



# Ecosystem Health Assessment Using a Fuzzy Spatial Decision Support System in Taleghan Watershed Before and After Dam Construction

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## Abstract

Developing new and practical methodologies in order to assess ecosystem health based on physical, ecological and socio-economic indicators is an essential field of environmental studies. Nowadays, because of the considerable importance of the spatiotemporal dynamics of ecosystem variables, scientists utilize technologies such as geospatial information systems and remote sensing to achieve different indicators. In this paper, the Taleghan watershed, in Alborz province in Iran was selected as a study area, which has been exposed to many stresses including the construction of a dam in 2007. First, an indicator system based on Driving force-Pressure-State-Impact (DPSI) model was established. Indicators were quantified before and after construction of the dam. At the end, the assessment was carried out by development of a spatial decision support system based on fuzzy analytical hierarchy process method. This system was made for calculating the weights of indicators, compositing the maps of various indicators, producing and displaying maps of DPSI indicators and regional ecosystem health, and identifying critical areas in terms of ecosystem health. The results show that ecosystem health values in the eastern (especially northeast) parts of the watershed (upstream of the dam) and the areas adjacent to the river have been lower in comparison with other areas before dam construction. However, after the dam construction, critical areas in terms of ecosystem health shifted to the downstream region in the western parts. 29.79% of the region in the first period and 23.37% in the second period had a very low and low level of ecosystem health.

**Keywords** Ecosystem health · Spatial decision support systems · Indicator · DPSI · Fuzzy AHP · Dam

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## 1 Introduction

There is currently inexhaustible proof that human activities are the most important driving forces and stresses of the ecosystem health. Therefore, restoring the health of the highly stressed and dysfunctional ecosystems is a considerable and essential record of environmental management and sustainable development (Rapport et al. 2001; Vitousek et al. 1997; Zhao et al. 2009). The pressures of human activities are caused by synergistic and complex physical, demographic, social, political and economic factors (Tapia-Armijos et al. 2017).

While humans depend on essential ecological goods to support their immediate needs, environmental procedures are often altered by human activities, which lead to the demolition of the numerous ecosystem services (DeFries et al. 2004). The services that ecosystems provide are components of nature and directly or indirectly are used and consumed for human well-being (Kourtis and Tsihrintzis 2017). Key ecological services, such as the clean air, fresh water purification, nutrient recycling, drought and flood protection, primary production and soil formation are disrupted. When fundamental ecosystem services are altered by the land use change, population growth, and indiscriminate use of natural resources, ensuring environmental health and sustainability is endangered (Kremen and Ostfeld 2005; Stürck et al. 2015; Styers et al. 2010). The services of watershed ecosystems include four categories of provisioning, regulating, cultural and supporting services. However, most of the services commonly associated with watersheds relate to features of water, including flow regulation, quality and quantity (Landell-Mills 2002; Muñoz Escobar et al. 2013; Wang et al. 2010).

Broadening the idea of “health” from its customary spaces of utilization to regional levels (ecosystems, catchment areas, basins and landscapes) provides new challenges to incorporate the natural, socio-economic and health sciences. Hence, we will need to develop ways and methods for evaluating the impacts of human activities on various ecosystem functionalities, while simultaneously considering the different biophysical, ecological and socio-economic variables in our assessments (Barrett and Rosenberg 1981; Rapport et al. 1999).

A healthy ecosystem is defined in such a way that it can sustainably provide various services to meet human needs (Peng et al. 2015). In order to assess ecosystem health, specific indicators based on the vigor, resilience and organization can be utilized. However, this sort of definition is thought to be confined to the range of biological physics, which emphasizes the natural ecological aspect of the ecosystem while ignoring the aspects of social, economic and human health (Costanza et al. 1992; Peng et al. 2007).

In order to investigate the complexities of an ecosystem, not only objective and subjective viewpoints but also multifaceted in nature parameters with a high number of mixes should be considered. Furthermore, spatial and temporal patterns should be included in the assessments. Also, the ecosystem should be regarded as a comprehensive and overall complicated system instead of simple independent components (Dolan et al. 2000; Patten et al. 2002; Zhang et al. 2010). In order to ensure the examination objectives, ecosystem health assessment should put additional thought on the temporal and spatial dynamics of regional ecosystem health rather than subjectively analyze ecosystem health in a certain time or place (Peng et al. 2007; Petropoulos et al. 2014).

Obviously, no one model can be expected to accomplish all biophysical, socioeconomic, human health dimensions and aspects at once, but any proper ecosystem health assessment must be entered in all these sectors (Rapport 1995). Absolute healthy or unhealthy ecosystem does not exist. Indeed, computations, values and results of different ecosystem health evaluations are not comparable, unless the entire ecosystem type, procedures and indicators be same (Peng et al. 2007).

Recent studies in the field of ecosystem health assessment look at this issue through special lenses and their assessments have their own characteristics. These include applying pressure-state-response (PSR) framework using principal component analysis (PCA) (Yu et al. 2013) or using the Analytic Hierarchy Process (AHP) method (Liao et al. 2018; Sun et al. 2016, 2017), and application of developed driving force-pressure-state-impact-response (DPSIR) model (Zhang et al. 2016). However, there is still lack of assessments which simultaneously consider new and advanced conceptual models and weighting methods. Another exquisite point to be mentioned is that watershed ecosystems with their complex ecological and socioeconomic status are less considered in ecosystem health assessment studies.

Access to data and information needed to assess the regional ecosystem health requires the incorporation of new technologies, such as remote sensing and geospatial information systems (GIS). These technologies accelerate and simplify the development of indicators that determine the status and dynamics of ecosystems, which can be used in monitoring ecosystem functionalities and making management decisions. Remote sensing is a quick and cost-effective method to achieve environmental structure and conditions information at multiple temporal and spatial scales. Furthermore, GIS provides the ability to analyze, evaluate, combine and display various biophysical, ecological and socio-economic information and indicators for displaying and assessing the status, communications, changes and impacts (Borrelli et al. 2013; Castillo-Rodríguez et al. 2010; Kolios and Stylios 2013; Patil et al. 2001; Pôças et al. 2011; Revenga 2005; Yu et al. 2013). Specifically, remote sensing data can be directly and indirectly used for achieving ecosystem health indicators, such as land use change, landscape diversity and vegetation. GIS data like digital elevation models provide valuable information about ecosystem structure. In addition, required spatio-temporal analyses of different indicators and visualization of the results in an understandable form are provided by GIS applications (Li et al. 2014; Liao et al. 2018; Zhang et al. 2017).

The application of remote sensing and GIS in combination with environmental frameworks such as PSR and DPSIR has been considered by many scholars in ecosystem health assessment. Nevertheless, few studies (Jihong et al. 2014) have looked at ecosystem health assessment as a decision making issue and used decision-making systems.

Construction of dams provide significant advantages for the environment and society. The dam creates the lake where water is stored and the water is used in agriculture, general purpose and industry. Dams are also useful in flood control and hydroelectric power generation, wildlife habitat and river navigation. However, physical and environmental changes caused by construction of dams can be associated with severe impacts on downstream river reaches, the coastal environment, and freshwater ecosystems and species. Both upstream and downstream ecosystems can be exposed to these destructive effects. Dams interrupt the connection between rivers and their floodplains and wetlands, and slow water velocity in riverine ecosystems. This consequently disrupts riparian habitat and species breeding grounds, impacts the fish migratory routes, traps sediments and affects coastal areas and deltas resulting from increased sedimentation and nutrient loads, causes chemical and temperature changes, and increases water-related diseases and evaporation in reservoirs (Cooper et al. 2017; Lin 2011; McCartney et al. 2001; Revenga 2005; Revenga et al. 2000). Hence, construction of a dam should be considered as a significant factor in assessing ecosystem health.

There are a few spatiotemporal studies on environmental changes throughout the Taleghan watershed, especially in relation to the effects of dam construction. Most previous studies were carried out at smaller scales (such as sub-watersheds) and have focused on land cover and land use changes. Investigation of socio-economic and environmental effects of dam using

structural equation modelling is one such study (Borimnejad and Salimian 2014). The results of this study indicate that the dam construction had no positive effects on the region development (Borimnejad and Salimian 2014). Pourfazel et al. (2015) investigated urban area physical changes and developments using 2 IRS images and a fuzzy model before and after dam construction. They discussed that very distressed areas should be evacuated and be preserved by watershed management (Pourfazel et al. 2015). Ahmadi et al. (2016) evaluated land use changes using Landsat TM and ETM data before and after dam construction in one of sub-watersheds in the downstream reach of a dam, and showed that between 2001 to 2015 the rangeland area was decreased and degraded (Ahmadi et al. 2016). Also, several authors (Ahmadi et al. 2016; Kiani et al. 2011; Mtkan et al. 2011; Nazari Samani et al. 2010) have studied land use change in their study areas. The focus of these studies was more on grassland patterns and all emphasized the need for grassland management plans in the region (Ahmadi et al. 2016; Kiani et al. 2011; Mtkan et al. 2011; Nazari Samani et al. 2010).

In relation to the studies carried out in Iran on the effects of dams, the following can be mentioned: Manouchehri and Mahmoodian (2002) investigated the environmental negative impacts of several dams in Iran. They concluded that these negative effects occur both during the construction of the dam and in the short or long time intervals after that (Manouchehri and Mahmoodian 2002). By reviewing seven large dams in Iran, it was found that large dams have some adverse and inconsistent physical, chemical, biological, socio-economic and health impacts (Heydari et al. 2013). Rezvani Mahmoudi et al. (2017) assessed cultural, socio-economic, biological and physical impacts of Syahoo Dam (Rezvani Mahmoudi et al. 2017). Landscape changes of the Minab delta were evaluated before and after dam construction. This study found that the landscape metrics are negatively affected by dam construction (Farajzadeh et al. 2015). The spatio-temporal dynamics of two desertification indicators including land use/land cover changes and land surface temperature due to the construction of Zayandehrood Dam were examined. It was indicated that salty and bare lands have been increased, while agricultural lands have been declined substantially from 1987 to 2014 (Jafari and Hasheminasab 2017).

Based on the above, there is a gap in relation to studies on the effects of dam construction on ecosystems; thus, applying a comprehensive model that spatiotemporally investigates various ecological, social and economic factors in a large region is needed. The main objective of this study is the spatiotemporal ecosystem health assessment of Taleghan watershed in two periods of time, aiming to recognize critical areas and the effects of the dam on regional ecosystem health.

## 2 Materials and Methods

### 2.1 Study Area

Taleghan region is located in the northwest part of the Alborz Province, Iran (Fig. 1) and extends between the Latitudes 36°05" and 36°25" North and Longitudes 50°25" and 51°10" East. The study area is Taleghan watershed composed of the Taleghan River as the main flow. This river in the southern part of the dam joins the Alamout River and they both run to the Shahroud River. The whole region with area of 1183.29 km<sup>2</sup> is generally located in lands with high elevations and slopes, and average height 2250 m above sea level. Mean annual precipitation and temperature are about 500 mm and 11.5 °C, respectively. Construction of a dam in this area started in 2002 and finished after 5 years in 2007.

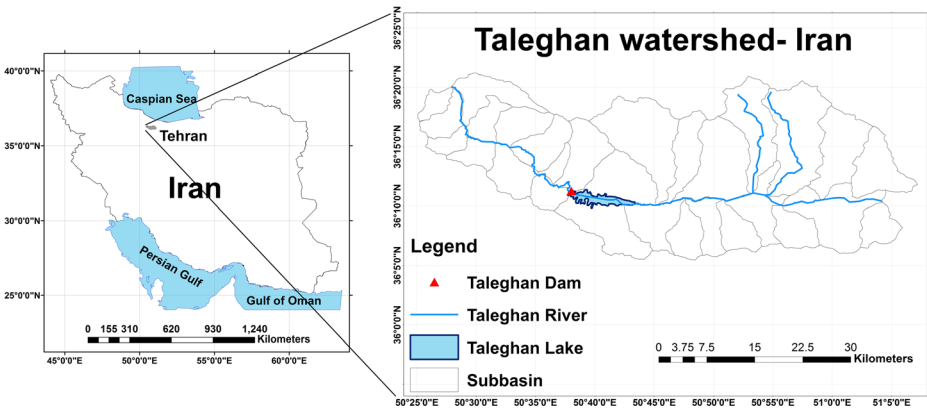


Fig. 1 Location of the study area

## 2.2 Data Used

Three cloud free Landsat surface reflectance images with 30 m spatial resolution acquired in summers of years 2002, 2007 and 2015 were used. Also, different spatial and non-spatial data were applied from various sources. The data used are presented in Table 1.

## 2.3 Ecosystem Health Assessment Process

Ecosystem health assessment has a long history in the world. Several issues should be considered in the process of ecosystem health assessment, and these key concepts are discussed in the following sections.

Table 1 Data used

Data type	Data used	Source
Image data	Landsat 7 ETM surface reflectance image in 2002 Landsat 5 TM surface reflectance image in 2007 Landsat 8 OLI surface reflectance image in 2015	United States Geological Survey (USGS)
GIS data	30 m digital elevation model 1:250,000 vector map of rivers and roads 1:280,000 soil erodibility map	Shuttle Radar Topography Mission (SRTM) Iran Ministry of Roads & Urban Development Iran Ministry of Agriculture Jihad
Other data	Population data based on the results of the national census in 2011 Annual precipitation data of ground meteorological stations inside and near the area Annual temperature data of ground meteorological stations inside and near the area Annual solar radiation data of ground meteorological stations inside and near the area	Statistical Center of Iran Iran Meteorological Organization

### 2.3.1 Assessment Methods

There are two approaches to assess the ecosystem health: First, evaluation based on the characteristics, structure and functions of different indicative species which reflect or predict the status and conditions of a particular ecosystem in a simple and easy way. But this method has its own limitations: difficulty and no specific standard for sensitive species selection, lack of clarity and inability to include the aspects of social, economic and human health (Dai et al. 2007; Peng et al. 2007; Siddig et al. 2016; Xu et al. 2012).

Second, establishing an indicator system. Indicators are measures which provide valuable information about various phenomena which are not directly accessible. Indicators are appropriate instruments for understanding complex systems (Kandziora et al. 2013; Zhang et al. 2016). Each index reflects a special feature of the ecosystem. A set of wisely chosen indicators lead us toward achieving status, structure, relationships and problems of a complex human dominated ecosystem (Miller and Rogan 1997). The challenge is to create an indicator system which reflects the key attributes of the ecosystem and will meet to the best the users' needs (Rice 2003). In addition, logistical constraints (e.g., time, cost) and difference in units and dimensionality of indicators complicate the selection of indicators. It is difficult to demonstrate how indicators represent ecosystem health. Hence, selecting and combining inappropriate indicators may lead to inaccurate evaluation (O'Brien et al. 2016; Sun et al. 2017).

Since the development of different indicators has been facilitated by the use of remote sensing and GIS (Yu et al. 2013), the indicator system model was selected for ecosystem health assessment method in this study, so that these indicators can be evaluated using these technologies.

### 2.3.2 Conceptual Framework

Applying indicators in integrated ecological and socio-economic system assessment, according to an approach based on decision making, requires a conceptual framework (Bell 2012; Gregory et al. 2013). Ever since Statistics Canada developed the Stress-Response (S-R) framework in 1979, numerous models have been designed by scientists (Friend and Rapport 1991). This evolved into the Pressure-State-Response (PSR) by OECD (OECD 1993) and Driver-State-Response (DSR) by UN (UN 1996) for evaluation of environmental performance. There are several frameworks around in order to develop and organize an indicator systems (Gari et al. 2015). Driving force-Pressure-State-Impact-Response (DPSIR) model was adopted by the European Environmental Agency (ESA) in 1995 to overcome the shortages of the PSR model and consider indicators that were not covered by that model (especially economic indicators) (EEA 1995).

Applying the DPSIR model involves a great deal of information gathering to formulate various indicators (Jago-on et al. 2009). The DPSIR model has many applications in different environment decision makings at different scales (Pullanikkatil et al. 2016).

### 2.3.3 Indicator System

According to the properties of the DPSIR model, this model was chosen as a basis for selection and categorization of the indicators in this study. Response indicators are related to such environmental and social activities that government, organizations and people involved with the environment conduct in order to preserve the nature. Unfortunately, no part of the study

area is in the natural reserved regions in the country and no conserving actions has been carried out over the past years in the study area. Therefore, the lack of access to data on activities related to the response indicator has been the limitation of this research. Hence, we were obliged to not include the response indicator in our model.

Subsequently, according to the objective of this study, which is the assessment of the ecosystem health, accessible data sources, characteristics of the region and published works, an indicator system was established including 11 indicators, as described in Table 2.

**Driving Force (D) Indicators** Solar energy is one of the main sources of energy for various chemical, physical, and biological processes on the earth's surface. In fact, solar radiation is an effective factor in the ecological, hydrological and bio-physical processes (Liu et al. 2011a). Solar radiation is determined as the sum of direct shortwave radiation of the sun and diffused radiation (Ambas and Baltas 2014). Potential solar radiation maps were created based on Co-Kriging interpolation of DEM and average annual temperature and average solar radiation values from ground meteorological stations inside and around the study area in ArcGIS software.

The growth of population density is associated with negative effects on ecosystem health (Sun et al. 2016). Population density maps were calculated by the population statistics (based on the results of the national census in 2006 and 2011) using ArcGIS. The border of urban and rural areas were defined and related population densities were assigned to them.

**Pressure (P) Indicators** Changing the land use dynamics by human activities have largely influenced the earth environment (Singh et al. 2015). Land use changes are usually associated with negative effects on ecosystem services (Pullanikkatil et al. 2016).

Landsat surface reflectance images were used to produce land use/land cover (LULC) maps. Regarding the features of the study area, the resolution of Landsat images, the desired indicators and field works, 6 classes including residential, agricultural, forest, vegetation, grassland, water and bare soil were identified for LULC maps. Besides, based on these features, it was observed that the separation of the classes using maximum likelihood procedure is associated with reliable results. After the production of LULC maps for the 3 years (2002, 2007 and 2015) in ENVI software, the accuracy of classifications were assessed using 210 ground samples. The calculated kappa coefficient for each map was 0.85, 0.83, and 0.90, respectively. Also, the overall accuracy for each map was 90.7%, 88.6% and 93.1%,

**Table 2** Indicator system for assessing the ecosystem health in the study area, based on the DPSI model

Indicator type	Indicator name	Effect on ecosystem health
Driving force	Population density	–
	Potential solar radiation	+
Pressure	Land-use change	–
	Human footprint	–
	Changes of NDVI	+
State	Vegetation coverage	+
	Grassland pattern	+
	Landscape diversity	–
	Topographic wetness index	+
Impact	Traffic impact	–
	Soil erosion	–



respectively. Then, land use change maps were prepared based on cross tabulation of the LULC maps in ArcGIS in two time periods, i.e., 2002–2007 and 2007–2015.

Changing natural lands to artificial land uses by human activities is a threat to the health of the ecosystem, because it has negative effects on the landform, climate and community structure. Human footprint presents the extent and intensity of anthropogenic presence and human actions (Chi et al. 2018; Tapia-Armijos et al. 2017). Human footprint maps were produced based on conversion of natural land covers (including forest and vegetation, grassland, water and bare soil) to artificial land uses (man-made land uses including residential and agricultural) as well in ArcGIS.

Normalized Difference Vegetation Index (NDVI) is useful in evaluation of ecosystem vigor. Spatial and temporal changes and trends of vegetation distribution, productivity, and dynamics can be assessed by NDVI (Sun et al. 2016). In this project, maps of NDVI changes were produced based on Landsat images in ENVI.

**State (S) Indicators** Vegetation coverage is the source of primary production. Hence, changes in vegetation pattern can affect many elements of an ecosystem (Gray and Azuma 2005). Grasslands are the main source for provision of feed for animals. Also, grasslands have major role in supporting biodiversity and in providing other benefits to the community such as biomass for bioenergy, carbon sequestration, climate regulation, ecological balance and recreational opportunities (Qi et al. 2018; Shao et al. 2018). Therefore, vegetation coverage and grassland pattern maps were created using the classification of NDVI maps in ArcGIS.

Ecological functions of spatial patterns of features inside the landscapes are important for ecologists (Roberts et al. 2011). Natural and human factors affect the landscape pattern associated with the geographic space. Landscape diversity and fragmentation influence the structures, functions, and processes of the ecosystem (Chi et al. 2018). There are many indices introduced for evaluating landscape structure and fragmentation based on statistical measures of dispersion, fractal geometry, information theory and percolation theory (Rommel and Csillag 2003). Each of these indices focuses on some certain aspects and properties of landscape, and thus, has its specific advantages and disadvantages.

In order to develop a landscape diversity indicator, three of the most important landscape indices, i.e., patch density (PD), Shannon's diversity index (SHDI), Interspersion and Juxtaposition index (IJI), were chosen to be combined. At first, as landscape units, 29 sub-watersheds were extracted using a 30 m DEM data in ArcGIS. Then, the three indices (PD, SHDI, and IJI) were computed using land use/land cover maps in FRAGSTATS software. Finally, one landscape diversity index was produced using PCA of these three indices.

Soil moisture is a significant factor in the assessment of vegetation composition, structure and functioning of different ecosystems. The spatial pattern of groundwater levels affects soil processes and as a result influences the properties of the soil. Topographic Wetness Index (TWI) is the most popular DEM-based index of soil moisture. TWI evaluates the changes of soil water distribution, which is affected by topography (Martin and Štěpánka 2010; Raduła et al. 2018; Sørensen et al. 2006). Topographic wetness index was developed using DEM based on Eq. (1) in ArcGIS:

$$TWI = \ln(A_s/\tan \beta) \quad (1)$$

where  $A_s$  denotes the specific catchment area in  $m^2$ ; and  $\beta$  is the slope of the terrain surface in radiance (Mohamedou et al. 2017).



**Impact (I) Indicators** Road traffic leads to many environmental and social impacts, with air pollution the most important of them (Condurat et al. 2017). Urban and rural road maps were used in order to produce a map showing the distance from roads. Finally, distance maps were united and merged in ArcGIS to create a map called traffic impact.

Soil erosion has significant impacts on ecosystem services, reservoir sedimentation, crop production, downstream flooding, reservoir sedimentation and economic costs (Haregeweyn et al. 2017). The RUSLE model is the most frequently used model by scientists and was used for calculating soil erosion (Jiang et al. 2012). It is appropriate for predicting long-term soil erosion rates over large regions (Teng et al. 2018). The RUSLE is expressed as Eq. (2):

$$A = R K L S C P \quad (2)$$

where A is the average annual soil loss in tons per acre per year; R is the rainfall-runoff erosivity factor in megajoules millimetre per acre per hour per year; K is the soil erodibility factor in tons hour per megajoules per millimetre; L is the slope length factor; S is the slope steepness factor; C is the cover-management factor; and P is the support practice factor. L, S, C and P are without unit (Efthimiou 2016).

Precipitation data, soil erodibility map, DEM and Landsat images were used for developing maps for each factor of Eq. (2). Maps were combined in ArcGIS and a soil erosion map was finally produced.

### 2.3.4 Weight of Evaluation Indicators

In order to define the priority of various indicators, a certain weight is assigned to each of them. These weighting values refer to the relative importance of each indicator (Liu et al. 2011b; Muñoz-Erickson et al. 2007). There are two main approaches for assigning weights to the indicators: objective and subjective methods. The objective method is completely dependent on the characteristics of the data regardless of any pre-knowledge or human experiences, opinions and judgements. Some of the most widely used approach involved in this category include: factor analysis, PCA, entropy model, standard deviation model, Pena Distance (DP2) method and information weight method. On the contrary, the subjective method requires expert consultation information and professional experiences, such as the AHP or Delphi model (Montero et al. 2010; Xu and Guo 2015).

So, as the ecosystem health assessment is a human subjective judgment, subjective methods are used in weighting indicators more. However, in objective methods detailed value of all evaluation indicators affect the weights (Peng et al. 2007). In view of what was mentioned, in this research we have used the multi-criteria decision making (MCDM) processes in order to weight indicators.

## 2.4 Spatial Decision Support Systems (SDSS) for Ecosystem Health Assessment

Ecosystem health assessment is a kind of spatial multi-criteria decision problem. MCDM is a set of methods for comparing, selecting, or ranking multiple alternatives (Levy 2005). Decision making processes based on multi-criteria analysis in GIS environment are intelligent systems that actually make up the basis of SDSSs, and are used in many cases

of environmental management, like environmental and regional planning, ecology management, hydrology, soil and water resources, forestry, agriculture, natural reserve and environmental health. In a GIS-based MCDM, spatial and non-spatial data are applied and different maps can be considered as the alternatives of MCDM and be assigned a weight as criterion values (criterion map) (Gbanie et al. 2013; Ghamgosar 2011; Malczewski and Rinner 2005).

A SDSS uses expert knowledge and specialized solution algorithms in the problem domain to address semi-structured planning problems (Gorr et al. 2001). In the SDSSs, the input data have a spatial component. In fact, SDSS can be used to understand and evaluate distributed spatial phenomena (Sakamoto and Fukui 2004). Spatial modelling, remote sensing and GIS data and MCDM can be combined in SDSS (Sugumaran et al. 2004).

### 2.4.1 Fuzzy AHP Process in GIS Application

Various methods have been developed based on MCDM and one of the most well-known is the AHP. In this method relative prioritization between alternatives is carried out in a hierarchical structure based on the expert judgment (Saaty 1980).

Although AHP is a popular method, it cannot efficiently handle the inevitable uncertainty and low accuracy in converting user sights and ideas into exact numbers (Deng 1999). This vagueness associated with decision making in AHP has led researchers into the use of fuzzy logic and combine it with this method to tolerate vagueness or ambiguity (Mikhailov and Tsvetinov 2004). Indeed, when humans deal with complex and multi-attribute decision making problems, they cannot express their opinion in the form of precise numerical parameters and prefer to give interval judgments and linguistic variables. Fuzzy AHP method has been developed in such a way that is capable to capture decision maker relative judgments (Erensal et al. 2006; Malczewski 1999).

### 2.4.2 Developing the AHP Hierarchy

As the first step in AHP method, the decision problem should be decomposed to different levels which consist of the most important components of the problem in a hierarchical structure. Hierarchical structure typically consists of the goal, objectives, attributes and alternatives. Accordingly, based on the conditions and specifications of this study, a 3-level hierarchy has been considered to demonstrate the spatial AHP procedure (Fig. 2). In our structure, the attribute level, i.e., the criterion map layer is related to the maps of 11 indicators, objectives are the maps of driving force, pressure, state and impact, and the goal layer is the map of ecosystem health.

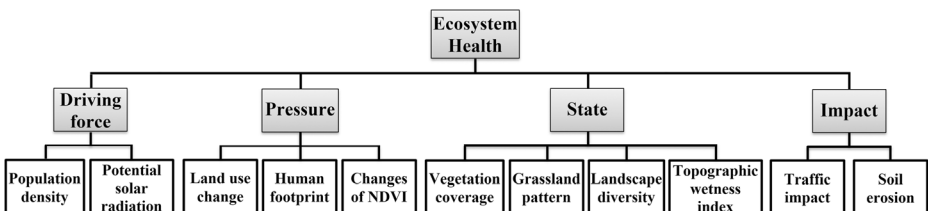


Fig. 2 Hierarchical structure of a three-level decision problem for ecosystem health assessment

### 2.4.3 Pairwise Comparisons

In AHP method for each layer of the hierarchy all the associated elements are compared in pairwise matrix, as in Eq. (3):

$$A = \begin{bmatrix} 1 & \frac{w_1}{w_2} & \dots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & \dots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \dots & 1 \end{bmatrix} \tag{3}$$

where A is the pairwise comparison matrix;  $W_i$  is the weight of element  $i$ ; and  $n$  is the number of elements.

In order to determine the relative preferences for two elements of the hierarchy in matrix A, Saaty (1980) proposed crisp scales for pairwise comparison. According to issues discussed above in connection with the ambiguity and vagueness of the judgments in the form of single numeric values, the crisp judgments were transformed into fuzzy judgments (Erensal et al. 2006). According to the Zadeh (1965) definition and description of the mathematics of the fuzzy sets, the fuzzy set theory is a generalization of classic set theory which allows the membership functions to operate over the range of real numbers [0, 1] (Vahidnia et al. 2010; Zadeh 1965).

In Fuzzy AHP method, uncertain comparison judgments are presented using fuzzy numbers. A triangular fuzzy number is the special class of fuzzy number whose membership is defined by three real numbers, expressed as (l, m, u). Triangular type membership function of a fuzzy set can be described as Eq. (4):

$$\mu_A(x) = \begin{cases} \frac{x-l}{m-l} & l \leq x \leq m \\ \frac{u-x}{u-m} & m \leq x \leq u \\ 0 & otherwise \end{cases} \tag{4}$$

The triangular fuzzy number is represented as follows (Fig. 3):

Using triangular fuzzy numbers, pairwise comparison matrix in AHP procedure will be as Eq. (5):

$$\tilde{A} = (\tilde{a}_{ij})_{n \times n} = \begin{bmatrix} (1, 1, 1) & (l_{12}, m_{12}, u_{12}) & \dots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1, 1, 1) & \dots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \dots & (1, 1, 1) \end{bmatrix} \tag{5}$$

where  $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$  and  $\tilde{a}_{ji} = \tilde{a}_{ij}^{-1} = (1/u_{ij}, 1/m_{ij}, 1/l_{ij})$  for  $i, j = 1, \dots, n$  and  $i \neq j$ .

### 2.4.4 Pairwise Comparisons Based on PCA

Since Fuzzy AHP is a subjective weighting method based on expert judgements, it may lead to a certain degree of arbitrariness and uncertainty in the assessment results. For this reason, we

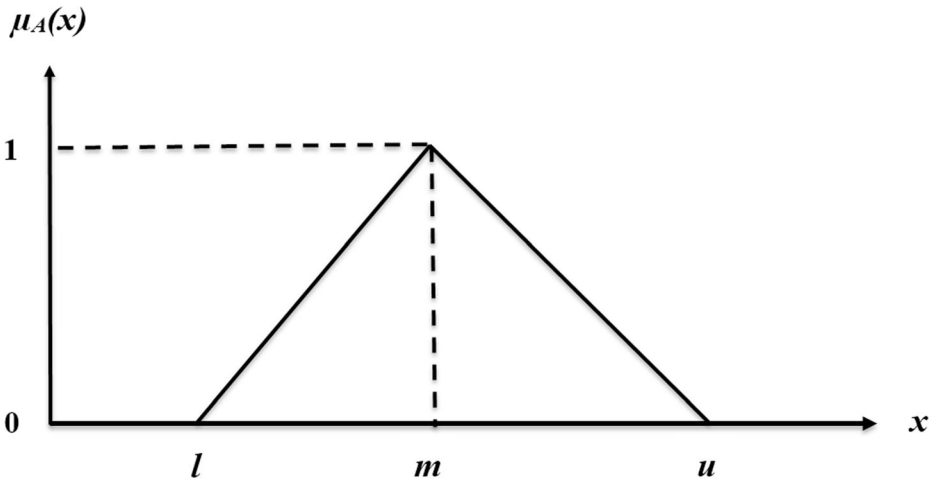


Fig. 3 A triangular fuzzy number A

propose to use an objective method in combination with Fuzzy AHP. Therefore, before the pairwise comparison phase, an objective model such as PCA can be applied to the indicators. Then, experts can use the PCA results to find a general overview of the indicators so that judgments are improved.

#### 2.4.5 Consistency of Pairwise Comparisons

The consistency of AHP judgements must be checked using consistency ratio based on consistency index and randomized index (Mustak et al. 2018). Gogus and Boucher (1998) proposed a method in order to calculate consistency ratio.

#### 2.4.6 Fuzzy Extent Analysis

There are different methods in the literature to calculate the weights and preferences of elements. Chang (1996) proposed their most well-known method using the extent analysis method in Fuzzy AHP (Chang 1996).

### 2.5 Conceptual Design and Implementation of the System

According to the discussions made earlier, in order to weigh indicators based on Fuzzy AHP method, we have three levels in the hierarchy structure of spatial decision problem in our system. First (goal) is ecosystem health, second (objectives) is DPSI indicators and the third (attributes or criterion map layers) is 11 indicators. Pairwise comparisons are made in 2 levels. Then, the weight of 11 indicators and Driving force-Pressure-State-Impact indicators are calculated.

After calculating the weights, maps of 11 indicators are obtained from spatial data base, and they are multiplied by their weights. As some indicators have positive effect on ecosystem health and the others have negative effect, positive or negative coefficients are assigned to each indicator. Subsequently, the maps of population density and potential solar radiation are added to create the driving force indicator, the maps of land-use change, human footprint and changes

of NDVI are added to make the pressure indicator, the maps of vegetation coverage, grassland pattern, landscape diversity and topographic wetness index are added to create the state indicator, and the maps of traffic impact and soil erosion are added together in order to develop the impact indicator.

After applying weights in these four indicator maps, these maps are merged to attain the map of ecosystem health which are produced based on Eq. (6). However, it is possible that positive and negative values are subtracted in the calculations, and subsequently, final results for ecosystem health may be inexact. Therefore, different indicator hotspots are specified and summed, so as to produce another map as risk area of ecosystem health.

$$HI = \sum_{i=1}^4 W_i \times C_i \tag{6}$$

where HI is the comprehensive index of ecosystem health;  $W_i$  is the weight of indicator  $i$  (DPSI indicators); and  $C_i$  is the quantitative and dimensionless value of DPSI indicator  $i$ .

Also, the system must have a user-friendly interface to enable users to easily perform varied operations such as: pairwise comparisons entrance, calculating weights, representing weights, applying weights, displaying indicators, ecosystem health and area-risk maps, and so forth. (Fig. 4).

A SDSS incorporating the previously mentioned features was designed and implemented as a module in ArcGIS 10.1 using Arc objects. Arc objects allow customization of the application using any Component Object Model (COM-compliant) development language (ESRI 2004). Visual studio- C# environment was used for programming with Arc objects. Therefore, the input data (the maps of different indicators) should be in standard ESRI formats. The output, DPSI maps, ecosystem health map and area-risk maps are raster data layers. Figure 5 shows the interface of the created SDSS for ecosystem health.

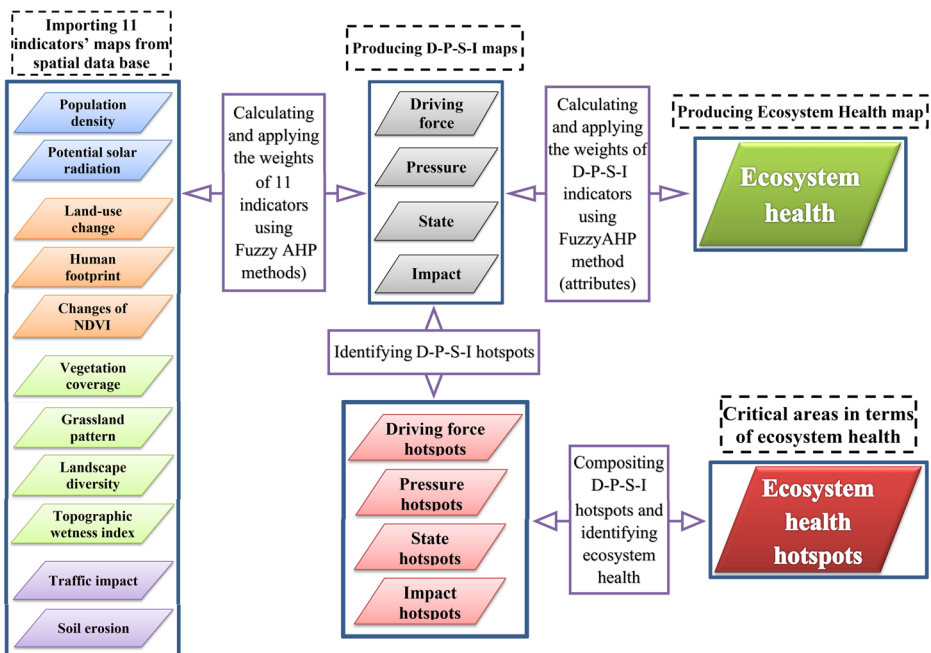


Fig. 4 General view of proposed model for a spatial decision support system for ecosystem health

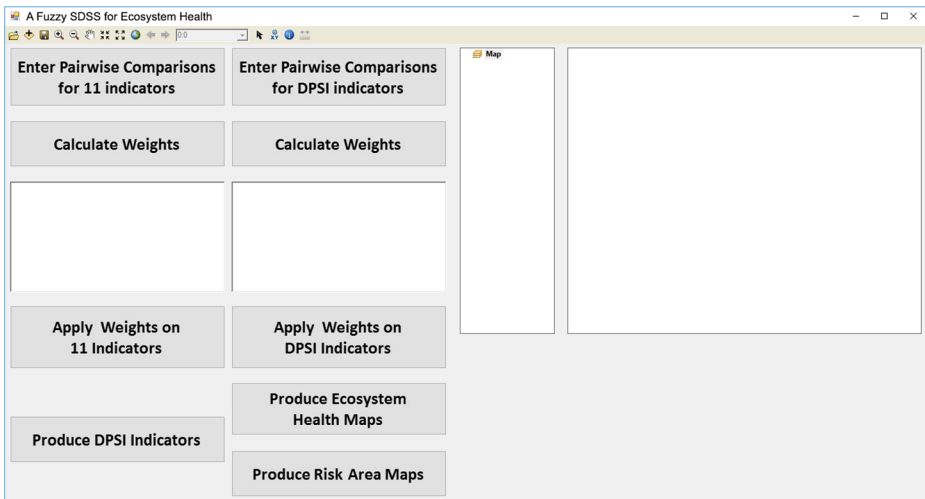


Fig. 5 The interface of the created SDSS for ecosystem health assessment

### 3 Results and Discussion

After preparation of maps related to different indicators in both periods of time, the maps were imported into the system as inputs in order to assess ecosystem health in study area.

#### 3.1 Weights

Consistency ratio of pairwise comparisons were less than 0.1. Hence, AHP judgements were consistent. Subsequently, the weights of all 11 indicators (sub-criteria layer) and DPSI model indicators (criteria layer) were calculated based on Fuzzy AHP method. Tables 3 and 4 show the weights.

Previously mentioned, the output of the system are the ecosystem health maps and ecosystem health risk area maps result from assessing different indicators.

**Table 3** The weights of 11 ecosystem health indicators

Indicator	Weight
Population density	0.0157
Potential solar radiation	0.0157
Land-use change	0.1851
Human footprint	0.1205
Changes of NDVI	0.1851
Vegetation coverage	0.1851
Grassland pattern	0.0954
Landscape diversity	0.0954
Topographic wetness index	0.0033
Traffic impact	0.0033
Soil erosion	0.0954

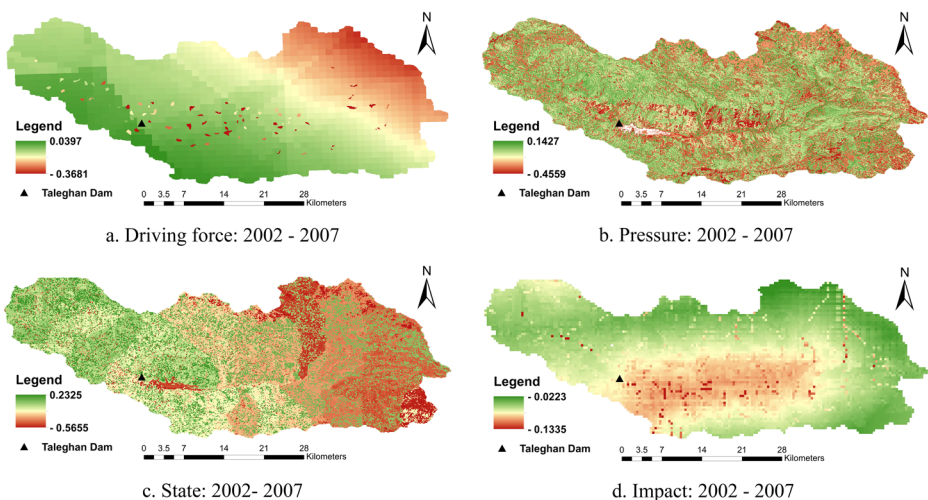
**Table 4** The weights of DPSI model indicators

Indicator	Weight
Driving force	0.1567
Pressure	0.3217
State	0.3217
Impact	0.2001

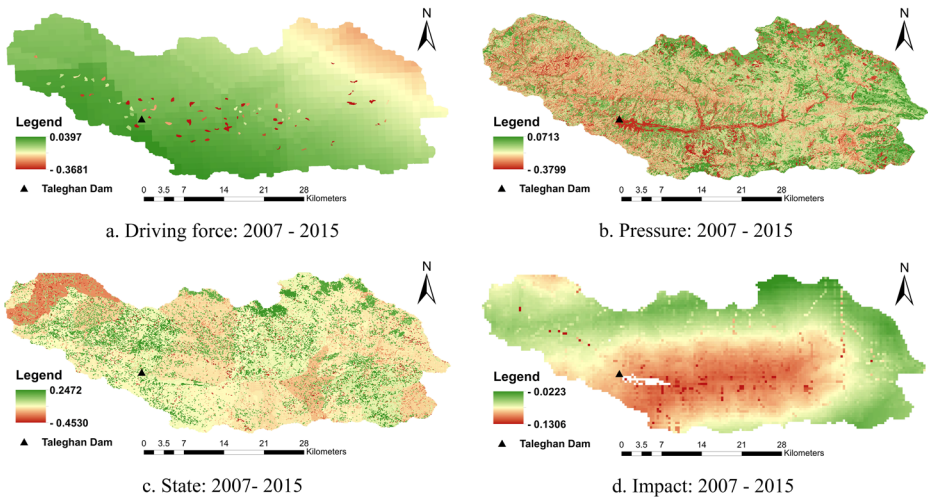
### 3.2 Ecosystem Health Assessment

In our model, the result of DPSI indicators have been identified in such a way that lower values of the indicators indicate more negative effect on the ecosystem health. As mentioned earlier, growth of population has negative effects on ecosystem health. On the other hand, potential solar radiation has positive effect, because the average monthly rainfall in the Taleghan watershed is high. Consequently, in regions with enough water, the increase in solar radiation is associated with increase in vegetation, which is considered as a positive factor in ecosystem health. So, in relation to driving force indicator (Figs. 6 and 7), areas with less potential solar radiation and with more urban and rural areas with people living there, have lower values of D indicator (higher driving force on the ecosystem). In the region of interest, the eastern area (upstream of the dam) has lower potential radiation. Urban and rural areas are mostly in the central region (along the Taleghan river path). In total, the status of D indicator was approximately the same before and after the construction of the dam, and the dam construction cannot be known as an effective factor on this indicator.

The Pressure (P) indicator includes 3 indicators and the status of it was as follows: In the first period, the land use changes had mostly occurred in the upstream and central area near the dam. However, in the second period, while there were still land use changes in the upstream and central area, they were increased in the downstream area. In the first period, the human-caused changes (human footprints), which basically include artificial and man-made land uses, had mostly occurred in the central area near the dam, but in the second period, these changes occurred not on one specific area but everywhere. Regarding the changes of NDVI indicator, it

**Fig. 6** Maps of: **a** Driving force; **b** Pressure; **c** State; **d** Impact indicators before dam construction





**Fig. 7** Maps of: **a** Driving force; **b** Pressure; **c** State; **d** Impact indicators after dam construction

has positive effect on ecosystem health based on Table 2, which means that the increase in NDVI is a positive factor in the health of the ecosystem. Based on the results, in both periods, we have witnessed an increasing trend in the values of the average regional NDVI; from 2002 to 2007 and from 2007 to 2015 the NDVI value has increased in each period approximately by 0.03 which means that from 2002 to 2015 the difference of the average regional NDVI was approximately 0.06. It should be noted that this increasing trend was almost the same in all areas (upstream, centre and downstream parts of the basin).

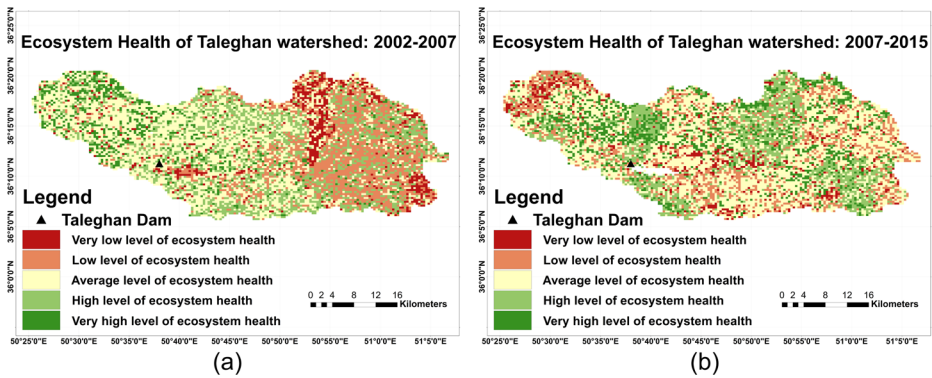
By mixing the indicators and creating P indicator maps (Figs. 6 and 7), we can witness that in both periods, first and second, the central area (near the dam and near the river) is considered as a critical area in terms of P indicator.

The grasslands were reduced in the downstream (western) region in the second period whereas the vegetation had a better condition. This shows that the agricultural lands have been expanded in the downstream area after the construction of the dam where the grasslands have been changed to agricultural lands. These findings support the results related to the other indicator of state (landscape diversity). According to this indicator, the eastern area (upstream) faced landscape diversity and fragmentation in the first period and, after the construction of the dam, the critical areas in terms of landscape diversity was transferred to the western (downstream) area. Then, the indicators related to state were combined and the maps of S indicator were produced for both time periods (Figs. 6 and 7).

Regarding the impact (I) indicator (Figs. 6 and 7), we can see almost an identical situation in both periods. In terms of this indicator, the critical areas are more common in the central areas due to the closeness to the rural and urban roads, as well as due to increased soil erosion.

In the final step, ecosystem health maps were derived for both periods based on Eq. (6) and the combination of D, P, S, and I indicators (Fig. 8). In the first period, the critical areas in terms of ecosystem health had occurred more in the eastern parts in the upstream area of the dam. After the construction of the dam, the critical areas were mostly in the downstream area (north west part of the region).

Between 2002 and 2007, 7.31% of areas had very low, 22.48% had low, 38.5% had average, 24% had high and 7.64% had very high level of ecosystem health. After 2007, these



**Fig. 8** Ecosystem health map of Taleghan Watershed: **a** before dam construction; **b** after dam construction

percentages were equal to 5.83, 17.54, 43.87, 18.04 and 14.72%, respectively. In fact, 29% of the area during the first period and 23% in the second period had a low and very low level of ecosystem health. Accordingly, there is not much difference in the size of the critical areas in the two periods. The main point is the shift in the critical areas from the upstream areas to downstream areas after the construction of the dam.

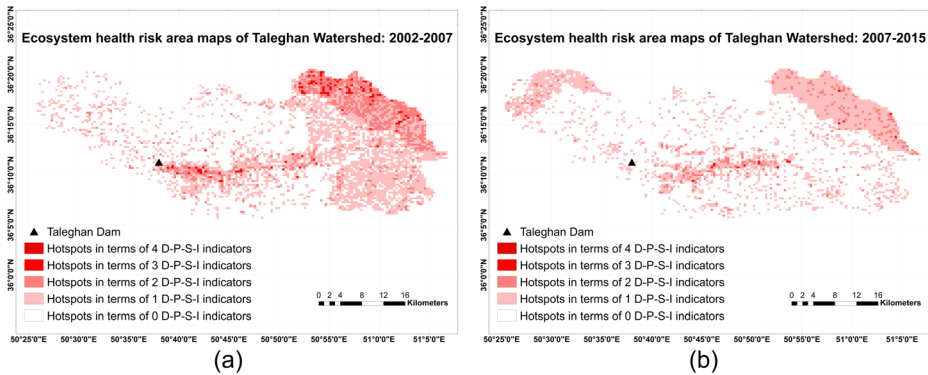
Since the unit of the different indicators varied, and the resolution of the grid data was different, we faced with the salt and pepper like outcome. Although, many other studies tend to consider larger ecosystem health assessment units (such as the administrative unit and sub-watershed unit) to get other kind of output format (Peng et al. 2015; Sun et al. 2016; Yu et al. 2013), this study was done on the grid unit to provide more details about the ecosystem health of the region, and this form of output was inevitable. In this way, accurate interpretation and determination of critical areas is possible in comparison with other studies (Zhang et al. 2017).

### 3.3 Ecosystem Health Risk Area

Since Eq. (6) is an aggregated formula for calculating ecosystem health and it is possible to neutralize positive and negative values in different indices, the analysis of the critical areas was also performed as follows. First, the critical areas were obtained over both periods for the 4 indicators (D, P, S, I). Second, the first and second period maps were combined with each other, and two maps were prepared (Fig. 9), which determined which areas were among the critical areas and which areas were quite healthy in terms of different indices for both periods.

The comparison between Figs. 8a and 9a and Figs. 8b and 9b shows that the spatial pattern of the ecosystem health status is approximately the same in both periods. In the first period, the critical areas in terms of the ecosystem health were more in the eastern parts in the upstream area, and in the second period they were placed more in the northwest parts in the downstream area of the dam. However, in the risk area maps, we are confronted with the fact that areas near the river were also in critical areas during both periods of time. While this subject is hidden in ecosystem health maps.

For the first period, the eastern parts (especially north east) of the region in the upstream of the dam were critical areas in terms of ecosystem health. Since a vast part of the central areas of the region, which are located in the upstream of the dam, have been healthy (except for areas adjacent to the river) and the critical areas had been relatively located in a far distance from the dam, it cannot be certainly stated that the construction of the dam directly affected the



**Fig. 9** Ecosystem health risk area map of Taleghan Watershed: **a** before dam construction; **b** after dam construction

ecosystem health of these areas. In relation to the second period, changes in the ecosystem health of the region have been associated with the shift of critical areas to the downstream areas. Therefore, it can be said that after the construction of the dam, we have seen its direct effect on the ecosystem health of the region.

### 3.4 Uncertainty Analysis of the Model

As mentioned above, in calculating the weight of the indicators by Fuzzy AHP method, at the stage of the pairwise comparisons, first a PCA was performed on the indicators. Hence, the experts reached an overview of the status of the indicators so that they could make judgments more accurately. In fact, in this study, we combined two widely used methods in weighting the indicators (Liao et al. 2018; Sun et al. 2016, 2017; Yu et al. 2013) along with fuzzy technique. Accordingly, in relation to the uncertainty discussion of the assessment indicators in this study, we can look at the calculated weights for each indicator. In addition, the very important issue that arises in the uncertainty is the data used.

Based on the weighting results, land-use change, changes of NDVI and vegetation coverage indicators had the highest weight. All these three indicators are directly obtained from Landsat images at the resolution of 30 m. These indicators are very important factors in the health of the ecosystem and affect it directly and indirectly. Therefore, these three indicators have the highest certainty in our model. After them, the human footprint indicator has a high weight. This indicator has less weight and certainty in comparison to the previous three indicators, for two reasons. At first, it is in some way dependent on the land-use change. Secondly, contrary to the opinion of some experts, all human made changes in the ecosystem are not necessarily a negative factor in ecosystem health. In the following, grassland pattern, landscape diversity and soil erosion indicators have an average certainty compared to other indicators. Some issues are raised in relation to these indicators which have decreased the certainty of these three indicators. Increase in grassland pattern is not always a positive factor in ecosystem health and sometimes the reduction of grasslands and conversion to orchards and agricultural lands can be beneficial. Furthermore, the unit of landscape diversity indicator was the sub-watershed and, when compared with other indicators which were in grid unit, it provides less detailed information on ecosystem health. Also, data on the soil erosion indicator are from different types and dimensions and the changes in

this indicator have been low over two periods. Population density and potential solar radiation indicators have low weight. Since the population density indicator was only used in urban and rural areas and its data was related to the 5-year census and were not up-to-date, there is little certainty about this indicator. In addition, the uncertainty about potential solar radiation indicator is high because not only is this indicator based on the interpolation of meteorological data, but also it does not have direct effect on ecosystem health. Finally, the least certainty is assigned to topographic wetness index and traffic impact because these two indicators were constant over two periods of time.

In general, if there were more accurate and up-to-date data on the various indicators, as well as the information on the response indicator as a part of the DPSIR model was available, the certainty of the indicators and outcomes of this study could be greater.

### 3.5 Achievements, Limitations and Future Studies

Other studies in the field of applying remote sensing and GIS in ecosystem health assessment usually had large-scale assessment units such as urban units, sub-watersheds, and so on. In this study, we worked on the grid unit to specify the hotspots that needed to identify with more precise specifications and coordinates. This information can be made available to policy and decision makers and local managers to define and carry out necessary actions in these areas to improve ecosystem health. Plus, in analyzing and weighting our various indicators, we used fuzzy methods, combined objective and subjective methods, and considered uncertainty of different indicators based on their characteristics, to achieve more accurate and reliable results. Furthermore, most other studies only used remote sensing data, but we used data from other sources along with satellite data. However, this study had some limitations:

- Some data was not up to date.
- There was no access to some of the required indicators.
- The evaluation of ecosystem health changes was not possible in shorter periods of time.
- The resolution of some data was not high.

In the absence of these limitations, more complete and precise results could be obtained from the ecosystem health status of the area and the effects of the dam construction on it.

Since we have developed a spatial decision support system, different users around the world can use our model to assess the ecosystem health of other regions. Also, this model will be able to be used on the other indicator systems and conceptual frameworks and in different ecosystems.

## 4 Conclusions

The developed Spatial Decision Support System for ecosystem health assessment is able to compute and apply the weights of indicators based on Fuzzy Analytic Hierarchy Process method. Since the weights have significant effect on the results of the assessment, it was found that the combination of subjective and objective weighting methods could lead to a more accurate evaluation of the indicators. After combining different indicators and preparing the output maps in the grid unit, the critical areas in terms of ecosystem health in the study area was determined by the system.

The final results of the ecosystem health assessment during both periods, i.e., before and after dam construction, showed that most of critical areas were located in the eastern parts of the watershed in the upstream area before the construction of the dam. However, after the dam construction, the critical areas shifted to the northwest parts in the downstream areas. This is due to reduction of grassland patterns and creation of agricultural lands which subsequently resulted in an increase in landscape diversity and fragmentation. About the effects of dam construction on ecosystem health of the region, it can be concluded that after construction of the dam, the ecosystem health of some downstream areas has encountered serious problems.

The critical areas were characterized by precise coordinates in the grid unit. In all these areas, it is clear which of the indicators have caused the low level of ecosystem health. Therefore, policy and decision makers and local managers can define and perform required actions on the basis of research results to improve the level of ecosystem health.

The developed model and system can be used in various ecosystem health studies. On the other hand, the SDSS has been developed in such a way that it can be used in other conceptual frameworks and indicator system. It can be recommended that if the application of this model and system in other regions be associated with data on the response indicator and the ecosystem health be assessed in shorter time periods, greater and more accurate results can be expected.

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