Towards a Flood Vulnerability Assessment of Watershed Using Integration of Decision Making Trial and Evaluation Laboratory, Analytical Network Process, and Fuzzy Theories

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Research Article

Keywords: Flood vulnerability, DEMATEL, Interdependency, Analytical network process, Fuzzy

Posted Date: March 18th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-276992/v1

Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on July 1st, 2021. See the published version at https://doi.org/10.1007/s11356-021-14534-w.

Towards a flood vulnerability assessment of watershed using integration of decision making trial and evaluation laboratory, analytical network process, and fuzzy theories

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Abstract

Among natural disasters, flood is increasingly recognized as a serious worldwide concern that causes the most damages in parts of agriculture, fishery, housing, and infrastructure, and strongly affects economic and social activities. Universally, there is a requirement to increase our conception of flood vulnerability and to outstretch methods and tools to assess it. Spatial analysis of flood vulnerability is part of non-structural measures to prevent and reduce flood destructive effects. Hence, the current study proposes a methodology for assessing the flood vulnerability in the area of watershed in a severely flooded area of Iran (i.e., Kashkan Watershed). First interdependency analysis among criteria (including population density, PD; livestock density, LD; percentage of farmers and ranchers, PFR; distance to industrial and mining areas, DTIM; distance to tourist and cultural heritage areas, DTTCH; land use; distance to residential areas, DTRe; distance to road, DTR; and distance to stream, DTS) was conducted using the decision-making trial and evaluation laboratory (DEMATEL) method. Hence, the cause and effect factors and their interaction levels in the whole network were investigated. Then, using the interdependency relationships among criteria, a network structure from flood vulnerability factors to determine their importance of factors was constructed and the analytical network process (ANP) was applied. Finally, with aim of overcome ambiguity, reduce uncertainty, and keep the data availability, an appropriate Fuzzy membership function was applied to each layer by analyzing the relationship of each layer with flood vulnerability. Importance analysis indicated that the variables of land use (0.197), DTS (0.181), PD (0.180), DTRe (0.140), and DTR (0.138) were the most important variables. The flood vulnerability map produced by the integrated method of DEMATEL-ANP-FUZZY showed that about 19.2% of the region has a high to very high flood vulnerability.

Keywords: Flood vulnerability; DEMATEL; Interdependency; Analytical network process; Fuzzy

1. Introduction

Flood is abundant water that flows rapidly and covers a large area of land, which has not been naturally submerged, and it is known as one of the most destructive disasters (Getahun and Gebre 2015). Among natural disasters, flood is increasingly recognized as a serious worldwide concern that causes the most damages in parts of agriculture, fishery, housing, and infrastructure, and strongly affects economic and social activities (Demir and Kisi 2016). During the past several decades, flood has led to high economic damages and human casualties in different regions of the world (Guo et al. 2014). Surveys showed that just in 2010, more than 178 million people worldwide have been affected by floods, and from 1960 to 2017 about 34% of natural disasters have been caused by floods, resulting yearly about 1254 deaths and $ 2.5 billion in socio-economic damage (Petit-Boix et al., 2017). In Iran, due to the arid and semi-arid climate, the rainfall is mostly short-term and intense which this condition will be exacerbated by climate change. After 1985 the frequency of more extreme floods because of rangeland degradation and intense deforestation has been increased in this country (Modarres et al. 2016). For instance, one of the most devastating events in the contemporary history of Iran was occurred in March 2019, that it involved 28 provinces and about 70% of the country's area with an economic cost of about $ 3.5 billion U.S.D. (Aminyavari et al. 2019; Hosseini et al. 2020). Thus, one of the basic steps to reduce the harmful effects of floods is to identify flood-prone areas and grade these areas in terms of flood vulnerability (Patial et al. 2008).

Sustainable management of natural resources requires the identification of vulnerable regions that is one of the main steps in the protection framework (Sahoo et al., 2016). According to the Intergovernmental Panel on Climate Change (IPCC) (2014), vulnerability is a degree of sensitivity in a system to the lateral effects of a particular hazard or strain (Field et al., 2014). Understanding effective factors is essential for assessing environmental vulnerability (Burger, 1997). In general, vulnerability refers to the economic, social, physical, and environmental conditions that show the sensitivity of the elements to hazard effects (UNISDR, 2009). Spatial analysis of flood vulnerability is part of non-structural measures to prevent and reduce flood destructive effects (Demir and Kisi 2016).

A major area of interest within the field of flood studies is paid attention to flood susceptibility/hazard assessment (e.g., Islam et al. 2020; Nachappa et al. 2020; El-Haddad et al. 2020; Costache et al. 2020; Costache and Bui 2020; Tang et al. 2020), but far too little attention has been paid to flood vulnerability assessment and there is not entirely a guideline for its analyzing. However, flood vulnerability analysis is usually conducted using decision-making approaches (Lee et al. 2013). Although, in a study, Connor and Hiroki (2005) analyzed the flood vulnerability using the multiple linear regression through considering the vulnerability as a function of the number of casualties, number of populations, and amount of costs; due to lack of any observed data that can assign as a dependent variable, application of other methods such as machine learning is not feasible. Among the decision-making approaches, analytical hierarchy process (e.g., Ouma and Tateishi 2014; de Brito et al. 2018), Delphi (e.g., de Brito et al. 2017; Boulomytis et al. 2019), TOPSIS (e.g., Lee et al. 2013; Yang et al. 2018) have been applied to flood vulnerability analysis. But the main limitation of these methods is that they have not considered interdependency among criteria (Khadivi and FatemGhomi, 2012). Some studies such

as de Brito et al. (2018) have addressed this issue by using the analytical network process (ANP) method which considers the interdependency among factors through network analysis. However, how to determine the interdependency among factors is another major issue that is not well documented in the flood vulnerability analysis. In this study, we tried to fill this gap by applying the decision-making trial and evaluation laboratory (DEMATEL) method, which can extract interdependencies among variables (Sajedi-Hosseini et al. 2018).

This study, therefore, set out to assess the flood vulnerability at the watershed level. We integrated the DEMATEL, ANP, and Fuzzy theories to develop a methodology for flood vulnerability assessment. It should be noted that one of the main aspects and effective ways in modern flood management and flood damage mitigation is increasing the awareness and perception of people to floods (Kellens et al. 2011). To achieve this purpose, having flood vulnerability maps may help managers to gain a deeper understanding of vulnerable areas.

2. Materials and methods

2.1. Study area

Kashkan Watershed located in the Lorestan Province, west of Iran, has an area of about 9510 km^2 which extends from longitudes 47° 12' 03" to 48° 59' 42" east and latitudes 33° 04' 24" to 34° 03' 36" north (Figure 1). The basin is an important tributary of the Karkheh River Basin (the main River Basin in the west of Iran). Variation of the elevation in the watershed is high and vary between 527 m to 3630 m. Cites of Khorramabad, Kuhdasht, Aleshtar, Firozabad, and Pol-e Dokhtar with a sum of about 800,000 people are in this watershed (National Statistics Center of Iran, 2016) (Figure 1). The long-term mean precipitation of the Kashkan Watershed is about 620 mm (JAMAB, 1999). According to available statistics during the last fifty years, this watershed is

the most flooded area in the Lorestan Province and Iran. For example, one of the biggest and most destructive floods in this watershed was occurred in March 2019, with a peak of 3000 m^3/s (~300-*yr* return period) (Geravand et al. 2020). Figure 2 indicates a small part of the damage of this flood in the region. The main land uses of the watershed are rangeland (34.87 %), forest (34.44 %), agriculture (27.57 %), residential (2.0 %), orchard (0.92 %), and others (0.2%).

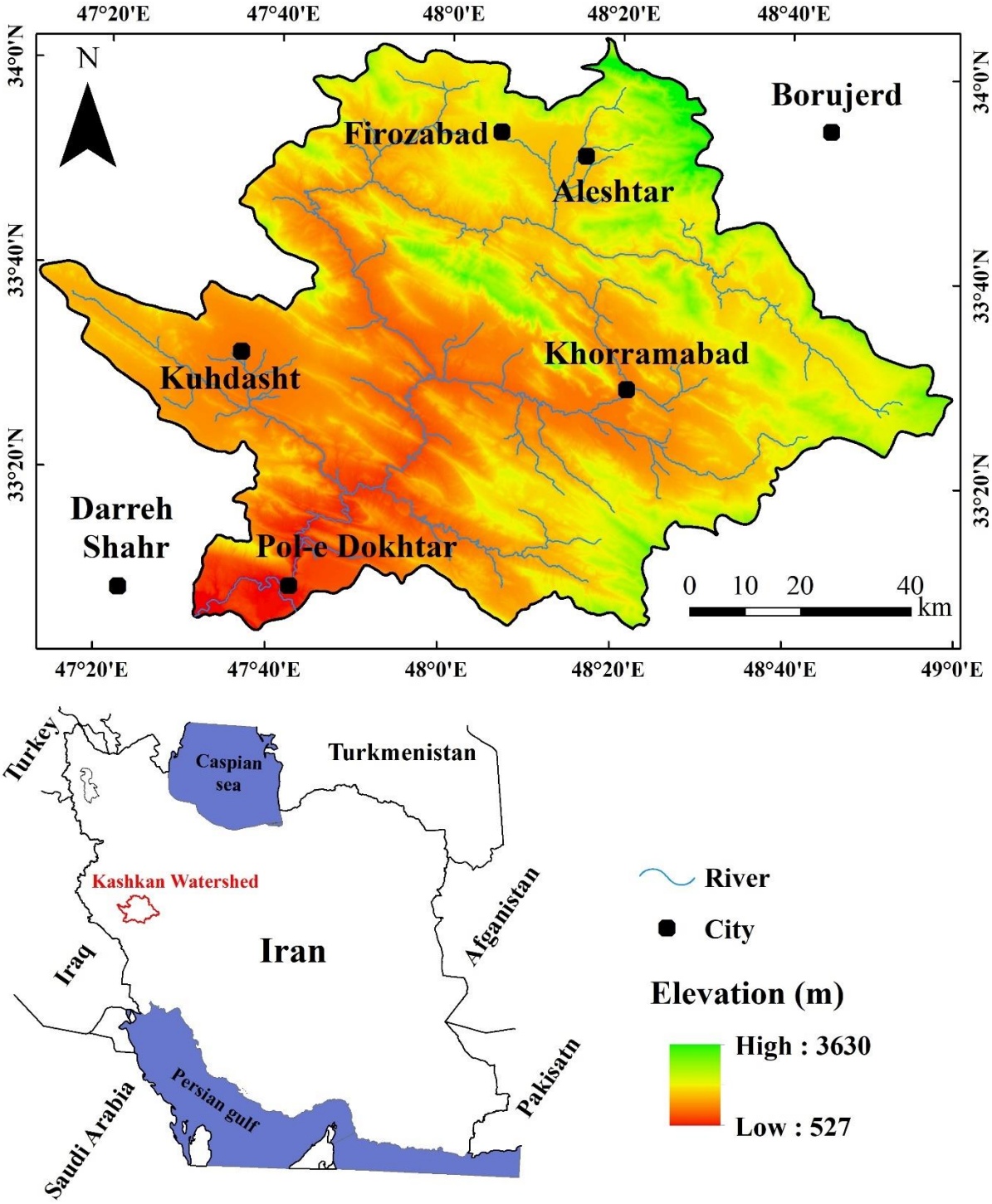

Figure 1. Location of the study area.

Figure 2. Some photos of the flood damage in March 2019. Photos were taken by Shahram Khalighi Sigaroodi.

2.2. Flood vulnerability factors

According to the surveys in literature, applied factors for vulnerability assessment are consist of physical, economic, and social conditions (e.g., Karmaoui et al. 2016; Sadeghi-Pouya et al. 2017; Kumar and Bhattacharjya 2020). Thus, in this study, we considered important physical and socio-economic factors based on the available data in the area of the watershed; that are described as follows:

2.2.1. Socio-economic factors

Socio-economic factors are including the population density (PD), livestock density (LD), percentage of farmers and ranchers (PFR), distance to industrial and mining areas (DTIM),

distance to tourist and cultural heritage areas (DTTCH), and land use (Figure 3a to 3f). For preparing the above-mentioned factors, data including the number of population, number of livestock, PFR, location of industrial and mining areas, and location of tourist and cultural heritage areas were obtained from the National Statistics Center of Iran according to the general population and housing census and agricultural census during 2016 (National Statistics Center of Iran, 2016). PD and LD indicate respectively the number of people and livestock in a given area (usually at km^2). Everywhere the PD and LD are more, the flood vulnerability is greater. PFR shows the percentage of people engage in agriculture and rancher, which vulnerability can increase as the PFR increases. To prepare the maps of DTIM and DTTCH, the Euclidean distance tools in ArcGIS 10.3 was used. By increasing the DTIM and DTTCH, the flood vulnerability is decreased. Land use was another effective factor that was used for flood vulnerability assessment. Different land uses have different values and different reactions to flood; for example, residential areas and infrastructures such as roads are most important, while they reduce soil infiltration capacity and increase runoff (Ouma and Tateishi, 2014). To prepare the land use map, the required frames of the Sentinel 2 in April 2017 were obtained. Then after taking the data samples from Google Earth and field surveys, the area was classified into seven categories (including forest, rangeland, agriculture, barren, orchard, residential, and waterbody) using the Maximum Likelihood Classification (MLC) method in ENVI 5.4 environment.

2.2.2. Physical factors

Physical factors are including the distance to residential areas (DTRe), distance to road (DTR), and distance to stream (DTS) (Figure 3g to 3i). By decreasing the distance to residential areas, roads, and streams, the vulnerability is increased. The location of residential areas was extracted by the land use map. The road layer was received from the Iranian Water Resources Management

Company (IWRMC). For extracting the stream layer, we used a Digital Elevation Model (DEM) with a pixel size of about 13 × 13 m (for the study area in Iran) which was obtained from Sentinel 1 satellite images. Then, the stream layer was prepared in the ArcGIS 10.3 software by extension of the ArcSWAT 2012.10.3.19. For preparing the all physical factors shown in Figure 3g to 3i, the Euclidean distance tools in ArcGIS 10.3 was applied.

It should be mentioned that all socio-economic and physical factors were resampled to a pixel size 13 × 13 m to be equal with land use and DTS layers obtained from the Sentinel images.

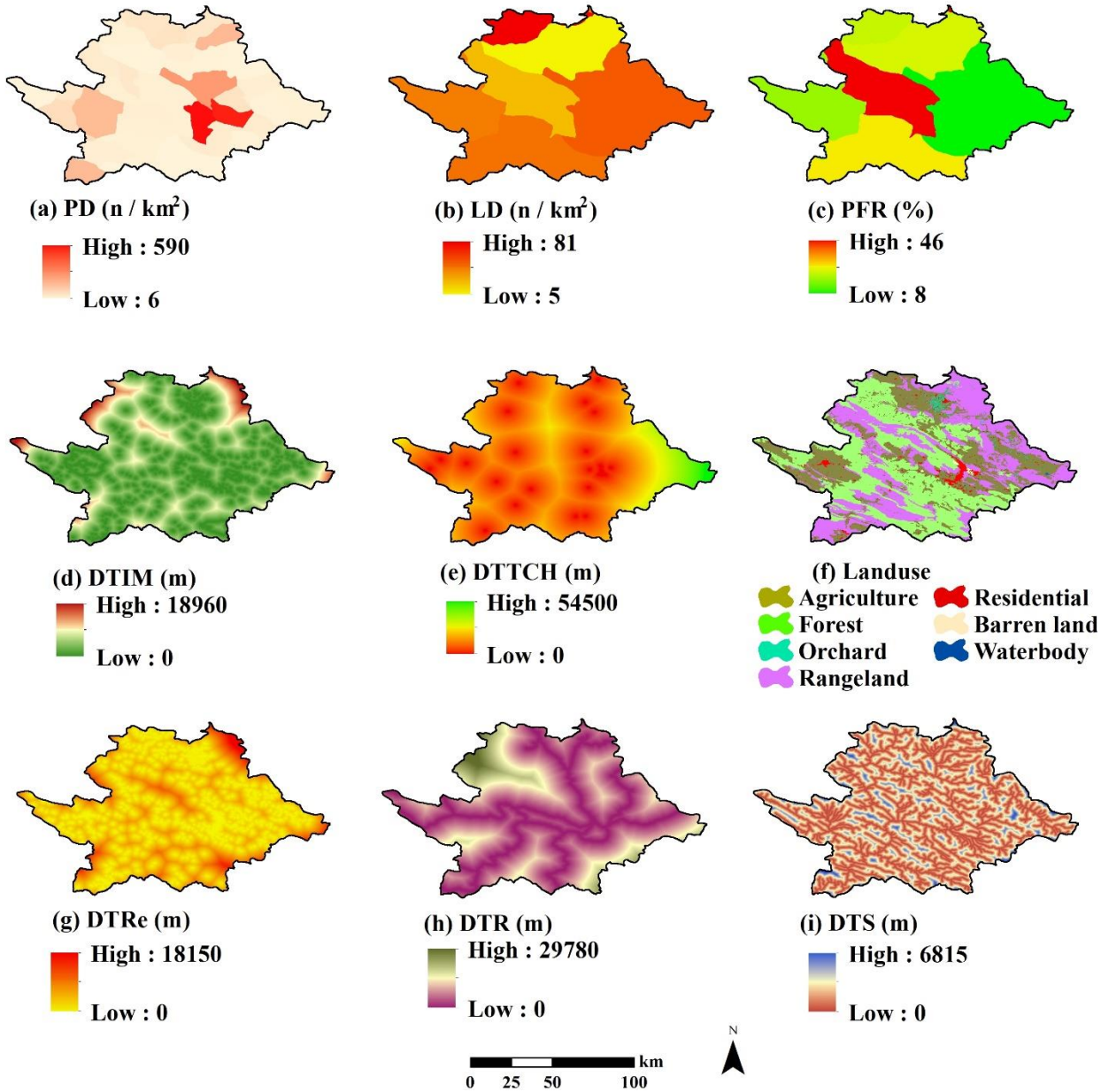

Figure 3. Flood vulnerability variables: (a) population density (PD), (b) livestock density (LD), (c) percentage of farmers and ranchers (PFR), (d) distance to industrial and mining areas (DTIM), (e) distance to tourist and cultural heritage areas (DTTCH), (f) land use, (g) distance to residential areas (DTRe), (h) distance to road (DTR), and (i) distance to stream (DTS).

2.3. Flood vulnerability assessment

The procedure of flood vulnerability assessment in this study is divided into four steps: (i) investigation of the relationships among factors using the Decision Making Trial and Evaluation Laboratory (DEMATEL), (ii) calculation of the weight of factors using the Analytical Network Process (ANP) and identified relationships from step (i), (iii) standardizing pixels based on the relevance fuzzy membership functions, and (iv) flood vulnerability mapping; which, they are described as follows:

2.3.1. Investigation of the relationships among factors using the DEMATEL

The DEMATEL method in this study was used to identify the causal relationships among the variables, that it is important in the designing network in the ANP method. According to this method, number of 30 questionnaires was distributed and completed by the related specialists, and the influence of the factors on each other was investigated via values of 0, 1, 2, 3, and 4 respectively for 'No', 'Very low', 'Low', 'High', and 'Very high' effects (Gabus and Fontela 1972; Azareh et al. 2019). The steps of the DEMATEL method can be summarized as follows (Gabus and Fontela 1972; Sajedi-Hosseini et al. 2018):

(i) A matrix $M_{n \times n}$ is prepared based on the experts' knowledge that indicates the influence of the factors on each other (base on the above-mentioned values).

(ii) The matrix $M_{n \times n}$ is normalized (N) using the Eq.s 1 and 2:

$$N = K \cdot M_{n \times n} \qquad \text{Eq. 1}$$

$$K = \frac{1}{max \sum_{j=1}^{n} a_{ij}} \quad and\ 1 \leq i \leq n \qquad \text{Eq. 2}$$

where K is the inverse of the maximum value among the sum of the rows and columns in the matrix $M_{n \times n}$, and a_{ij} denotes the influence of factor i on factor j.

(iii) Total relation matrix (T) is calculated by using the identity matrix (I) through the Eq. 3:

$$T = N\,(I - N)^{-1} \qquad \text{Eq. 3}$$

(iv) Finally, the causal relationships among variables are identified using Eq.s 4 to 6:

$$T = \left[\, t_{ij} \,\right]_{n \times n} \quad \text{and} \quad i,j = 1,2,\cdots,n \qquad \text{Eq. 4}$$

$$R_i = \left[\sum_{i=1}^{i=n} \mathrm{t_{ij}}\,\right]_{1 \times n} \qquad \text{Eq. 5}$$

$$C_i = \left[\sum_{i=1}^{i=n} \mathrm{t_{ij}}\,\right]_{1 \times n} \qquad \text{Eq. 6}$$

where t_{ij} is the value of matrix T in row i and column j. R_i and C_i are respectively sum of rows and sum of columns within the matrix T, which respectively indicate the amount of cause and effect of the variables in the whole network.

In the current research, the DEMATEL method was run in the MATLAB R2016b.

2.3.2. Weight calculation of the factors using the ANP

In this study, the ANP method was used to determine the weight of factors. The method is one of the last multi-criteria decision-making methods represented by Saaty in 2001 to solve the problems related to dependency among the factors (Saaty 2001). In this method, the problem is shown as a network that nodes display levels. Elements in a node may affect all or part of the elements in other nodes. In the network structure, the relationships between elements are shown with arrows, and the direction of the arrows determines the direction of the dependency. The interdependence between two nodes is called the external dependence that represented by the two-way arrow, and the internal interdependence between the elements in a node is represented by a loop arrow (Saaty 2005). According to Saaty (2001), the ANP method can be summarized in five steps as follows:

(i) Design and conversion of the problem to a network structure. In this study, the cause and effect factors and their dependencies were determined by the DEMATEL method.

(ii) Pairwise comparison. In this step, the comparison of factors was done using the linguistic terms and scale 1 to 9 Saaty (2001).

(iii) Creation of the primary supermatrix according to the weights obtained from step (ii).

(iv) Creation of the weighted supermatrix by multiplying the primary supermatrix by weight of clusters.

(v) Eventually, calculation of the limited supermatrix was done by multiplying the weighted supermatrix n times by itself.

More information about the ANP method has been described by Saaty (2001). In this study, the ANP method was implemented within the environment of SuperDecision 2.8 software.

2.3.3. Standardizing pixels based on the fuzzy membership functions

After calculating the layers' weight using the DEMATEL-ANP method, the pixels of each layer were standardized based on the relative fuzzy membership functions. According to the scholars (e.g., Sajedi-Hosseini et al. 2018; Azareh et al. 2019), providing the continuous values based on the Fuzzy keep the data variability of variables that is more realistic than other ways such as categorizing inputs. Also, the Fuzzy can overcome ambiguity and reduce uncertainty (Samanlioglu and Aya 2016; Sajedi-Hosseini et al. 2018). Thus, by analyzing the relationship of each layer with flood vulnerability, an appropriate fuzzy membership function was applied for standardizing each layer between 0 and 1. In this study, we used the Fuzzy membership tools in the ArcGIS 10.3 for this objective.

236 *2.3.4. Flood vulnerability mapping*

237 Following the above steps, the flood vulnerability map was calculated using the Raster Calculator
238 Tools in the ArcGIS 10.3 by the Eq. 7:

239 $$FV = \frac{\sum_{i=1}^{i=n} W_i \times N_i}{\sum_{i=1}^{i=n} W_i} \qquad \text{Eq. 7}$$

240 where FV indicates the flood vulnerability, W_i is the weight of variable i calculated by the
241 DEMATEL-ANP method, N_i is a normalized layer of variable i by the related fuzzy membership
242 function, and n is the number of variables. A higher value of the FV shows a higher flood
243 vulnerability.

244 After calculating the FV layer, it is reclassed into five classes of very low, low, moderate, high,
245 and very high flood vulnerability using the Equal interval method (via an interval 0.2 from 0 to 1)
246 in the ArcGIS 10.3.

247

248 **3. Results and Discussion**

249 *3.1. Causal relations between factors based on the DEMATEL method*

250 Finding the causal relationships between factors is important for designing an appropriate network
251 from the problem across the ANP method. Results of causality analysis by the DEMATEL are
252 presented in Table 1 and Figure 4. R_i and C_i are respectively sum of rows and columns within the
253 total relation matrix (Eq. 3), which indicates the magnitude of the cause and effect of each variable.
254 Accordingly, $R_i - C_i$ is named as 'relation' that is used to determine whether a variable is a cause
255 ($R_i - C_i > 0$) or effect ($R_i - C_i < 0$) factor in the whole network (Sajedi-Hosseini et al. 2018; Azareh
256 et al. 2019). According to the results (Table 1 and Figure 4), variables of distance to stream (DTS),
257 distance to industrial and mining areas (DTIM), distance to residential areas (DTRe), and distance

to road (DTR) are causal factors in the whole network, while variables of land use, distance to tourist and cultural heritage areas (DTTCH), percentage of farmers and ranchers (PFR), population density (PD), and livestock density (LD) are effect factors in the whole network. $R_i + C_i$ is named as 'prominence' that is used to indicate which variables have the highest total interaction in the whole network. The results indicated that the variable of distance to road (DTR), land use, population density (PD), and distance to stream (DTS) have the highest interaction with other variables (Table 1 and Figure 4).

Finally, according to the DEMATEL results by defining a threshold on values of the total relation matrix, the structure of the network among the flood vulnerability factors are designed (Figure 5). The direction of the arrows shows the effect of a factor on another. The interdependency effect between two variables represented by a two-way arrow (Figure 5).

Table 1. Results of causality analysis by the DEMATEL method

Factor	*Ri* (Cause)	*Ci* (Effect)	*Ri – Ci* (Relation)	*Ri + Ci* (Prominence)
Distance to stream (DTS)	3.34	2.14	1.2	5.48
Distance to industrial and mining areas (DTIM)	2.39	1.69	0.7	4.08
Distance to residential areas (DTRe)	2.7	2.27	0.43	4.97
Distance to road (DTR)	3.27	2.9	0.37	6.17
Land use	2.94	3.07	-0.14	6.01
Distance to tourist and cultural heritage areas (DTTCH)	1.12	1.55	-0.42	2.67
Percentage of farmers and ranchers (PFR)	2.24	2.72	-0.49	4.96
Population density (PD)	2.64	3.27	-0.63	5.91
Livestock density (LD)	1.07	2.1	-1.03	3.17

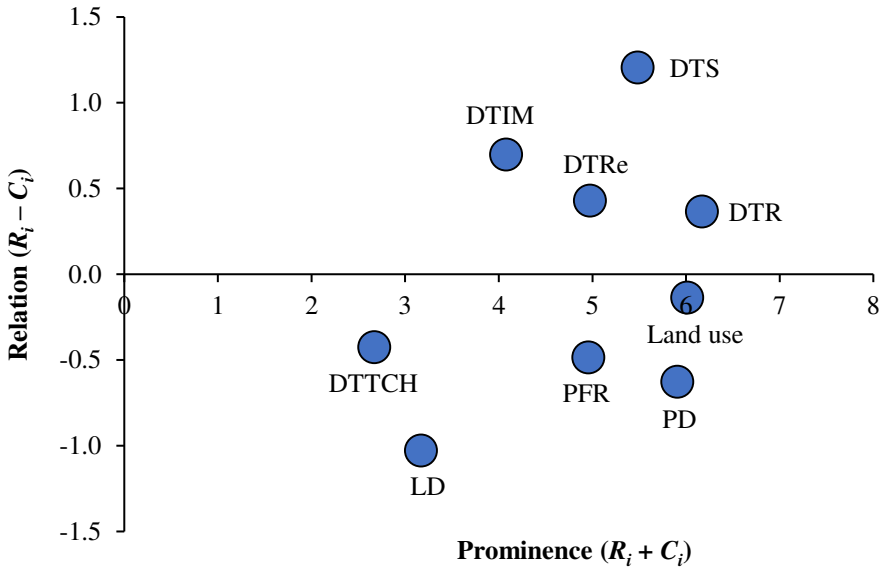

Figure 4. Causal diagram representing the relation (cause/effect) and prominence (interaction) of the variables in the whole network.

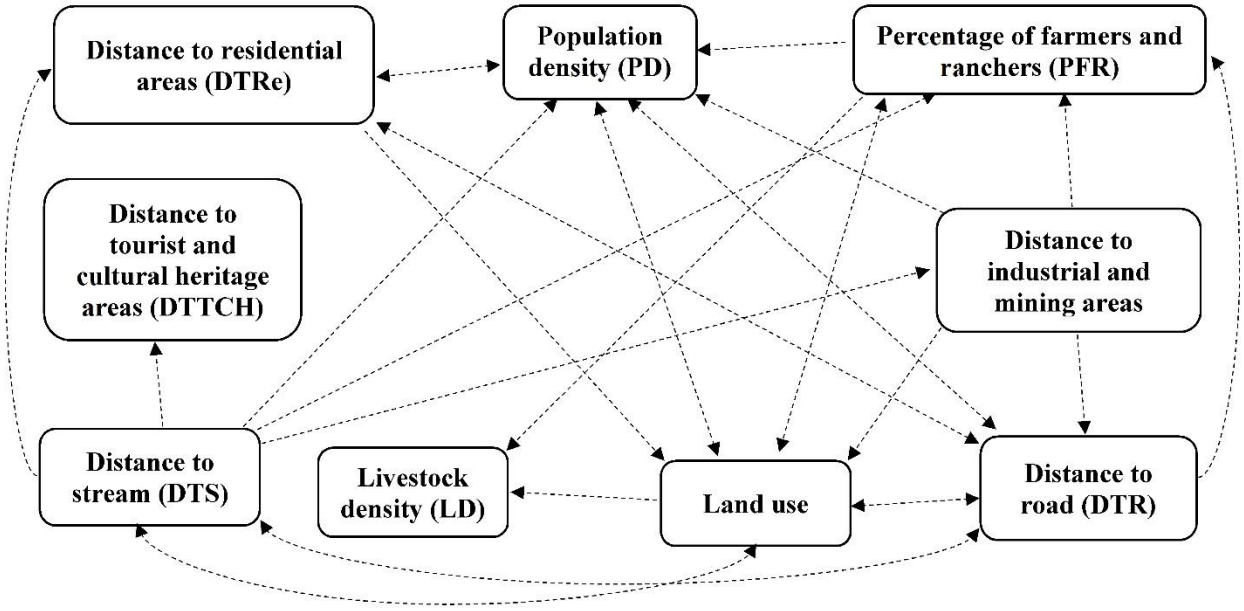

Figure 5. Designed network structure among the flood vulnerability variables by the DEMATEL method

3.2. Importance of the variables based on the ANP method

After determining the relationships between variables and designing the network structure, the ANP method was used for extracting the importance and weight variables. According to the ANP-DEMATEL results, variables of land use (0197), distance to stream (DTS) (0.181), population density (PD) (0.180), distance to residential areas (DTRe) (0.140), and distance to road (DTR) (0.138) were the most important variables, respectively (Table 2). While, variables of distance to tourist and cultural heritage areas (DTTCH) (0.010), livestock density (LD) (0.019), distance to industrial and mining areas (DTIM) (0.065), and percentage of farmers and ranchers (PFR) (0.070) were the less important factors, respectively, that calculated by the ANP- DEMATEL method (Table 2).

No reference has used the DEMATEL-ANP method for flood vulnerability assessment in the area of the watershed. So, it is not possible to compare the results with previous studies. Although in other fields such as flood susceptibility mapping this method has been used (e.g., Azareh et al. 2019), the comparison of the results is not the right way because the concepts and effective factors of the flood susceptibility are different from the flood vulnerability. Indeed, the flood vulnerability detects the potential weaknesses and strengths in the region, not the actual flood hazard (Fekete, A., 2009.).

Table 2. Importance of the factors based on the ANP method

Factors	Weight
Land use	0.197
Distance to stream (DTS)	0.181
Population density (PD)	0.180

Distance to residential areas (DTRe)	0.140
Distance to road (DTR)	0.138
Percentage of farmers and ranchers (PFR)	0.070
Distance to industrial and mining areas (DTIM)	0.065
Livestock density (LD)	0.019
Distance to tourist and cultural heritage areas (DTTCH)	0.010

3.3. Validation of the results

One of the most important steps in network analysis is to assess the validity and consistency of pairwise comparisons. It derives us to decompose complexity into a network structure for a better understanding of the relationship between its components and to create priorities for them within that structure (Ozdemir 2005). The issue of consistency is important in complex and multi-criteria issues, hence, the existence of a technique that can comment on the consistency of any decision is of great importance. Inconsistency causes errors and a lack of certainty to get logical and true results (Davvodi 2009). Inconsistency rate (IR) is an indicator that reflects the possible contradictions and inconsistencies in the pairwise comparison matrix. A valid result is obtained when the inconsistency rate is less than 0.1 (Tummala and Wan 1994). Accordingly, the inconsistency values of the pairwise comparisons for each node across the ANP method are presented in Table 4. The pairwise comparisons in all the nodes indicate the validity of the results (IR < 0.1).

Table 3. Inconsistency value of pairwise comparisons for each node across the ANP method

Node	Inconsistency rate

Land use	0.097
Distance to stream (DTS)	0.00
Population density (PD)	0.091
Distance to residential areas (DTRe)	0.028
Distance to road (DTR)	0.061
Percentage of farmers and ranchers (PFR)	0.015
Distance to industrial and mining areas (DTIM)	0.00
Livestock density (LD)	0.00
Distance to tourist and cultural heritage areas (DTTCH)	0.00
Flood vulnerability	0.079

3.4. Flood vulnerability mapping

After validation of the ANP-DEMATEL model and ensuring the results, an appropriate membership function (MF) was applied for standardizing each layer between 0 and 1. The applied fuzzy MF for each variable is presented in Table 4. Linear-increasing MF was used for standardizing the layers of LD, PD, and PFR. It means that by increasing the pixels' value of these layers, the flood vulnerability is increased. Linear-decreasing MF was applied for standardizing the layers of DTS, DTR, DTRe, DTIM, and DTTCH. It means that by increasing the pixels' value of these layers, the flood vulnerability is decreased (Table 4). So, in linear-increasing (linear-decreasing) MF, the higher (lower) value of a layer converts to 1 and the lower (higher) value converts to 0, and other values change between them. For land use layer, fuzzy values of 0.2, 0.4, 0.4, 0.4, 0.7, 0.8, and 1 respectively for barren land, rangeland, forest, waterbody, orchard, agriculture, and residential area were considered (according to the expert knowledge). By defining an appropriate membership function to each layer, each pixel gets a value that indicates vulnerability of that pixel to flooding. Accordingly, values of pixels in each layer convert into a

continuous scale from 0 to 1 based on the target (i.e., flood vulnerability) that keeps the data availability in the overlaying process (Sajedi-Hosseini et al. 2018; Azareh et al. 2019). Figure 6 shows the normalized factors after applying the fuzzy MF to each layer.

Table 4. Applied fuzzy membership function for each layer

Factor	Membership function
Livestock density (LD)	Linear-increasing
Population density (PD)	Linear-increasing
Distance to stream (DTS)	Linear-decreasing
Distance to road (DTR)	Linear-decreasing
Distance to residential areas (DTRe)	Linear-decreasing
Distance to industrial and mining areas (DTIM)	Linear-decreasing
Distance to tourist and cultural heritage areas (DTTCH)	Linear-decreasing
Percentage of farmers and ranchers (PFR)	Linear-increasing
Land use	User defined (0.2, 0.4, 0.4, 0.4, 0.7, 0.8, and 1 for barren land, rangeland, forest, waterbody, orchard, agriculture, and residential area, respectively)

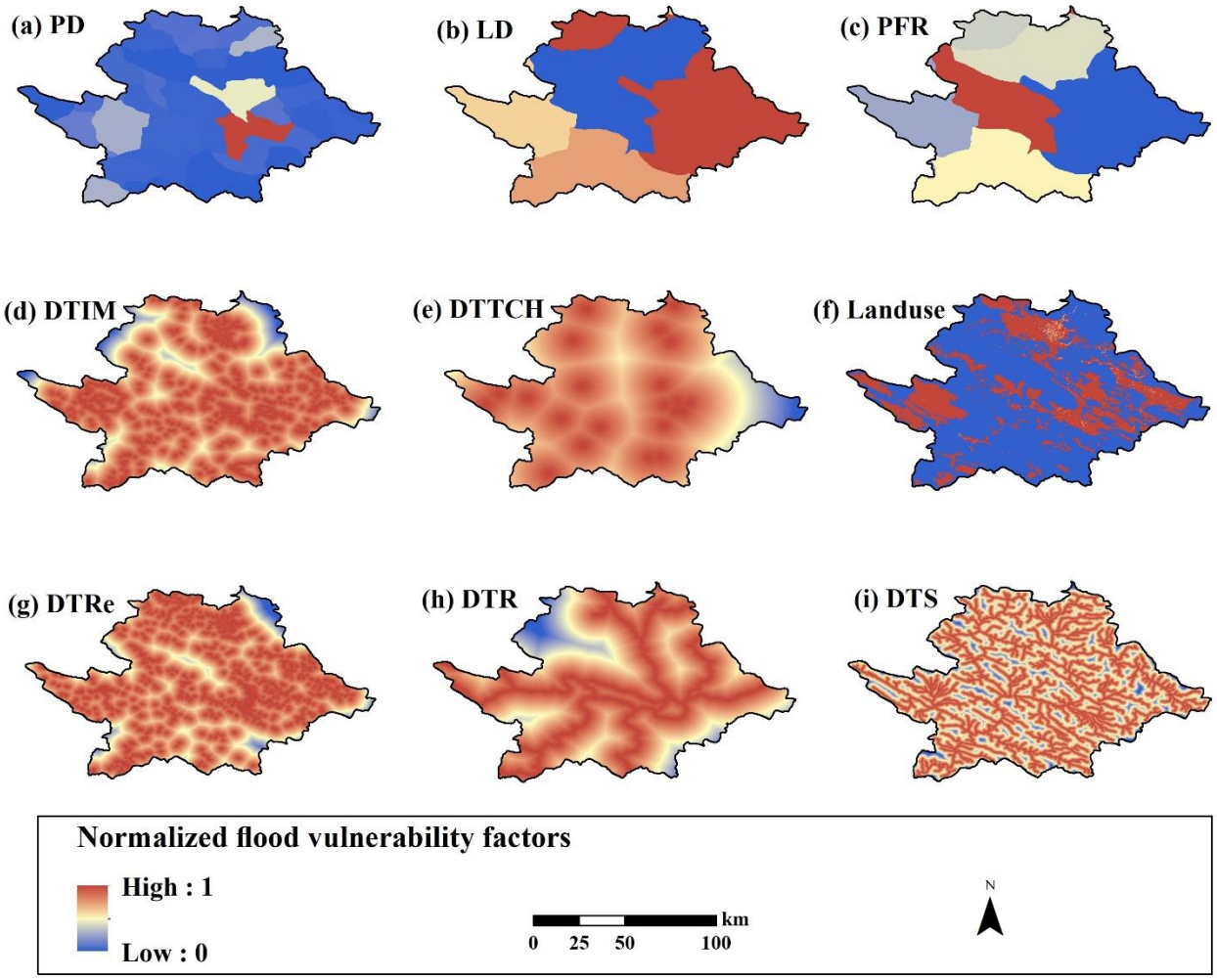

Figure 6. Normalized flood vulnerability factors: (a) population density (PD), (b) livestock density (LD), (c) percentage of farmers and ranchers (PFR), (d) distance to industrial and mining areas (DTIM), (e) distance to tourist and cultural heritage areas (DTTCH), (f) land use, (g) distance to residential areas (DTRe), (h) distance to road (DTR), and (i) distance to stream (DTS).

Finally, by applying the weights achieved from the DEMATEL-ANP method into each Fuzzy layer within ArcGIS 10.3, the overlaying of the layers was conducted using Eq. 7. So, a flood vulnerability map with pixel size 13 × 13 m for the area of Kashkan watershed was produced (Figure 7). According to the flood vulnerability map (Figure 7), 47.2 % area of the region (about 4489.5 km^2) indicates a moderate vulnerability, while other classes of very low, low, high, and

very high contain 1.9% (182.5 km^2), 31.7% (3010.5 km^2), 16.9% (1605.2 km^2), and 2.3% (222.6 km^2) of the region, respectively. Results indicated that the high and very high vulnerability areas correspond to high population density, land use of residential, and low distance to streams. The very high class in Figure 7 is correspond with the location of Khorramabad, Pol-e Dokhtar, and Kuhdasht cities (presented in Figure 1). Some of these very high vulnerable locations (such as vulnerable areas in the Pol-e Dokhtar city) have been previously confirmed by the authors observations from flood damages in March 2019 (Figure 2), after occurring one of the biggest and most destructive floods in this watershed.

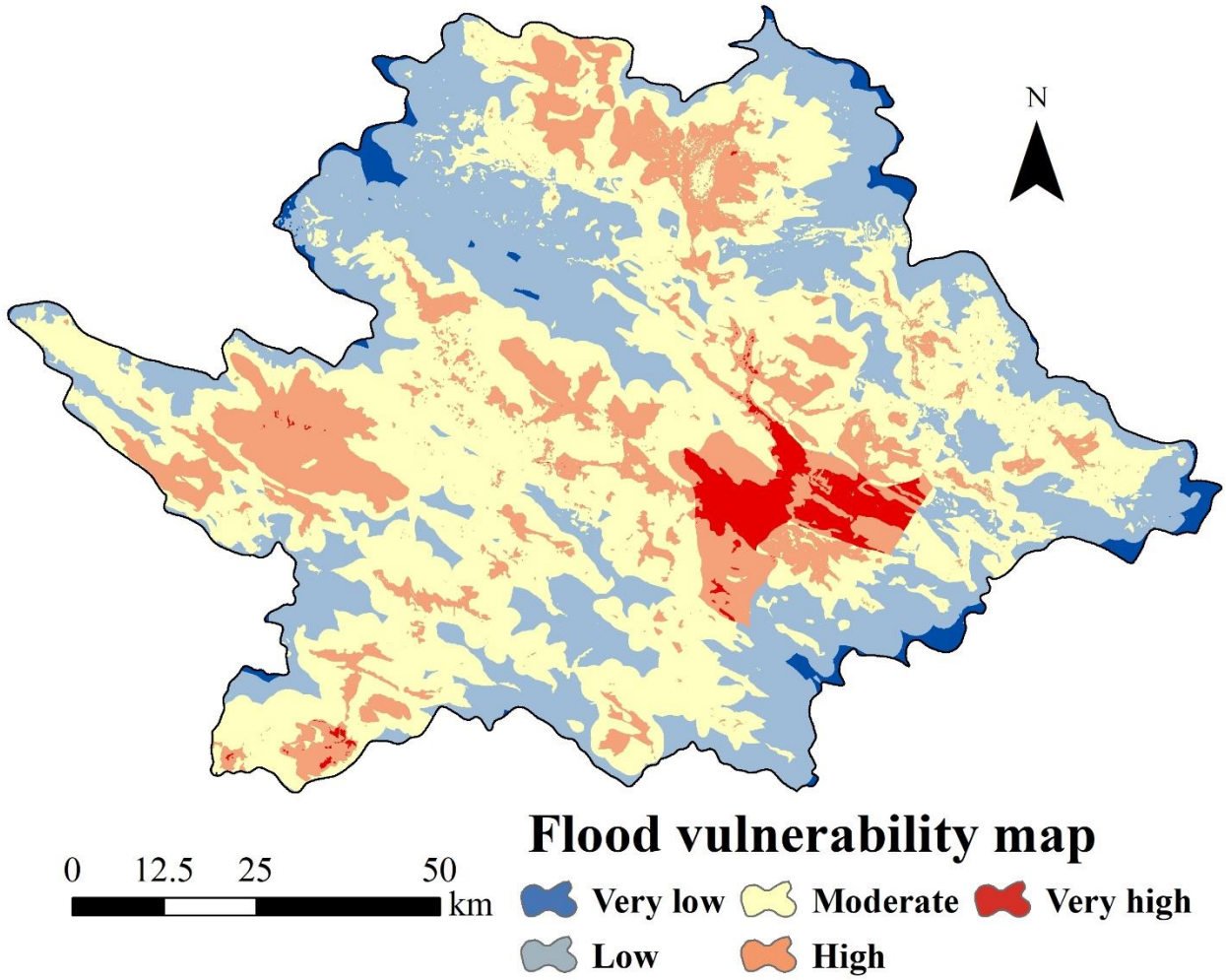

Figure 7. Flood vulnerability map in the Kashkan watershed.

Conclusion

The current study tried to develop a flood vulnerability analysis using an integrated approach by combining the DEMATED, ANP, and Fuzzy methods. The DEMATEL, as a causality analysis method identified the interdependency among factors of flood vulnerability, the ANP determined the importance of factors, and the fuzzy was used to keep the data availability by assigning a

continuous scale to each layer (based on its relationship with flood vulnerability). The ANP-DEMATEL results indicated that the variables of land use (0.197), distance to stream (0.181), population density (0.180), distance to residential areas (0.140), and distance to road (0.138) were the most important variables. According to the flood vulnerability map, 16.9% (1605.2 km^2) and 2.3% (222.6 km^2) of the region, respectively are located in high and very high flood susceptibility, which are correspond to high population density, land use of residential, and low distance to streams. Validation of the vulnerability areas is an inevitable limitation in the vulnerability studies, even though some of the very high vulnerable locations have been validated by the authors' observations from flood damages after occurred flood in March 2019. Unlike the flood hazard studies, there is not any data for validation of the flood vulnerability map, because the flood vulnerability only detects the potential weaknesses and strengths in the region, not the actual flood hazard. So, the flood vulnerability is regarded as independent of the flood hazard and the location of flooded areas can not be used for flood vulnerability validation. However, in this research, the validity of the DEMATEL-ANP method was confirmed by assessing the inconsistency rate in the network structure. Thus, it is not surprising that there is not any feasible way for additional validation, yet, and it can be an outlook for future researches.

Declarations

Ethics approval: Not applicable

Consent to participate: Not applicable

Consent to Publish: Not applicable

Authors Contributions: Conceptualization, FSH; Data preparation, FSH; Formal analysis, FSH, AS, and BC; Investigation, FSH, AM, and AS; Methodology, FSH and SKS; Project administration, FSH and SKS; Supervision, SKS; Validation, SKS; Visualization, FSH and BC; Writing – original draft, FSH and BC; Writing – review & editing, SKS and AM

Funding: The authors received no specific funding for this work.

Competing interests: The authors declare that they have no conflict of interests.

Availability of data and materials: The data that support the findings of this study are available from the corresponding author, [S.K.S.], upon reasonable request.

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Figures

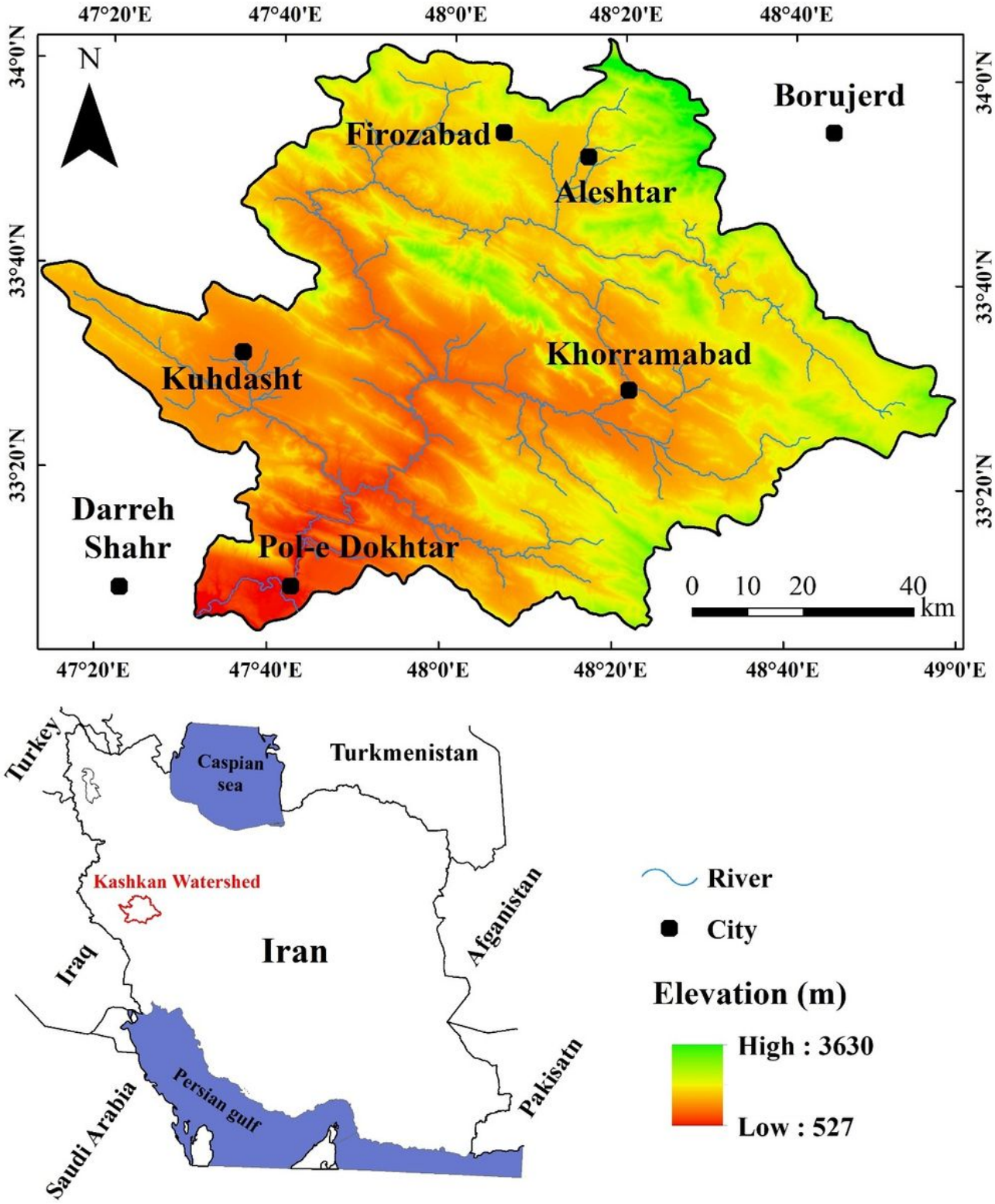

Figure 1

Location of the study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning

the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Some photos of the flood damage in March 2019. Photos were taken by Shahram Khalighi Sigaroodi.

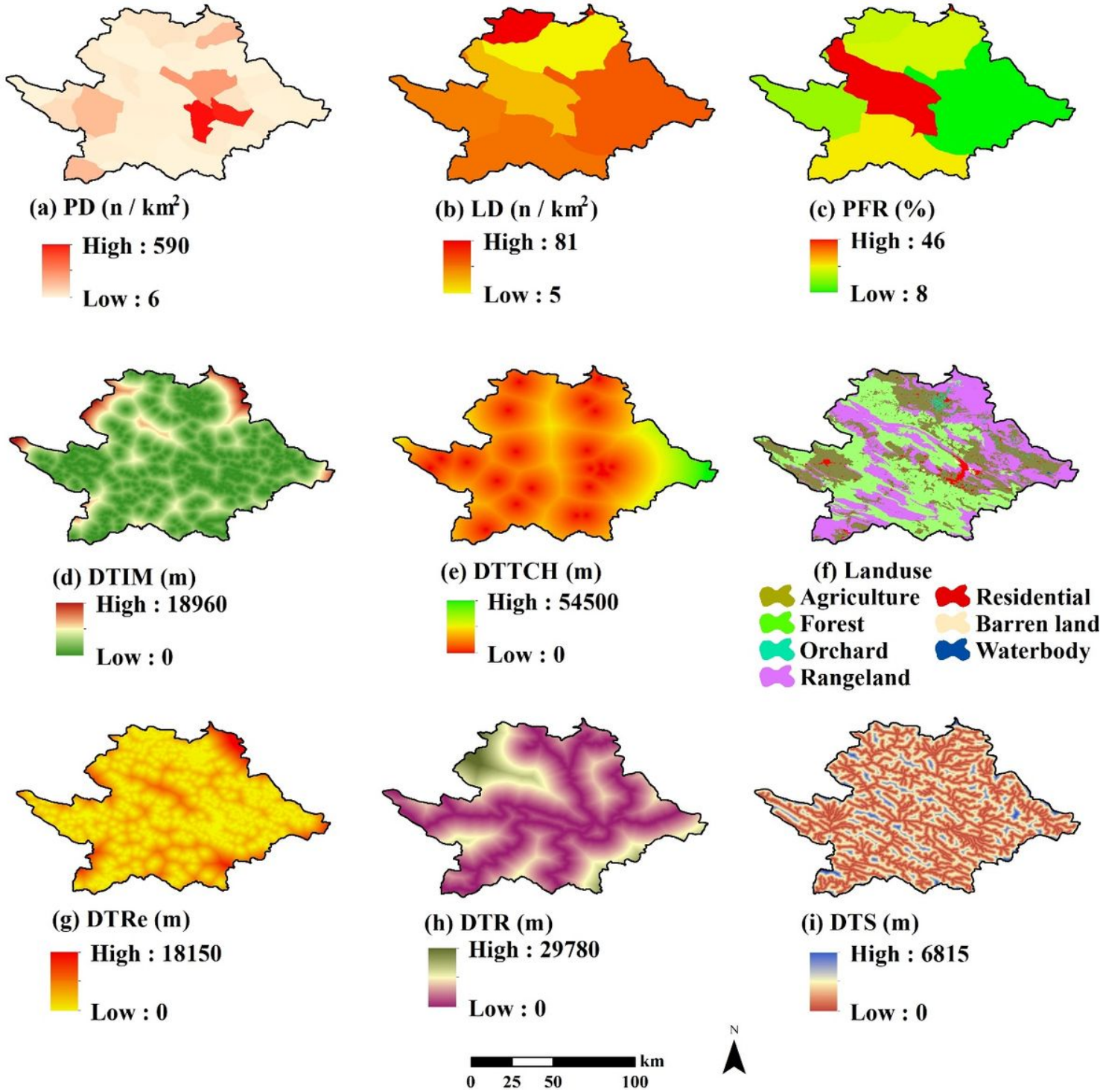

Figure 3

Flood vulnerability variables: (a) population density (PD), (b) livestock density (LD), (c) percentage of farmers and ranchers (PFR), (d) distance to industrial and mining areas (DTIM), (e) distance to tourist and cultural heritage areas (DTTCH), (f) land use, (g) distance to residential areas (DTRe), (h) distance to road (DTR), and (i) distance to stream (DTS). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research

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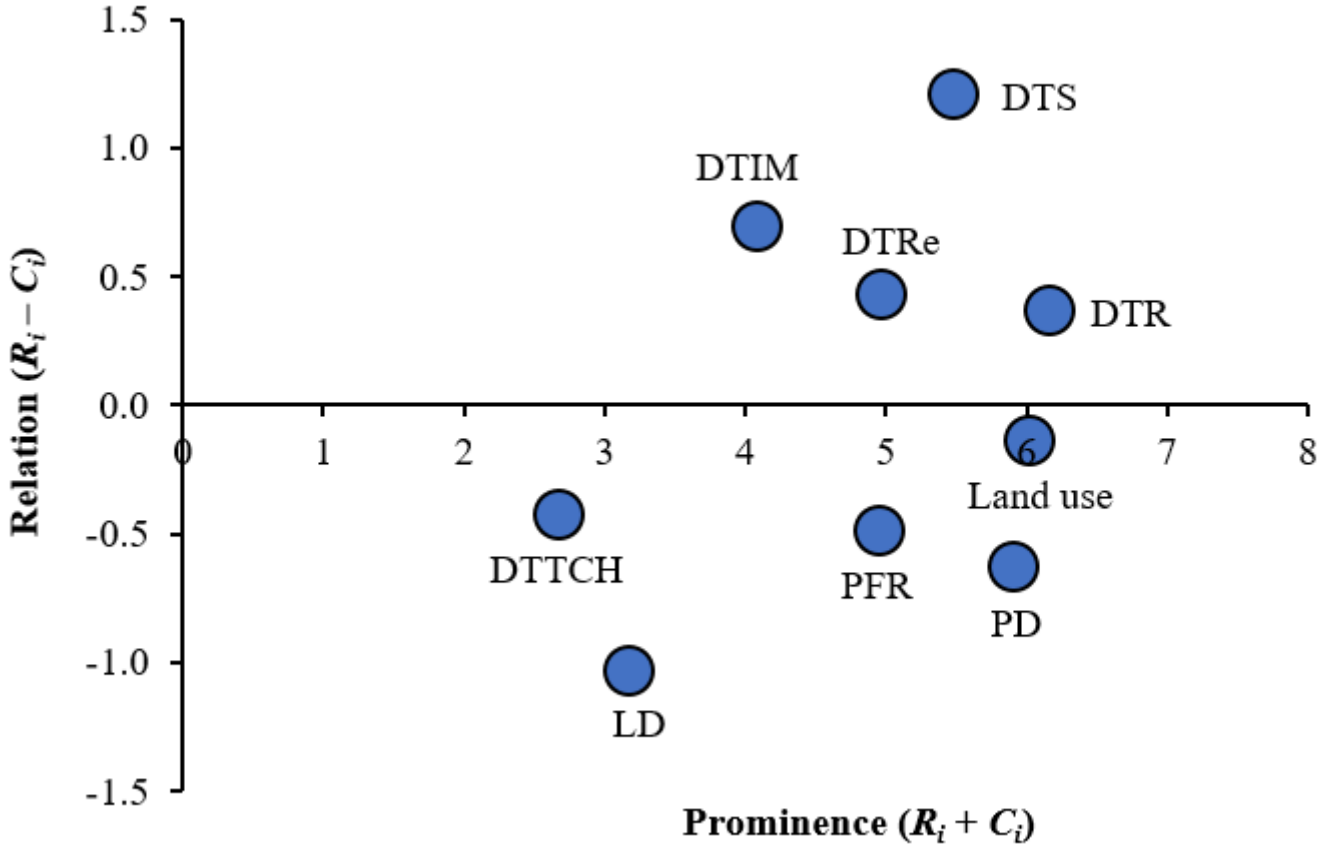

Figure 4

Causal diagram representing the relation (cause/effect) and prominence (interaction) of the variables in the whole network.

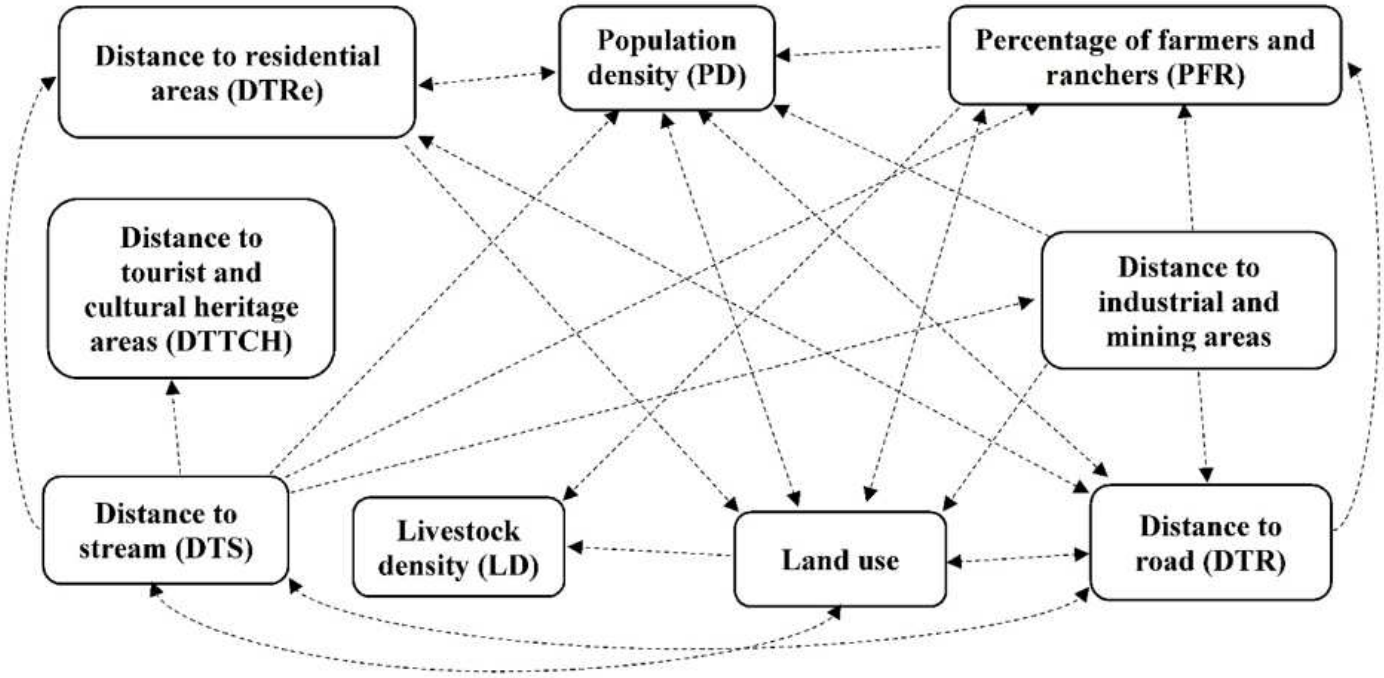

Figure 5

Designed network structure among the flood vulnerability variables by the DEMATEL method

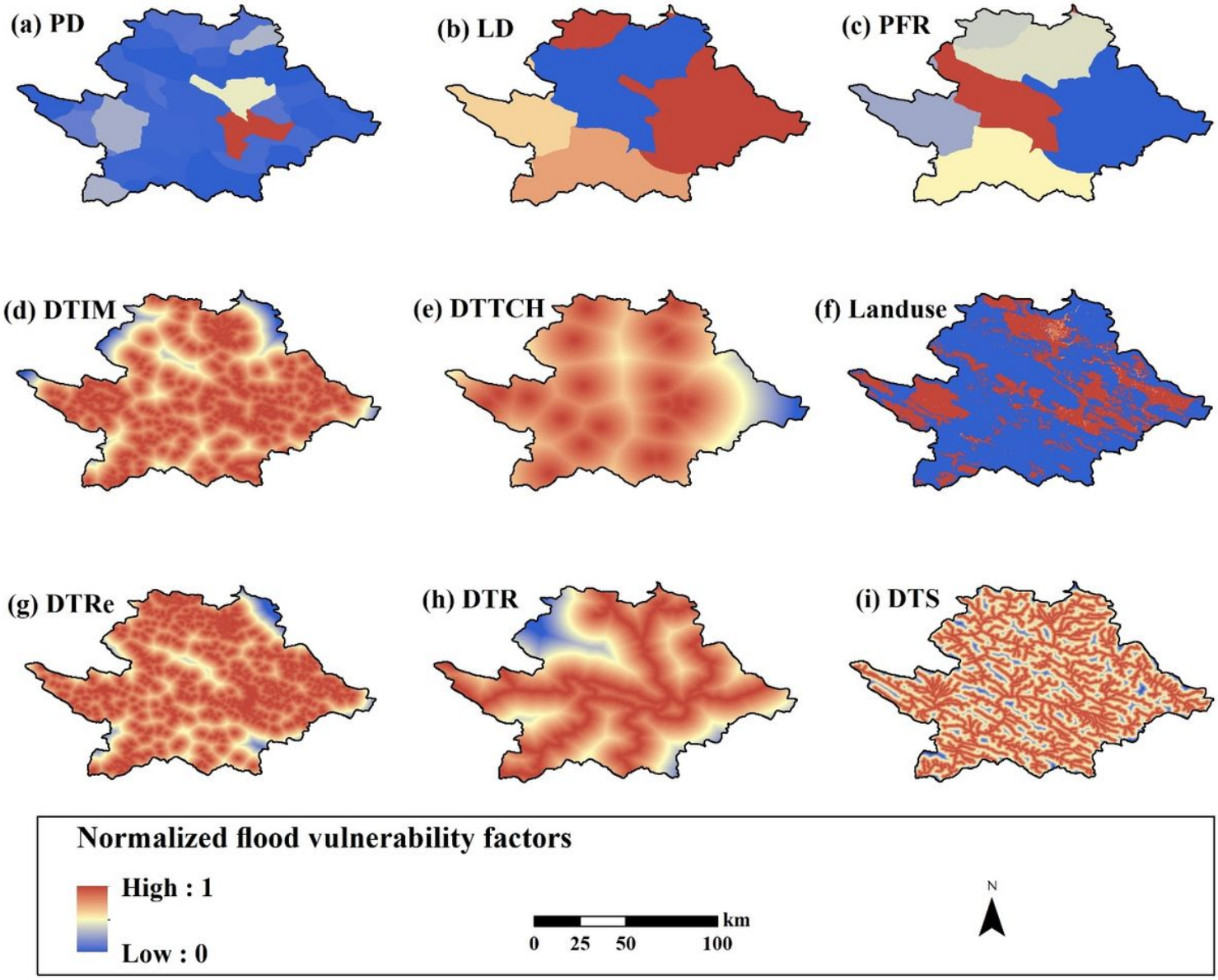

Figure 6

Normalized flood vulnerability factors: (a) population density (PD), (b) livestock density (LD), (c) percentage of farmers and ranchers (PFR), (d) distance to industrial and mining areas (DTIM), (e) distance to tourist and cultural heritage areas (DTTCH), (f) land use, (g) distance to residential areas (DTRe), (h) distance to road (DTR), and (i) distance to stream (DTS). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

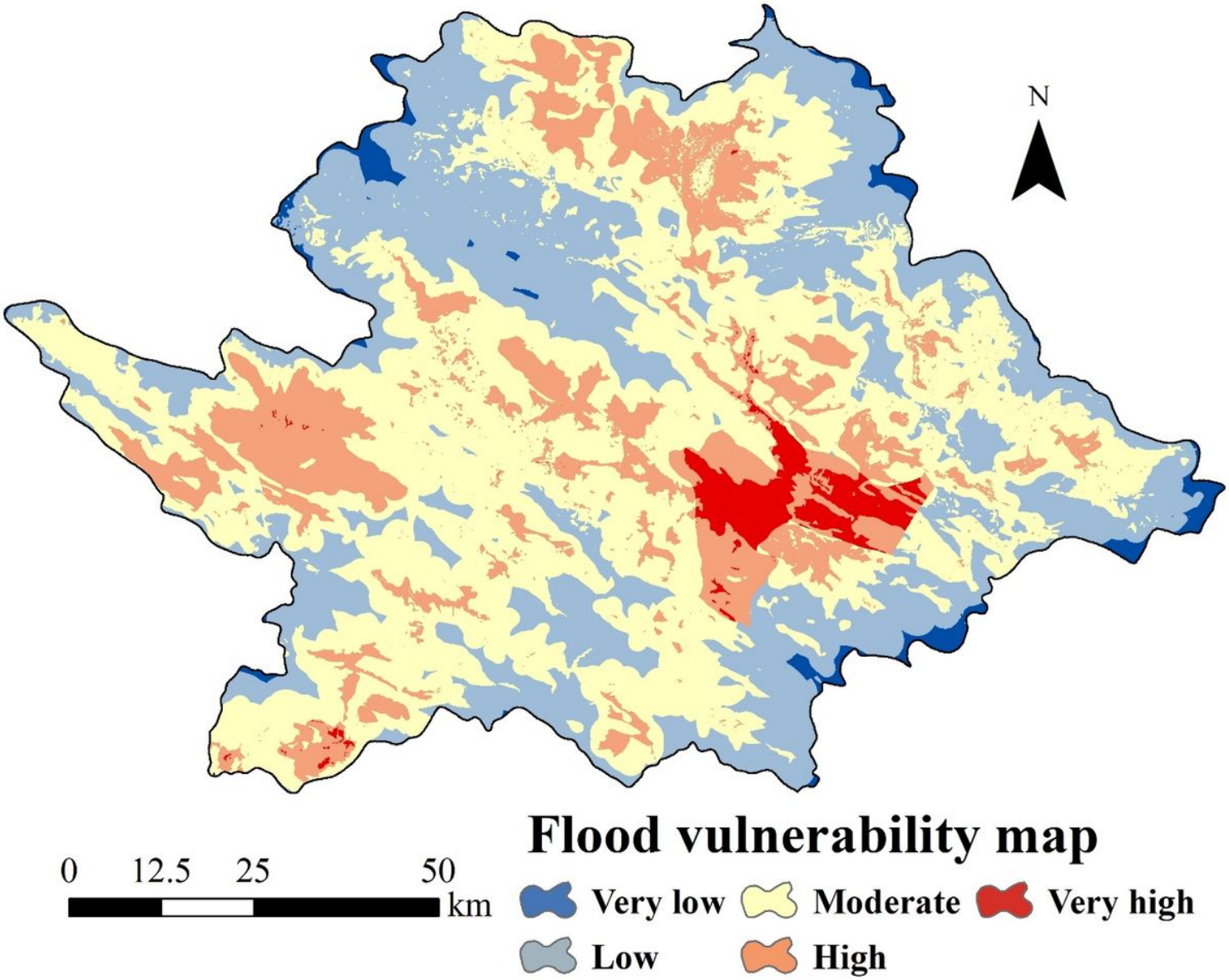

Figure 7

Flood vulnerability map in the Kashkan watershed. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.