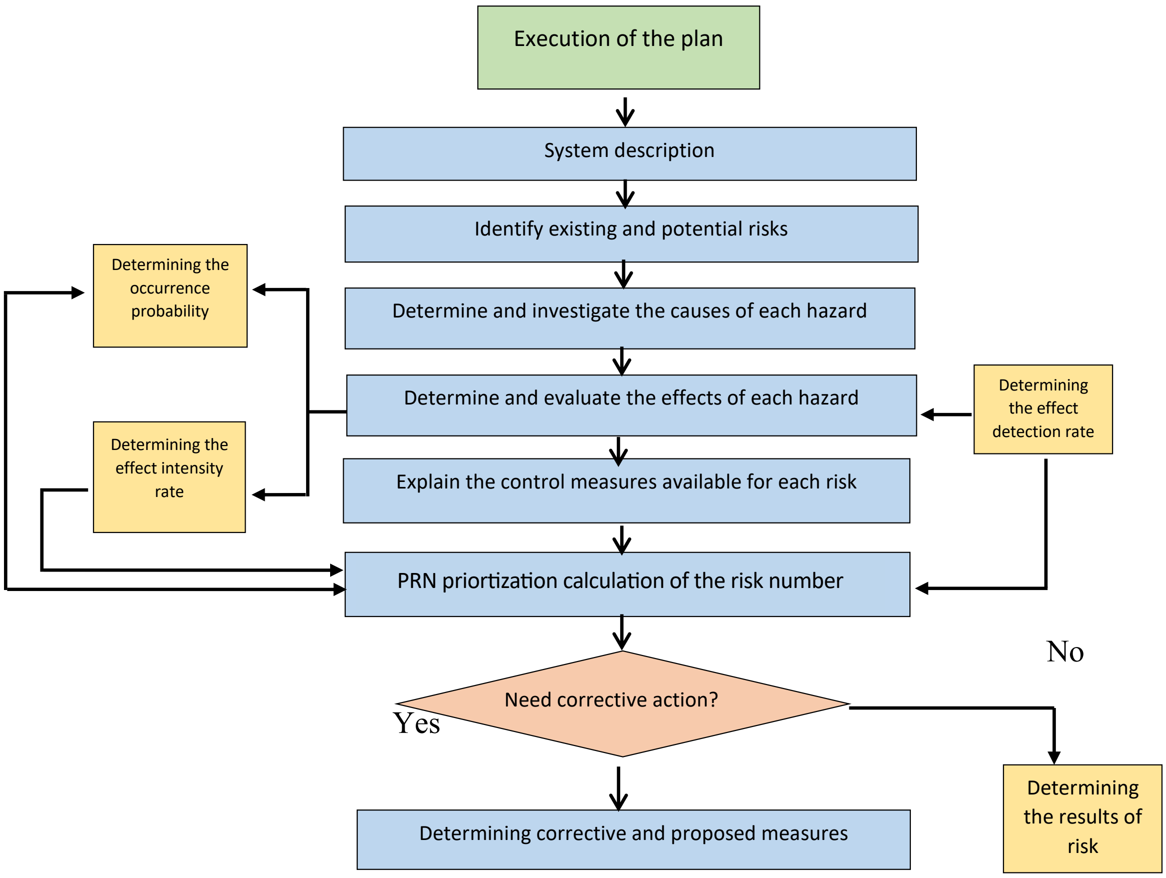

Figure 1. Flowchart of steps for describing and assessing risk by the FMEA method

Numbers were assigned between 5 and 1, and the RPN number was calculated by multiplying all three points for the occurrence probability, the effect severity, and the error detection ability. In this study, the experience and knowledge of water, sewage, health, and environment experts were used to assess the risks (12 managers and experts).

Risk Priority Number (RPN)

RPN is calculated as an indicator for classifying errors and taking corrective and preventive action (Tables 1-3) (Equation 1).

1) *error detection rate×effect intensity (severity)×probability of occurrence=RPN*

Determining the confidence level or risk index

Determining the reliability or risk index for an RPN depends on the logic, experience, and system conditions. First, the average of RPNs and their standard deviation are calculated for confidence level or risk index and high and low-risk limits. It should be noted that these calculations have been done in Excel software [25, 32, 33].

First, the arithmetic mean of the data is calculated using Equation 2:

2) $X=\frac{1}{N}\sum_{i=1}^{N} xi=\frac{x1+x2+\ldots\ldots+xn}{N}$

x=arithmetic mean

N=number of data

Xi=Data (RPN)

Then the standard deviation number of the data was calculated using the Equation 3:

3) $\sigma=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(xi-X)}$

σ=standard deviation

xi=data (RPN)

X=average data

Then the Equations 4 and 5 was used to determine the risk levels (high, medium, and low) to prioritize corrective and control measures:

4) $\sigma+X=high\ risk$

Table 1. Ranking of error probability occurrence

Score	Occurrence Probability of Error Mode
5	Too high - An error that usually occurs
4	Top - Repeated error - This error occurs once in every 100 cases
3	Moderate - Error that occurs once in a while - This error occurs once in every 200 cases
2	Low - An error that occurs relatively low - This error occurs once in every 1000 cases
1	Very rare - An error is unlikely to occur - This error occurs once in every 10000 cases

Table 2. Ranking of the error effect severity index

Score	Description of Injury and Damage
5	Death or loss of one of the main functions of the body
4	Permanent reduction of one of the functions of the body
3	A temporary injury that increases the patient's hospitalization or requires more care
2	A temporary injury that requires intervention and treatment measures
1	No harm to the patient; there is only a need to monitor the patient

Table 3. Ranking of the error detection rate capability

Score	Probability of Error Mode Occurrence
5	Very little - The error (or cause of the error) may not be detected until after the patient is discharged, or its detection requires testing and additional steps outside the scope of the process. Zero out of 10 cases are detected.
4	Low (or cause of the error)- The error may be discovered in the next steps of the process after the occurrence in case of attention and vigilance of other service providers in the next steps of the process. Two out of 10 cases are detected.
3	Medium - The error (or cause of the error) is detected during the occurrence in case of the attention and vigilance of the direct service provider. Five out of 10 cases are detected.
2	Top - The error (or cause of the error) is usually detected during the occurrence according to the existing work process by the direct service provider. Seven out of 10 cases are detected.
1	An error (or cause of the error) is prevented by a well-defined instruction or device. Nine out of 10 cases are detected.

5) σ-*X=low risk*

Moreover, the risks are between high limit (unacceptable level), low limit (acceptable level), and medium risk level (tolerable level).

3. Results and Discussion

The results of field inspections of water supply systems revealed that water supply treatment plants had serious problems in some cases, such as pressure boosting stations, chlorination, water filtration, which could play a significant role in the occurrence of health hazards in the process of water treatment and drinking water supply of the population.

FMEA risk assessment

The most important risks identified in rural water supply systems in the study area were evaluated and prioritized from the distribution network and consumption point, respectively, so that the degree of risk of the RPN number was considered equal to 119 as the upper limit of that risk. The level of these risks is indicated by "H" in the risk assessment tables (Tables 4, 5). It can also be concluded from the results of the assessment of existing and potential risks by the FMEA method that risks with an initial RPN of less than 90 were considered low-level risks, risks ranging from 91 to 119 moderate and acceptable risks, of which 4 critical and 10 cases were in the moderate range. These numbers were determined following corrections and interventions: 101 for high risks, 66-100 for medium risks, and less than 65 for low risks;

Table 4. Identification of hazardous events in the distribution network and point of consumption

Row	Description of the Activity	Potential Hazard Scenarios/Dangerous Event	Causes of Danger	Potential Effects of Danger
1	Water distribution network	Erosion, breakage, and leakage of transmission lines in the distribution network	Long network life, lack of maintenance and preventive repairs	Physical, chemical, microbial
2	Water distribution network	Reduction of water supply and pressure in the network	Water corrosion and leakage, wear, pipe breakage, unauthorized branches, faulty connections, and valves	Physical, chemical, microbial
3	Water distribution network	Water losses and water leaks in the distribution network route	Wear, pipe breakage, presence of unauthorized services, defective connections and valves, lack of leakage control	Physical, chemical, microbial
4	Water distribution network	Sudden onset of water turbidity in the network	Failure to observe water safety issues during repairing pipes, not washing and disinfecting pipes after repair	Physical, chemical, microbial
5	Water distribution network	Existence of unauthorized services in the distribution network route	Inefficient management, illegal use of non-standard connections from the main pipeline, lack of legal action against violators, impossibility of timely detection of unauthorized services due to underground and secrecy	Physical, chemical, microbial
6	Water distribution network	Accumulation of sediments at blind and endpoints of the network	Insufficient water velocity, lack of sediment discharge, pipe breakage	Physical, chemical, microbial
7	Water distribution network	Access of subversive agents and bioterrorism and irresponsible individuals to the distribution network	Failure to apply a protection system and proper monitoring in the distribution network	Physical, chemical, microbial
8	Water distribution network	Lack of free chlorine of residual water in the network	Absence or failure of chlorination station in the route of water supply pipeline to distant points, the existence of blind spots in the network, long distance to the farthest points of the distribution network from the treatment plant, breakage and wear of the water supply pipeline	Microbial
9	Water distribution network	Microbial contamination in the network	Biological growth in water supply pipes, pipe breakage and network wear, lack of preventive maintenance, high water temperature, presence of pipes and non-standard connections, unauthorized services, long water retention time in pipes, presence of sediments in blind spots of the network, reducing the concentration of disinfectant due to the long retention time in the pipes	Microbial
10	Water distribution network	Production of purified water containing inorganic chemical contaminants	Poor and non-standard material of pipes and fittings, use of pipes in contaminated soil and penetration of chemical contaminants into the pipeline, passage of the pipeline through agricultural lands	Chemical
11	Water distribution network	A constant increase in water turbidity	Breakage and wear of the water transmission line, lack of preventive repairs in the system, mud entering the pipeline during repairs	Physical
12	Consumption point	Contamination of water entering the network due to any uncontrolled danger in the water supply system	Inefficient management, lack of pollution control in the system	Physical, chemical, microbial
13	Consumption point	Increase water turbidity	Installation of pressure supply pumps installed by subscribers after the meter at the point of consumption	Physical, chemical, microbial
14	Consumption point	Contamination in subscriber service pipes	Breakage and wear of pipes, valves, and connections of subscribers, failure to fix technical defects in the shortest time	Physical, chemical, microbial

1 case was in the critical range, and 13 cases were in the moderate range (Table 6).

Despite the major role of the Karun River in supplying drinking water to most villages around the city, it receives a huge volume of municipal and industrial wastewater that flows into the river in raw and untreated forms. In addition to adversely affecting the health and safety of water and consumers' health, it also poses a serious threat to the ecological life of the river. The essential polluting industries in the study area include Arvandan Shipbuilding Company, Pasargad Oil Company, and Bani Pasteurized milk factory. Moreover, agricultural drains, fish ponds, and the establishment of traditional animal husbandry units in rural and suburban areas along

Table 5. Assessment and prioritization of risk and control and corrective actions based on worksheets in the distribution network and point of consumption of FMEA

Evaluation of 1 before the control measure						Control and corrective action	Evaluation of 2 after control measure				
Risk code	O*	S**	D***	RPN	Risk level		O	S	D	RPN	Risk level
01	5	5	4	100	H	Requirement to replace old and worn networks and transmission lines	5	5	4	100	H
02	5	5	4	100	H	Requirement to repair and modify the worn network, washing the network and chlorination of the pipeline after repair, anti-corrosion painting of pipes	5	5	4	100	H
03	5	5	3	75	M	Replacement of old and worn network and transmission lines Execution of PM, implementation of leak control plan, identification and control of unauthorized services/replacement of old and worn network and transmission lines, cutting of unauthorized services	4	5	3	60	M
04	5	5	4	100	M	Washing the distribution network after repair and before operation, informing consumers during repair/replacement of old and worn network and transmission lines, cutting of unauthorized services	4	5	4	80	M
05	5	5	4	100	M	Establishment of inspection team to identify illegal services /replacement of old and worn network and transmission lines, cutting of unauthorized services	4	5	3	60	M
06	4	5	5	100	M	Installation of drain valves/ pressure pump installation in necessary places	3	5	5	75	M
07	5	5	5	125	H	Establishing a suitable mechanism for forming a group of patrol officers in the distribution network route and flexible network points/Creating passive defense requirements, creating fences and security barriers in sensitive points	4	5	5	100	H
08	5	5	4	100	M	Proper and continuous injection of chlorine in chlorination stations, repair of pipeline fractures /installation of liquid chlorine injection stations in the pipeline route	4	5	4	80	M
09	5	5	4	100	M	Repair of broken pipes, replacement of defective connections and valves, identification and disconnection of unauthorized services, discharging and washing of the network, installation of liquid chlorine injection stations along the pipeline in areas with long distances to the treatment plant	3	5	5	75	M
010	4	5	5	100	M	Timely replacement of defective connections and valves, preventive repairs in the network, selection of standard pipe material, piping in safe places	3	5	5	75	M

Evaluation of 1 before the control measure						Control and corrective action	Evaluation of 2 after control measure				
Risk code	O*	S**	D***	RPN	Risk level		O	S	D	RPN	Risk level
011	5	5	4	100	M	Carrying out preventive repairs, observing safety issues during repairs, informing people not to use water during repairs/replacing old and worn networks and transmission lines, cutting off unauthorized services	4	5	4	80	M
012	5	5	5	125	H	requirement to replace old and worn networks and transmission lines, cutting off unauthorized services	5	5	5	125	H
013	5	5	5	125	H	requirement to replace old and worn networks and transmission lines, cutting off unauthorized services	3	5	5	75	M
014	5	5	5	125	H	Repairing and replacing worn and old pipes and valves of subscribers' connections, fixing other technical defects	4	5	4	80	M

*Occurrence; ** Severity; *** Detection

with the study route lack a wastewater treatment system, and their raw sewage enters the Karun River.

The results of the evaluation of the 14 risk factors identified in the distribution network and the point of consumption indicated that 71% were at medium risk level, 28.5% were at high (critical) risk level, which reached 92.9% of the risks in the medium sector (manageable) and 7.1% in the critical sector after determining control and corrective measures (Tables 4). This result indicates that critical risk can be reduced by implementing risk control and corrective measures.

The WSP approach is widely recognized as the safest and most effective way to manage drinking water resources to maintain public health continuously. Many water suppliers and governments have implemented WSP since its introduction in the third edition of the WHO Guidelines on Drinking Water Quality (GDWQ) and the International Water Association (IWA) charter for Safe Drinking Water in 2004. More than 90 countries worldwide have implemented WSP, and nearly 70 countries have WSP policies or regulations in place or under development, according to preliminary results of a WHO/IWA global survey on WSP (or equivalent risk assessment and risk management approaches) [34].

In 2017, 14 African countries reported implementing the WSP, and Uganda is one of the pioneers in developing and implementing WSP on the continent [21, 35, 36]. WSP development in Uganda began in 2002, and the program was implemented in 20 urban centers by 2009 [35]. Local governments in some countries accepted the implementation of WSP. For example, the National Program for Healthy Villages and Schools (VEA) was launched in the Democratic Republic of the Congo as an initiative to provide safe drinking water to rural and urban areas. The plan uses the WSP framework to ensure safe and sustainable water services in schools and villages. Because of the low quality of drinking water observed in the household, improvement of home water purification and safe storage methods has been recommended [37-40]. Technical risk management in Germany was also developed following the recommendations of the World Health Organization (WHO) for WSP, which met the standard requirements for drinking water

Table 6. Determining the approximate level of risk in FMEA

Risk Level	Limitation of the Initial Risk	Limitation of the Secondary Risk
Low risk (L)	RPN≤90	RPN≤65
Medium risk (M)	RPN=91-119	RPN=66-100
High risk (H)	RPN≥120	RPN≥101

FMEA: Failure Mode and Effects Analysis; RPN: Risk Priority Number.

treatment in this country [23]. This plan has already been done in several drinking water treatment plants with different sizes and treatment processes in Germany. Risk factors affecting water quality, sustainability, and water supply capacity from irrigation to treatment and distribution can be identified systematically, and appropriate control measures have been defined [28].

Davison et al. also introduced the drinking water quality guidelines and WSP as one of the critical components in all Bangladesh water resources. The water supply department in Bangladesh did this, and the results showed that WSPs could be used for water resources with small management of the developed community and improve the health status and water quality of water resources [36].

Evaluation of the efficiency of three water treatment plants, storage tanks, and distribution networks in this study also indicates that water treatment plants in the villages cannot apply complete water purification and desalination, and one of the serious problems of drinking water is the salinity and turbidity of water. Correction and prevention of industrial and agricultural effluents into the river and application of conventional treatment system are inevitable because of the conditions of Karun River, and the volume of pollutants and investigations showed that 35% of treatment plants lack a sedimentation system, 40% lack a filtration system, and 35% lack a gas chlorination system and some of them incorrectly use liquid chlorine. They do not follow the standard of chlorination. Moreover, 100% of treatment plants lack an emergency power generator system, which occurs when the water supply is completely cut off in the network. About 65% of transmission lines in the distribution network lack a chlorination station system. This shortcoming has caused many villages farthest from the treatment plant, such as the villages covered by the West Karun treatment plant, to receive raw, chlorine-free water on most days. This situation has caused microbial contamination of water in these villages because of the old age and wear of the distribution network and the mix of sewage with water in the network path.

4. Conclusion

Major dangers threaten rural water supply systems. Implementation of a WSP means reaching the stages of development and evolution of all the methods that have been used for a long time by water researchers around the world and is known as the most effective method in implementing a step-by-step plan. Thus, it is suggested that control and corrective measures be taken to complete and develop treatment units and replace and repair defective distribution networks. Since different pollutants and development plans can affect water quality and have destructive effects; therefore, identifying and evaluating the risk factors and applying control and corrective measures can reduce or eliminate the risks in the shortest possible time. For this purpose, a safety plan can be used in all water supply systems. The following items are recommended according to our research.

First, it is suggested that the WSP team should be formed to implement and expand the WSP for rural water supply systems in Khorramshahr to ensure the protection and safety of water resources, reduce and control existing risks and maintain the health of consumers. Second, many villages, especially those covered by the West Karun treatment plant, receive water with zero residual chlorine because they are far from the treatment plant or face a definite water outage for several consecutive days. It is necessary to invest in constructing pressure boosting stations and chlorination stations in the water supply network. A study should be conducted to identify and assess the risk of unauthorized water delivery services and water losses in the distribution network of rural water supply systems in Monikh, especially in the village of Moamreh Sangour, where most households use unauthorized water delivery services.

Ethical Considerations

Compliance with ethical guidelines

There were no ethical considerations to be considered in this research.

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Authors' contributions

Conceptualization and Supervision: Iman Naseri; Methodology and Investigation:Verij Kazemi and Cheraghi; Data analysis, Writing-original draft, and Writing-review & editing: Jalilzadeh.

Conflict of interest

The authors declared no conflict of interest.

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