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Vulnerability Assessment of the Water Network by Considering the Interdependency with other Critical Infrastructures - Case Study: the Water Network of Neyshabour City

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Abstract
Lifelines are the determining components of survival in today's modern world and if the service of these infrastructures is threatened or destroyed due to natural disasters (especially earthquakes) and military threats, the activities of the society are disrupted and the severe failure of these systems will prolong the reconstruction period. One of the most important vital infrastructures that has a direct relationship with people's lives is the need for a water network. A review of the past earthquakes of the world and Iran shows that the components of the drinking and non-drinking water supply system have historically been considerably poor. The main goal of this paper is to prepare a model to analyze the seismic vulnerability of the water network by considering its dependence on other networks. To determine the vulnerability analysis of the water network by considering dependencies, two models were used, graph theory and Leontief. Then, after drawing the network architecture, the proximity and uncertainty matrix of all features were extracted. By multiplying the transpose of the uncertainty matrix in the independent damage analysis of each feature, the dependent damage was determined. The analysis showed the significant impact of dependence on the damage estimate of water network infrastructure; in some elements, the damage increased up to 45 times compared to the independent state. The risk of water reservoirs, water pumping stations, and water wells increased by 92%, 87%, and 62%, respectively, from the independent situation compared to the dependence in the studied area. In the case of robustness of the water network compared to the current situation, the vulnerability of water tanks, water pumping stations, and water wells will be reduced by 25%, 22% and 32%, respectively.

Keywords: Water Network, Seismic Vulnerability, Dependence, Graph Theory.

1. Introduction

Lifelines are the vital arteries determining urban survival in today's modern world. These arteries serve to produce and distribute goods and services in urban units, and the quality and quantity of their functioning, such as water and sewage pipelines, electricity, gas, and public transportation systems, affect urban life directly. The serviceability of these systems can be measured by the ratio of consumers within each area where they flow to the total number of consumers in that area. If the services provided by these infrastructures are threatened or destroyed as a result of natural disasters such as hurricanes, earthquakes, or human-made incidents and events, commercial and economic activities within society are disrupted, production is reduced or completely halted, and consequently, social welfare will be destroyed (Eskandari et al., 2018).

Furthermore, considering the level of demand on infrastructures, the capacity of these systems' components to meet this demand after such incidents will be highly uncertain. Therefore, assessing the vulnerability of infrastructures and paying sufficient attention to maintaining various network arteries (in different sections of production, transmission, and distribution) during crises not only reduces network damage but also facilitates and assists in emergency service provision after the occurrence of a disaster (Eskandari et al., 2020).

The damage inflicted on vital artery networks during past earthquakes in Iran (such as the 1990 Rudbar earthquake and the 2003 Bam earthquake) and around the world (such as the 1923 Kanto earthquake in Japan, 1964 Alaska earthquake, 1964 Niigata earthquake in Japan, 1971 San Fernando earthquake, 1994 Northridge earthquake in the USA, 1995 Kobe earthquake in Japan, 1999 Izmit earthquake in Turkey, and the 2011 Fukushima earthquake and tsunami in Japan) all confirm the high vulnerability of infrastructures to ground movements and shaking. Water, as the most essential element of life, is considered one of humanity's fundamental needs and has always influenced human life. The primary stages of water production and supply include water sources, raw water reservoirs, pumping stations, raw water transmission lines, water treatment plants, treated water reservoirs, and distribution networks. As observed, these components cover vast areas and are highly vulnerable to earthquakes and hostile threats, the overview of water network vulnerability is presented in Table 1 (Eskandari, 2011; Sullivant, 2007).

Alongside the direct vulnerability of networks to disasters, another phenomenon known as interdependence among networks can indirectly affect them during disasters. Concurrently with the advancement and evolution of infrastructures, their interdependence has been introduced and expanded (Rinaldi et al., 2001). Explaining this phenomenon, it can be said that while certain components of a particular infrastructure may remain unaffected and not suffer significant damage from a specific disaster, their performance may decrease or be completely disrupted due to their dependence on another artery that has incurred substantial damage. Therefore, in studying network vulnerability, it is not sufficient to focus solely on the vulnerability of individual components of a network. It is essential to consider all interconnected systems to obtain an accurate assessment.

To overcome existing limitations in traditional analysis methods and address the complexities and wide spectrum of threats, there is a growing need for the development of more advanced analytical capabilities in studies of this nature. Towards this goal, risk assessment and management policies are of paramount importance. Since its not feasible to eliminate all risks and create a completely risk-free society, the need for effective risk management to achieve an acceptable level of risk is crucial (Omidvar et al., 2013). Continuing, national research on how to model the interdependence of infrastructure networks will be presented first. Then, international research in this field will be described.

In order to model interdependence, research utilized the Petri network model to examine the interaction between the water and electricity networks in Tehran. The Petri network is a highly suitable and powerful tool for modeling the relationship between infrastructures. However, the model does not consider reconstruction strategies within a network (Hojati Malekshah, 2010).

In another study, the interaction between water and electricity networks in Tehran was analyzed using the Fault Tree Analysis method. Fault Tree Analysis is a structural process that identifies potential reasons for system failure. It displays interactions between different events using logical gates and illustrates how events may lead to system failure, i.e., become primary events (Naeimi, 2012).

In further research, the interaction between water and electricity networks in Tehran was investigated using the Network Flow Model (minimum cost flow). The network flow model, or simply the flow model, is an efficient tool for examining the dependency between two infrastructures, and it was also employed in this study (Abdollahi, 2012).

To analyze earthquake hazard based on two seismic hazards, ground shaking and ground rupture, while considering uncertainty, a model based on spatial information systems was proposed. Earthquake shaking risk analysis, considering the uncertainties in earthquake occurrence (including earthquake magnitude, depth, and earthquake epicenter location), was repeated randomly using two attenuation relationships in each analysis iteration. Outputs include maximum values of acceleration, velocity, and maximum ground displacement. In the presented model for ground rupture risk analysis, based on the type of region and provided algorithms, three secondary earthquake hazards (liquefaction, landslides, and faulting) were analyzed (Eskandari et al., 2019).

To assess the vulnerability of water, electricity, and

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Table 1. An overview of the water network vulnerability in earthquakes and other threats

No	Date	Description of the incident	Damage
1	Kanto, Japan (1932)	The 7.9 Richter earthquakes damaged water pipelines. There were also more failures at the pipe connection to facilities, pumping stations, tanks, or main facilities.	The failure rate was equal to 0.199 per kilometer in 972 kilometers of the city's pipe network.
2	Holland (1672)	Against the French attack on the Netherlands, the destruction of the dams by the Dutch turned the country into an impenetrable water border.	
3	Los Angeles, America (1913-1907)	Bombing the pipes on the river	Preventing the transfer of water from the Owen Valley to Los Angeles
4	North Korea (1951)	North Korea opened the valves of Hwacheon and water flowed with great pressure	Failure of suspension bridges
5	Mexico City earthquake (1985)	The 7.8 magnitude earthquake in Mexico City caused the destruction of drinking water reservoirs, treatment plants, and main drinking water pipelines.	More than 4 million people were without drinking water for three weeks. Pipelines were repaired and reconstructed in 5100 locations.
6	Angola (1988)	A clash between Angolan and Cuban forces on Kalog Dam	Damage to the dam wall, interruption of the power supply of the dam, destruction of water pipelines in Uambuland
7	North Ridge Earthquake (1994)	In the 6.8 magnitude North Ridge earthquake, four main water pipelines were damaged.	The urban water distribution network was leaking in 1500 locations. The population without water in this earthquake was reported between 100 and 500 thousand people.
8	Lusaka, Zambia (1999)	Bomb explosion in the main water pipelines	Lusaka city with 3 million people was cut off
9	Guatemala, Colombia (2003)	By attacking a part of Kornas oil pipelines, the terrorists brought 7000 barrels of crude oil into the Simitar River.	It resulted in environmental pollution and water cuts for about 5000 people
10	Baghdad (2003)	Sabotage and bombing of the main water pipelines in Baghdad	Water cut and destruction of the pipeline network
11	Bam Earthquake (2003)	The 6.5 Richter Bam earthquake seriously damaged the water supply systems of Bam and Barawat cities.	Eleven wells were damaged, and most of the damage included power failures and displacement of pumps. On the first day, six failures in the main pipelines in the central areas of the city and also one failure in Barawat were broken.

fuel infrastructures independently, a model based on spatial information systems was presented. In this model, to consider uncertainty, two simulation methods, Monte Carlo simulation and Latin Hypercube, were used for evaluation and analysis (Eskandari et al., 2020).

In studies conducted worldwide, Shinzuka and colleagues modeled the structural damage to water distribution networks using the Monte Carlo method, considering earthquake risk (Shinozuka et al., 1992). Chang and colleagues also utilized this method to estimate the economic losses resulting from earthquakes (Chang et al., 2000). Kuwata and Takada evaluated water accessibility in a hospital using a probabilistic approach. To determine this probability, the probability of failure of the water tank, the communication lines between the tank pipes and the hospitals and the equipment in the hospital building are used. This method will be beneficial if the connections between the equipment and tools are completely in series. Other cases were not seen in this study (Kuwata and Takada, 2003).

A study has been conducted to examine mutual dependencies in the severe cascading consequences of the September 2013 floods in Colorado, USA. This research provides insights into what might happen in the future by demonstrating the risks to people and their vital systems (food, energy, and water) resulting from a low-probability event with high impact. The study models the impact of interdependent infrastructures on cascade effects and also illustrates stakeholders' understanding of the impact of actions, institutions, and interdependent infrastructures in an integrated manner. These mutual dependencies create conditions for vulnerability that are the product of multi-scale and dynamic socio-demographic, economic, technological, environmental, and governance interactions (Romero-Lankao and Norton, 2018).

One study has investigated the resilience of a shared water-electricity system for irrigation in a southeastern Idaho agricultural region. Drought, equipment failures, or unintended disruptions in infrastructure pose challenges to delivering water to farmers.

In this research, the resilience of water and electricity systems is analyzed through an integrated approach using a model that connects dependencies between these two systems. Using a multi-agent system model that captures both water and electricity system components as well as their linkages, the mutual dependencies of these systems are depicted, highlighting opportunities for improvement in the face of disruptions. The results show that the effects of low-flow years are more pronounced in the electricity system (Toba et al., 2021).

In a study, a resilience assessment framework is proposed for interconnected water and transportation infrastructures. This framework encompasses the physical network of infrastructures, social vulnerability indicators, and predictive analyses to evaluate socio-technical resilience, measuring the impact of random failures due to infrastructure aging, natural disasters, and their cascading failures. This proposed framework was analyzed in the city of Tampa, Florida. The results showed that areas with higher social vulnerability are more susceptible to cascading failures resulting from random failures and natural disasters. The findings of this study highlight the need to consider the mutual dependency between infrastructure and the consequences of cascading failures in assessing and planning infrastructure resilience (Rahimi-Golkhandan et al., 2022).

The research models interdependent Critical Infrastructure Systems[1] using a simulation approach based on High-Level Architecture[2] that integrates available data and models for each infrastructure domain. In this model, the propagation of failures through interdependent critical infrastructures under three different types of disturbances (random, topology-based, and flow-based) is simulated. Based on the simulation outputs, the framework of Dependency Effects (IE) quantifies the impacts by comparing the performance losses of the system resulting from disturbances, measured under dependent and independent conditions with three different performance metrics.

A case study of two interconnected power and water network systems was used for model implementation. The results of the case study revealed several new insights into the vulnerability of interdependent critical infrastructure systems under various disturbance scenarios, which have significant implications for risk assessment and flexible management of interdependent critical infrastructure systems in practice (Li et al., 2022).

In recent years, methods have been proposed for analyzing infrastructures independently, but these analyses were not easily applicable to other networks because they were designed specifically for a particular network. Moreover, most of the models proposed were subject to uncertainty.

However, even models that considered uncertainties had a fundamental problem- they did not accurately reflect reality, where all networks are interdependent, leading to significant deviations between the analysis results and reality. Therefore, this article presents a model that takes dependencies into account. It is worth mentioning that even in the few studies that addressed the analysis of dependencies between arteries, several issues were overlooked.

Firstly, most discussions focused on individual infrastructures, making it difficult to generalize to other infrastructures. Secondly, little attention was paid to the significant issue of uncertainty in existing methods. Thirdly, discussions on mutual dependencies between more than two infrastructures were limited. Fourthly, the presented model is not only applicable to natural disasters and earthquakes, as discussed in this article, but also usable for hostile threats.

Based on that, this article seeks to further explore these dependencies and focuses on how to establish the network, flow patterns within the network, and optimal inter-system performance. To achieve this, a comprehensive algorithm for analyzing dependent damages is first presented. Then, the study network is introduced, and following seismic risk analysis and independent damage analysis of the region's water network, an interaction analysis of the water network with other networks, such as electricity and city fuel in Neyshabour, is conducted. Finally, a portion of the research results is presented.

2. Methodology

The presented model for assessing the vulnerability of the water network, considering dependencies, is based on a combination of graph theory and the Leontief adjacency matrix method according to the algorithm shown in Fig. 1. The main sections of this algorithm include preparing and drawing the network architecture, scenario selection, risk analysis or threat identification, independent damage analysis of the water network based on Monte Carlo simulation, and dependent damage analysis of the water network. The process of the proposed algorithm includes the following stages (as per the diagram in Fig. 1).

[1] Critical Infrastructure Systems (CIS)
[2] High- Level Architecture (HLA)

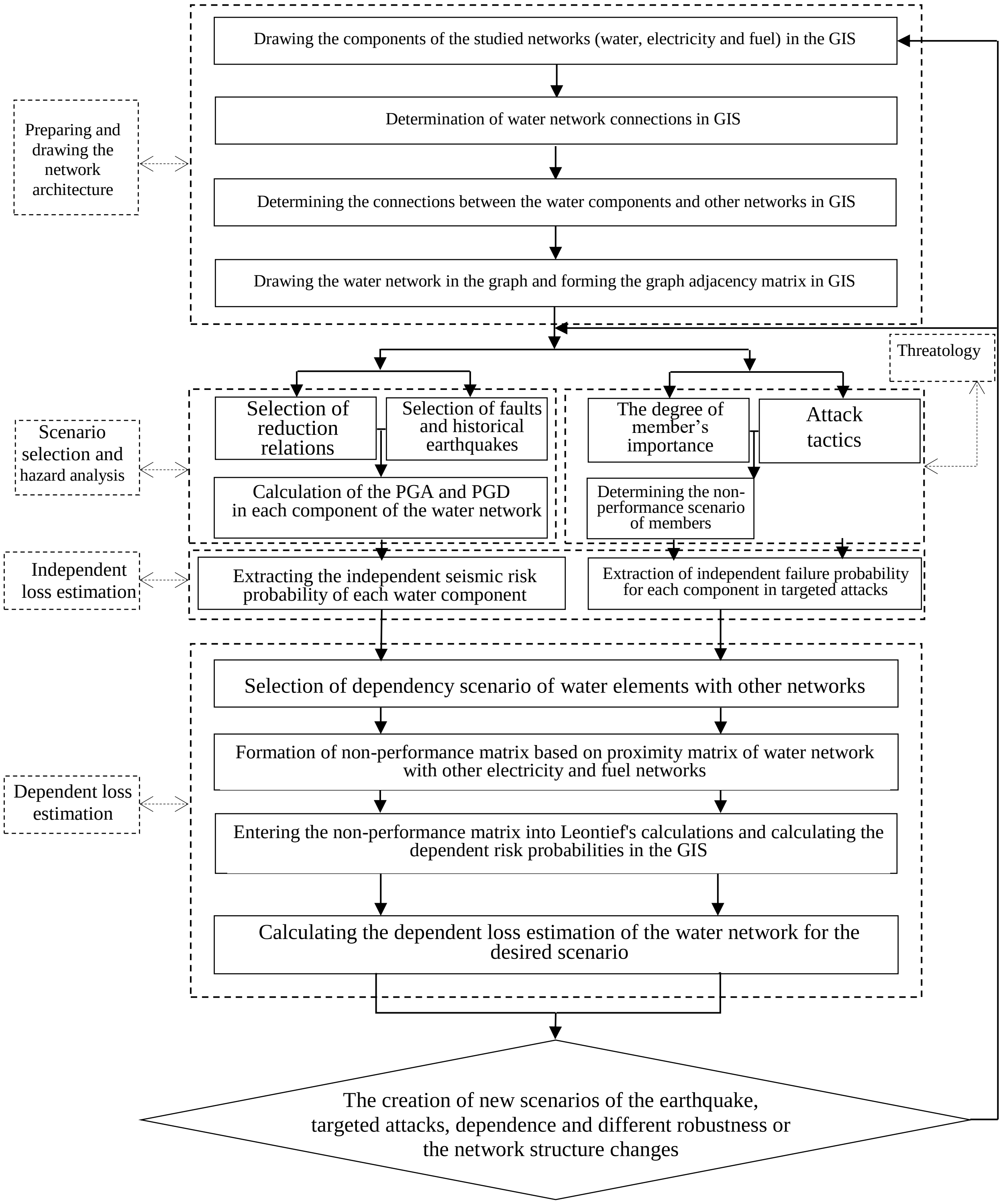


Fig. 1. Algorithm of infrastructure vulnerability model considering interdependency

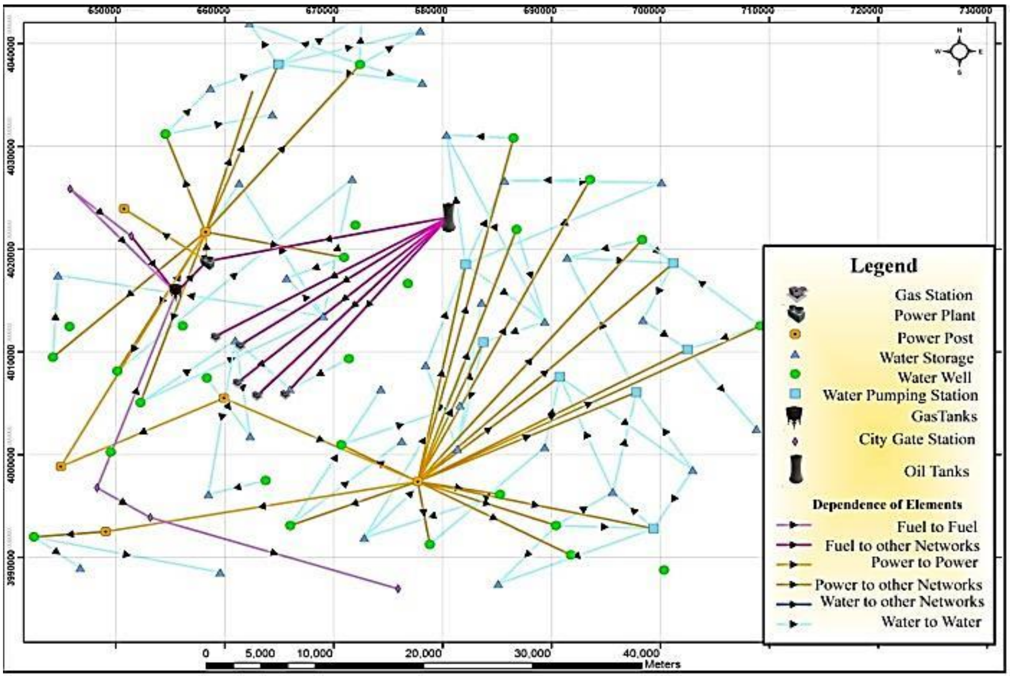


Fig. 2. The schematic display of internal and external dependence of water, power and fuel networks of Neyshabour City

2.1. Step 1: preparation and drawing of network architecture

Initially, the existing networks under investigation need to be modeled as graphs, and the connections between the elements, including intra-network and inter-network connections, should be specified. The network under study in this research includes three networks: water, electricity, and fuel in Neyshabour City.

Neyshabour City is one of the northern counties of Khorasan Razavi Province. It borders Quchan city to the north, Chenaran and Mashhad to the east, Torbat-e Heydarieh and Kashmar to the south, and Sabzevar to the west. Of the total geographical area of Neyshabour City, which is equivalent to 892,530 hectares, 5500 square kilometers are plains, and the rest consists of mountains. Neyshabour Plain, which is part of the Kalshur River basin, is situated at the southern foothills of the Binaloud Mountains and in the northeastern part of the Central Desert. The region has a semi-arid and arid climate, with an average temperature of 12 degrees Celsius and reported rainfall of 292 millimeters. The evaporation rate is also high due to the high temperature, with an average of 2335 millimeters per year for the entire basin, and its elevation above sea level is 1100 meters. The main source of water supply for the region is wells, which are fed from the underground aquifer of Neyshabour Plain (Sakhdari et al., 2011).

The water network of Neyshabour City consists of 27 well rings, 35 reservoirs, and 8 pumping stations. The electricity network of Neyshabour City comprises 7 power substations and one power plant. Additionally, the fuel network of the city consists of 5 petrol pumps, an oil depot, a fuel gas tank for the power plant, and 5 pressure reduction stations (CGS). In Fig. 2, the architecture of the water, electricity, and fuel networks of Neyshabour City can be observed schematically, considering both internal and external dependencies with other networks.

2.2. Step 2: drawing the adjacency matrix

In this stage, based on the created graph, the adjacency matrix of the studied networks (with elements of 90*90) is extracted. Accuracy in extracting this matrix ensures the validity of the remaining steps and calculations, as due to the large number of network elements under investigation, large and dense matrices are created. The adjacency matrix of network graphs is a unique and square matrix that represents how elements are connected to each other in a network. The topological properties of the network are the first interpretation that can be derived from this matrix. In simple graphs, this matrix consists of 0s and 1s that are symmetric with respect to the main diagonal. However, for directed graphs such as infrastructure networks where flows of goods and services occur, the elements of this matrix may not necessarily be 0 and 1, and they may take on any arrangement depending on the type of network under investigation. In Table 2, a portion of the adjacency matrix of the networks in the studied region can be observed.

2.3. Step 3: earthquake hazard analysis

The process of earthquake hazard analysis is a fundamental step in analyzing the earthquake-induced damage to the water network and other networks. Simply put, in this stage, the amount of energy released by the earthquake (for the provided earthquake scenarios), is

Table 2. Summary of the adjacency matrix of the case study

	Power plant	Folad Post	Attar Post	Attar 2 post	Fathabad post	Kamalolmalok post	Binalod well	Bar well	Bar storage	Chegne pumping	Chegne well	Khorsofla pumping	Khorolia pumping	Oil tank	Gas station1	Gas station2	Gas tank	Ghadmagah CGS	CGS 4	CGS 2	CGS 1
Power plant	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0
Folad Post	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Attar Post	0	0	0	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Attar 2 post	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fathabad post	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kamalolmalok post	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Binalod well	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bar well	0	0	0	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bar storage	0	0	0	0	0	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chegne pumping	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chegne well	0	0	0	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Khorsofla pumping	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Khorolia pumping	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oil tank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas station1	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0	0	0	0	0	0	0
Gas station2	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0	0	0	0	0	0	0
Gas tank	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0
Ghadmagah CGS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0
CGS 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CGS 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CGS 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0	0

determined. The earthquake risk estimation in this study is based on the research "Presentation of a seismic hazard map model in spatial information systems considering uncertainty," presented by (Eskandari et al., 2019).

Earthquake risk analysis in this research is conducted using attenuation relationships and is based on the geological, geophysical, and geotechnical conditions of the region; and through direct methods or numerical analysis software, the maximum acceleration, velocity, and displacement changes in the bedrock are determined for the desired hazard level. In this method, it is necessary to perform earthquake risk analysis for the desired hazard level by specifying the earthquake scenario so that the seismic hazard parameters (Peak Ground Displacement[1], Peak Ground Velocity[2], and Peak Ground Acceleration[3]) can be obtained at the desired levels. Therefore, the level of damage incurred by the network components, based on each of the regional seismic parameters under earthquake scenarios is determined. Earthquake risk analysis provides values for scenario selection as follows:

• Earthquake Magnitude: The history of historical and instrumental earthquakes indicates both high-magnitude earthquakes occurring at various times inside and around Neyshabour City (with at least 8 historical earthquakes

[1] Peak Ground Displacement (PGD)
[2] Peak Ground Velocity (PGV)
[3] Peak Ground Acceleration (PGA)

and 3 instrumental earthquakes ranging from 6 to 7.5 Richter within less than 100 kilometers from this city) and numerous occurrences of lower-magnitude earthquakes (between 4 to 6 Richter) (Mirzaei et al., 2002). Based on this, to cover the majority of earthquakes in the target area, the potential magnitudes are randomly selected in the range between 4 and 7.5 Richter using a uniform distribution function.

• Earthquake Epicenter Depth: Considering that more than 85% of previous earthquakes in this area have occurred at depths between 3 and 32 kilometers, the depth of the earthquake epicenter is randomly selected in the range between 3 and 32 kilometers using a uniform distribution function (Mirzaei et al., 2002).

• Earthquake Epicenter Coordinates: The location of the earthquake epicenter is randomly selected within a radius of 100 kilometers from the vicinity of this city on a map.

Monte Carlo simulation is a widely used sampling technique employed to simulate the behavior of physical and mathematical systems. The Monte Carlo method is particularly useful in systems and models with a large number of uncertain parameters (random variables). In other words, Monte Carlo simulation utilizes a stochastic process (Goodarzi et al., 2013). In general, Monte Carlo simulation requires a number of simulations to achieve a certain level of accuracy and precision (Akkar and Cheng, 2015).

Therefore, in this article, Monte Carlo method was utilized for earthquake risk analysis in the specified region. Accordingly, a random value with a uniform distribution for each scenario parameter is selected in each analysis iteration, and in the next loop, another random value is chosen. To calculate the output parameters of seismic risk, including PGA, PGV, and PGD, in each iteration, one of the attenuation relationships by (Zare et al., 1999; Ghodrati et al., 2007; Campbell and Bozorgnia, 2008), is randomly selected, and this process is repeated 10,000 times.

2.4. Step 4: earthquake independent loss estimation

To estimate seismic vulnerability, the use of vulnerability functions for each element is necessary. A vulnerability function is a relationship that expresses the expected damage for a structure as a function of severe ground motion or any seismic parameter. It can be expressed in various forms such as vulnerability functions for pipelines, fragility curves, or damage state surfaces. In this study, seismic vulnerability estimation is based on the research "Modeling seismic damage analysis of critical infrastructure based on geographic information systems," presented by (Eskandari et al., 2016).

In this paper, vulnerability functions for the three networks of water, electricity, and fuel were used based on HAZUS methodology. These functions were tailored to different types of hazards (such as ground shaking (PGA) or ground failure (PGD)), types of structural systems, and types of elements within each network. Median and beta parameters associated with each element were utilized. In each iteration, the level of independent vulnerability of network elements (such as treatment plants, wells, pumping stations, and reservoirs for water networks; substations with different voltages and power plants for electricity networks; gas pressure reduction stations, pressure boosting stations, refineries, and gas storage tanks for fuel networks) in the city of Neyshabour was calculated.

2.5. Step 5: determining the non-performance matrix

In the fifth step, the matrix of system dysfunction is determined. System dysfunction is defined as the inability of the system to perform its expected functions and can be a continuous value between 0 and 1, where 0 represents a state of normal functioning of the system, and 1 represents complete system failure. A defective system is one that, compared to a perfect system, only has a portion of its functionality, thus resulting in a dysfunction value greater than 0. For example, a television with a picture but no sound, or a drinking water supply systems with insufficient water quality and water that is contaminated, are systems with dysfunction values greater than 0.

The failure matrix is created based on the adjacency matrix of the modeled networks. This matrix is prepared for different dependency scenarios under consideration. The degree of dependency between the two network elements may not be either zero or one. Therefore, for different degrees of dependency scenarios, 25%, 50%, and 75% are considered to cover all dependency cases. For example, a pumping station may have different degrees of dependency on a power station, such as the following:

- If a pumping station receives its power supply only from one power station, the degree of dependency between them is 100%.
- If a pumping station receives its power supply from two power stations, the degree of dependency between them can be 50%, 75%, or even 25%.
- If a pumping station receives its power supply from a diesel generator in addition to a power station, the degree of dependency between them can be 25%.

In this study, scenarios of complete network interdependency (100%) and dependencies less than that (75%, 50%, and 25%), as well as networks independent of each other with only intra-network dependencies, are investigated.

In this stage, four interdependency scenarios plus one scenario where the elements are considered without any connections form a total of 5 interdependency scenarios. This matrix, which is the transpose of the network adjacency matrix considering the status of its dependencies, will be based on the interdependency scenario under study.

2.6. Step 6: earthquake dependent loss estimation

The sixth step involves determining the probability of interdependent damage. Interdependency is a connection or relationship between two infrastructures, whereby the performance quality of one infrastructure affects the performance of another. Hence, the concepts of interdependency are diverse, each with its own unique characteristics and specific effects on infrastructure components. In summary, interdependencies can be classified into four main classes: physical, cyber, geographical, and logical, and each is examined and defined accordingly (Lee II et al., 2007; Rinaldi et al., 2001).

The model used in this paper to simulate the effects of interdependency between the water network and other networks is based on the adjacency matrix of the graph and the Input-Output (I-O) model of Leontief. The Leontief Input-Output model is essentially a framework for studying equilibrium behaviors in economics (Leontief, 1951). It analyzes the economic system in which n types of goods are produced as outputs using primary resources as inputs. In the proposed model, n infrastructures with complex internal and external communications are considered. Additionally, the output includes the risk of malfunctioning due to one or more failures caused by their complexity, incidents, or hostile threats. The system's inputs can also include failures due to natural disasters or targeted attacks.

In general, Equation (1) is used to assess the vulnerability of infrastructures considering their dependencies with other networks (Eskandari, 2018)

$$x_{kj} = a_{kj} * x_j,\ j, k= 1, 2, ..., n \quad (1)$$

Where

- X_{kj} is the degree of target failure experienced by infrastructure j due to one or more failures caused by accidents or adversarial threats, which infrastructure j incurs due to its internal and external connections with infrastructure k.
- a_{kj} is the probability of failure that infrastructure k introduces to infrastructure j due to the complexities of their interconnections. In other words, akj describes the degree of dependency of infrastructure k on infrastructure j. For example, if akj=1, a complete failure in infrastructure j will lead to a complete failure in infrastructure k. By this definition, the elements on the main diagonal of the dependency matrix, A, represented as akk, are considered as 0.

To consider the effects caused by the infrastructure itself, the following proportionality equation should be used:

$$x_k = \sum_{j=1}^{n} X_{kj} + c_k k = 1,2,..., n \quad (2)$$

c_k Represents the additional risk of failure for infrastructure k, which is assumed to have inherent complexities (such as intra-system and inter-system communications) and can also be induced by random events, natural disasters, and adversarial threats. The risk index is decomposed into two factors: probability and degree of failure. By establishing the proportionality assumption, the following relationships are obtained:

By combining equation (1) with equation (2), an equation based on Leontief for modeling infrastructures can be obtained:

$$x_k = \sum_{j=1}^{n} a_{kj} * x_j + c_k . k = 1, 2, ..., n \quad (3)$$

To write the above relationship based on matrix notations, we define the existing parameters as follows (all these parameters are non-negative):

$$x = [x_1, x_2, ..., x_n]^T \text{ for } 0 \le x_j \le 1,\ c= [c_1, c_2, ..., c_n]^T,\ A= [a_{kj}]_{(n*n)},\ I = [\text{Identity Matrix}]_{n\times n} \quad (4)$$

With these definitions, the following relationship is obtained:

$$X= A^* x+C \quad (5)$$

Which can also be written as follows:

$$(I- A) * x=c \quad (6)$$

Assuming non-zero of (I - A), the Leontief equation can be solved for all infrastructure failure risks as follows:

$$x= (1-A)^{-1} * c \quad (7)$$

- X: Dependent failure probability matrix
- I: Identity or unit matrix
- A: Network non-operation matrix
- C: Independent failure probability matrix

By entering these matrices and the independent failure probabilities of the elements into the above equation, the dependent failure probabilities for each earthquake scenario and targeted attacks as well as each dependency scenario will be obtained. In this way, the independent earthquake damage probabilities, as an example, will be obtained for 5 different dependency scenarios. Alongside these dependency scenarios, one scenario that encompasses failure probabilities without considering dependency analysis is considered to enable a suitable comparison between dependency and non-dependency considerations. These latter scenarios clearly illustrate the actual differences between reality and our expectations from the network.

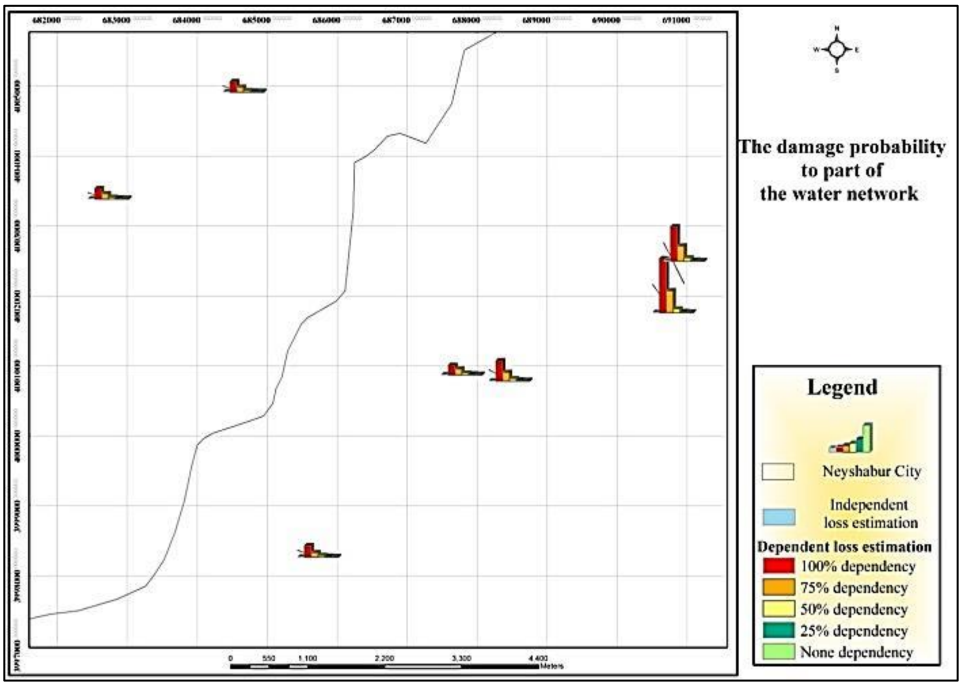


Fig. 3. Vulnerability probability to the pumping station of water network considering interdependencies with other networks

2.7. Step 7: the creation of robustness scenarios

In this stage, to observe the difference in damage levels between the seismic reinforcement state in networks (better state than the current state) and the current state, as well as the state without considering seismic restraint for all network components (worse state than the current state), all steps from 2 to 4 are repeated, and analyses are conducted on the outputs.

3. Results and discussion

3.1. Results of dependent damage analysis of the water network in Neyshabour

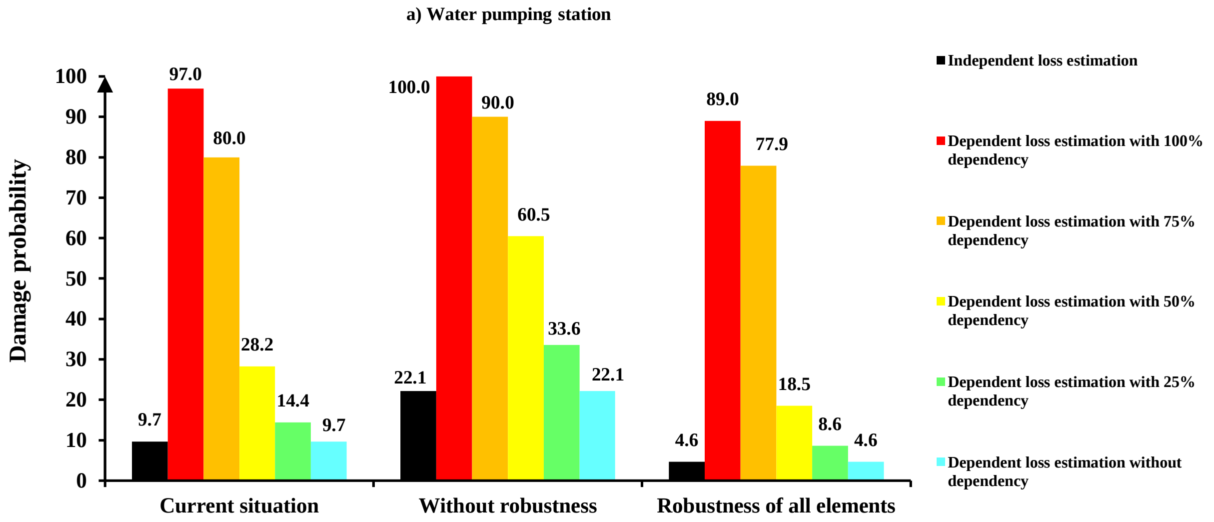
Fig. 3 displays a graph illustrating the extent of damages incurred on a portion of the water network in Neyshabour City for each incident. As evident in this figure, infrastructures such as wells, which are both water-and electricity-dependent, are subjected to a higher probability of dependent damage compared to infrastructures such as reservoirs, which are solely water-dependent. In Table 3 and Fig. 4, the results of independent and dependent damage probabilities for some incidents can be observed. The results of independent damage probability are entirely similar to the results of dependent damage probability with zero dependency between components. This indicates that the existing relationships for considering dependency are completely accurate and logical. Additionally, the results show that the water network, despite having the highest dependency on the electricity network, experiences a significant increase in dependent damage when influenced by the electricity network, even though the water network itself has a low probability of independent damage in incidents. Infrastructures such as the Binaloud water well, which are independent of other networks, have equal probabilities of independent and dependent damage; however, this situation results in an approximately 20-fold increase in damage from independent to dependent states for the Qadamgah water well.

Another notable point is the difference in dependent damage probability rates for different dependency scenarios. It seems that the difference in damage probability rates for different dependencies is almost linear for fuel network incidents, as shown in Fig. 5, while it is nonlinear for electricity and water networks. However, even for electricity and water networks, they follow a nearly linear trend from zero to 50% dependency. Another observation is that after network dependency increases from 50% to 75% and then to 100%, the vulnerability rates increase at a higher rate.

Table 4 and Fig. 6 illustrate the importance of addressing dependency issues. Without considering these patterns, for example, the average damage probability for water reservoirs in Neyshabour City is estimated to be 2%. However, by considering dependency issues, the average damage probability for water reservoirs increases to 94%, aligning the analyses with reality. As evident in Table 4 and Fig. 6, infrastructures with higher dependencies on other incidents exhibit more noticeable differences in damage probabilities. For instance, considering that the dependency of pumping stations on the electricity network is much higher than the dependency of water wells, the dependent damage probability for pumping stations is much higher than that

Table 3. Summary of independent and dependent loss estimation for some components

Feature	Independent loss estimation	Dependent loss estimation				
		100% Dependency	75% Dependency	50% Dependency	25% Dependency	Without dependency
Binalod well	2.7	2.7	2.7	2.7	2.7	2.7
Bar well	4.4	70.4	36.2	17.6	8.3	4.4
Bar storage	1.1	71.4	28.2	9.9	3.1	1.1
Chegne olia pumping	5.8	74.5	32.3	14.9	8.2	5.8
Chegne well	1.1	67.1	32.9	14.3	5.1	1.1
Chegne storage	2.3	73.1	26.8	9.6	4.0	2.3
Khor sofla pumping	11.6	100	64.0	22.5	14.5	11.6
Khor Olia pumping	12.1	100	60.9	22.1	14.8	12.1
Ghadamgah well	5.4	100	51.7	21.1	9.9	5.4
Ghadamgah pumping	10.4	100	55.8	22.9	13.6	10.4
Ghadamgah storage	1.8	100	42.1	12.8	4.7	1.8
Neyshabour power plant	17.2	56.4	43.7	33.6	24.7	17.2
Attar post	30.3	96.2	72.6	43.5	34.2	30.3
Kamalol molk post	9.6	66.0	42.4	26.4	15.8	9.6
Oil tank	26.0	26.0	26.0	26.0	26.0	26.0
Gas station 1	18.9	45.0	38.5	32.0	25.5	18.9
Gas station 2	21.6	47.6	41.1	34.6	28.1	21.6
Gas tank	29.7	52.3	44.6	39.5	34.2	29.7
Ghadamgah CGS	15.8	47.1	36.5	27.8	20.9	15.8
CGS 4	14.6	14.6	14.6	14.6	14.6	14.6
CGS 2	18.4	18.4	18.4	18.4	18.4	18.4
CGS 1	16.8	31.3	27.7	24.1	20.4	16.8
CGS 3	16.6	35.1	30.4	25.8	21.2	16.6



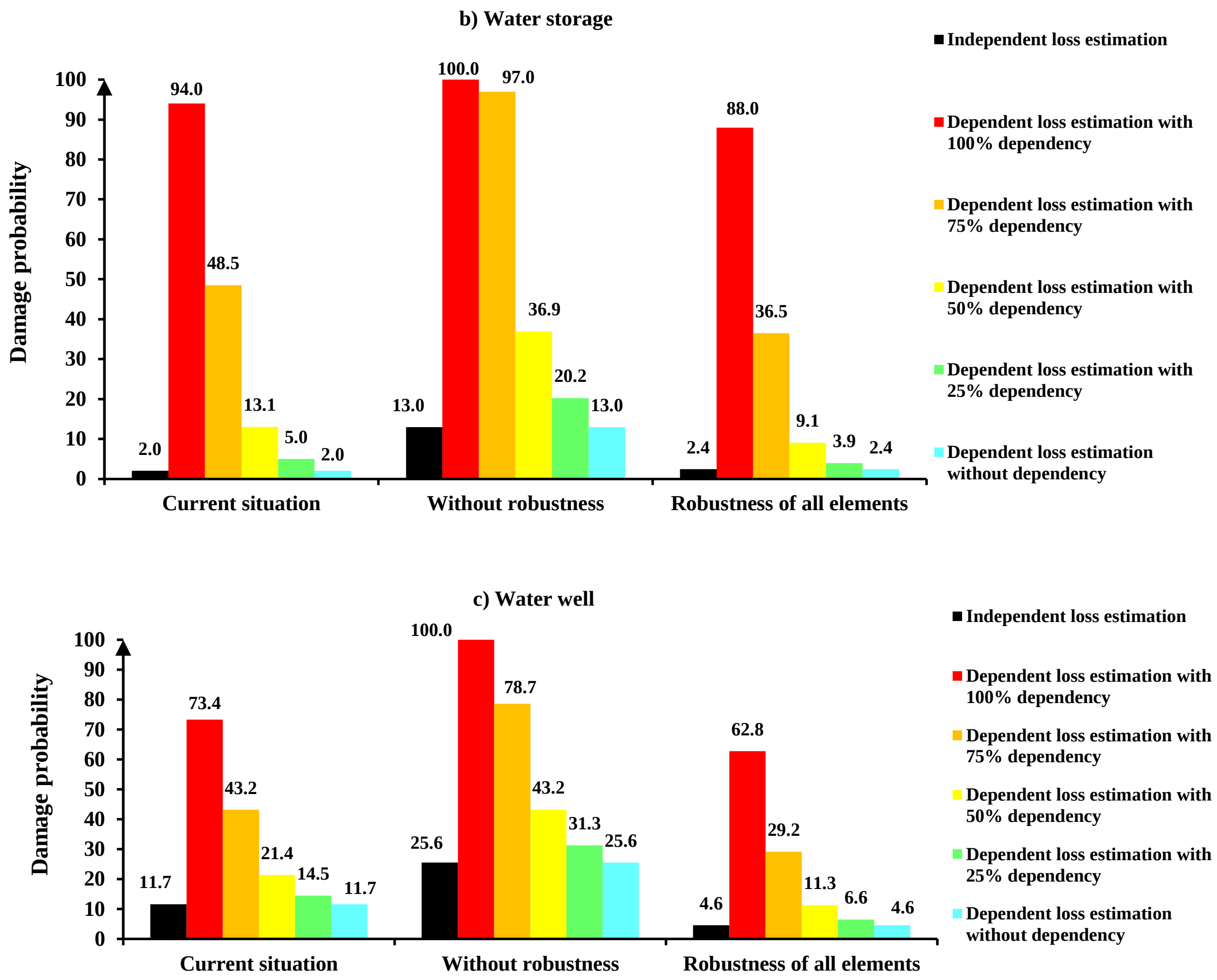


Fig. 4. The average comparison of loss estimation of the water network in different situations

Table 4. Comparison of independent and dependent loss estimation for different infrastructures

Infrastructure	Independent loss estimation	Dependent loss estimation with 100% dependency	Amount of difference	Percentage difference
Water storage	2.0	94.0	92.0	4592.8
Water pumping station	9.7	97.0	87.3	903.1
Water well	11.7	73.4	61.7	528.9
Power post	11.6	89.5	77.9	672.3
Power plant	17.2	56.4	39.2	227.6
Oil tank	26.0	26.0	0.0	0
Gas tank	29.7	52.3	22.6	76.4
Gas station	19.5	45.5	26.0	133.4
CGS	16.4	29.3	12.9	78.3

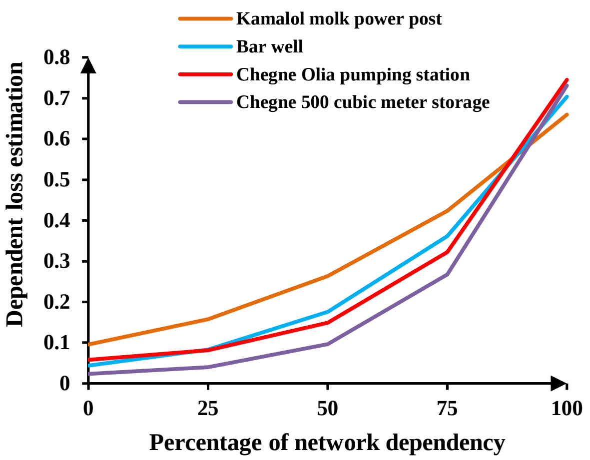


Fig. 5. The rate of changes in the loss estimation with increasing dependency in some components

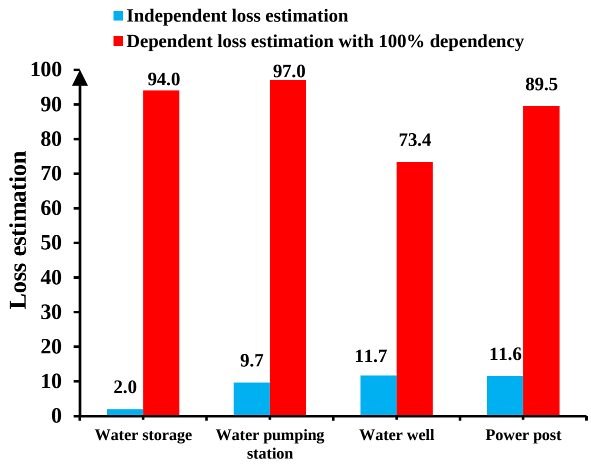


Fig. 6. The average comparison of loss estimation of independent and dependent

Table 5. Comparison of dependent loss estimation for different robustness situations

Infrastructure	Dependent loss estimation with 75% dependency			Percentage of difference	
	Current situation	Without robustness	Robustness of all elements	Between the current situation and without robustness	Between the current situation and robustness
Water storage	48.5	97.0	36.5	+99.9	-24.8
Water pumping station	100.0	100.0	77.9	0	-22.1
Water well	43.2	78.7	29.2	+82.3	-32.4

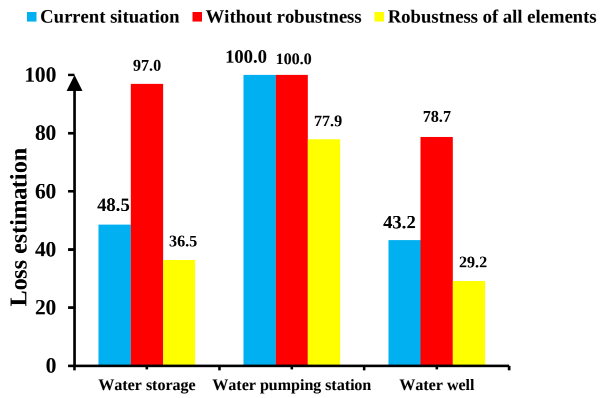


Fig. 7. The average comparison of dependent loss estimation for different situations

for water wells in Neyshabour City.

3.2. Results of dependent damage analysis considering robustness

One of the resilience solutions against earthquakes is the implementation of seismic restraints. This involves the installation of seismic restraints to increase the structural resistance and reduce the vulnerability of each infrastructure. Its impact is reflected in vulnerability functions such as mean and beta. In this stage, three conditions were considered for this study:

1- Current Status: This is the condition analyzed based on available and actual infrastructure data. In this state, some infrastructures have seismic restraints installed, while others are devoid of seismic restraints.

2- State without Restraints: This condition, which is worse than the current state, occurs when none of the elements in the water network have seismic restraints installed. This is a pessimistic scenario.

3- State of Full Resilience: In this condition, it is assumed that all elements of the water network are equipped with seismic restraints. This state represents the ideal scenario for the elements. Thus, the results of independent and dependent damage probabilities in three states - current, without restraints, and resilience - for the water network are presented in Table 5 and Fig. 7. As evident in these figures, the effectiveness of seismic restraints in water network elements can be observed. According to Table 5 and Fig. 7, the percentage difference between the current state and the two states without restraints and full resilience is clearly visible. For instance, for water reservoirs, if seismic restraints are not utilized, the probability of damage increases by approximately 100% compared to the current state. Furthermore, for the same incident, if seismic restraints are used and the network is made resilient, around 24% of damages can be reduced compared to the current state. Also, considering the larger difference between the current state and the state without restraints compared to the resilient state, it can be inferred that most water reservoirs in the city had seismic restraints, as the difference between the current state and the resilient state is less than the state without restraints.

Another point to note is that the level of resilience for water pumping stations compared to other elements of the water network can reduce damage. This is because the probability of dependent damage for water pumping stations is higher than other elements of the water network. Another important aspect to consider is that the impact of making dependent networks independent compared to network resilience is much more pronounced. In other words, while network resilience is effective in reducing vulnerabilities, adding backup systems and enhancing them in dependent elements can have a much greater impact on reducing vulnerabilities.

4. Conclusion

Iran is a seismic country located on the Alpine-Himalayan seismic belt, and the possibility of earthquakes occurring there is constant. Modern life today is heavily reliant on vital networks. Continuity in providing services through these networks is of paramount importance for the sustainability and functionality of modern societies. The vulnerability of these lifelines to disasters and emergencies is the subject of many studies today because the damages inflicted on these infrastructures, especially water and sewage networks, not only contribute to the overall damage but can also complicate and exacerbate the consequences of other damages, making the recovery process more difficult and complex.

In recent years, methods have been developed to analyze infrastructures affected by natural disasters such as earthquakes. However, most of these methods have focused on estimating the seismic vulnerability of infrastructures independently, and the analyses of dependencies cannot be generalized to other networks. In this article, to analyze the damages incurred by the water network considering dependencies, the water, electricity, and fuel networks of Neyshabour City were first modeled graphically with existing connections, including both intra-network and inter-network connections. Then, a network adjacency matrix (with 90*90 elements) was prepared square-wise for the studied networks. Next, seismic risk analysis was conducted considering uncertainties using Monte Carlo simulation, and in the subsequent stage, the seismic vulnerability of each element was calculated based on vulnerability functions for each component. In the next step, the failure matrix was created based on the modeled network adjacency matrix for different degrees of dependency scenarios at 25%, 50%, 75%, and 100% coverage for all dependency scenarios. Then, the probability of dependent damage for each component of the water network, considering dependencies with other networks, was evaluated based on the Leontief pattern. Finally, by presenting resilience scenarios, the best possible strategy to reduce dependent damages to the water network was identified.

Analyzing dependent damages essentially involves closely approximating the extent of damages in infrastructure networks. The results obtained from considering dependency probabilities validate expectations regarding the significant impact of dependencies. The results from the analysis of failure probabilities of individual components compared to the failure probabilities of water network components in conjunction with other networks underscore the importance of considering the parameters of interaction among vital lifelines in disasters.

On average, the extent of damages incurred by the water pumping station infrastructure in Neyshabour City increased by approximately 87% from independent to dependent states. Similarly, for the water reservoir infrastructure in Neyshabour City, there was an approximately 92% increase in damages from independent to dependent states, and for the water well infrastructure in Neyshabour City, there was an approximately 62% increase in damages from independent to dependent states. Here are some general results from dependency analyses that are extendable to other networks:

The main issue is the presence of redundancy in systems. As the results indicate, components that only receive flow from a single path tend to experience an increased probability of failure during analysis. Conversely, components that receive flow from multiple paths, due to the existence of alternative routes, have a slower rate of increase in the probability of failure with increasing dependency. However, the presence of parallel paths and increased redundancy can lead to reduced probabilities of failure in the network and significant improvements in network performance indicators.

Another issue that affects the increase or decrease in the probability of component failures is the degree of interdependency between two corresponding networks. For example, if the water network is 100% dependent on the power network, compared to a scenario where it is only 50% dependent, the probability of failure in the water network is much higher.

Therefore, another appropriate solution is to reduce the inherent interdependency between the two networks so that each network can meet the needs of the other networks. For instance, instead of relying on the power grid, elements can be equipped with backup power sources such as diesel generators to meet their power needs for a short period until the other network is repaired.

Another issue in reducing the probability of component failures is the use of resilience strategies such as implementing earthquake-resistant measures for all components.

As the results show, resilience also has a considerable impact on the probability of component failures.

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