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Original Research Article

Evaluation of Water Risk through Fuzzy Cognitive Maps (FCMs)-

A Case Study of Tehran City*

Parichehr Saboonchi**

Ph.D. in Landscape Architecture, School of Architecture, Faculty of Fine Arts, University of Tehran, Iran.

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Abstract | Among the 40 identified natural hazards, Iran is vulnerable to 30. Tehran, as the largest metropolitan in Iran, was fraught with perils of which drought and water stress are the most significant. Apart from, damaging the environment and creating or intensifying secondary natural calamities, drought can impair social, economic, political, and physical aspects of life. Unfortunately, the management based on the development of grey infrastructure has exacerbated the vulnerabilities and diminished Tehran's resilience. This research aims to address the effective factors causing the risk of drought and water stress in the city of Tehran and asses these factors. The study attempts to scrutinize what are the most important priorities of vulnerability. Addressing priorities can serve as a basis for decision-making and multi-scale planning of drought risk reduction. Such urgencies contribute to adopting preventive measures rather than crisis management. The theoretical literature of the current research is analytical-descriptive, for which data was collected from books, articles, reports, and upstream projects. Also, to evaluate the risk landscape, the risk matrix was developed based on the interactive model, and then the most important causes of vulnerability were extracted, assessed, and analyzed using fuzzy cognitive maps (FCMs). Research findings and the main drought risk scenarios of Tehran show that at the micro level, "high waste of water resources", "change of land use and destruction of natural infrastructure", and "urban development disproportionate to water capacities" are the main drivers. At the macro level, this issue is caused by repeating the cycle of "physical-natural-perceptual" damage and discounting the city as a human-environmental system.

Keywords | *Climate Change, Multi-hazard Risk, Drought Resilience, Water Scarcity, Natural Hazard Risk Asessment, Fuzzy Cognitive Maps (FCMs).*

Introduction| Iran is broadly known as one of the regions with a high degree of climate risk and ranked fifth country for its high water stress and drought among the first 17 countries (WRI, 2015). Approximately 97% of the country is in drought conditions and the prediction is that in less than 25 years, 50 million Iranians will have to relocate (Shahi, 2019). Climatic changes, precipitation decline, temperature rise, and evaporation rate have resulted in the lack of water resources and the rise in heavy rains (Goodarzi & Fatehifar, 2022). Moreover, the unsustainable plans and strategies of urban management and surpassing water supplies (in the agricultural, domestic, and industrial sectors) have made the country susceptible to desertification. Water bankruptcy can cause economic, social, and security problems in the medium and long run (Madani et al., 2016).

Grounded in international disaster risk reduction strategies (Sendai), Iran is committed to using governance, social, natural, economic, and cultural capacities to boost the safety and resilience of cities (UNDRR, 2015). Thus, evaluating the effects of drought risk and water stress conditions for developing a road map based on the principles of sustainable development requires the use of holistic approaches and adopting preventive measures as well as society's adaptation to risk. Applying such strategies, the issue of water risk will not be limited to environmental factors, but an issue encompassing the social, economic, political, cultural, and physical facets of the city.

Drought is a serious risk for Tehran demonstrating its gradual yet deep effects. Tehran is generally in normal climatic conditions, but the time interval for the occurrence of dry and wet conditions is short (Hanafi et al., 2012). The consequences of such intervals can be dry periods in the late 90s and 2000 (Doostan, 2015). Tehran has been through a drought

**Corresponding author: +989121903077, saboonchi.parich@ut.ac.ir

phenomenon at least once in every decade, the most severe of which was in 2008 and was an antecedent to the dust pollution of Tehran in 2010 (Abounoori, 2019). Subsequently, in 2015, another severe drought occurred. Surveys in crop years 2014-2015 indicate mild to severe drought. The drought trend in different regions of the province has increased over time, mainly from the north to the south (Eskandari Damaneh et al., 2016). This background has highlighted the necessity of a detailed examination of the dimensions of the water problem in Tehran to create a progressive plan. So far, the strategies to deal with the water scarcity crisis have generally been technology-oriented and based on intervention in the environment and physical environment. The current research first investigates what factors are involved in the occurrence and escalation of drought in Tehran and what are the key drivers and consequences. The answers to these questions can determine whether the current urban management plans and methods are appropriate to the importance of the issue, and what parts of these plans have been neglected. This research attempts to evaluate the role of institutional factors and social groups in determining the structure of the problem with a holistic perspective, identifying the economic, social, and cultural structures. Finally, this research looks into the deepest layers of people's perception of the issue of water stress in Tehran. Measuring this multifaceted and complex category could be an important step in redefining the concept of water risk management and changing patterns in preparation for the occurrence of severe drought.

Theoretical Foundations

• Risk assessment of natural hazards

Risk as a phenomenon encompasses two elements "hazard" and "vulnerability" and its evaluation means identifying the type and possibility of risk incidence, the degree of vulnerability, and the possibility of putting society and city at risk. To assess risk, analyses must be done from three perspectives: 1)identifying the risk network influencing a city (risk assessment); 2)Identifying the network of vulnerability triggers (vulnerability assessment); and 3)discovery of causal relationships between risks and vulnerability variables (risk analysis).

1)Hazard assessment: In the human-environmental system of the city, natural hazards can be in the form of an interactive risk network. That means that several different hazards (such as landslides, earthquakes, and floods) occur in different periods in a specific area, or overlapping hazard layers disturb an area simultaneously (Shi et al., 2015). In this situation, multi-risk approaches can support holistic assessment (Gill & Malamud, 2016). In such an approach, the connections between natural hazards, human activities, and the built environment create a complex network of risk interactions or risk cascades (Choine et al., 2015). Many studies and executive guidelines emphasize multi-risk assessment (see UNISDR, 2015, Julià, & Ferreira, 2021; Zhou & Zhai, 2023; Mladineo et al., 2022; Trogrlic et al., 2024; Ferreira & Santos, 2024; Mascheri et al., 2024).

2)Vulnerability assessment: At large, the vulnerability in risk assessment determines whether a specific event can become a disaster or not. Former vulnerabilities of society can escalate the adverse effects of disasters. A review of vulnerability literature shows that all damages can fall into six natural, institutional, economic, social, physical, and cognitive clusters (see Gebreyes & Theodory, 2018; Moghadas et al., 2019; Wang et al., 2020; Tanim et al., 2022; Mabrouk & Haoying, 2023; Roy et al., 2024; Bernardini et al., 2024). Like risks, Damages have an interactive feature. This complex network requires understanding the relationships between the variables of each cluster as well as identifying the most critical relationships. Network analysis at the micro (identification of relationships between indicators) and macro level (identification of relationships between main clusters) can significantly contribute to assessing the overall risk of natural hazards.

3)Risk analysis: Risk analysis through the combined assessment of the "hazard network" and "vulnerability network" is affected by human-natural dynamic systems. This system is based on principles such as multi-scale, time dimensions, place-based, dynamics, multiple stakeholders, and holistic (Masnavi et al., 2021; Saboonchi et al., 2023) and the risk of natural hazards and environmental management in this system is also a phenomenon consisting of material, social, and discursive institutions and processes (Neisser, 2014; Asadafrooz et al., 2020; Saboonchi & Abarghouei Fard, 2020). Therefore, it will be necessary to consider three physical, functional, and mental dimensions in risk analysis1:

- **Physical-spatial dimensions:** latent physical threats, natural or caused by human activities, will have palpable effects on the city's form. These effects are location-based; Like the risk of rising water due to climate change, which can only be felt in a coastal area. Also, environmental changes and the time factor affect the dynamics of the material dimension of risk.
- **Functional dimensions:** risk landscapes are caused by material and non-material human activities, and these activities can produce new risks. Risk is dependent on actions and based on uncertainty (Müller-Mahn et al., 2018).
- **Subjective dimensions:** the importance of risk for different stakeholder groups (local groups, experts, decision-making institutions) is not the same, and this causes different interpretations of risk. Divergence and plurality in risk perceptions have an effect on practical methods and actions in facing the risk so much so that some actions support the interests of all stakeholders, while others cause conflict of interests (Stephan, 2019). Also, the degree of power of interest groups plays a decisive role in reducing or preventing risk; For instance, experts' decisions can dominate political agendas and public perception, while the risk perceived by other groups may not have an impact on political and social organizations (Müller-Mahn, 2012).

Research Method

Encountering the consequences caused by water stress requires comprehensive strategies and the cooperation of the stakeholders. The cooperative methods and models by increasing the interests of stakeholders and encouraging them to intervene (Mehryar & Surminski, 2022) have contributed to cohesive conceptual models, joint actions, and strategies, joint different expertise and interdisciplinary skills, and a collection of different opinions (Zomorodian et al., 2018; Olazabal et al., 2018). In this research, a group model based on the method of FCMs was developed. Analyzing Qualitative cognitive maps based on neural networks and matrix models shows the cycle of a phenomenon by revealing hidden causal relationships (Özesmi & Özesmi, 2004). This method carries out the prioritization process in a fuzzy manner and transforms qualitative evaluations into quantitative analyses in detail by deeply examining mental patterns. The construction of cognitive maps takes place at two levels: individual (formation of problem structure) and collective (achieving consensus) (Fig. 1).

• Data collection

The drought risk network was identified using available studies and an interactive risk matrix model (Gill & Malamud, 2014). The purpose of the network was to create a space for discussion about Tehran's water risk. To understand the vulnerability network at the individual level, data was carried out by semi-structured interviews. Due to the exploratory nature of the research and the great amount of time required for the method, a total of 11 people were selected (based on the saturation of causal propositions). After analyzing the content of the interviews and making individual graphs, the list of variables was finalized by the collaborative panel. Then the experts determined the relationships and weighting of variables based on fuzzy variables. In the next step, a diffuse and normalized aggregate matrix was created to determine the degree of membership of variables and clusters, and based on the variables with the highest degree of centrality (upper limit of 0.7), three main strategic paths for drought risk were drawn.

• Data analysis

Matrix analysis: To quantify the impact of each factor on another factor, the weight of the factors was measured (Table 1). After calculating the average of the fuzzy numbers, the calibration process.

Cognitive map analysis: After identifying the most key variables (the highest degree of centrality), important scenarios were identified on the map. The highest numerical weights between the two variables indicate the strategic directions of the map (Fig. 2).

• Findings

Findings from the collaborative panel show in the drought risk

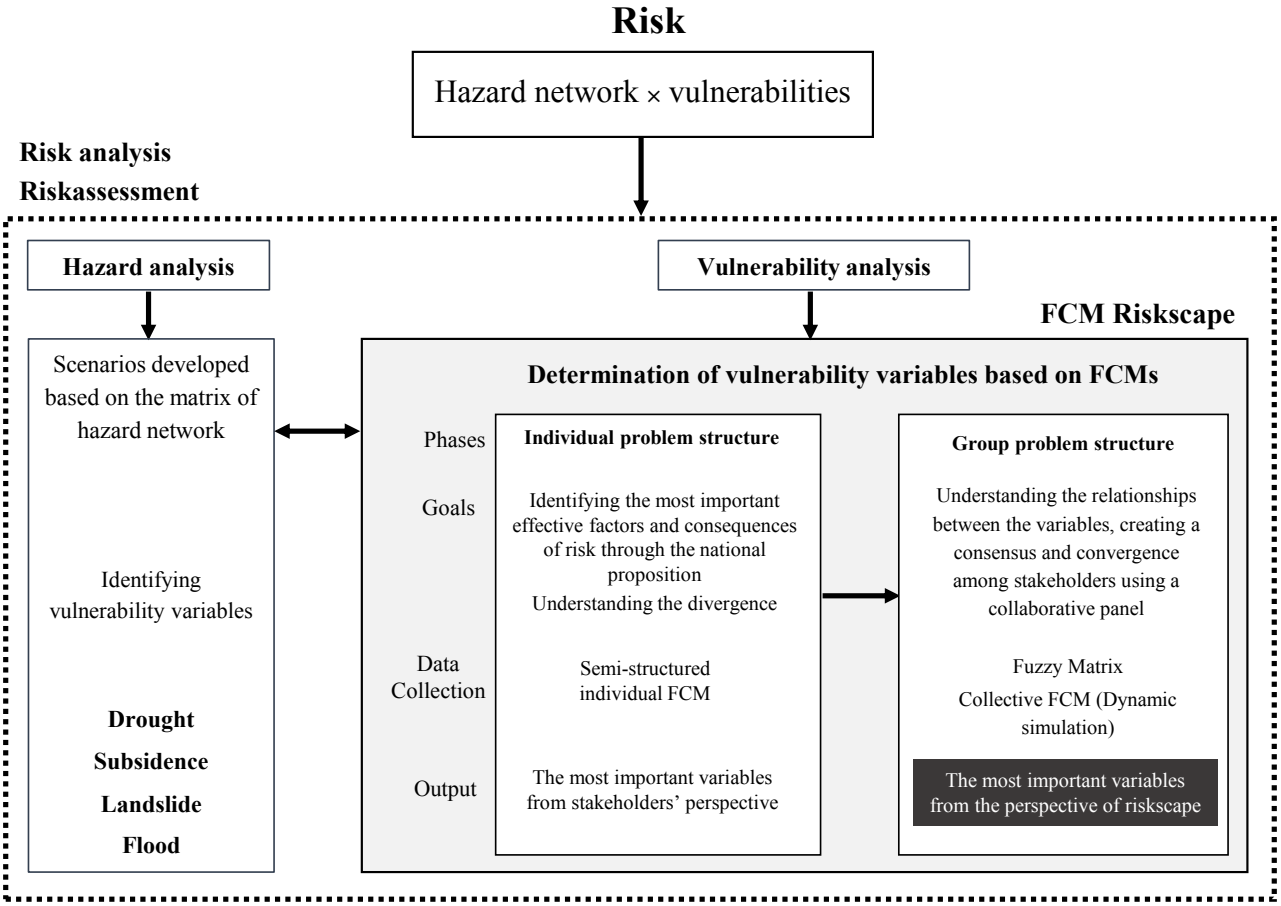

Fig. 1. The process of developing an FCM in two individual and group phases. Source: Author.

matrix of Tehran, the subsidence-landslide-flood cycle is the most likely network (Fig. 3).

To determine the network of vulnerabilities, first, in semi-structured individual interviews, the perceived causality chain was described based on "risk-vulnerability causes-primary effects-secondary effects". In the descriptions, divergent propositions about causes and consequences were observed; For example, some experts considered the lack of cooperation and scientific clearance between the academic community and executive institutions as an obstacle to effective measures to reduce risk, and others emphasized the conflict of interests or weak inter-institutional structures. From the total propositions, 34 variables were identified in the form of 6 main clusters for the drought of Tehran, and after merging similar variables, finally, 21 variables were agreed upon by the experts (Table 2).

After determining the weight of the relationships of the variables, the final summary matrix was prepared. "Reduction and waste of water resources (C13)", "Land use change and destruction of natural infrastructure (C15)" and "Urban development disproportionate to water capacities (C14)" with the highest degree of centrality have played a central

Table 1. Triangular fuzzy numbers of the 5-degree Likert spectrum. Source: Habibi et al., 2013.

Variable	Fuzzy value	Triangular fuzzy number
Very much	5	1.00, 1.00, 0.75
A lot	4	1.00, 0.75, 0.50
Average	3	0.75, 0.50, 0.25
Low	2	0.50, 0.25, 0.00
Very little	1	0.25, 0.00, 0.00
Ineffective	0	0.00

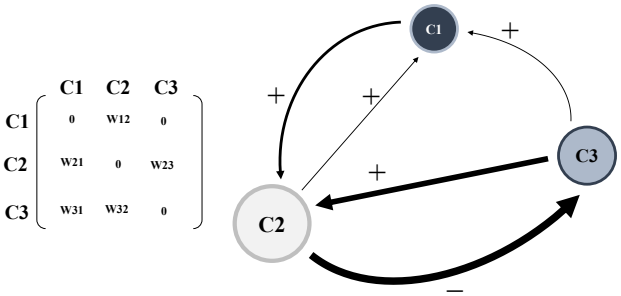

Fig. 2. A sketch of an FCM in which C2 is the key variable and the path C2-->C3-->C2 is the strategic path.
Source: Author based on Martín et al., 2020.

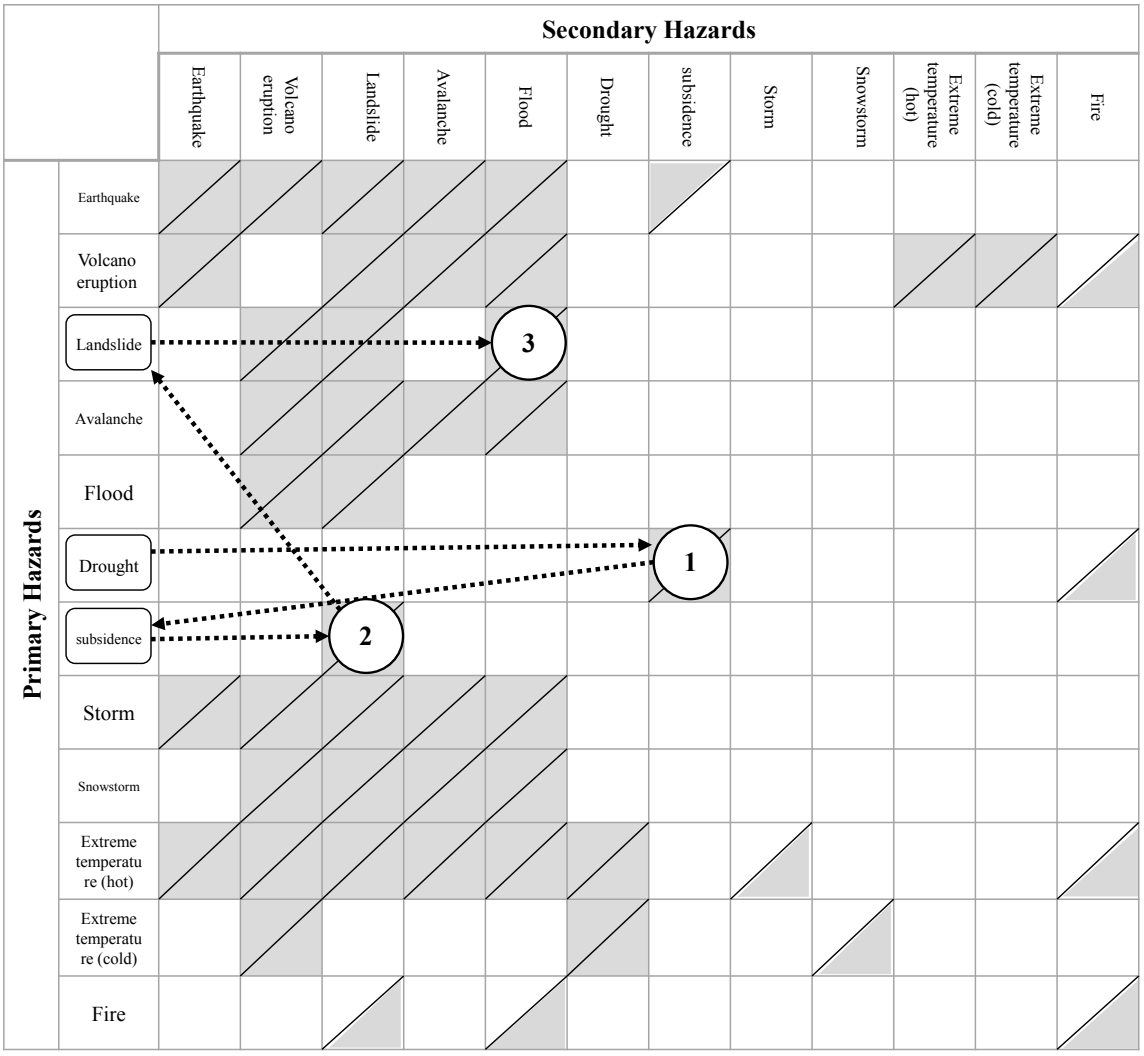

Fig. 3. Drought risk network for Tehran. Source: Author based on Gill & Malamud, 2014.

role in Tehran's drought and the most effective cluster is the cluster is physical. Extraction and excessive consumption of underground and surface water and water surpass in different sectors have increased the vulnerability of Tehran. Also, the ineffectiveness of natural infrastructure due to the destruction of natural lands and uncontrolled constructions, the loading of multiple functions and the creation of water-consuming industries, traditional agriculture, and the incompatibility of the city form with the problem of drought (such as the use of inappropriate plant species in green spaces) are other axes of increasing water risk (Table 2).

The main scenarios are made based on three main variables (C13-C14-C15) (Figs. 4, 5 & 6). These strategic paths show which factors have the greatest impact on creating or intensifying a variable (trigger) and which factors are the most important results of the occurrence of that variable (consequence).

Discussion

Tehran's drought has witnessed turning points due to physical indices and human interferences in the shape of the city (the way of consuming, recycling water, land uses, protection and management, natural, physical, and nonphysical urban development and grey infrastructure and indices associated with urban management decisions. In contrast with the stress that experts had on natural factors in the initial interviews (climatic changes, precipitation and temperature features in Tehran), developing the aggregate matrix showed these

Table 2. Out degree, In degree, centrality of variables, and degree of density of FCMs' clusters. Source: Author.

Cluster		Variables	Cluster density	Cluster density average	Out degree	In degree	Centrality
	C1	Drought and water stress	-	-	-	-	-
Individual-perceptual	C2	Weakening the connection of citizens with nature	43.05	14.35	6.67	6.73	13.4
	C3	Lack of understanding and subjective awareness of drought among citizens			9.06	6.63	15.69
	C4	Depreciation of water value in the eyes of citizens			7.00	6.96	13.96
Social	C5	Loss of citizens' trust	51.47	12.86	6.00	6.55	12.55
	C6	Weakening cooperation and collective participation among citizens			6.64	6.92	13.56
	C7	Weakening of social structures			4.06	5.72	9.78
	C8	Migration and population growth			7.93	7.65	15.58
Economical	C9	Lack of economic stability and livelihood	27.26	13.63	7.14	7.71	14.85
	C10	Cheap water and energy			8.26	5.15	13.41
Natural	C11	Climate change and ecological balance disturbance	30.59	15.29	8.88	8.48	17.36
	C12	Limitation in the natural features of the environment			7.30	5.93	13.23
Physical	C13	Reduction and waste of water resources	80.26	20.06	9.72	11.65	21.37
	C14	Urban development disproportionate to water capacities			9.10	9.88	18.98
	C15	Change of land use and destruction of natural infrastructure			9.86	11.48	21.34
	C16	Creating destructive artifact infrastructure			8.23	10.34	18.57
Institutional	C17	Weakness of institutional relations and lack of responsibility	104.67	17.44	9.08	8.60	17.68
	C18	Knowledge and implementation weaknesses in drought management			9.92	7.97	17.89
	C19	Compartmentalisation of institutions			9.89	8.48	18.37
	C20	Lack of foresight and lack of investment			8.91	9.50	18.41
	C21	Lack of realism of institutions			7.83	8.08	15.91
	C22	The importance of power relations and conservative management			8.64	7.77	16.41

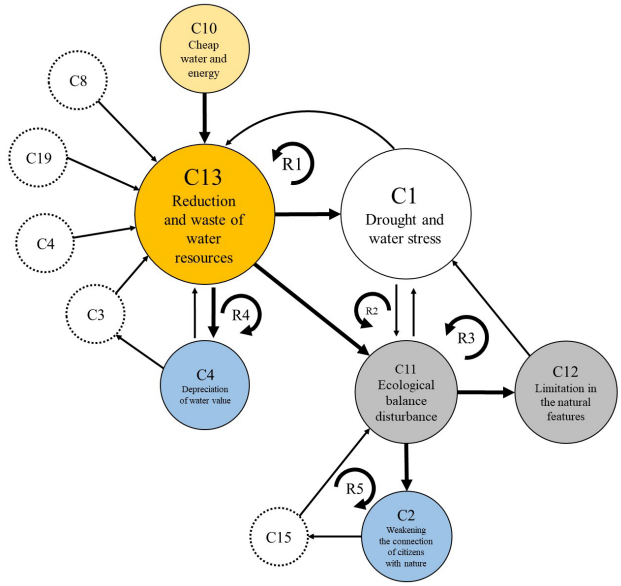

Fig. 4. Strategic path based on C13. Source: Author.

variables were in the middle ranks, moreover, the institutional indicators outweighed them. The mental patterns of experts suggest that human interventions have a more key role than non-human factors. Moreover, in individual interviews, the lack of social participation, education, cultural development, etc., were introduced as key factors in the risk of drought and water stress, but in the group phase, the comparison of ratings shows that the physical aspects and building components of the city (natural or artificial) are more important since they include social or economic dimensions. Therefore, the three clusters at the bottom of the table (cognitive, economic, and social) can be complementary factors to the upper clusters (physical, institutional, and natural). This cluster weighting helps to find more effective solutions to the problem. For instance, there may be activities to improve the financial and social capital of citizens. Though this action is necessary in the process of reducing water risk, it may not be sufficient in creating long-term resilience.

Institutional, natural, cognitive, and economic clusters are

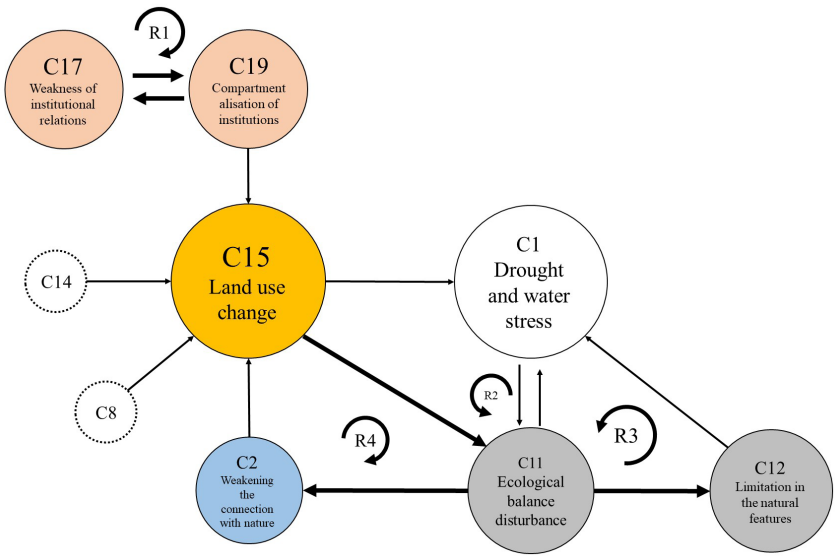

Fig. 5. Strategic path based on C15. Source: Author.

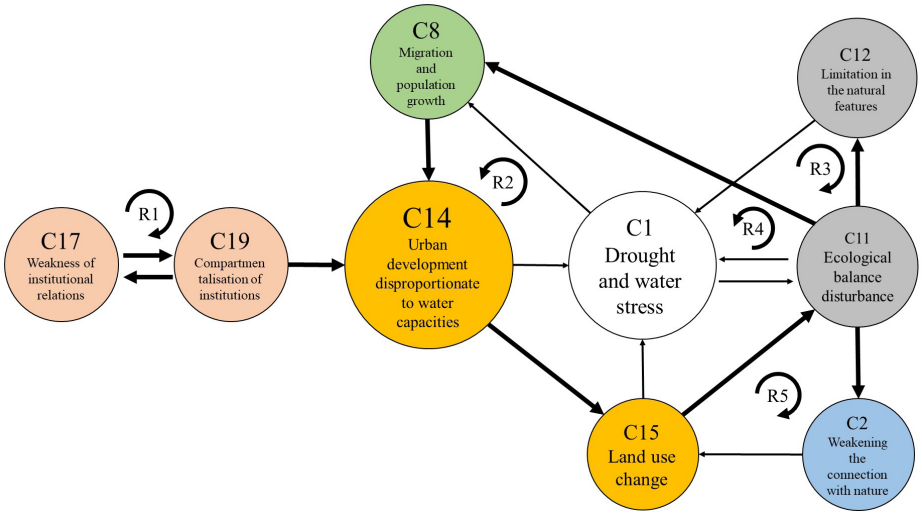

Fig. 6. Strategic path based on C14. Source: Author.

the most important contributors, respectively. Although according to experts, natural factors have a direct effect on drought, institutional factors are more fundamental to creating or intensifying water risk. In many cases, experts consider environmental damages and limitations to be dependent on the actions of large institutions and believe that with proper management, the effect of natural factors can be neutralized to a large extent. The degree of influence of the natural cluster on the cognitive cluster is high; this means that people's perceptions to face the problem are affected by their interpretation of the natural environment. At the same time, the cognitive cluster is a strong stimulus for the physical cluster; this means that people's perceptions affect their activities to intervene in cities. The recurrence of this cycle in all three scenarios shows that human activities by changing the natural environment can change people's perception in the long term. The separation of people's mentalities from the environment has a direct effect on the adoption of unsustainable measures. At the same time, the institutional components with the highest out degree are the main drivers of this cycle. The economic cluster also influences the four institutional, social, physical, and cognitive clusters, but finally, the experts concluded that the economic factor cannot have a strong impact on other variables.

The analysis of three strategic paths reveals that different factors influence the physical-functional structures of the city and its natural components (especially water resources). Experts concord that Tehran is dealing with a lack of natural resources due to the uncontrolled development of the built environment and mismanagement of resources, and this problem has hindered the possibility of maintaining or expanding the natural environment within the city. The graphs show that the consequences of the city's physical planning have more specific results than other drivers, especially on the state of the city's natural capital. Therefore, negative changes in the natural infrastructure through the destruction of the city's ecosystem will directly cause water stress and increase the severity of drought. This cycle is repeated in all three graphs.

Although there is a difference of opinion in identifying the main drivers in the aggregate graph, the results are largely the same. In this graph, the "physical-natural-perceptual" cycle of vulnerability is an important node in the category of drought in Tehran (Fig. 7). In this way, the set of human actions and interventions in the body of the cities cause damage to the natural components of the city and as a result of the separation of the built environment from the natural structure, the mentality of the beneficiaries of the city is transformed. The continuation of the change of mental patterns leads to unstable physical actions and activities. Institutional factors and decisions are an external stimulus for the cycle and increase the effect of the cycle. Therefore, from a macro perspective, the main cause of Tehran's resilience against drought and increasing water stress is the failure to consider the city as an integrated human-environmental system in which the role of human activity and their mental effects are considered separate from the natural and artificial environment of the city. The combination of variables and strategic paths also shows that despite the difference of opinion, experts are unanimous in addressing the structure of Tehran's drought problem.

Conclusion

The evaluation of the risk of natural hazards as a multi-dimensional issue requires the evaluation of interactive networks of risk and vulnerabilities for the human-environmental system of the city. In this research, Tehran's drought and water risk landscape was evaluated based on physical, functional, and mental characteristics and based on the principles of holistic and dynamic and considering multiple stakeholders in different scales (Fig. 8). To adopt a systematic approach, the variables were identified and prioritized using the method of analyzing FCMs. This method, by examining the mental patterns of people, made it possible to discover their real mentality about the problem. Despite the initial notions that natural factors (such as climate change), and social factors (such as weak participation or citizens' lack of awareness of the consequences of drought) are often the main obstacles to carrying out adaptation measures, the weighting of variables and clusters shows that in the absence of resilient physical systems and effective institutional decisions, providing social or economic solutions (such as efforts to educate and inform citizens or create sustainable economic resources) do not necessarily lead to increased resilience against water scarcity crisis.

As cognitive graphs show the most important factor of drought risk is related to the physical-functional development pattern of Tehran, and the "physical-natural-cognitive" vulnerability cycle

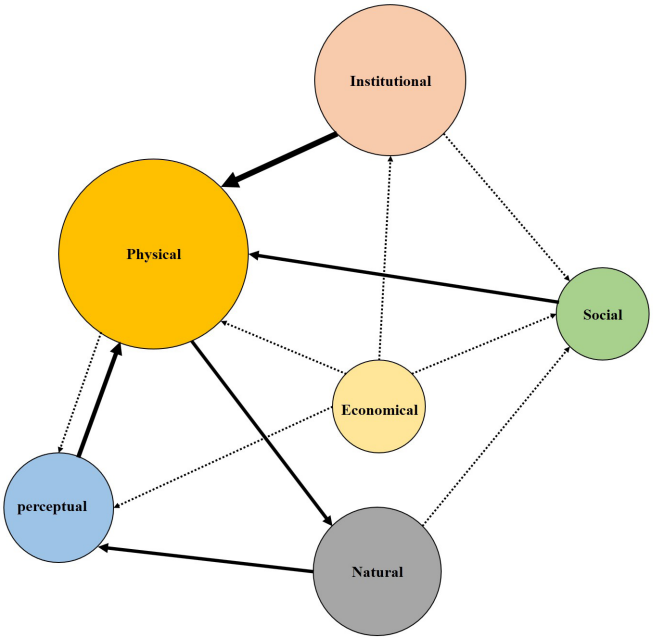

Fig. 7. The size of each cluster is drawn based on the degree of centrality and importance of the cluster. Source: Author.

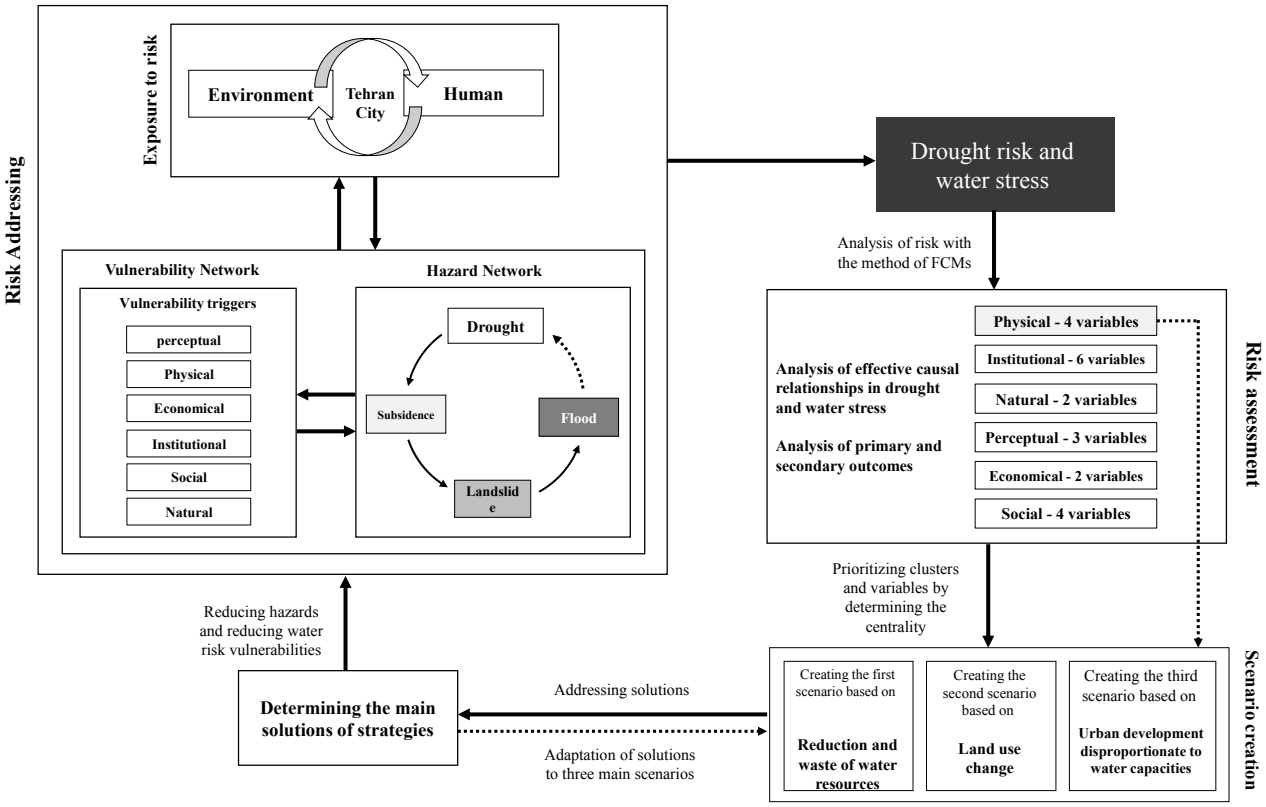

Fig. 8. Water risk evaluation and analysis process in Tehran. Source: Author.

is an important node in this issue. On a macro scale, physical indicators play a more key role in this system, and at the same time, institutional factors (especially compartmentalization and lack of systematic approaches to the water issue) as an external stimulus, exacerbate the negative effects of the cycle. At the micro-scale, actions such as extensive harvesting of water resources and changes in uses lead to the destruction of the natural environment. This has not only changed the mentality of the beneficiaries of the value of the element of water and the concept of drought but also caused their unstable activities by intensifying physical damage to the city. Therefore, the main issue of water risk in Tehran is caused by ignoring the city as a human-environmental system (risk perspective). The results of collective votes based on problem recognition and weighting of factors in this research can help to propose a set of strategies, approaches, and practical solutions for water risk planning in Tehran through decision-making based on uncertainty.

Endnotes

*This article extracted from Ph.D. thesis of "Parichehr Saboonchi" entitled "Integration of the City landscape and Natural Infrastructures(NI) to Reduce Natural Disasters Risk emphasizing Nature-based Solutions(NbS), The case of Tehran city" under supervision of Dr. "Mohammad Reza Masnavi and Heshmatollah Motedayen" which has been done at School of Architecture, Faculty of Fine Arts, University of Tehran, Iran in 2023.

1. In this research, the term risk has been conceptualized as Riskscape and has been defined based on the human-environmental system of the city. The risk perspective defines 5 areas in natural hazards: 1)the scope and field of risk definition in the form of an objective-subjective issue; 2)the relationship between human and non-human components and the environment caused by risk; 3)risk-causing factors (sum of human or natural and artificial factors); 4)risk audience (individual or society); 5)Risk conditions (time-space scale).

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