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Original Research Article

Strategies to Mitigate Drought and Water Stress in Tehran through Nature-based Solutions (NbS), A Decision-making Based on Fuzzy Cognitive Maps (FCMs)*

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Abstract | Drought and water stress in the metropolis of Tehran can adversely impact the environmental, social, economic, and political areas of life while increasing the vulnerability of the society and the city. Tehran's resilience against drought has been exacerbated by a range of factors such as the management's atomistical view of the integrated human-environmental system of the city, the loss of water resources, the disproportion between the change of land uses and the water capacities, as well as human interventions and the development of gray infrastructure. This situation has turned decision-making and identifying priorities regarding the water tension into a serious challenge. This research aims to provide multi-scale solutions to reduce drought based on the capacities of Tehran's landscape and answer the question of what main risk reduction strategies can be adopted at the macro level and what appropriate tools are available at the micro level. To address this question, the experts' opinions in collaborative panels were analyzed and the causes of Tehran's vulnerability were identified through Fuzzy Cognitive Maps (FCMs) and related-driven scenarios. The findings show that the strategies for encountering and reducing the consequences of drought in Tehran are a combination of nature-based and gray solutions. Changing urban management strategies, modifying population patterns and city development, restoring natural ecosystems, and changing the mentality of citizens towards the issue of water shortage are other proposed solutions. Among Nature-based Solutions (NbS), river valleys play a key role in modifying the city's development pattern. Using these solutions requires the adoption of integrated strategies at the institutional-physical levels along with the promotion of social and economic programs.

Keywords | *Climate Change, Water Scarcity, Drought, Nature-based Solutions (NbS), Urban Resilience, Adaptive Strategies.*

Introduction| Based on the report of the World Economic Forum, failure to decrease the impacts of climate change and failure to adapt to disasters are the most significant global risks (Provan, 2023). Thus, managing risks such as drought and flood requires governments to move from adaptation to adaptability to practice how to deal with uncertainties (Schipper, 2020). The consequences of climate risks and the global water crisis have led to the development of adaptive strategies (Savari et al., 2024; Barendrecht et al., 2024; Zhu et al., 2024; Dabrowska et al., 2023; Elnashar & Elyamany, 2023). Lack of water, high water demand, and the risk of drought in Iran and Tehran are a serious crisis; risk management has not moved towards adaptive practices yet. For instance, despite the stress on NbS as an adaptation policy to face drought (Yimer et al., 2024), nowadays, there is widespread destruction of natural structures and an increase in gray infrastructure in Tehran. For this reason, the prediction of a holistic and adaptive plan for this metropolis is of great importance.

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The present research aimed at identifying and evaluating innovative multi-scale strategies to lessen drought and water stress based on the natural capacities of Tehran. First, a holistic assessment of the vulnerability aspects of the drought risk network was conducted based on FCMs. Then, the most important strategies for planning and managing Tehran's water resources were examined. Moreover, the study scrutinized which tools can enhance resilience and reduce vulnerabilities caused by drought and to what extent natural infrastructures are effective. To find solutions, two challenges need to be addressed: 1) Divergence in the definition of the problem from the point of view of different stakeholders, and 2) lack of consensus in proposing solutions (Nabinejad & Schüttrumpf, 2023). This plurality causes challenges for the regional aspects of the risk and poses difficulties for the technical, operational, and managerial dimensions of risk reduction. For that reason, this study draws upon collaborative discourse. Considering the water crisis in a large part of Iran, it is hoped that the findings and employed research method in this study can serve as a model for planning and sustainable management of water resources in other cities.

Theoretical Foundations

• Hazard risk mitigation

Hazard risk mitigation refers to preventive plans and preparation, physical coping or adaptive measures, and community capacity. Soft approaches or technical methods can be used to reduce the risk of disasters. Soft approaches refer to policies such as participation, education, awareness raising, social, economic, and institutional cooperation, and technical methods comprise the use of artificial infrastructure, physical facilities, and natural and semi-natural ecosystems. In the past, in the traditional management of cities, technical methods such as gray infrastructures were the most important way of defense against natural disasters. However, due to the limitations imposed by their infrastructures, they were replaced by nature-based methods. The reason is that creating interconnected green-blue networks can improve adaptability while maintaining the function of ecosystems (Saboonchi et al., 2018). Ecosystem services and natural protection minimize the risk of disasters by reducing physical exposure to hazards while reducing social vulnerability and enhancing livelihood resilience (Kato & Huang, 2021). Economically speaking, natural structures are better than structural measures they are more sustainable and cost-effective (Tiggeloven et al., 2022).

• Implementation of NbS in risk reduction

Along with the spread of ecological problems in cities, the need to provide large-scale innovative solutions and coherent planning has increased. Today, reducing risk through natural tools requires measures more than protecting biodiversity. Nature-based strategy as an approach in response to environmental challenges provides the well-being of communities and the preservation of biodiversity while managing and restoring ecosystems. An example of such a strategy can be avoiding development and settlement in disaster-prone areas or using a structured ecosystem as a natural barrier to protect people and physical assets (Dissanayaka et al., 2021).

"NbS" focuses on the dynamics, place orientation, multi-functional, and multi-scale aspects of the city that can impact the environment and society (Masnavi et al., 2021; Saboonchi & Abarghouyi Fard, 2020). Such strategies facilitate the implementation of solutions by defining comprehensive, resilient, flexible, and forward-looking policies. However, for implementation, they are associated with challenges such as time constraints, process orientation, and the acceptability of stakeholders (Saboonchi et al., 2023). A realistic assessment of the benefits of "NbS" requires measuring their effects on natural hazards and analyzing costs and benefits. It also needs attention to time changes and uncertainty about the status and development of measures (Kumar et al., 2021; Dorren & Moos, 2022). Due to the time constraints to observe the effectiveness of "NbS", a blend of short-term and long-term strategies is recommended. Also, to encourage stakeholders to accept these solutions, it is necessary to foster their participation, and enhance their awareness of the benefits (Anderson & Renaud, 2021; Giordano et al., 2020).

Materials and Methods

• Study area

The studied territory is the city of Tehran and its natural structures, which has three main parts:

- Green infrastructure including green patches (large scale and small scale), green corridors (rivers and three-lined streets);
- Water infrastructure including surface water (rivers and seasonal and permanent channels, streams and streams, water transfer channels, and surface water disposal network) and underground water network;
- Natural soil and lands including topographies (northern slopes of Alborz, hills and valleys, southern plains), complications resulting from natural and human events (faults and folds, subsidence) (Fig. 1)

• Data collection procedure

Identifying the problem and creating a collective decision-making process is the most important step for risk planning. This requires overcoming two obstacles: the ambiguity in the definition of the

Fig. 1. Tehran's natural infrastructure: green infrastructure, water infrastructure, and natural lands. Source: Author based on Bomsazgan Consulting Engineers, 2015.

problem, which hinders the development of collective actions and acts as an obstacle to the implementation of strategies (Ferretti et al., 2019), and the differences of the interest groups in terms of attitudes towards the risk, which diminishes the desire to implement collective actions (Mazzoleni et al., 2024). In this study, the group model of FCMs was employed, and collaborative expert panels were formed to address the ambiguity in the perception of the social-environmental system of Tehran. The research was carried out in two phases:

• Identifying the problem and risk assessment

The important damages at both individual and collective levels were identified through the analysis of semi-structured interviews with the collaborative expert panels consisting of 11 experts. In the next phase, the relations and weighting of the components were determined in a diffuse aggregate matrix, and then the scenarios (based on the variables with the highest degree of centrality) were drawn and strategic paths were determined.

• Proposing optimal strategy to mitigate the risk

Experts first offer strategies individually based on default scenarios. In the first collaborative panel, by discussing the strategies, the most frequent propositions were selected and classified using content analysis. The strategies were adapted to the existing scenarios and prioritized by considering the commonalities, time scale, scope, and type of intervention. After summarizing the strategies in an iterative process, a single scenario was determined as the most comprehensive scenario for Tehran's drought. In the second collaborative panel, experts prepared the most effective strategies and tools based on the state of Tehran's infrastructure and natural capacities (Fig. 2).

Findings

After analyzing individual and group interviews which were carried out in two phases, 21 indicators were extracted and their causal relationships were weighted, and then indicators were ranked. The three indicators "reduction and loss of water resources", "change of land use and destruction of natural infrastructure", and "disproportion between urban development and water capacities" had the highest numerical weight, based on which, three scenarios were determined to address the problem. (driver > vulnerability index > consequence) (Saboonchi, 2024).

Scenario 1: modifying economic structures > restoring water resources and preventing loss > restoring ecosystems/ changing the mindset of citizens

Scenario 2: changing urban management policies > changing land use and restoration of natural infrastructure > restoration of ecosystems/ change of citizens' mentality

Scenario 3: Changing urban management policies/modifying population development patterns > modification of city development pattern > revival of ecosystems/change of citizen mentality

The collaborative panel was rightly formed about the scenarios as a starting point for the convergent thinking phase. This panel had two main goals: 1) reaching a consensus for solutions to reduce the vulnerability and consequences of drought, and 2) proposing the most suitable solutions (green or gray) (Table 1).

The group panel proposed both soft and technical solutions based on nature or gray. In terms of time, the solutions included short-term protective measures and long-term measures with indirect impacts. For instance, building a wall or barrier against floods caused by drought is a temporary measure but preserving the natural beds of rivers, and improving soil and vegetation to surge soil permeability with long-term impacts. Also, the proposed solutions were multifunctional. For instance, a solution can prevent the reduction of water resources and at the same time control

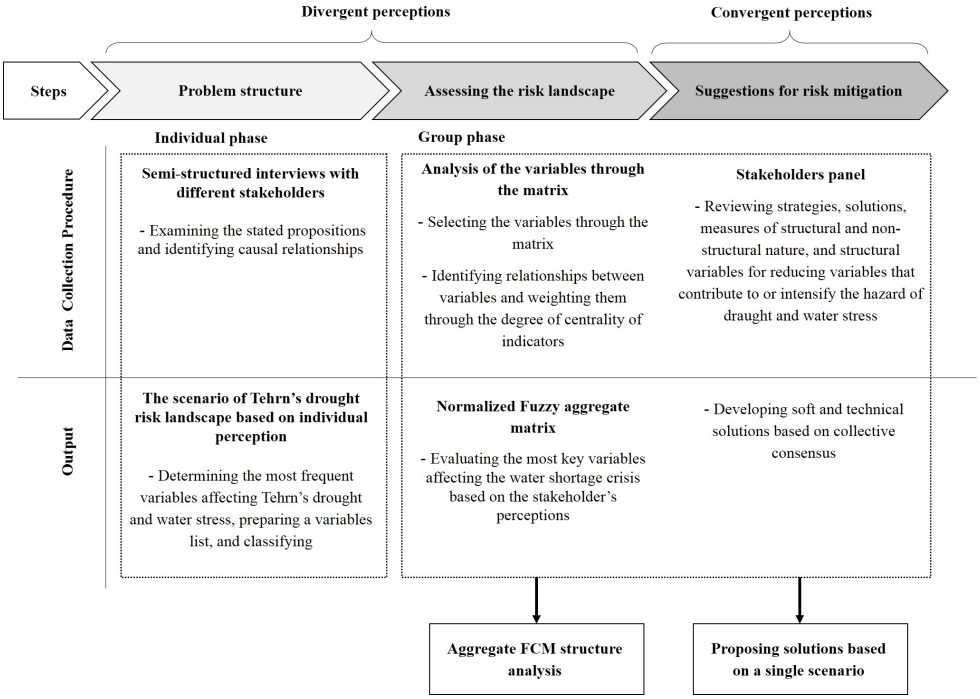

Fig. 2. Step-by-step research process in two individual and group phases. Source: Authors.

floods, runoff, and subsidence. The solutions can be categorized into four axes (Table 2).

Discussion

Changes in macro approaches and inter-institutional cooperation

Table 1. The main issues discussed in the collaborative discourse based on the analysis of fuzzy adjacency matrices. Source: Based on Saboonchi, 2024.

Reducing vulnerability drivers	Mitigating expected effects and consequences
- Preventing the loss of surface and underground water sources - Aligning Urban development with water capacities - Reducing land use change and destruction of natural infrastructure - Determining the reasonable cost of water and energy - Increasing institutions' systemic and integrated attitude -Reducing immigration and population growth	- Mitigating the impact of climate change and creating environmental balance - Mitigating the impact of natural environment restrictions - Increasing citizens' connection with nature

Table 2. The solutions proposed by experts in the form of macro strategies, the type and time frame of the solution, and its impact on the drought risk. Source: Authors.

Strategies		Solutions	Type of solution	Time Scale	Avoiding or reducing triggers of vulnerability/preventing or reducing consequences	Intervention Cluster
Change from atomistic approaches to holistic approaches	Meta-institutional	- The incorporation of resource management and the definition of operational hierarchies to organize the relations of institutions - Creating a joint decision-making horizon centered on water	Soft solution	Long-term	Increasing the systemic perspective and the integrity of institutions	Institutional
	Inter-institutional	- Creating an organizing, inter-institutional, and responsive body for the water stress crisis - A systemic approach to the drought risk network				
Changing Tehran's development pattern	Control of physical development	- Controlling the population of the city - Relinquishing the policies of centralization and consolidation of facilities - Allocation of resources and budget to social justice - Sorting out environmental problems in crisis cities to prevent migration - Adaptation of physical domains to the ecological structures of the city	- Soft solution	- Long term - Medium term	- Reducing land use change and destruction of natural infrastructure - Aligning urban development with water capacities - Reducing immigration and population growth - Determining the reasonable cost of water and energy - Mitigating the impact of climate change and creating environmental balance - Mitigating the effect of natural environment restrictions	- Institutional - Structural - Social - Economica
	User development control	- Considering programs and measures based on the location and climate of each region (monitoring of zones) - Preparation of plans considering environmental capacities, talents, and resources				
Considering agriculture as a strategic livelihood	Managers	- Training farmers on how to use technologies Encouraging farmers to preserve agricultural land and increase participation in local agriculture - Raising water costs to control consumption and encourage industries and agriculture to use low-consumption practices - Trust building to accept programs	- Soft solution - Nature-based technical solution	- Medium term - Short term	- Preventing the loss of water resources and reducing surface and underground water - Reducing land use change and destruction of natural infrastructure - Reducing the effect of climate change and creating environmental balance - Reducing the effect of natural environmental restrictions - Reduce immigration	- Structural institutional and natural
	Framers	- Changing traditional methods and using digital and smart to predict climate conditions, irrigation management, runoff management, flood warning - Strategic change of agricultural products and planting native and drought-resistant plants				

Rest of Table 2.

Strategies		Solutions	Type of solution	Time Scale	Avoiding or reducing triggers of vulnerability/preventing or reducing consequences	Intervention Cluster
Restoration and management of natural ecosystems and infrastructures of Tehran	Lands	- Defining legal frameworks for the protection of lands and natural habitats - Conserving and strengthening the soil to store water - Prioritizing land protection over city development	Soft solution Nature-based technical solution Gray technical solution	long term medium term short term	- Preventing the loss of water resources and reducing surface and underground water - Reducing land use change and destruction of natural infrastructure - Reducing the effect of climate change and creating environmental balance - Reducing the effect of natural environmental restrictions - Increasing citizens' connection with nature	
	Blue structures	- Preserving natural beds of rivers and aqueducts - Investigating the characteristics of morphology and modifying the lithology of the water bed - Creating an interconnected water network based on organic water paths - Using permeable materials instead of hard materials to store water - Separating drinking water network and wastewater recovery - Using renewable energy instead of water energy - Flood water storage through water channelling infrastructure - Restorating artificial infrastructure for water supply - Redesigning and revitalizing worn-out water and sewage infrastructure, canals and drainage				
	Green structures	- Increasing vegetation to increase soil permeability and reduce the effects of climate change - Modifying destructive natural landscapes and invasive species - Using technology in the restoration of natural landscapes - Creating a green network between areas and corridors				

are significant in the onset of the risk mitigation program. A top-down management can help to resolve the problem, but later involvement of other stakeholders will be essential for collaborative planning. Such a result highlights the importance of group discussions in positively changing views and positions. For example, in individual interviews, the role of citizens' participation, or the provision of financial resources for the implementation of programs, is considered one of the most important causes, while following-up discussions by the group highlighted that economic investments or improvement of social capital (such as citizen participation or trust building) play more supportive and complementary roles in the long term solutions and attempts to address the physical variables will have more tangible effectiveness. In the stated solutions, experts simultaneously emphasized long-term macro strategies and short-term operational solutions. This means that risk assessment is by default a dynamic issue at different time scales in their subjectivity. On the other hand, the proposed solutions are multi-functional and respond not only to the hazard of drought but also to other risks associated with the drought network (flood, landslide, and subsidence).

The analysis of the solutions shows that the lack of institutional coordination and the absence of a holistic approach to the human-environmental system of Tehran hinder the actual implementation of risk-adaptive strategies. Therefore, the proposals focused on providing soft solutions aimed at drawing the attention and prioritization of institutions towards the water issue and increasing their ability to create integrated management. Also, from the technical perspective, most of the solutions are nature-based and less emphasis is placed on gray solutions. Experts believe that gray infrastructure will only support part of the problem. However, they emphasize that the improvement of gray infrastructure (especially the revival of worn-out water and sewage infrastructure) in Tehran is inevitable. Thus, combining "NbS" instead of one-dimensional solutions will be the most appropriate way to manage water risk.

After re-adjusting the solutions in Table 2 to the scenarios, three issues need to be considered:

- The drivers (first component) in all three scenarios are a subcategory of the institutional cluster. Social and economic components serve an intermediatory role and are less effective.
- Under the physical cluster falls "change of land use and destruction of natural infrastructure" are placed under the variable " disproportion between the pattern of development and water capacities" (part of the issue of land use development). In addition, the variable "reduction and loss of water" has been discussed mainly about agriculture. Therefore, agriculture is a strategic activity in the development of land uses to mitigate drought.
- The consequences (last component) caused by physical cluster injuries are the same. Physical variables first affect the state of the natural environment and increase the effect of climate change. Weakening the connection between the built and natural environment gradually transforms the perception of the stakeholders. By changing the mental patterns, the activities carried out in the human-environmental system of the city (landscape) again form physical injuries in a cycle.

The result of this group discussion has become a single scenario "transforming an atomistic attitude into a holistic attitude in institutions > changing the pattern of city development > conserving and restoring the environmental balance > strengthening the mental patterns and perceptions of the stakeholders of the city" (Fig. 3).

The scenario, "Changing Tehran's development pattern" was identified as a key axis to mitigate drought. In the second panel, experts proposed the main tools for mitigation through adopting protection, restoration, and development policies:

Conservation of natural lands: the policies of building cities and satellite towns around Tehran, developing residential areas within the city, and creating multiple uses while destroying these lands have greatly increased the load on Tehran's natural structures. The first solution is to control the construction and establish rules for the conservation of lands and open spaces (especially the northern slopes, central hills, southern plains, vast green areas, and barren lands) to control the expansion and development pattern of the city.

Creating a green network: merging and connecting small green areas, connecting the four main green areas of Tehran (Lavizan, Abbas Abad, Pardisan, and Chitgar) through urban roads and highways, and creating and revitalizing green corridors are among the most important NbS for networking (Fig. 4). The existence of corridors and green areas and the development of the green belt (especially in the southern parts) in addition to providing ecosystem services can control the physical development of the city. Merging the green belt with agricultural lands in these areas while controlling the development of land uses is an important solution for water storage and permeability. The green belt in the northern parts also plays a significant role in controlling landslides, reducing flood flows, and creating physical privacy.

• Management of rivers

The river network has great potential to change the development pattern of the city. Reviving river valleys and expanding the green space to the watershed (regardless of the provincial geography) can create a suitable space for distancing and controlling inner city development. The lands adjacent to the river valleys can apply watershed techniques to control and distribute flood flows and infiltration of water into underground networks and recharging aquifers. Currently, many parts of the rivers of Tehran are channelled underground (Dar Abad, Darband, Velenjak River), but by focusing on the remaining parts (especially in the Kan River) and long-term planning for the release of other parts, we can help to restore these natural components. Also, the management of

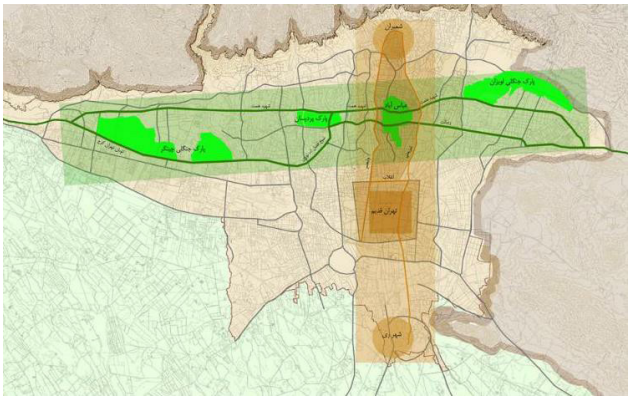

Fig. 4. Connecting the four main areas of the city for the integration of the green network. Source: Pars Naqsh Jahan Consulting Engineers, 2014.

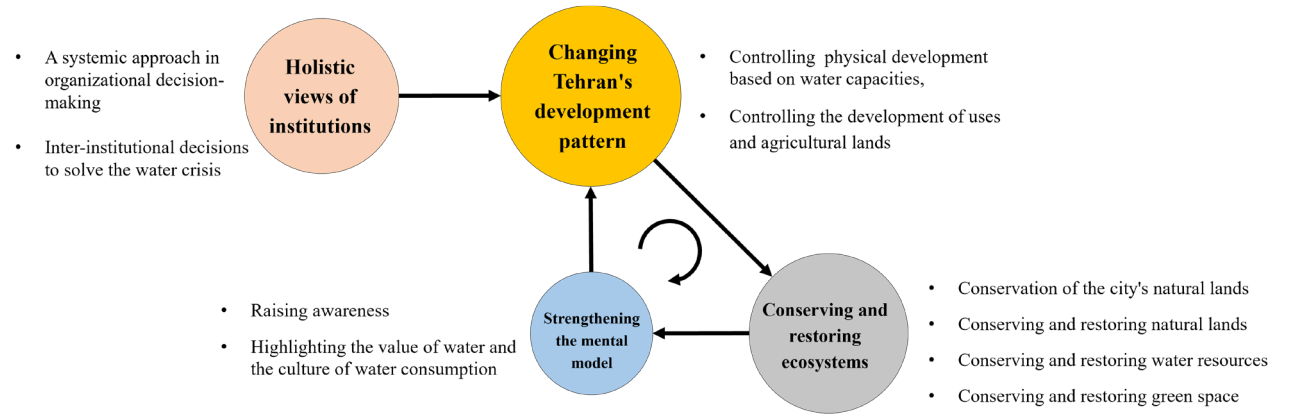

Fig. 3. The single scenario in the group discussion based on the adaptation of the solutions to the initial scenarios. Source: Authors.

river catchment areas and water distribution in the southern plains will prevent the intensification of extensive subsidence (Fig. 5).

After examining the features and strengths of the above three tools, it is clear that the rivers of Tehran, with the ability to combine functions at the same time, are the most optimal natural solution to reduce drought and water stress in different time frames. Urban greening (in the form of expanding small green spaces such as rain gardens), aquifer feeding, using low-water cultivation of rainfed crops, and controlling the water returning from agricultural lands are other complementary measures to increase resilience.

However, the atomistic approaches of institutions, poor awareness of the consequences of drought, and low level of institutional cooperation serve as deterrents to implementing solutions and generating the expected common benefits from NbS. Experts believe that providing integrated "institutional-physical" solutions will be the starting point of problem-solving for macro-planning under the support of NbS. Socio-economic solutions also have a complementary role (not the main solution) in the better implementation of programs. For example, collaborative decision-making, and creating a mechanism for cooperation between different stakeholders will be an important step in the executive actions. Participation can increase awareness of stakeholders' perception of the drought and water crisis, and the practicality of solutions in risk management and decision-making.

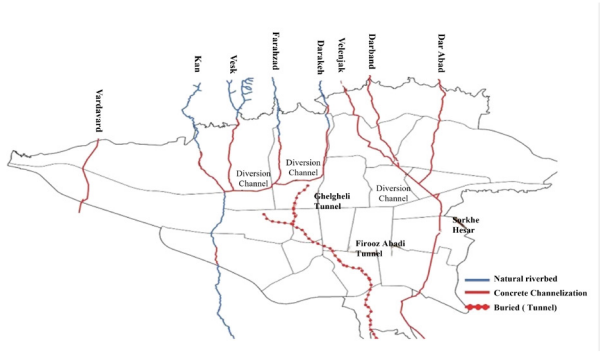

Fig. 5. The river network in Tehran and the sections that can be restored to control water resources. Source: Asgarinia, 2019.

Conclusion

The analysis of FCMs shows that the key factor in increasing the risk of drought is associated with the physical-functional development model of Tehran while the lack of systemic approaches to the water issue acts as a strong external driver. Aligned with this result, a set of strategies and practical measures were proposed to increase resilience and prevent the consequences of drought. The strategies suggested consider the capacities and preservation of water resources, restoration, and development of natural components as tools to solve the problem at both macro and micro levels. Soft solutions prioritize the water scarcity crisis and technical solutions are based on four axes: 1. Employing holistic approaches, 2. changing the physical and functional pattern of the city, 3. viewing agriculture as a strategic livelihood, and 4. revitalizing and managing ecosystems and natural infrastructure. In addition, dynamism (time scale), multi-scale, and multi-functionality are among the most important features of the presented solutions.

In aligning between scenarios and proposed solutions, "Changing the pattern of city development" has been identified as the key strategy. Conservation of natural lands, creation of the green network, and management of the rivers of Tehran are nature-based techniques. Among these strategies, planning for water structures and river valleys is known as a potential tool for combining solutions simultaneously in water stress control. Also, the use of artificial infrastructures (such as water and sewage infrastructures to prevent loss and recovery of water) is unavoidable; Thus, adopting integrated solutions (centered on NbS) to synergize the positive effect of the solutions will be the most suitable method for water risk planning in Tehran. Also, the integration of institutional-physical solutions along with the development of social and economic measures can help to better implement programs and remove implementation obstacles.

Endnotes

*This article was extracted from the 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 the supervision of Dr. "Mohammad Reza Masnavi" and Dr. "Heshmatollah Motedayen" which was done at the University of Tehran, Faculty of Architecture, Tehran, Iran in 2023.

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