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Urban Resilience and Climate Change: Developing a Multidimensional Index to Adapt against Climate Change in the Iranian Capital City of Tehran

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Abstract: Urban resilience studies have increased during recent years due to the significance of climate change as an alarming issue in centralized and highly populated cities where urban functionalities are disintegrated. Towards this aim, an Exploratory Factor Analysis (EFA) was enrolled to streamline the urban resilience to climate change over the 22 districts in Tehran after assessing the resilience objectivity. Based on the results, the city coverage was classified into best (41%), moderate (15%), low (14%), and least resilient (30%). In addition, the urban municipal districts were classified into five functional zones including Wellbeing-wealth (WWZ), Ecological Conservation (ECZ), Core (CZ), Downtown (DZ), and Neutral Zone (NZ) after evaluating the concept of urban functionality in the resilience framework. The results indicated that the socio-cultural component is considered as the fundamental necessity, along with eco-environmental and economic components in capacity building to urban climate resilience. In fact, more than half of the Tehran coverage is regarded as resilient. Thus, the rest should be prioritized, despite the need to inspire from top-ranked districts, especially D4. However, downtown and neutral zones, especially D9 and D21, which account for up to 12% of the least resilient areas, should be evaluated seriously. Finally, the robustness of the proposed methodology was compared to the studies addressing the same concept, and we offer some preparatory and adaptive measures for urban planners and policymakers.

Keywords: urban resilience; climate change; multidimensional indexing; multivariate analysis; exploratory factor analysis

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1. Introduction

In general, cities can hardly be pushed to be denser, because half of the world's population lives in urban areas. Therefore, the space left is gradually nibbled regardless of environmental concerns, leading to grounds with more impervious surfaces and less manageable situations. In addition, the interdependence of functioning units in cities plays a significant role in their resilience against changing environments [1]. A broad consensus is observed for making the cities more resilient and bundling sustainable development efforts with urban resilience, although no agreement has ever covered the entire concept related to resilience among scientists. Different resilient patterns are reported within or across cities, resulting in increasing the costs of implementing resilient strategies due to the inequalities which lead to unevenly distributed urban services [2].

Urban resilience has attracted a lot of attention within the studies focused on cities, climate change, and sustainable development. Cities should be able to bounce back from disturbances due to the risks related to natural or anthropogenic incidences. Policy and decision makers always consider climate-driven events such as flooding and droughts seriously due to the level of damage and casualties, as well as their shocks and stresses [3]. Climate and meteorological events occur less often compared to the past, and the return period is regarded just as a figure, not necessarily indicating their occurrence. Thus, the individual strategies should be transformed into curriculum-oriented ones derived from a robust climate framework in order to move towards sustainability [4].

Based on the Asian Cities Climate Change Resilience Network (ACCCRN) definition, climate resiliency in urban areas should be operationalized by a sweeping framework considering theoretical and empirical knowledge. Such a framework integrates urban systems, people, and institutions in a governable method, without which individual efforts cannot contribute to adaptation significantly. Therefore, people become capable through an improved urban system and better accept the policies and measures made by institutions, resulting in building a resilient city under the exposure of climate change. Although the aforementioned framework is inspired in all manners, resilience against natural hazards generated by climate change cannot be created easily as a better representative for disasters [5]. The adaptation and mitigation strategies designed in compliance with the aforementioned framework guarantee the best outcomes while considering the possible drawbacks on other sectors, especially in arid and semi-arid areas. Thus, the urban systems with more protection and preparedness (resistance), less eco-hydrologic disintegration (absorption), and sustaining economy (recovery) are regarded as intrinsically more resilient against climate extremes [2,6].

Tehran, which is located on the south side of the Alborz Mountains, has exhibited a decrease in annual average rainfall and an increase in temperatures on average during the past decades [7]. The Iranian capital of Tehran was selected as a case study to examine the resilience capacity in its 22 municipalities to climate change, especially drought, flooding, and scorching temperatures, considering the continuous environmental pressures, demographic growth, and urban complexity. The Climate Resilience Index (CRI), as a multidimensional concept, remains a great challenge amid the studies conducted. Accordingly, contributing to creating management instruments to be useful in decision-making processes resulted in developing a composite CRI bearing several dimensions of the urban systems, including Socio-cultural Resilience (SCR), Economic Resilience (ER), Inst-infrastructural Resilience (IIR), and Eco-environmental Resilience (EER) dimensions/components.

Based on the Organization for Economic Co-operation and Development (OECD) [8], the types of obstacles, nature of data, and objectives are among the parameters to be included while constructing a multidimensional index. A large number of researchers proposed an index for multi-hazards [9–12], along with the current resilience metrics designed to deal with a particular hazard [6,13–15]. Filling the knowledge gap and better understanding urban resilience have been addressed in the literature through engaging different spatial scales and varied approaches. Batica [16] investigated urban resilience at different scales including block cells, districts, and a whole city using the FAST approach over the case studies of Homburg, Beijing, and Barcelona. Ordination and Spatial Multi-Criteria Decision-Making (SMCDM) methods were recognized to be popular in the literatures reviewed. For example, Kotzee and Reyers [17] analyzed PCA to weight underpinning factors in order to reach a flexible multidimensional index. The spatial distribution of flood resilience over the landscape was mapped corresponding to the most contributing factors including social, ecologic, and economic components.

In addition, Ghaedamini Harouni et al. [18] proposed a multidimensional health index for Tehran utilizing factor analysis followed by a sensitivity assessment. Based on the results, the most significant health factors in Tehran included mental, social, and physical health status, respectively. Furthermore, Movahhed et al. [19] studied poverty based on the concept of political economy in the capital city of Tehran. Combining MCDM (VIKOR) and orientation methods indicated that housing, economic, social, and educational poverty are among the most influential components affecting citizens in the city. Furthermore, Zheng et al. [20] reviewed urban resilience to climate change in Beijing, applying an EFA as an objective scoring method, and iterpreted the derived loading of urban areas (municipal districts) on each factor according to their origins. The researchers adopted varied MCDM approaches to deal with urban resilience, while the AHP was considered the common method to adjust the indicator weights. Disaster vulnerability [21], earthquake preparedness [22], and urban physical resilience [23] were analyzed using the AHP, FAHP, and ANP approaches. In another study, Zhang et al. [24] analyzed the conceptual frameworks as a perfect example related to engaging time-series in urban resilience and assessed the Chinese cities of Beijing, Chongqing, and Yiwu over a period of six years. Chen and Leandro [15] evaluated time-series indicators for event and recovery phases, respectively. It is worth noting that the share of driving factors was regarded as disparate among the aforementioned areas.

In addition, Satour et al. [6] examined flood resilience in three coastal areas placed in the Moroccan semi-arid region considering social, physical, economic, and natural dimensions. The geographical information system (GIS) was utilized uniquely since mapping was performed in finer-resolution cells than that of the urban districts. Furthermore, Brunetta and Salata [25] investigated the fine-scale resilience mapping of Turin, Italy by engaging a holistic approach to detect vulnerable areas and generated state and pressure variables including shocks and disturbances according to ecosystem service features. Furthermore, Zheng et al. [20] studied urban resilience in the Chinese city of Panzhihua as a representative of resource base cities. A nearly two-decade assessments revealed that the city's resilience including health and well-being, infrastructure and environment, economy and society, as well as government capacity increase and a move toward stability, despite some momentary fluctuations. In another study, Chen and Quan [26] reviewed urban resilience to the Covid-19 pandemic applying TOPSIS and AHP and reported that the spatial distribution of the resilience across the city faces challenges including agglomerating clusters of high-resilience areas versus dispersed moderate- to low-resilience ones, despite an ever-growing increase in resilience toward the pandemic. The aforementioned researchers analyzed the significance of governance during pandemics. Moghadas et al. [27] prioritized municipal areas in Tehran from the perspective of flash flood resilience using TOPSIS. The hybrid AHP-TOPSIS model ranked the resilience components based on their contribution in a descending order including critical infrastructures, environment, economy, social, institutional, and community resilience.

The dimensions of urban resilience to change climate have not been well understood, mostly due to uncertainty in data-scarce areas, although a large number of studies have been conducted in this field [28]. As indicated, the urban resilience across the Tehran municipalities was assessed utilizing the EFA compared to the hybrid MCDM method integrating ANP and DEMATEL, as well as enrolling in the recent submission [29]. This study therefore aims to develop a multidimensional index to examine the resilience of cities to climate change. Preparing a list of different indicators related to the subject and combining them in a logical way is considered in this way. The Tehran metropolis has been chosen to test this new index.

2. Materials and Methods

In the present study, the resilience to climate change in Tehran was evaluated basically considering the capabilities and limitations in its 22 municipal districts. The proposed composite index aims to bear multidimensionality under the four resilience macro criteria including Socio-cultural, Economic, Inst-infrastructural, and Eco-environmental dimensions, as well. Accordingly, a couple of recommended resilience metrics implemented by researchers were selected, and the final list was formed in compliance with data availability and robustness. Then, a correlation analysis was performed to examine whether there is any sizable and explicable dependence between manifest variables (resilience indicators) before prioritizing urban districts followed by extracting resilience factors (construct variables). Finally, the statistical contribution of sampling units (urban districts) in the final resilience score was interpreted based on their respective functional zone. The degree to which an urban district belongs to a given functional zone is regarded as an abstract measure considering human development criteria and marginal indices defined by official reports such as land use, commercial activities, taxes paid, and the like. Therefore, there are five different functional zones in Tehran including Wellbeing-welfare (WWZ), Ecological Conservation (ECZ), Core (CZ), Downtown (DTZ), and Neutral Zone (NZ), as well [30].

2.1. Conceptual Framework

The conceptual framework in the study is based on reducing the risk of climate change by making the cities more resilient [2,6]. Towards this aim, the countertendency changed to interdependency, and the realistic framework was drawn (Figure 1).

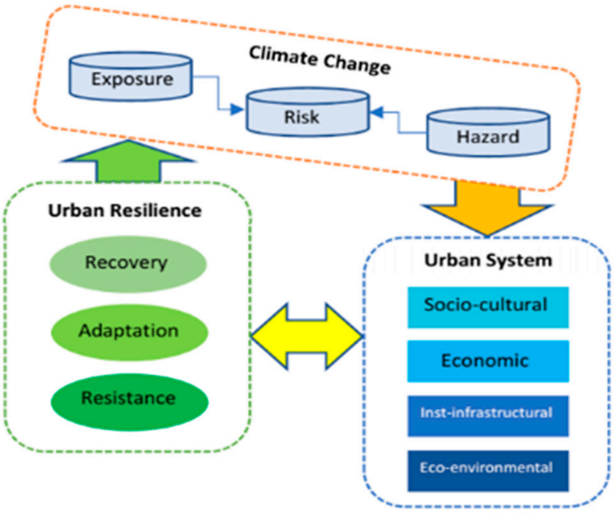

Figure 1. Conceptual framework applied in the study.

2.2. Study Area

Tehran is the capital of Iran, and Tehran province, with a population of around 8.7 million, is host to 22 districts (Figure 2) and has been a destination for mass migrations from all over the country since the 20th century. In addition, Tehran is considered the most populous city in Iran and Western Asia, with the second largest metropolitan area in the Middle East after Cairo, and is ranked 24th in the world by the population of its metropolitan area [31]. Furthermore, Tehran is regarded as a mountainside city spreading at the south domain of the Alborz Mountains with an altitude of 900–1700 meters above sea level and is exposed to earthquakes, floods, droughts, storms, and surrounding watery watersheds. The city has not experienced much flooding, despite being prone to such hazards. Floods usually occur in spring after heavy rainfalls mostly through water-logged streets, and earthquakes remain the most harmful threat. It is noteworthy that industrial-traffic-induced air pollution is considered the most recurrent hazard in the city. Meanwhile, informal settlements, the homeless, especially in winter, and drug abuse are left as common social concerns [32].

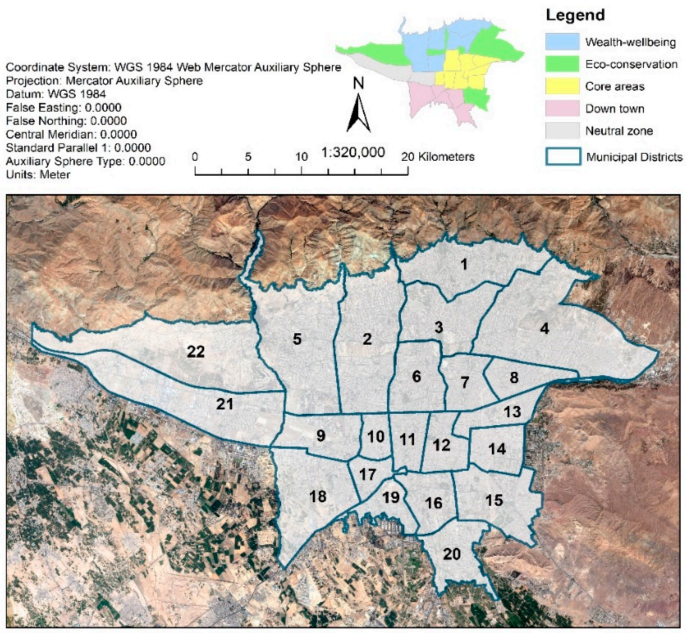

Figure 2. Municipal districts in Tehran.

2.3. Data in Use, Variable Selection

In the present study, the data were mostly collected from the Statistical Center (SCI; amar.org.ir), Municipality (MOF; tehran.ir), and Provincial Government Office of Tehran (PGOT; ostan-th.ir) through exploring annals and atlases related to the capital city of Tehran. However, a large amount of information was obtained by reviewing the literature related to Tehran from different perspectives including green space [33], life expectancy [34], extreme weather parameters [7], spatial inequality [35], earthquake preparedness [22], physical resilience [23], and poverty [19]. Table 1 indicates the complete list of indicators to form the multidimensional index. In addition, a descriptive and analytical view of the datasets used in the study is reflected in the following sections (Figure 3 and Table 1).

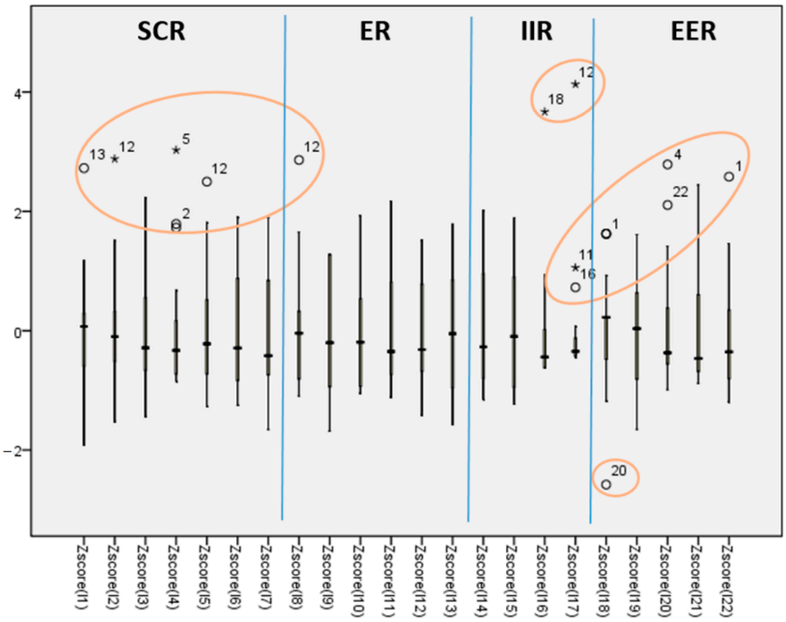

Figure 3. The standardized distribution of resilience indicators. * Plots in circle and star indicate outliers based on their divergence from mean.

Table 1. A list of dimensions, indicators, and their definition.

Resilience Dimensions	Resilience Indicators (Direct/Unit)	Definition	References
Socio-cultural (SCR)	+ Public awareness (I_1); %	Public awareness (I_1) and education are regarded as signs of openness in the society to adapt to the unexpected climate alterations.	[18,23,36–38]
	- Consumerism (I_2); %	Consumerism (I_2) is defined as a function of solid wastes and wastewater per capita, which loads reversely on the supply chain during long-run crises.	
	- Population density (I_3); n per hectare	Population density (I_3) is negatively connected with sustainability.	
	+ Migration (I_4); n	Migration (I_4) usually occurs among vulnerable and low-resilience populations. However, most migrants in Tehran are considered wealthy families willing to reside in the northern states of the city.	
	- Death rate (I_5); per 100,000	Rising death rate (I_5) increases the intricacy of the life system in the city.	
	+ Life expectancy (I_6); year	Life expectancy (I_6) is explicitly related to the willingness to recover from crises. A hopeful community bears the aftermath of disasters better.	
	+ Health overall index (I_7); multidimensional	A health overall index (I_7) reflects the total functionality of a city health system.	
Economic (ER)	- Commercial land use (I_8); percent	Commercial land use (I_8): The possibility of proximity between dangerous and safe uses is regarded as an appropriate indicator for urban resilience. Thus, commercial zones are considered as vulnerable due to the density and usual unsafe environments.	[6,19,20,24,36,38]
	- Poverty line (I_9); multidimensional	The poverty line (I_9) indicates the ability of a given community to incur and bounce back during backlashes.	
	- Urban worn-out areas (I_{10}); n	Urban worn-out texture (I_{10}) is regarded as another indicator contributing to resilience in line with other economic ones. Such areas pose the most potential threats from the perspective of energy consumption and residents' safety.	
	+ Accident insurance (I_{11}); n	The proportion of people covered by insurance (I_{11}) allows for recovering as fast as possible.	
	+ Employment (I_{12}); % + Welfare (I_{13}); multidimensional	Employment (I_{12}) and welfare (I_{13}) positively contribute to the readiness of the society for climate resilience.	
Inst-infrastructural (IIR)	+ Crisis management centers (I_{14})	Crisis management centers (I_{14}) are considered as a necessity during disasters when deploying back; force and administering help are regarded as a matter of time.	[20,22,23,27,39]
	+ Access to health and rescue centers (I_{15}) + Access to urban services (I_{16})	Access to health and rescue centers (I_{15}), as well as urban service sectors (I_{16}), acts as a buffer against the intensity of crises.	
	- Infrastructure vulnerability (I_{17})	The vulnerability of critical infrastructure (I_{17}) plays a significant role in the battle against catastrophes, especially climate-oriented issues, and is inversely related to urban resilience.	
Eco-environmental (EER)	+ Water quality index (I_{18}) - Air quality index (I_{19})	Water (I_{18}) and air quality (I_{19}) acts as a buffer, allowing the local areas to have more resistance against harsh conditions negatively and positively, respectively. Better environmental quality increases the capacity to absorb impositions.	[6,20,27,40]
	+ Green space ratio (I_{20})	Green space ratio (I_{20}) helps understand the resistance and relief during a crisis. Arboreal and vegetative covers can help, while agrarians weaken extreme climate events.	
	+ Slope (I_{21}) + Elevation (I_{22})	Slope (I_{21}) and elevation (I_{22}) were selected as indicators related to stability, which contribute to urban resilience positively from the perspective of eco-environmental resilience.	

2.4. Climate Resilience Index (CRI)

The multidimensional index of urban resilience to climate change was formed to provide urban managers and policymakers with some generic knowledge and solid understandings, resulting in creating practical adaptation strategies. A large number of expert meetings were held to screen the most appropriate and applicable criteria to the city of Tehran in addition to the aforementioned studies [29]. The architecture of the resilience framework was based upon the factor analysis as a more tangible mechanism, unlike previous studies which focused on expert-based weighting. In fact, the disparity or similarity amongst the indicators was determined by extracting common factors which define the loading of each manifest indicator and the contribution of sampling units in creating the construct factors, which in turn avoids conducting subjective resilience weighting all the way through generating an objective scoring process. It is worth noting that CRI for each urban district was retrieved by summing the amount of variance explained multiplied by the given factor loading. Accordingly, the high-speed factor covering the most explained variance during the rotation process plays a significant role in forming the significance and direction of the resilient indicators. The aforementioned factor can be explicated by reflecting the share of the main resilience dimensions such as SCR, ER, IIR, and EER on the extracted factors, as well.

2.5. Multivariate Analysis

Factor analysis outperforms its multivariate rivals such as PCA, CA, and the like by limiting the data boundary issues such as normal distribution supposition, giving the researchers the ability to investigate whether the data are in compliance with their null structure (confirmatory) or to discover multidimensionality inside the data, as well as providing novel extraction techniques, such as a rotated component matrix. According to Moghadas et al. (2019), the factor analysis reduces data dimensionality and standard errors reflected on component loadings simultaneously. The statistical structure describing the factor analysis conducted during the study is as follows [20].

$$X_i = \propto_{i1} f_1 + \propto_{i2} f_2 + \ldots + \propto_{ik} f_k + e_i \ (k < n \ i = 1, 2, 3, \ldots, n) \quad (1)$$

where, X_i is n original indicators, f_i (j = 1, 2, 3, . . . , k) represents the k latent factors, and e_i is regarded as the difference of the ith indicator factor. In addition, $\propto\_ij$ indicates the loading coefficient of the ith indicator on the jth latent factor (f_i), reflecting the correlation degree between the original indicator and respective common factor. The lower $\propto\_ij$ decreases the weight of X_i in the common factor (f_i). The routine analytical process is described as follows.

2.6. Data Pre-Processing

The statistics, including descriptive, correlation, and confirmatory factor analysis, as well as respective fitness tests, were applied using SPSS version 16 (released 2007). The resilience indicators, which are usually normalized based on Equations (2) and (3) for positive and negative contributions, respectively, were not modified while obtaining the CRI regarding leaving the factor and sample loads intact.

$$X_{ij} = \frac{X_{ij} - minX_j}{maxX_j - minX_j} \quad (2)$$

$$X_{ij} = \frac{maxX_j - X_{ij}}{maxX_j - minX_j} \quad (3)$$

where i represents the ith sample (i = 1, 2, 3, . . . , n), j is considered as the jth indicator (j = 1, 2, 3, . . . , m), Max indicates the maximum value of a certain indicator, and Min is regarded as the minimum value of the same indicator.

2.7. Conducting the Factor Analysis

The factor analysis populates the construct factors based on the contribution of manifest indicators. In this regard, the variables exceeding the loading brink of 0.50 can be attributed to the construct factors. Accordingly, a Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity were implemented to find whether the data in use are considered as adequate and co-dependent. A Principal Component Analysis (PCA) powered by the rotation method of Varimax and Kaiser Normalization was performed after the factor analysis to extract the main factors. In addition, the objective technique of weighting was based on the rotation sums of the squared loading.

2.8. Visualization

All of the spatial operations including visualizing resilient indicators and CRI classes, as well as ranking, were conducted enrolling ArcGIS (Ver. 10.6).

3. Results

A multidimensional metric populated by the manifest indicators was designed following the conceptual framework proposed in the study to review urban resilience to climate change in the capital city of Tehran.

3.1. Baseline Situations

The descriptive statistics (Table 2 and Figure 3) and correlation analysis (Table A1—Appendix A) show the evidence-based optics about the status quo ongoing in the 22 urban districts in Tehran. The zero-contained outliers such as I3, I6, I7, I9, I10, I11, I12, I13, I14, I15, I19, I21 generally originate from the ER and IIR resilience dimensions, although they are not quite uncommon in urban resilience studies where some inequalities are observed [19,34,35,41].

Table 2. Descriptive statistics.

Resilient Indicators	N	Minimum	Maximum	Mean	SD	CV
I1	22	80.00	101.00	88.68	4.52	0.05
I2	22	0.00	1.00	0.35	0.23	0.66
I3	22	36.00	418.00	186.45	104.02	0.56
I4	22	3428.00	27,953.00	8788.50	6328.90	0.72
I5	22	366.00	1089.00	609.68	191.92	0.31
I6	22	74.50	79.10	76.32	1.46	0.02
I7	22	6.93	7.98	7.42	0.30	0.04
I8	22	0.53	6.94	2.31	1.62	0.70
I9	22	1.00	5.00	3.27	1.35	0.41
I10	22	3.00	619.00	220.23	206.64	0.94
I11	22	2436.00	45,067.00	16,936.00	12,954.43	0.76
I12	22	86.00	94.00	89.86	2.73	0.03
I13	22	−12.92	14.66	0.00	8.21	-
I14	22	2.00	11.00	5.27	2.85	0.54
I15	22	2.00	24.00	10.68	7.05	0.66
I16	22	0.30	5.00	0.98	1.09	1.11
I17	22	0.03	12.12	1.24	2.63	2.12
I18	22	17.30	41.90	32.40	5.85	0.18
I19	22	13.00	130.00	72.23	35.85	0.50
I20	22	0.64	16.79	4.87	4.28	0.88
I21	22	1.36	10.81	3.87	2.84	0.73
I22	22	80.00	101.00	88.68	4.52	0.05

As represented in Table A1—Appendix A, there are a large number of cases paired with a strong correlation greater than 0.7. However, the present study seeks to analyze those indicating solid grounds, in which the positive relationships between Migration and Life expectancy (I4-I6), Life expectancy and Insurance (I6-I11), Commercial land use and Urban worn-out areas (I8-I10), Commercial land use and Infrastructure vulnerability (I8-I17), Poverty line and Urban worn-out areas (I9-I10), Welfare and Elevation (I13-I22), Water quality and Slope (I18-I21), Water quality and Elevation (I18-I22), and Slope and Elevation (I21-I22) appear more tangible during interpretation. In addition, a negative meaningful link is observed between the Life expectancy and Poverty lines (I6-I9).

3.2. Factor Analysis

To conduct the intended exploratory factor analysis, the assumptions related to dependent observations and normal distribution fully complied, meaning that almost all of the data had a normal distribution save for I17 (Infrastructure vulnerability) and I21 (Slope). Then, the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity were implemented to find whether the data in use are regarded as adequate and co-dependent. Finally, the EFA analysis was performed after complying with the interdependence (rejecting the Bartlett null hypothesis) and adequacy results (0.75 < KMO = 0.89 < 1) (Table 3).

Table 3. Rotation in sums of squared loadings.

Factors	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	8.234	37.429	37.429	8.234	37.429	37.429	6.898	31.353	31.353
2	3.556	16.163	53.593	3.556	16.163	53.593	3.516	15.980	47.333
3	2.356	10.708	64.301	2.356	10.708	64.301	2.856	12.982	60.315
4	2.077	9.441	73.742	2.077	9.441	73.742	2.682	12.193	72.508
5	1.324	6.016	79.758	1.324	6.016	79.758	1.419	6.448	78.956
6	1.072	4.871	84.629	1.072	4.871	84.629	1.248	5.673	84.629

3.3. Variable Loadings (Resilience Dimensions and Indicators)

The construct factors followed by the percent of the variance explained were retrieved after forming the EFA. In this respect, the most contributing manifest indicators can be observed loading the respective factor(s) in bold (Table 4). To illustrate a more vivid picture of the conducted EFA, a 3D component plot and the causal network were drawn, as well (Figures 4 and 5). Based on the results, 16 out of 22 resilience indicators, including I22-f1, I21-f1, I13-f1, I4-f1, I6-f1, I9-f1, I18-f1, I11-f1, I17-f2, I15-f2, I14-f3, I20-f3, I3-f4, I2-f4, I16-f5, and I7-f6 were directly loaded on their most corresponding construct factor, and the rest, including Air quality index (I19), Commercial land use (I8), Death rate (I5), Employment (I12), Public awareness (I1), and Urban worn-out areas (I10) could not heavily contribute to any factors.

Table 4. Rotated component matrix.

Indicators	f_1	f_2	f_3	f_4	f_5	f_6
	SCR/ER/EER	IIR	IIR/EER	SCR	IIR	SCR
I22	**0.927**	−0.067	0.019	−0.176	−0.027	0.211
I21	**0.896**	−0.115	0.130	−0.206	−0.054	0.057
I13	**0.873**	0.196	−0.289	0.130	0.068	−0.018
I4	**0.864**	−0.113	0.210	0.181	0.102	−0.220
I6	**0.818**	−0.136	0.443	−0.167	0.026	0.069
I9	**−0.780**	0.115	0.005	0.452	0.280	0.066
I18	**0.741**	−0.120	0.086	−0.087	−0.213	0.339
I11	**0.719**	−0.206	0.376	−0.167	0.075	0.185
I17	−0.233	**0.854**	−0.059	−0.057	−0.146	−0.099
I15	0.411	**0.840**	0.089	−0.024	0.125	−0.019
I14	0.133	−0.092	**0.817**	−0.013	0.231	−0.261

Table 4. *Cont.*

Indicators	f_1	f_2	f_3	f_4	f_5	f_6
	SCR/ER/EER	IIR	IIR/EER	SCR	IIR	SCR
I20	0.153	0.171	**0.787**	−0.145	−0.068	0.273
I3	−0.126	0.063	−0.185	**0.940**	−0.049	0.037
I2	−0.047	0.554	−0.093	**−0.749**	−0.099	−0.010
I16	−0.096	−0.106	0.015	−0.037	**0.889**	0.000
I7	0.155	−0.077	−0.018	0.065	0.012	**0.905**
I19	−0.209	0.614	−0.610	0.237	0.083	0.049
I8	−0.328	0.645	−0.243	0.467	−0.287	0.045
I5	−0.359	0.537	−0.467	−0.225	−0.310	−0.063
I12	−0.539	0.508	0.226	0.259	0.392	−0.088
I1	0.499	0.227	−0.566	−0.012	0.181	0.063
I10	−0.496	0.408	−0.069	0.651	−0.027	−0.002

Data in bold face indicate that their corresponding indicators have a common factor greater than 0.7.

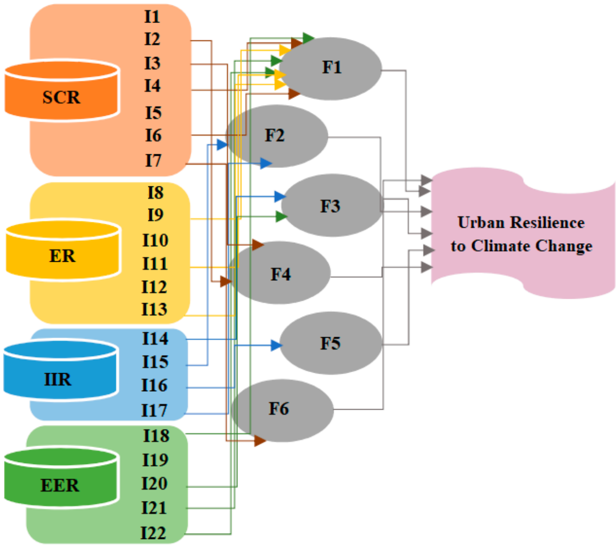

Figure 4. The causal network of Tehran resilience to climate change derived from construct factors.

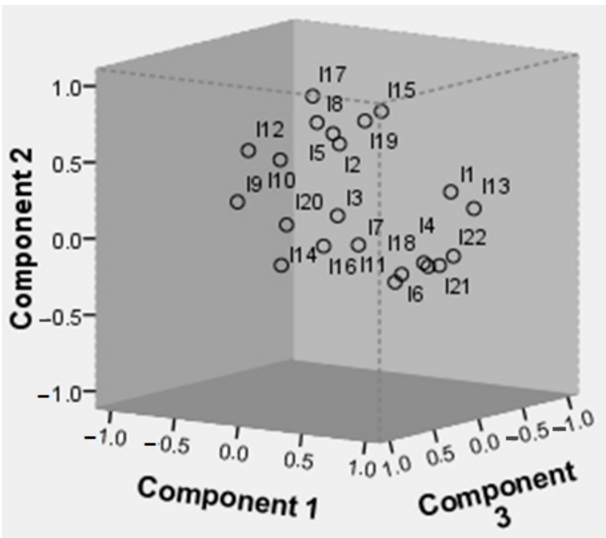

Figure 5. Component plot in a rotated space: 3D (f1, f2, and f3). Extraction method: PCA; rotation method: Varimax with Kaiser Normalization.

3.4. Sample Loadings (Districts)

To obtain the CRI, urban district loadings including shares of sampling units were calculated and summarized (Table A2—Appendix A and Figure 6). Cross-investigating the contribution of urban districts based on their respective resilience class and functional zone is considered as a step toward providing an analytical view regarding the amount of resilience in Tehran. The resilience classes including best, moderate, low, and least were mainly populated based on the CRI range observed. In addition, the functional zones including WWZ, ECZ, CZ, DTZ, and NZ represented commerce, wealth, residential, and infrastructures across the city.

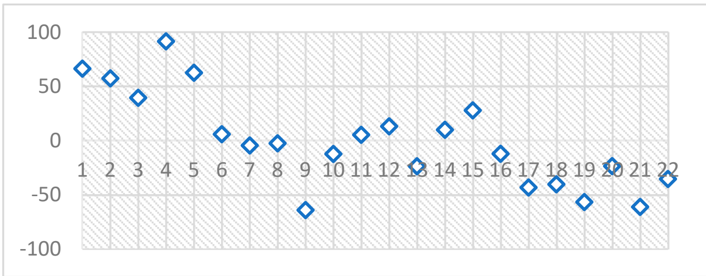

Figure 6. Tehran municipal districts' resilience score.

As shown in Table A2—Appendix A and Figure 6, the CRI scores are in a range between −63 and +92. Based on the ranking, the descending sort of the districts in urban municipal areas is illustrated as D4 > D1 > D5 > D2 > D3 > D15 > D12 > D14 > D6 > D11 > D8 > D7 > D16 > D10 > D20 > D13 > D22 > D18 > D17 > D19 > D21 > D9. In addition, districts D4, D1, D5, D2, and D3 are regarded as the best (41% coverage), districts D15, D12, D14, D6, and D11 are considered as the moderate (15% coverage), districts D8, D7, D16, D10, D20, and D13 are regarded as the low (14% coverage), and districts D22, D18, D17, D19, D21, and D9 are considered as the least resilient (30% coverage). Furthermore, urban districts have even been classified into WWZ (15991 ha), ECZ (17487 ha), CZ (11198 ha), DTZ (9435 ha), and NZ (7151 ha) based on their urban functionality. Accordingly, EC and NZ are regarded as the biggest and smallest functional zones covering nearly 29 and 12% of the total urban areas in Tehran, respectively.

3.5. Mapping CRI

All of the municipal districts in Tehran were ranked from top to bottom and classified into the intended resilience classes from most to least resilient (Figure 7) after visualizing resilience indicators based on their entity (Figure 8).

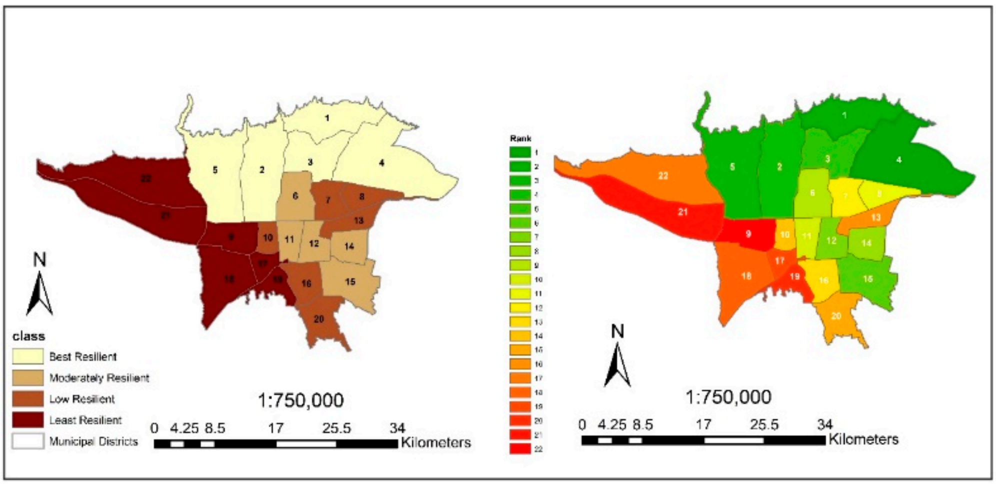

Figure 7. Tehran resilience to climate change: CRI classes (**left**) and municipal districts ranking (**right**).

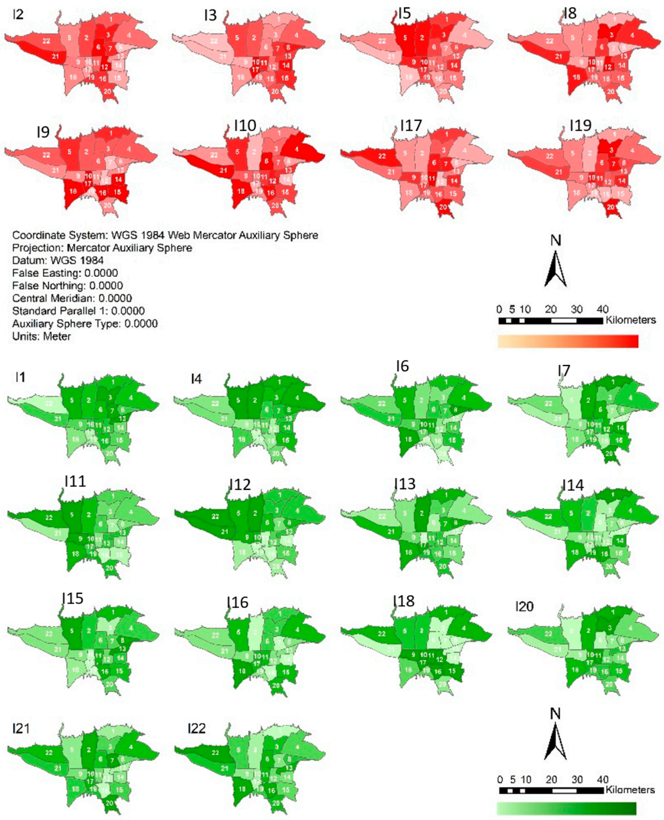

Figure 8. The visualized resilience indicators, in which red and green ramps account for negative and positive contributions to the resilience process, respectively.

4. Discussion

Urban resilience is considered as a complex and challenging issue, though measurable, which can be addressed subjectively, unlike most studies conducted in this field. The studies which internalize the resilience theory by their own language are increasingly assorted. In this regard, the paradigm of scale, dimensionality, and timeline is regarded as a controversial matter among the scientific community. The present study aims to analyze the current knowledge and understandings by assessing Tehran's resilience over its 22 municipal districts. Conducting a single-hazard study plays a significant role in focusing on urban resilience to climate change and measuring the levels of preparedness as long as the hazards turn up. Accordingly, an EFA was enrolled based on PCA and Varimax as factor extraction and rotation methods.

The CRI proved to be a robust and informative framework due to its flexibility, integration, and applicability, although the multidimensional index (CRI) presented is not considered as the perfect instrument in characterizing climate resilience in urban areas. Based on the aforementioned studies, a list of resilience indicators was shortlisted based on data availability and veracity. Towards this aim, the urban system was defined having four resilience components including SCR, ER, IIR, and EER, and the 22 manifest indicators were assigned. Then, pre-processing was conducted to examine whether the inter-dependence and the adequacy tests complied well (KMO = 0.89, Bartlett sig 0.00).

The datasets utilized to characterize the resilience of Tehran, as the capital and the most populous city in Iran, demonstrated a normal pattern related to distributing all of the resilience indicators except for critical infrastructure vulnerability (I17) and slope (I21). Few outliers were observed on SCR and EER components after evaluating the data descriptively. In fact, the ER was regarded as a nearly zero-content outlier component. Based on the coefficient of variation (CV), life expectancy (I6) was considered as the most centralized variable, while access to urban services (I16) and infrastructure vulnerability (I17) were regarded as the most decentralized ones.

Some remarkable relationships were detected after investigating the resilience indicators in paired format. For example, the positive link between migration and life expectancy is considered as a direct matter related to wealth and welfare, as the privileged tend to reside from other areas than the WWZ zone such as D1, D2, D3, and D5. Similarly, the welfare–elevation relationship illustrates that the privileged are genuinely interested in uptown with higher elevations. High classes of slope improve the quality of the residents' water. Ecologically, dwellers might actually benefit from extremely better water and air quality in higher elevations in uptown. The mixture of slope/elevation addresses the issue likewise.

The direct positive correlation between accident insurance and life expectancy indicates the resilience perfectly once hazards are guaranteed, at least financially to those with better living standards. In addition, the positive correlation between urban worn-out areas and commercial land use represents low resilience, because the commercial zone is placed in hazard-prone areas. Population density is regarded as another significant issue making the situation worse during the crisis. The positive correlation between vulnerable infrastructure and commercial land use proves the necessity to implement adaptive measurements and retrofit such areas. Urban planners and policymakers should focus on the concurrence of the poverty line and urban worn-out areas, since expecting some climate-oriented hazards and being in a basket case lead to bad consequences. Further, the negative relationship between life expectancy and the poverty line can be apprehended intuitively. Therefore, the lack of social and economic advantages reduces the preparedness to hazards.

Reviewing the resilience indicators independently reveals interesting results, since such indicators which positively/negatively impact the construct factors hardly contradict the studies conducted so far. For instance, references [6,19,21,27] found that migration (I4) contributed to urban resilience negatively, although the multivariate analysis displayed a positive contribution of migrants based on available data. The migration of the rich was reported to be the case regarding the dataset applied, although there are possible sources of uncertainty which lead to systematic errors. The employment rate (I12) was regarded as another contradictory issue detected during investigations, which populated the construct factors negatively according to the statistical analysis, despite being classified under the positive contributors. To justify the phenomenon, low- to moderate-income households are supposed to embark on jobs even under the super-competitive economic and job market situation ongoing in the city. Accordingly, the reverse contribution of the indicator can only be justified by the rich relying on their deposits and less applying to the jobs based on official surveys conducted by the CSI. Other studies indicated an adverse contribution compared to the present one [19,21,24,27,36]. Access to urban services (I16) was considered as another indicator which was classified as a positive contributor, despite loading the construct factors negatively. The indicator was no longer regarded, since its statistical significance could be neglected completely. The slope appears to be a negative resilience contributor [22], while data indicate a direct correlation between the aforementioned indicator and other strong contributors. Finally, the EFA classified the 22 indicators into the two groups including I2, I3, I5, I8, I9, I10, I12, I16, I17, I19 and I1, I4, I6, I7, I11, I13, I14, I15, I18, I20, I21, I22 with negative and positive directions, respectively, based on the direction of communication in urban resilience.

Based on the rotation in squared sums of loadings, the extracted factors accounted for up to 85% of the total variance. It is noteworthy that f1 and f2, as the first two factors, accounted for nearly 50% of variance combined. As Table 4 shows, the factors extracted appear in a decent order. However, the notable distinction between the Extraction and Rotation sums of squared loadings is observed in the values of the first factor (f1) where the Rotation falls behind the Extraction method by an approximately 6% margin. Furthermore, the EFA was analyzed by dividing the results into the following phases of variable and sample loadings.

4.1. Variable Loadings

Based on the Rotated Component Matrix, the strong communication of 16 out of 22 resilience indicators demonstrated that SCR played an active role in forming f1, f4, and f6. Inst-infrastructural resilience (f2, f5) and Eco-Environmental resilience components (f1, f3) were considered as the second active resilient components, while the Economic resilience (ER) only appeared in factor f1. In other words, f1 is influenced by SCR, ER, and EER, while f2 and f5 are affected by IIR. In addition, f3 is influenced by IIR and ER, while f4 and f6 are affected by the SCR.

The main outcomes of the resilience-concerned studies mostly designed to bear natural hazards such as earthquakes, flooding, and climate change are discussed as follows. Kotzee and Reyers [17] prioritized flood-resilience-contributing dimensions as social > ecologic > economic components, which is surprisingly consistent with climate resilience findings (f1: SCR > EER > ER) (Table 4). The observed compliance stems from the similar nature of the hazards, including climate change and floods.

However, Zhang et al. [24] reached the priority of Inst-infrastructural > eco-environmental > economy > social components in preparing for climate resilience, while Moghadas et al. [27] prioritized flash flood resilience components, the result of which is in line with that of the previous studies (critical infrastructures > environment > economy > social > institutional and community resilience). Zheng et al. [20] found that economic resilience is considered as far more significant compared to other resilience dimensions including infrastructural, institutional, managerial, and environmental. In addition, Movahhed et al. [19] reported that housing, economy, as well as social and cultural sectors were the most contributing dimensions in the resilience to poverty, respectively. Furthermore, references [6,26] used equal weights in combining resilience indicators, while others utilized at least one objective or subjective weighting method based on statistical analysis and panel decisions, respectively, to prioritize the resilience components.

4.2. Sample Loadings

The CRI ranking followed by resilience classes in Tehran (Figure 8) demonstrated that the most resilient districts are located in northern Tehran, mainly surrounded by WWZ and EC (D4, D1, D5, D2, and D3). D4 was recognized as the top-ranked district mostly due to its ecological status and resulting functionality across the city. District 22 failed to pass the first-level standards required, despite being situated in the ECZ. Being situated within the CZ and ECZ helped moderate-resilience-level districts (D15, D12, D14, D6, and D11) to partly resist, absorb, and adapt to the climate-oriented crises.

However, the low-resilience urban districts including D8, D7, D16, D20, and D13 are densely populated, while they benefit from accessing services due to their mixed situation in CZ and DTZ. The least resilient class, including D22, D18, D17, D19, D21, and D9, is regarded as a combination of NZ and DTZ, in which the districts are not regarded to be rich enough to bounce back fast and not privileged with infrastructures and services available throughout the city. It is worth noting that the corresponding districts have been less included in land use planning as far as districts D9 and D21 are isolated in part. Analyzing the situation showed that district 22 suffers from a lack of services and infrastructures, despite benefiting from less population density, well-structured highways, and enough green space.

Based on Table A2—Appendix A, more than half of the city coverage is placed in the best/moderate resilience classes, and urban planners and policymakers should focus on the rest of the city. The low-resilience areas surrounded by DTZ and NZ should benefit from adaptive measures first. Comparing the previous study with the present one indicates some compliance regarding the unquestioned role of environment and social dimensions. However, some inconsistencies are observed in the objectivity of the approach (ANP vs. EFA) and the data used. Based on the results, both studies show consistency on the most and least resilient areas, and inconsistency is observed in the middle classes. In addition, district 22 was considered as the most challenging area in assigning a resilience class.

5. Conclusions

Urban resilience to climate change increased decisively due to climate-oriented hazards in a large number of centralized and highly populated cities where urban functional units are not well-distributed across the cities' domain. The present study seeks to enhance the understanding of climate resilience in the metropolitan area of Tehran in the absence of enrolling a sweeping framework. Thus, a tangible approach equipped with GIS was adopted to outline and illustrate the resilience hotspots over the 22 municipal districts in Tehran. Interpreting the EFA results coupled with CRI classification and functional zoning gave more insight than applying a simple subjective MCDM method. The repetitiousness of the proposed multidimensional metric was regarded as the other concern following its applicability in varied scales. Further studies can be conducted by engaging other resilience components such as physical and ecosystem-based service dimensions due to the high flexibility observed in the framework of the study. However, a finer scale and time-series should be utilized where applicable.

Based on the results, socio-cultural dimension including eco-environmental and economic components with other degrees of significance should be considered during capacity building for urban climate resilience. More than half of the Tehran coverage is observed in resilient areas, among which D4 should be further studied, because the literature is unanimously consistent as to the foremost ranking among other urban districts in Tehran. However, nearly 14 and 30% of the total areas in Tehran were classified as low- and least-resilience classes, respectively, indicating below-zero resilience scores. Based on the assessments conducted on corresponding functional zones, districts 9 and 21 should be involved in immediate and futuristic development planning. In other words, the existing neutral functional zone covering almost 12% of the total urban areas should not be disregarded as usual.

The adaptive measures proposed for empowering the capabilities and enhancing resilience status include increasing public awareness towards building capacity among moderate-income families to the same extent as the resilient rich, planning to repair and retrofit critical urban infrastructures while granting incentives and tax exemptions to those in critical risk of climate hazards, especially low-income households, updating hazard headquarters' workforce and fleet, as well as land use and population engineering. Finally, the conformity and robustness of the proposed framework were compared with other studies, despite the affirmative compliance in most and least resilient areas. The middle-resilience-ranged districts can only be focused on by finer-scale information. This study may have some potential limitations. The main limitation associated with these models is their reliance on a combination of criteria. Different criteria can lead to different results. Moreover, dealing with data uncertainties in such models is difficult due to large amounts of data. The most important limitation of this study was access to the necessary data. There is also a lack of real data to evaluate the accuracy of the model.

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Appendix A

Table A1. The interdependence among resilient indicators derived from Pierson coefficient of correlation (r).

r	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	I20	I21	I22
I1	1.000	0.116	−0.005	0.320	0.118	0.133	0.161	0.028	−0.305	−0.136	0.153	−0.212	0.564	−0.282	0.366	−0.074	0.041	0.227	0.399	−0.260	0.245	0.357
I2		1.000	−0.601	−0.218	0.520	−0.018	−0.106	0.111	−0.218	−0.213	0.023	0.018	−0.032	−0.163	0.399	−0.098	0.575	−0.041	0.216	0.078	0.052	0.038
I3			1.000	−0.005	−0.051	−0.335	0.072	0.584	0.508	0.673	−0.312	0.264	0.060	−0.202	−0.032	−0.069	0.029	−0.188	0.441	−0.289	−0.336	−0.280
I4				1.000	−0.532	0.760	0.007	−0.304	−0.574	−0.386	0.675	−0.381	0.675	0.405	0.225	0.029	−0.262	0.552	−0.369	0.149	0.776	0.688
I5					1.000	−0.529	−0.094	0.568	0.127	0.371	−0.563	0.148	−0.076	−0.398	0.204	−0.237	0.586	−0.339	0.578	−0.327	−0.324	−0.342
I6						1.000	0.228	−0.540	−0.751	−0.579	0.812	−0.415	0.515	0.494	0.271	−0.042	−0.347	0.632	−0.578	0.421	0.864	0.825
I7							1.000	−0.014	−0.103	−0.070	0.258	−0.111	0.102	−0.115	−0.058	−0.048	−0.182	0.292	−0.048	0.117	0.239	0.302
I8								1.000	0.465	0.752	−0.507	0.405	−0.058	−0.396	0.271	−0.224	0.719	−0.308	0.645	−0.200	−0.477	−0.416
I9									1.000	0.769	−0.562	0.643	−0.581	−0.107	−0.220	0.319	0.216	−0.595	0.349	−0.130	−0.828	−0.805
I10										1.000	−0.516	0.569	−0.240	−0.157	0.068	0.009	0.474	−0.447	0.471	−0.212	−0.579	−0.589
I11											1.000	−0.495	0.466	0.370	0.108	0.033	−0.346	0.586	−0.573	0.405	0.720	0.746
I12												1.000	−0.380	0.170	0.292	0.228	0.482	−0.647	0.358	0.005	−0.560	−0.584
I13													1.000	−0.149	0.524	−0.035	−0.089	0.530	0.159	−0.045	0.695	0.791
I14														1.000	0.047	0.180	−0.197	−0.024	−0.567	0.525	0.240	0.044
I15															1.000	−0.064	0.516	0.179	0.425	0.332	0.236	0.331
I16																1.000	−0.118	−0.129	−0.029	−0.086	−0.066	−0.062
I17																	1.000	−0.206	0.488	−0.055	−0.248	−0.262
I18																		1.000	−0.297	0.338	0.749	0.817
I19																			1.000	−0.323	−0.421	−0.301
I20																				1.000	0.167	0.203
I21																					1.000	0.909
I22																						1.000

Table A2. Municipal districts loadings in Tehran.

Functional Zone	District Code	District Area	Factor Loadings f_1	f_2	f_3	f_4	f_5	f_6	Resilience Score	CRI Class *	Rank
WWZ (15,991 ha~26%)	D1	3454.6%	1.841	0.101	−0.077	−0.453	0.155	1.001	66.409	1	2
	D5	5910.10%	1.958	−0.806	0.097	0.341	−0.305	−1.469	62.580	1	3
	D3	2938.5%	1.036	0.377	−0.406	−0.597	0.745	1.232	39.461	1	5
	D2	4956.8%	1.519	−0.322	0.390	−0.220	0.628	−0.721	57.474	1	4
ECZ (17,487 ha~29%)	D15	2846.5%	−0.363	0.473	1.888	1.265	0.290	−0.468	27.922	2	6
	D4	7243.12%	1.608	0.662	1.784	0.317	−0.239	0.764	91.568	1	1
	D22	6140.10%	−0.406	−1.058	1.785	−1.330	−1.625	1.338	−35.458	4	17
CZ (11,198 ha~18%)	D6	2144.4%	0.423	0.787	−1.000	−1.325	0.088	0.018	5.878	2	9
	D7	1537.3%	0.129	0.038	−1.519	−0.023	1.091	−0.258	−4.508	3	12
	D8	1324.2%	0.322	−0.838	−0.772	1.339	−0.892	−1.492	−2.551	3	11
	D10	806.1%	−0.377	−0.164	−0.846	1.904	−0.757	1.426	−12.315	3	14
	D11	1187.2%	−0.136	0.853	−0.701	0.567	−0.201	−0.491	5.321	2	10
	D12	1356.2%	−0.739	3.409	−0.194	−0.705	−0.911	−0.248	13.195	2	7
	D13	1389.2%	−0.027	−0.421	−1.509	−0.061	0.131	1.398	−23.698	3	16
	D14	1456.2%	−0.369	−0.030	0.401	1.705	0.652	−0.354	10.008	2	8
DTZ (9435 ha~15%)	D16	1645.3%	−0.809	0.814	0.141	−0.238	0.934	−0.225	−12.240	3	13
	D17	827.1%	−1.197	−0.436	0.017	1.324	−0.695	1.555	−43.241	4	19
	D18	3785.6%	−1.155	−0.919	0.365	−0.501	3.092	0.243	−40.275	4	18
	D19	1149.2%	−1.208	−0.637	0.522	−0.730	0.020	−0.288	−56.716	4	20
	D20	2028.3%	−0.919	0.217	1.027	−0.329	−0.077	−1.631	−23.578	3	15
NZ (7151 ha~12%)	D21	5196.8%	−0.495	−1.255	−0.106	−1.706	−0.845	−0.253	−61.163	4	21
	D9	1955.3%	−0.636	−0.842	−1.287	−0.540	−1.279	−1.079	−64.074	4	22

* Resilient classes include best, moderate, low, and least.

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