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Hazard identification and integrated risk assessment of drinking water supply system from catchment to consumer based on the World Health Organization's Water Safety Plan

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ABSTRACT

Given the scarcity of water resources and the rising costs of providing safe drinking water, identifying hazards and assessing relevant risks is critical for optimizing water supply systems. This study aimed to identify the hazards and provide an integrated risk assessment of the main water supply system components in Torbat-e-Jam using the World Health Organization's Water Safety Plan. It also aimed to provide appropriate control measures to reduce the existing risks. Based on the results of risk analysis, access to healthy drinking water in the water supply system in the city of Torbat-e-Jam requires the following: determining wellhead protection area for all of the water resources, renovation, and replacement of worn-out and broken pipelines, maintaining a desirable distribution system pressure, supplying sufficient chlorine residual in the distribution system and storage tanks, increasing consumers' awareness and regular review to investigate the reliability of control measures. Also, the research results suggest that the most important advantages of managing and assessing risks in water supply systems include a better understanding of the system and potentially damaging factors, provision of control measures to reduce direct and indirect losses caused by incidents, reduction of systems breakdown, and finally protection of water generated in all drinking water supply chain.

Keywords: Control measures; Hazard identification; Risk assessment; Water safety plan; Water supply system

1. Introduction

Management and preservation of water resources are of high importance in both developing and developed countries [1]. Considering climatic, economic, and social developments across the world, most countries are facing serious water crises. Thus, the desirable utilization of water resources, the prevention of contamination, and the optimization and management of water resource systems are

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considered the main components of sustainable development [2]. Today, the main concerns of water-supplying organizations are access to a comprehensive, flexible, and reliable performance assessment which accurately helps provide information about the existing water supply system situation, and former mistakes are corrected to improve future conditions. Monitoring water supply systems are meant to be a continuous and sensitive assessment of the general health and acceptable safety checks of water supply systems [3].

Water resources should be regularly monitored and controlled by quality officials so that control measures are taken to prevent any potential contaminants. Safe drinking water is water whose physical, chemical, biological, and radioactive properties may not cause any short and long-term complications for mankind. Since the supply of safe water plays the main role in reducing the number of water-borne diseases, measures to improve water resources and a safe and secure water supply can considerably reduce many diseases worldwide [4]. Urban water supply and distribution systems are large-scale systems that provide services to a large number of consumers. Thus, water quality can greatly affect the health of society from a microbial and physicochemical perspective. These systems include water supply resources, transfer pipelines, treatment plants, storage tanks, water distribution systems, and consumption points [5]. The vastness and connection of water supply systems with the surrounding environment, as well as the pertinent contamination potentiality, requires the establishment of a powerful regulatory and control system to control all system points from source to consumption and to ensure water quality and safety [6]. In large-scale systems with various control parameters, risk assessment is an appropriate method to identify and analyze the hazards and predict the risks [3,6]. Considering the complexity of the water supply process, the most effective way to ensure a reliable water supply system is to use a comprehensive risk assessment and management approach to involve all water supply stages from catchment to consumer [3,7].

World Health Organization (WHO) and International Water Association (IWA) proposed Water Safety Plan (WSP) as the most effective instrument to ensure the safety and quality of drinking water [8]. The World Health Organization's Guidelines for Drinking Water Quality (3rd Edition) have emphasized the development of water safety plans using comprehensive risk assessment and management in all drinking water supply stages from catchment to consumer [4]. The water safety plan provides a systematic approach to ensure the quality of distributed water and its compliance with standards. This plan is a preventive management approach that includes all stages of water supply from catchment to consumer and is based on a comprehensive management and risk assessment [8,9]. Consistent with the practical guides provided by the WHO and IWA, the water safety plan consists of several consecutive implementation steps, providing the principles related to various hazard management methods, such as HACCP and multiple barrier models, as well as hazard assessment. WSP included the following steps: (i) formation of a multidisciplinary team; (ii) description of the water supply system and flow diagram development; (iii) identification of hazards and hazardous events and risk assessment by semi-quantitative risk matrix approach (Table 1); (iv) determination and validation of control measures and reassessment of risks; (v) development of an improvement plan; (vi) development of a control measures monitoring plan; (vii) development of a verification plan to control the effectiveness of the WSP; (viii) provision of management procedures; (ix) development of supporting programs; (x) and periodic review of the WSP [8]. One of the most important of these stages is the identification of hazards, and water supply system management. At this stage, hazards and relevant risks in any of the main water supply chain components (e.g., water resources, distribution system, treatment, and points of use) are identified, and the appropriate control measures are taken to control and manage them.

Table 1
Semi-quantitative risk matrix approach and the risk rating

		Severity/Consequence				
		Insignificant or no impact	Minor compliance impact	Moderate aesthetic impact	Major regulatory impact	Catastrophic public health impact
		Rating: 1	Rating: 2	Rating: 3	Rating: 4	Rating: 5
Likelihood / 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 y) Rating: 1	1	2	3	4	5
Risk score (likelihood* severity)		6>	6–9		10–15	15<
Risk rating		Low	Medium		High	Very high

Considering water safety plan advantages, many studies have used this approach to identify and manage water supply hazards [3,10–12]. For example, Nijhawan et al. [13] used the water safety plan approach to identify water supply system hazards, especially vulnerable network points. This study concluded that the entry of domestic sewage into the river was the main hazard threatening raw water resources. Furthermore, consumers' limited knowledge and restricted access to health data were deemed to be the main hazards of water consumption points. In another study, a water safety plan with the application of steps 1 to 4 was used to provide a complete and systematic assessment of hazards related to each water supply stage, concluding that the level of initial risk identified in the water supply system could decrease by 30.2% to 17.7% if control measures were taken [14]. Van Den Berg et al. [12] pointed out that a safe water supply requires the employment of a comprehensive risk assessment and management approach (RA/RM) like the Water Safety Plan.

Looking at the history of the water supply system and the lack of integrated hazard identification and risk assessment plan in the approach to drinking water quality management, this study aimed to (1) identify key hazards affecting the safety of the water supply system in the city of Torbat-e-Jam in each of the main water supply system components including the catchment, distribution system, treatment, and points of use, (2) assess the key hazards identified using the semi-quantitative risk matrix approach, (3) propose corrective actions to reduce the risks and (4) reassess the risks by taking into account the effects of control measures, and finally identify the weaknesses that can be avoided in managing drinking water quality. Present study is the first comprehensive study conducted to identify and categorize the risks threatening the public health through water supply chain in Torbat-e-Jam city. The results of this can be useful to prevent weaknesses in managing drinking water quality. Successful application of the findings of this study along with the employment of proposed control measures can significantly reduce the risks identified and improve the efficiency of the water supply systems in providing safe drinking water.

2. Materials and methods

2.1. Study area

This study was descriptive-cross-sectional, which aims to identify the major hazards affecting the water supply system safety. Torbat-e-Jam covers a piece of land with an area of 8,184 km^2 and a population of 100,477 in north-eastern Iran (Fig. 1). This city is located at a northern latitude in 60° and 15′ to 60° and 30′, and eastern longitude 34° and 35′ to 35° and 47′, at 950 m above the sea level. It has a mild climate and a maximum and minimum temperature level of +40°C in summers and –13°C in winters. The average annual precipitation is 100.6 mm. Groundwater resources supply the city's drinking water through 22 wells, which pour into 20.000 m^3-storage tanks from water transfer pipelines. The water, having been chlorinated, is supplied to the subscribers via a long 247 km water distribution network with 30,280 service lines. Twenty-seven percent of the water extracted from these resources is removed from the consumption cycle as Unaccounted-For Water (UFW) or Non-Revenue Water (NRW) [15].

2.2. Identification and prioritizing hazards and hazardous events

The identification of factors that may potentially damage the health and environment in each of the main water supply system components is an inseparable part of the water safety plan development [8]. This study investigates credible research sources, interviews water organization officials, conduct field visits of water installations and assess past data on water supply system to identify potential physical, chemical, and biological hazards affecting the water quality in the main water supply system components, including resources, distribution system, storage tanks, treatment and points of consumption as well as possible hazards which may occur during the process. Later, the 54-item tool used to identify the hazards affecting the water safety in the water supply system of the city of Torbat-e-Jam was designed based on each main component of the system. Then, to prioritize the hazards identified and analyze the relevant risks, people with adequate knowledge of the steps of drinking water supply, health and environmental issues, and hazards related to water safety from catchment to point of use were selected. These people should have the ability to understand and control the relevant risks. Next, the experts were asked to use the inventory developed to prioritize the hazards in the water supply system at each stage of the water supply based on their importance. Thus, to assess the hazards, their rating was determined by counselling water supply system experts, and scores were assigned.

2.3. Measuring validity and reliability of the hazard identification tool

To verify the designed checklist for hazard assessment, face and content validity were performed using an expert panel [16,17]. To this aim, the checklist was reviewed by 10 experienced experts before it was given out. The checklist, having been reviewed by experts, its face and content validities were confirmed. To determine the reliability of the checklist, the test re-test method was used. For this, the checklist was repeated by experts for a 10 d interval to achieve the reliability of the answers given by each and every individual. Accordingly, the reliability test of the items was assessed in two stages using Spearman's correlation coefficient and SPSS.23.

2.4. Risk assessment of hazards using the semi-quantitative risk matrix approach

This stage aims to distinguish between high-risk hazards from low-risk hazards. To this aim, the risk from each hazard was calculated by estimating the likelihood/probability and severity/consequence of its occurrence using a semi-quantitative 5 × 5 risk assessment matrix adopted by the WHO and IWA (Table 1). The risk assessment matrix is an effective tool to estimate risk. This matrix is advantageous in that it allows for the involvement of all hazardous parameters and critical control points (CCP) [18,19]. This matrix consists of 5 lines and five columns, with the

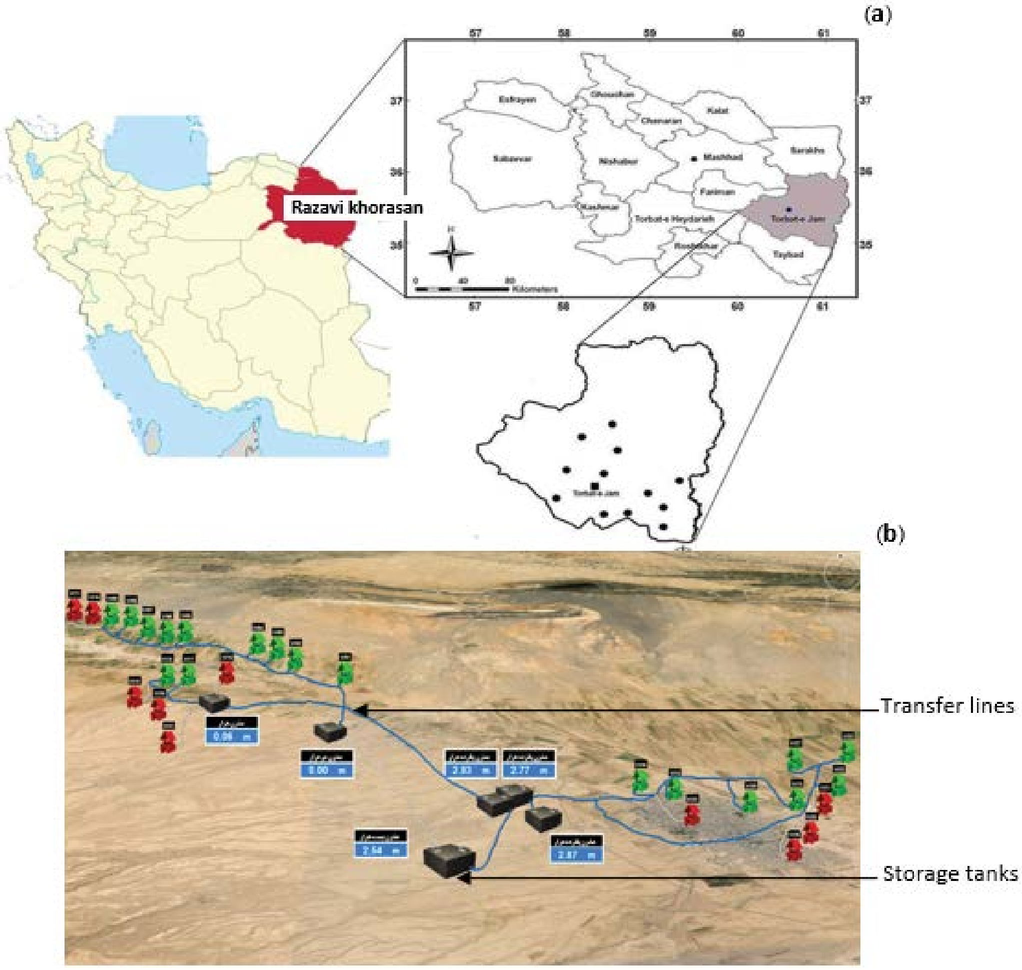

Fig. 1. (a) Location and map of water resources and (b) transfer lines and storage tanks in the city of Torbat-e Jam.

former showing the likelihood of each hazard occurring and the latter showing the severity of each hazard (Table 1). Table 1 defines the hazard severity as a result of outcome caused by the existing fault, which falls under insignificant or no impact, minor compliance impact, moderate aesthetic impact, major regulatory impact, catastrophic public health impact, and the likelihood of hazard occurrence is categorized as almost certain, likely, moderate, unlikely and rare states [8]. Some values are obtained by calculating the severity and likelihood of each hazard. These values indicate the existing situation. Thus, the water supply organization needs to provide accurate concepts of severity and likelihood before initiating the risk assessment process to avoid subjective impressions and to create the necessary balance within the risk assessment process. Consistent with the water safety plan guidelines, when data fail to demonstrate the high or low risks, the risks should be regarded as important until further assessments [8]. This study uses descriptors given in Tables 3 and 4 to investigate the severity and likelihood of each hazardous event. In the next stage, the risk of each hazard is rated using Equation 1, and four levels, that is, low (>6), medium (6–9), high (10–15), and very high (<15), are used to describe it, as given by Tables 1 and 2.

Table 2
Risk categories and resulting priority for taking management actions

Risk rating	Action plan
Low	Manage using routine procedures, keep under review
Medium	Action required, plan and prepare
High	Priority action required to mitigate hazard in short time
Very high	- Urgent action required to prevent hazard; - Action required to mitigate hazard in short time.

$$\text{Risk} = \text{Likeihood} \times \text{Serverity} \quad (1)$$

2.5. Implementation of control measures and risk reassessment

Corrective actions were proposed in all water supply stages to control and reduce the hazards following the identification of the hazards and risks analysis. Later, risk reassessment was performed by considering the effects of corrective and control measures for each of the identified

Table 3
Definitions of severity of consequences/the descriptive information on risk level

Level	Descriptor	Description
1	Insignificant	- No detectable, or insignificant health impact; - Little disruption to normal operation; - Low increase in normal operation cost.
2	Minor	- Short term or localized aesthetic or not health-related; - Some manageable operation disruption; - Some increase in normal operating costs.
3	Moderate	- Widespread aesthetic issues or long term not health-related; - Significant impact to normal operation but manageable; - Operating costs increased.
4	Major	- Potential long-term health effects or chronic toxicity; - System significantly compromised and abnormal operation it at all; - High level of monitoring is required; - Disruption to consumers in the supply.
5	Catastrophic	- Potential illness or acute toxicity; - Major impact for large population; - Complete system failure.

hazards. Next, at each stage of the water supply process, the identified hazards, together with risk assessment and control measures, were shown in analysis tables. Fig. 2 illustrates the hazard identification and risk assessment of the water supply system process, as consistent with the Water Safety Plan.

3. Results and discussion

3.1. Identification of hazards and hazardous events

Consistent with the water safety plan, the hazard identification and risk assessment step addresses the diagnosis of the existing and potential hazards at each component of the water supply chain, determines the risk level from each hazard, and finally provides appropriate control measures to control and reduce known risks [8]. For this, the water safety plan team requires meticulously investigating all main points of the flow diagram to identify the types of hazards and hazardous events which may occur at each step of the water supply chain. Following the identification of potentially harmful factors including sanitary, safety, and environmental issues at each of the major water supply system components, this study designed a checklist to prioritize the hazards affecting water safety in the water supply system. The face and content validity of the inventory was confirmed by all members of the expert team. The Spearman correlation coefficient from the test-retest method was below the acceptable level at (>0.6) in five items, which, with the removal of those five items, the validity and reliability of the scale were finally confirmed with 49 items.

3.2. Risk assessment of identified hazards in the water supply system

Tables 5–8 give the results from a risk analysis of the most important hazards identified in the major water supply system components (e.g., water resources, treatment, distribution system, and points of use) and proposed corrective actions. Later, the most important hazards are identified and relevant control measures are expressed.

3.2.1. Risk assessment of the most important hazards identified in the water resources

In its report on the world water situation, the International Development Research Center announced that the most important problem in the water crisis is improper water resource management. In this regard, the qualitative preservation of water resources is one of the most important responsibilities that officials should undertake to supply and distribute drinking water. The preservation of water resources involves all the measures aimed at optimal consumption and reducing water resource stress through identifying and controlling threatening hazards [20,21]. This study identifies the key hazards affecting the safety of Torbat-e-Jam drinking water resources and provides corrective actions to control and reduce them as follows (Table 5):

- Non-determination of the wellhead protection area (WHPA)

The preservation of wellhead protection areas (WHPAs) is a technical and managerial tool to protect water resources against all types of environmental contaminants. In this connection, the optimal assessment of the wellhead protection zone using scientific basics is highly important [22,23]. Included in the most important criteria to determine the wellhead protection area are the criteria of distance, time of motion, and flow boundaries to absorb and reduce contamination [24]. Field visits of active wells revealed that failure to observe the wellhead protection area of some wells (especially wells No. 2, 3, and 4) could be considered the main reason for the high risk of this hazard (Table 5).

Table 4
Definitions of likelihood of occurrence/the descriptive information on risk level

Level	Descriptor	Description
1	Rare	- Possibly 5 yearly (more than 1 to 5 y); - Has not happened in the past and is highly improbable that it will happen in the future; - May occur only in exceptional circumstances but has not been observed in the field and water quality data show not indication of any risk.
2	Unlikely	- Possibly yearly (more than 1 month to 1 y); - Has happened in the past, is possible and cannot be ruled out completely; - Could occur at some time but has not been observed in the field and water quality data has some outliers but not trends that confirm risk.
3	Moderate	- Possibly monthly (more than 1 week to 1 month); - Has happened in the past, it possible and under certain circumstances could happen again; - Might occur at some time/the event should occur at some time as it has been observed occasionally with few recordings in the field but water quality data has no significant trends that confirm risk.
4	Likely	- Possible weekly (more than 1 d to 1 week); - Has occurred in the past more than once, is likely to happen again; - Will probably occur in most circumstances as it has been observed and recorded occasionally in the field and is also confirmed by water quality data.
5	Almost certain	- Possible daily; - Has occurred in the past, is an on-going problem, and is very likely to happen again; - Is expected to occur in most circumstances as it has been observed and recorded regularly in the field and it also confirmed by water quality data.

Results on the movement and survival of the viruses and bacteria suggest a maximum distance of 100 m around the well to be the health limit [25]. Oluwasanya et al. [26] investigated hazards related to 99 drinking water wells, concluding that the proximity of the drilled well to contamination sources, together with such problems as non-observance of appropriate protocols to construct wells, were among the most important hazards identified in water resources. In another study that used an integrated risk management model to identify key contaminants in high-risk areas in northern Taiwan, the findings concluded that the types of land use around the water resources, especially agriculture and recreational activities, could reduce the quality of water resources. In this connection, measures to preserve the cleanliness of recreational areas, and public training, were recommended as control measures [27]. The results of the study conducted by Aali and Kishipour [28], also showed that microbial water contamination due to a lack of wellhead protection area is one of the high-risk hazards identified in water resources.

Table 5 is summarizing the control measures for minimizing the correlated risks of the identified hazards.

- High water hardness and total dissolved solids

Qualitative drinking water parameters can greatly affect consumer satisfaction. If they are not, there is a risk that they will use less safe alternatives [29]. These parameters are mainly associated with agriculture activities, waste and sewage disposal, etc., around the water resources. Physical and chemical impurities in drinking water, in large amounts, can cause damage to humans in the long run [30]. TDS is a major parameter that affects the taste of drinking water. High water hardness could cause corrosion and precipitate in the pipes and other home appliances. According to the World Health Organization, the maximum levels of TDS and hardness of drinking water allowed is 500 and 500 mg/L as $CaCO_3$, respectively [4,29,31]. Wang et al. [32] demonstrated that using the electrolysis method could help reduce the TDS of water by 22.7%. Furthermore, heating water to 50°C decreases TDS by 16%. They also found that the addition of little amounts of sodium bicarbonate ($NaHCO_3$), when reacting with magnesium ions, removes water hardness and improves water taste, while increasing water pH.

Suggestions about how to control and minimize the risks of the identified hazard is given in Table 5.

- Pollution caused by corrosion and rusting of the water well pipes

The selection of good pipes for the design section is the main factor in ensuring the quantitative and qualitative preservation of drinking water, the proper functioning of the pipe during the utilization period, and also considerable saving of the costs incurred by the repair and maintenance of the pipes [33,34]. The characteristics of water passing through the pipes can also be an effective parameter against corrosion and rusting of the pipes. For example, water hardness, alkalinity, and pH can cause corrosion and rupture of the pipes, which, if controlled, damages can be prevented [35]. Since pipes are metal, their exposure to the salts in water, and soil can cause corrosion [29]. Previous studies demonstrated that corrosion in water pipes not only causes an unpleasant odor and taste, but it also dissolves various heavy metals such as cadmium, copper, lead, and arsenic

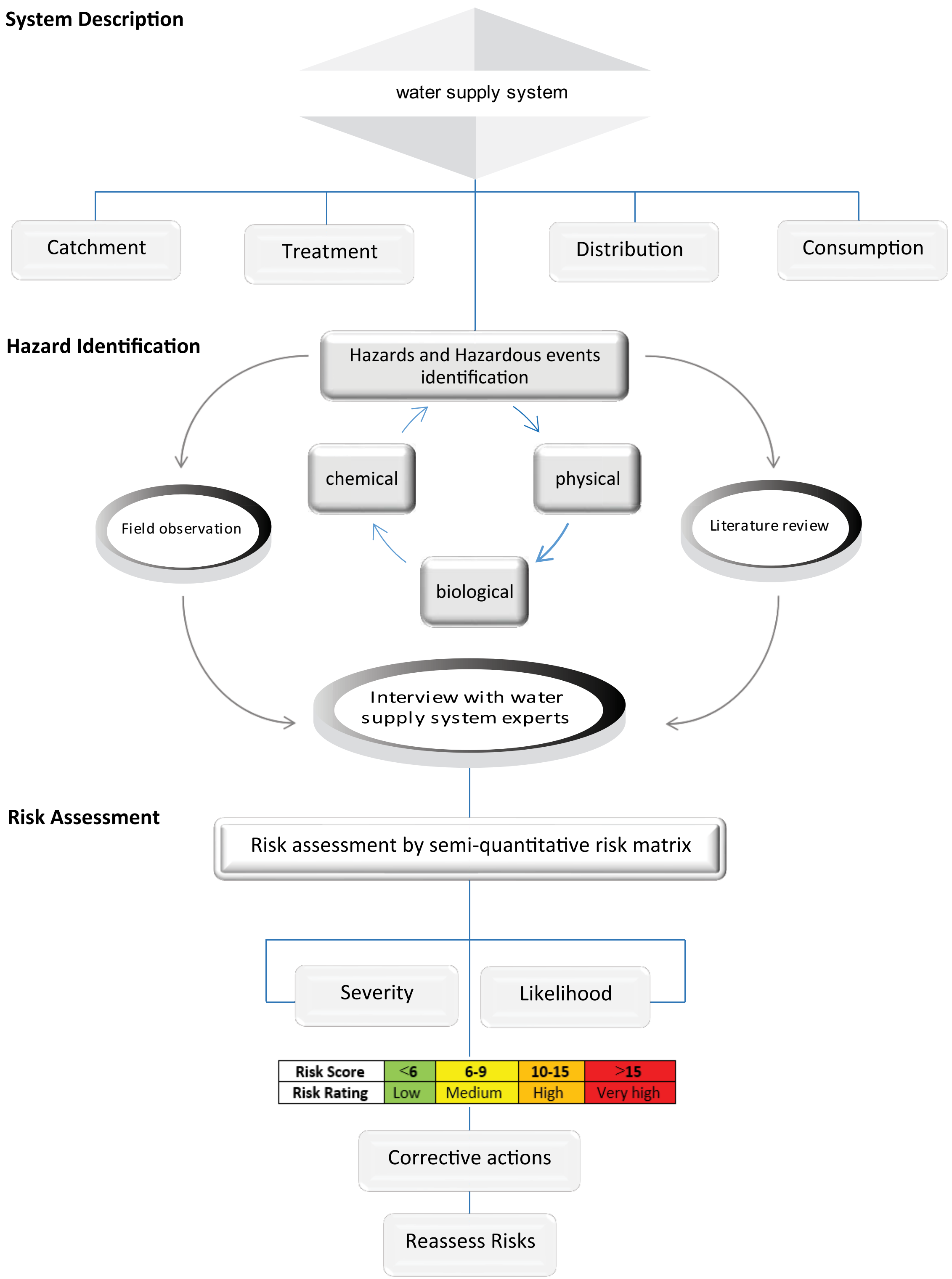

Fig. 2. The research framework hazard identification and risk assessment in drinking water supply system.

into the water [36,37]. Thus, various criteria, including physico-chemical characteristics of water, material and technical specifications of pipes, effects of administrative factors and utilization, and economic factors, need to be considered [29,38,39]. The overall percentage of steel and iron tubes in working networks of Poland, the USA, and Italy is estimated to be 53%, 56.6%, and 67.2%, respectively [34]. Well pipes in most water resources of Torbat-e-Jam are also made of iron and could suffer from rust and corrosion over time, which cause detrimental health impacts.

Table 5
Risk assessment of the most important hazards in water source

Type of hazard	Hazardous event	Risk assessment			Risk rating	Proposed control measure	Risk re-assessment			Risk rating
		Likelihood	Severity	Risk score			Likelihood	Severity	Risk score	
Physical/ Chemical	High water hardness and total dissolved solids (TDS)	4	3	12	High	- Separation of calcium and magnesium salts using chemicals; - Use of the ion-exchange methods; - Boiling of drinking water; - Use of home desalination plants.	3	1	3	Low
Physical/ Chemical/ Microbial	Non-determination of the well-head protection area (WHPA)	4	4	16	Very high	- Determination of wellhead protection area and water quality protection area for all the wells; - Control of the uses of land around all the wells; - Appropriate fencing around all the wells; - Restriction of access to water resources; - Accurate identification and management of pollution resources around the wells; - Regular inspections for monitoring and validating the control measures.	2	3	6	Medium
Chemical	Pollution caused by corrosion and rusting of the water well pipes	3	5	15	High	- Use of corrosion-resisting pipes; - Replacement of worn-out pipes; - Control of physical and chemical properties of water (hardness, alkalinity, and pH). - Control of dissolved solid concentration (TDS); - Regular internal inspection of the wells; - Use of corrosion-protecting coating.	2	2	4	Low

The corrective actions for the identified hazard has been summarized in Table 5.

3.2.2. Risk assessment of the most important identified hazards in the treatment plant

Failure to pay attention to the proper functioning of various treatment processes and vulnerable points of water treatment plants can endear society's health [18]. Hazards threatening water safety in water treatment plants can have a natural origin like floods and earthquakes or a functional origin like managerial errors, lack of an appropriate design plan, and regular monitoring and control plan for different components of a treatment plant [40]. Currently, the city of Torbat-e-Jam only uses the chlorination process to purify water before it enters the grid. Water is first mixed in storage reservoirs and then transferred to collection reservoirs to directly enter the distribution networks following chlorination. The most important hazards identified in this stage, as well as relevant control measures, are as follow (Table 6):

- Inappropriate preparation and distribution of chlorine

Due to their low costs, ease of use, and ability to remove pathologic microorganisms, chlorine and its derivatives are widely used to disinfect water [41]. The preparation and injection of chlorine at standard levels in all points of the water distribution network is one of the major issues in qualitative water management in Torbat-e-Jam's water supply system [42]. It is also important to set standards and safety precautions for stations where chlorine devices are commissioned. This has a considerable effect on chlorine gas leakage and early breakdown of the devices, while it can cause freezing of the devices and connections in winter and failure of the injection part [43,44]. Also, technical glitches, faulty chlorination devices, and users' unfamiliarity with and experts' low skills at maintenance or inaccessibility of the spare parts at the site are some of the problems with the preparation and distribution of using chlorine.

For minimizing the risks of the hazards, the corrective measure have been summarized in Table 6.

- Power outage and lack of subsidiary energy sources

Since the water supply process is a continuing process, any failure, including a power outage, can cause dysfunctional water supply processes, which may endanger the health of consumers and entail dissatisfaction. Power supply equipment failure can sometimes contribute to the incidence of dangerous events at water treatment plants [45,46]. It is imperative to provide a comprehensive power supply plan and power-related repair and maintenance program in water treatment plants. Thus, the corrective actions are suggested to avert power outages and relevant hazards in Table 6.

- Inadequate disinfection

Considering the existing risks of inappropriate preparation and distribution of chlorine at the water treatment plant, the risk of inadequate and faulty disinfection is also identified as one of the major hazards in Torbat-e-Jam's water supply system. As chlorine-containing water moves in the distribution pipes, chlorine reacts with the various matters inside the water and has its amount diminished in the network. Thus, if not enough free chlorine residual in the distribution network is available, there will be a high risk of pathologic and microbial agents as well as secondary contaminations, which could finally threaten consumers' health. This is especially important concerning resisting microorganisms, including Giardia [47]. Tsvetanova and Najdenski [48] reported that insufficient water disinfection can increase the biofilm formation potential of enteropathogenic bacteria. Because this step is directly related to society's health, investment in this area can also reduce treatment costs. To mitigate the potential adverse effects of the hazards control measures are given in Table 6.

3.2.3. Risk assessment of the most important hazards identified in the water distribution system

Because of their large extent, urban water distribution networks are usually vulnerable to accidental or intentional contamination. The incidence of various events in water transfer and distribution networks such as rupture, failure, corrosion, leakage, and growth of biofilms on the pipe walls can disintegrate the network and cause water shortage and unhealthy water distribution [49–51]. For this, water contamination in distribution networks accounts for 29% of diseases spread through water. Thus, attention to water quality in transfer and distribution systems is one of the most important tasks of water quality control units [52]. The most important hazards identified in this regard, as well as the control measures to reduce them, are as follows (Table 7):

- Water loss and contamination caused by pipes and connection rupture and leakage

Rupture and leakage of urban water distribution systems greatly account for water losses [49]. Leakage and rupture in the system, especially in pipes and transfer lines, occur under environmental and chemical conditions, the most important of which include the movement of the soil around the pipe, corrosion and structure failure, high system pressure, defective connections and supplements, aging of the water distribution system, use of inappropriate materials for coating and pipe bedding, and non-standard installations [53,54]. The main strategies to reduce water loss in the water supply system include pressure management, leakage management, improvement of speed and quality of repairs, and network repair and rejuvenation. As mentioned, the Unaccounted-For Water (UFW) or Non-Revenue Water (NRW) was found to be directly associated with pipe and connections failure and leakage [55]. The Unaccounted-For Water is calculated from Eq. (2).

$$\mathrm{UFW}_{\mathrm{total}} = \mathrm{V}_{\mathrm{in}} - \mathrm{V}_{\mathrm{out}} \tag{2}$$

where $\mathrm{UFW}_{\mathrm{total}}$ is the total unaccounted-for water in a region in a specified time period, V_{in} is the incoming water

Table 6
Risk assessment of the most important hazards at treatment plant

Type of hazard	Hazardous events	Risk assessment			Risk rating	Proposed control measure	Risk re-assessment			Risk rating
		Likelihood	Severity	Risk score			Likelihood	Severity	Risk score	
Microbial/ Physical/ Chemical	Inappropriate preparation and distribution of chlorine	5	3	15	High	- Continuous monitoring; - Observance of standards related to chlorination unit; - Observance of standards required for hypochlorite storage; - Provision of guidelines for the use of hypochlorinators and monitoring over implementation it; - Maintenance of equipment under appropriate ambient conditions; - Supply of chlorine as projected for various water supply sources; - Regular calibration of safety systems and use of standard devices; - Proper and coordinated planning and organization of health inspectors to monitor the way chlorination is performed; - Instruction of the chlorination operator about the amount of chlorination and its specifications; - Training of utilizing staffs at chlorination installations and holding of training workshops for utilization, repair, and maintenance of chlorination devices.	1	2	2	Low
Microbial/ Physical	Power outage and lack of subsidiary energy source	4	4	16	Very high	- Enough electricity supply parallel with the needs; - Observance of safety issues at the switchgear; - Continuous inspection, repair, and maintenance of power facilities; - Determination and supply of emergency tools required in case of a power outage; - Repair of power equipment and wiring only by authorized and qualified staff; - Complete replacement of defective power-electronic system according to standards; - Installation, testing, and regulation of electrical means only by technically qualified staff; - Installation of protective layers for electrical hardware in order to prevent electrical shocks and fire.	2	3	6	Medium
Microbial/ Physical/ Chemical	Inadequate disinfection	3	4	12	High	- Consideration of alternative devices to chlorination injection; - Continuous monitoring of three parameters including free chlorine residual, pH, and turbidity; - Continuous monitoring of contact time (T) and disinfectant concentration (C); - Strict determination of required disinfectant; - Control of organic matters existing in water; - Training of staff at chlorination unit.	2	2	4	Low

measured and V_{out} is the outgoing water (for consumption) measured in the same time period. Studies in various countries have indicated that apparent losses have varied from 5% in Germany to 50% in Bulgaria [56]. According to the researches, unaccounted-for water in Iranian distribution networks ranges from 35% to 40%, 51% of which pertains to real or physical losses (leakage from tanks, taps, pipes, service lines, and rupture of main and secondary pipes), while the rest pertains to non-physical losses (meter errors, meter manipulation, unauthorized subscribers) [57]. Because 27% of the water extracted from the Torbat-e-Jam city resources as unaccounted-for Water is removed from the consumption cycle, it is thus required to investigate the unaccounted-for water reduction by the network responsible for distributing urban water. On the other hand, leakage is not only an economic issue, but it is also potentially a health and safety issue. As noted by Adedeji et al. [58], Leaks may have an impact on water quality by introducing infection into low-pressure water distribution networks. Similarly, in another study of assessment of drinking water network safety, it was found that pipeline erosion and corrosion are the primary causes of leakage and pollutant entry into the distribution network [6]. The control measures for the water loss and contamination in the studied area is summarized in Table 7.

- Insufficient chlorine residual in the distribution system

One of the water quality indicators in distribution networks is the level of free chlorine residual at a standard level at all points in the network [59]. By considering the lack of control measures to reduce hazards related to the inappropriate distribution of chlorine, the insufficient chlorine residual in the next stage of the water supply chain, that is, the distribution network, was also identified as a high-risk hazard. Consistent with the standards set by the World Health Organization, the concentration of free chlorine residual must be set at 0.2–0.5 mg/L to prevent microbial re-growth and secondary water contamination at distribution networks. As water moves inside the distribution networks, the chlorine existing in water simultaneously reacts with matters in water as well as sediments on the wall of the pipes, which gets its amounts reduced inside the network. Furthermore, unusual variations of free chlorine residual in the distribution network may be due to leakage and rupture in the water supply system [4]. Several studies have reported the correlation between the prevalence of waterborne diseases and inadequate chlorination of drinking water [60]. For instance, Eslami et al. [6] reported that one of the most significant identified risks in the water distribution network is insufficient remaining chlorine, which can lead to the formation of microbial biofilms in water storage tanks. If corrective actions are taken (Table 7), the concentration of free chlorine residual in the network can be normally distributed and minimize the secondary contamination and possibility of water-borne diseases, thus reducing risks associated with this hazard.

- Worn-out pipes and connections

The aging and worn-out water distribution system can cause a large number of incidents each year, contamination of water, and water losses through pipe rupture and leaks especially in water transmission lines [53,54,61]. According to the data of Iranian Water and Wastewater Organization, the amount of water loss in Iran is several times higher than the world standards as the water distribution system is already worn-out. It is also reported that over one million incidents occur in the urban water supply system in Iran, with 20% of the total Water and Wastewater Organization's revenue spent on repair and maintenance [62]. An estimation of costs from incidents, repair, and water losses reveals that worn-out pipes should be identified and replaced in order to qualitatively improve and manage the water distribution network. A study by Aali and Kishipour [28] on risk assessment of drinking water supply system by means of WSP revealed that a large number of fractures in the distribution network and transmission lines, followed by entry of contamination into the distribution system are among the risks caused by old and poor-quality pipes. The 50-year-old water distribution network of Torbat-e-Jam is one of the oldest water distribution networks in Iran, causing a large amount of water loss as well as problems with supplying pressure to meet subscribers' demands. Because the complete rejuvenation of the water distribution network requires much time and capital, it is thus required to prioritize the water distribution system rejuvenation and to retrofit and replace those parts of the system exposed to higher risks. This saves water, reduces contamination due to accidents in water supply facilities, and improves drinking water. To control costs and reduce hazards related to worn-out infrastructure, and to improve the microbial and chemical quality indicator of water consumed, the control measure are given in Table 7.

3.2.4. Risk assessment of the most important risks in points of use

The internal network of the buildings and consumption sites are the last part of the drinking water distribution system (DWDS); thus, it is important to supply and preserve water quality [19,63]. Despite this, few studies have focused on the impacts of piping and internal building facilities on the quality characteristics of water consumed. In many European countries, however, it is impossible to fully monitor the quality of drinking water inside the buildings, which is due to the restricted drinking water authorities' access to the interior spaces of the peoples' houses [64]. In the meantime, one would say one of the weak points of water supply systems is the failure to diagnose the hazards and assess the risks at points of consumption. Thus, it is imperative to understand the consumers and the type of water consumption as well as to pay attention to the water quality needs of consumers, especially sensitive points of use such as hospitals and schools; it is also required to identify the hazards threatening water health at points of consumption [8]. This is a major component of the risk assessment of the water supply network. Plotting an accurate flow diagram of the water supply system from source to consumer can help better identify the hazards, and existing controls at the points of use [8]. Any unidentified or uncontrolled hazard in the water distribution network can cause risks at points of consumption. On the other hand, such problems as not providing drinking

Table 7
Risk analysis and assessment of the most important hazards in the water distribution system

Type of hazard	Hazardous event	Risk assessment			Risk rating	Proposed control measure	Risk re-assessment			Risk rating
		Likelihood	Severity	Risk score			Likelihood	Severity	risk score	
Microbial	Insufficient chlorine residual in the distribution system	5	3	15	High	- Daily monitoring of free chlorine residual at various network points, especially in vulnerable areas; - Making consumers aware to boil drinking water before consumption, if required; - No direct pumping of water to the network before chlorination; - Replacement of worn-out pipes to avoid leakage, fracture, and contamination; - Accurate estimation of chlorine needed in the distribution network; - Regular disinfection of water; - Secondary disinfection using additional dosage throughout the distribution network; - Use of trained forces for chlorination operations.	2	2	4	Low
Physical/ Chemical/ Microbial	Water loss and contamination caused by pipes leakage	4	4	16	Very high	- Continuous monitoring and recording of pressure levels; - Replacement of worn-out pipes and connections; - Use of pipes with an appropriate diameter; - Control and modification of pressure in the network; - Installation of pipes and service lines by trained staff; - Use of high-quality materials commensurate with climatic characteristics; - Use of flexible and non-rigid connections to reduce damages caused by pipe displacement in soil; - Strict monitoring of contracting and installation of pipes; - Use of highly-accurate meters for household customers; - Use of preventive maintenance (PM) ; - Observance of standards set for tap distance, the area covered by each tap/valve, and the maximum number of taps for switching off pipe water to fix leakage or fracture.	2	3	6	Medium
Physical/ Chemical/ Microbial	Worn-out pipes and connections	4	3	12	High	- Use of resisting pipes; - Providing the necessary funding for the network renovation by prioritizing vulnerable points; - Continuous visits to check for leaks; - Identification of old pipes with high water loss; - Identification and replacement of faulty connections.	2	2	4	Low

water with the desired quantity and quality can result in unsanitary storage or water treatment at many points of consumption [8]. The most important hazards identified in this part of the water supply chain are as follows (Table 8):

- Low-quality material of pipes

The quality of drinking water must be maintained from the treatment plant to the point of use. However, interactions between water and pipe materials can have an impact on water quality at the point of consumption; these interactions can result in leaching, internal corrosion, biofilm, scale formation, and other issues [65]. Therefore, the selection of pipe materials and their proper assembling are one of the parameters affecting the water quality control at points of consumption. The material of the pipes used by consumers is usually categorized into three major metal, cement, and plastic groups [38]. Considering the direct association between the corrosion and rottenness of the pipes, corrosion is a major factor that contaminates drinking water and serves as the most important mechanism to increase the concentration of a metal ion in drinking water [33]. This mechanism is a major factor in pipes that have metal structures. The most important of these metals include lead, copper, zinc, and iron. Thus, a large part of lead and copper in urban drinking water relates to the raw material used in making domestic pipes and valves [65]. Many studies have found that the presence of metals in drinking water such as Pb, Cu, Fe, Zn, Cr, Cd, and Al is related to the pipe material leaching [65]. A study on the risk assessment of a drinking water supply system using the WSP approach found that the main risks identified at the consumption points were pipe corrosion and the presence of metal pollutants in drinking water as a result of pipe material leaching [6]. Furthermore, the type of water pipe used in buildings must be sufficiently resistant to temperature, pressure, and water speed. The high quality of the pipe against precipitates and corrosion, resistance against soil compounds, as well as ease of installation and maintenance are other major parameters that should be investigated in selecting the type of pipe. [29]. To control the risks of the current hazard, control measure are summarized in Table 8.

- Water pressure drop at points of use

Pressure at points of use is one of the most important hydraulic parameters in managing water distribution networks [66]. High pressure increases leaks, water losses, and a higher number of incidents in the network. On the other hand, low pressure in the network results in a lack of required water supply and enough pressure for consumers [66,67]. The minimum water pressure in the water distribution network should provide the drop in the meter and fittings, water level changes at the storage tanks, and the minimum pressure required for the top floors during peak times of the year, especially during hot seasons. According to Monsef et al. [68], pressure management in water supply systems should be such that adequate water is provided to consumers with the minimum acceptable pressure throughout the operation time, particularly during peak hours on peak days. Given the importance of enough pressure to meet the consumers' demands, it is thus important to use corrective actions and investigate the factors that affect the changing pressure at points of consumption (Table 8).

- Non-observance of health and safety principles to use domestic storage tanks

In many of the buildings, domestic storage tanks are used for the following reasons: (1) to meet pressure levels at peak hours in high-rise buildings, (2) to store water in areas with water shortages, and (3) to reduce the effects of hourly fluctuations in water consumption. Failure to meet health and safety measures to use domestic storage tanks can be a cause of water contamination before consumption [69]. Evision et al. [70] studied the quality of water stored in domestic tanks made of polyethylene, fiberglass, and cast iron. The findings suggested that microbial growth (log 5.2–5.8 CFU/mL) was noted at all tanks, and such factors as long retention times (4–7 d), lack of chlorine residual, and temperature higher than 15°C are the most important factors which affect the bacterial growth and reduced water quality. Also, TOC concentration, which mostly pertains to the growth of algae, bacteria, and precipitation of particles in water, was found to be one of the factors affecting microbial growth at domestic storage tanks. Other studies also stressed that the presence of precipitates in domestic storage tanks would help microorganisms access nutrients, thus increasing the growth and proliferation of nematodes, insect larvae, protozoa, and bacteria [71,72]. According to the 2004 World Health Organization report, around 2.3% of the fatalities and 4.2% of the diseases worldwide were attributed to diarrhea caused by contaminated water [69]. Roberts et al. [73] concluded that domestic water contamination significantly increases diarrhea in children under 5, as potential microbial growth increases with the increase of long retention time. Studies have revealed that the duration of water storage affects the microbiological quality of water. Also, non or reduced consumption of water at some hours of the day causes the water at the tanks to stagnate, reduces the concentration of residual disinfection, increases the hazard of organic matter leaking from the interior wall of the tank, creates a reaction between water and the tank wall, and help microorganism grow, etc. This provides conditions to change the physical, chemical, and microbial quality of water. Thus, one would say that water retention time is one of the major variables affecting the drinking water quality at household water storage tanks [74]. Tokajian and Hashwa [75] investigated the effects of two types of polyethylene and cast-iron storage tanks on water quality, concluding that microbial growth had occurred in both tanks, and retention time was the parameter most affecting the reduced microbial quality of water in the tanks. Thus, one would say that the storage method of drinking water at household storage tanks greatly affects the drinking water quality. The World Health Organization (WHO) declared that a special water safety plan should be also introduced for buildings, in addition to the water treatment plants and distribution systems [8]. Table 8 is summarizing the control measure to minimize the risks of the identified hazards.

Table 8
Risk analysis and risk assessment of the most important hazards at consumption points

Type of hazard	Hazardous events	Risk assessment			Risk rating	Proposed control measure	Risk-reassessment			Risk rating
		Likelihood	Severity	Risk score			Likelihood	Severity	Risk score	
Physical/ Microbial/ Chemical	Low-quality material of pipes	4	3	12	High	- Continuous control and monitoring of domestic piping components; - Monitoring the selection of pipe and connections material and their proper installations at points of use; - Replacement of worn-out pipes with new and standard ones; - Raising public awareness of health hazards related to using inappropriate pipes.	2	1	2	Low
Physical/ Microbial	Water pressure drop at points of use	4	4	16	Very high	- Balancing and managing pressure in the distribution system; - Selection of the appropriate place for the storage tanks; - Control of water levels at storage tanks; - Use of one-way taps; - Implementation of the pressure zoning plan; - Water consumption management at peak hours; - Use of other water resources to supply the required pressure level.	2	2	4	Low
Chemical/ Microbial	Non-observance of health and safety principles to use domestic storage tanks	4	3	12	High	- Providing enough pressure at the distribution network, especially at peak hours of consumption; - Training of consumers on how to store water at home; - Boiling of water before consumption, if required; - Meeting the appropriate level of disinfectant concentration at domestic storage tanks; - Periodic monitoring and washing of domestic tanks.	2	2	4	Low

4. Conclusion

An integrated risk assessment in complicated and high-risk systems such as water supply systems, which involves extensive control parameters, is an appropriate method to identify and monitor the system's hazards. This study aimed to identify the hazards and provide an integrated risk assessment of any of the main water supply system components in the city of Torbat-e-Jam using the World Health Organization's Water Safety Plan. First, the hazards in the main components of the water supply system, including sources, distribution system, treatment, and points of use, were identified and prioritized. Then, a risk assessment of the most important hazards was performed using a semi-quantitative risk matrix approach provided by the World Health Organization and the International Water Association based on the likelihood and severity of consequences model. Later, control measures and corrective actions were identified for each of the hazards, and a risk reassessment was performed to take into account the effects of control measures. The findings of this article showed that there is a high potentiality of high-risk contaminations at various components of the water supply system, especially through vulnerable system areas, which could affect the quantitative and qualitative aspects of water used. Thus, to access healthy drinking water in Torbat-e-Jam, the following need to be met: determining a wellhead protection area for all of the water resources, renovation, and replacement of old and broken pipelines, maintaining a desirable pressure of distribution system, supply of sufficient residual chlorine in the distribution system and storage tanks, increasing of consumers' awareness and regular review to investigate the reliability of control measures. Traditional management of water quality is mainly based on monitoring end-product water (end-point testing), which requires an inclusive plan to identify and assess the risks in water supply systems. Considering the scarcity of drinking water resources and rising costs of a healthy drinking water supply system, it is imperative to identify the hazards and assess the relevant risks in order to optimize the water supply systems in the area of drinking water quality management. Tables 5–8 reveal that a comprehensive risk assessment in the water supply system and the employment of proposed control measures can significantly reduce the risks identified. Adequate knowledge of the system and potentially harmful factors, providing appropriate control measures to reduce direct and indirect losses caused by incidents, reducing the failure duration and system dysfunction, and providing a conducive environment to improve the efficiency of the water supply system are the benefits of using a comprehensive management and assessment process in water supply systems.

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Conflicts of interest/competing interests

The authors have no conflict of interest to declare.

Ethics approval

Not applicable to this study.

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