Assessing the health and ecological security of a human induced watershed in central Iran

Seyyed Hamidreza Sadeghi, Mehdi Vafakhah, Vahid Moosavi, Sanaz Pourfallah Asadabadi, Padideh Sadat Sadeghi, Abdulvahed Khaledi Darvishan, Reza Bagheri Fahraj, Seyed Hossein Mosavinia, Abdolghasem Majidnia, Sudabeh Gharemahmudli and Hamidreza Moradi Rekabadkolaee

ABSTRACT
Assessment of the watershed health and associated ecological security is crucial for the proper land resources management, notably when sufficient money and time have lacked. The present study aimed to prepare health and ecological security for the Pishkhu Watershed in Yazd Province, central Iran. To prepare the health atlas of the Pishkhu Watershed, the conceptual framework of pressure, state, response (PSR) was employed. The pressure index was investigated by analyzing the driving forces of natural and human-induced factors. Then, the existing conditions of the natural environment and the watershed performance were analyzed using the state index. Besides, the response index was also calculated as a criterion for expressing the degree of community response or different watershed outcomes to the driving forces imposed on the watershed system. The study results revealed that some 91 and 9% of the watershed were classified as moderately healthy and relatively unhealthy. The results of the ecological security index further showed that some 41% of the area was categorized as relatively poor status. The results of the current study can be used by local managers and decision-makers to adaptively designate appropriate, economic, and goal-targeted solutions for the resources management in the region.

Introduction
The population growth and human biological needs, especially in developing countries, have led to improper use of land resources (Sadeghi et al. 2020b). The strategy of increasing production by over-exploitation of resources has faced many countries worldwide, with a severe crisis today, particularly in water and the environment. The state of the watersheds is collapsing due to the imbalance between humans and the environment leading to various environmental, social, economic, and political consequences (Sadeghi and Sharifi Moghadam 2021). On the other hand, improper management of water and land resources has threatened the country’s water and food security (Khajoi 2017; Hazbavi, Sadeghi, and Gholamalifard 2018d). In this regard, the assessment and comprehensive management of watersheds have recently been discussed in international scientific forums as an effective and efficient approach to water, land, and related resources management and balancing the socio-economic needs of watershed communities (Hazbavi et al. 2018a, b and c). It has been emphasized that watershed health assessment is one of the most fundamental pillars for sustainable watershed management (Yu et al. 2013; Sadeghi, Hazbavi, and Gholamalifard 2019b).

The watershed health is a broad term that includes water resources, ecological quality (i.e., vegetation, plant, and animal communities), geomorphological features, rainfall-runoff processes, and morphological features (Jat et al. 2008; Hazbavi et al. 2018b). Also, healthy ecosystems are naturally dynamic and often remain in healthy status. However, in many ecosystems, due to land-use change, uncontrolled increase in groundwater exploitation, and dam construction, the natural regime has been disrupted increased watershed vulnerability (Yaghmaei et al. 2018; Wang et al. 2018; Momenian et al. 2019). On the other hand, a healthy watershed should have the necessary structure and function to maintain the health of aquatic...
ecosystems, water margins, and land, and also include the appropriate vegetation status to support dynamic hydrological and geomorphological processes within the range of their natural changes (Liang, Liming, and Guijie 2010).

Watershed health is one of the essential concepts in the conservation and sustainable management of watersheds (Jat et al. 2008). Watersheds are related to socio-economic systems because the health and welfare of human societies are closely intertwined with the health and welfare of the watersheds (Sadoddin et al. 2019). In many studies, ecological concepts, approaches, and frameworks have been used directly in defining and assessing watershed health. At the same time, it should be noted that ecological processes are only one of the watershed components. Hence, the holistic processes of the bio-physical environment, human society, and relationships have to be incorporated in the watershed health assessment (Hazbavi et al. 2018a).

The comprehensive and health-based management of the watershed consists of measures such as changing the pattern of utilization of natural resources, optimization of water utilization systems, and conservation agriculture appropriately designated by managers, policy-makers, experts, and other stakeholders, ultimately leading to ecological balance, and socio-economic improvements (EPA (Environmental Protection Agency) 2014). Watershed health indicators are used to quantify watershed health metrics that reflect current watershed conditions. Different indices of the watershed are used to quantify the watershed health criteria and are the way to obtain information about degradation due to anthropogenic or natural factors (Vitousek et al. 1997; Jat et al. 2008). Healthy and sustainable watersheds provide the services of many ecosystems in various fields of physical, biological, social, and economic welfare and methods. They should be developed based on the degree of health and level of sustainability of watersheds (Hazbavi and Sadeghi 2017).

Today, watershed sustainability is essential for both watersheds and the sustainability of life in their ecosystems, although little attention has been paid to this issue (Asadiliwan et al. 2018). Key indices and indicators from a set of anthropogenic, climatic, hydrological, geological, soil and vegetation factors representing current health conditions are introduced and developed to assess the watershed health. In this regard, the use of any of these criteria alone cannot correctly indicate the health status of the study ecosystem. Accordingly, a combination of these criteria has to be considered. However, combining these criteria and indicators varies depending on the study conditions and is one of the main challenges in assessing ecosystem health (Hazbavi et al. 2018b). For this purpose, various conceptual frameworks have been presented to explain the effective criteria and indicators and the manner of the compiling (Dai et al. 2007; Hazbavi and Sadeghi 2016). In this regard, the conceptual framework of pressure, status, and response index (PSR) has been introduced and used to assess ecosystem health comprehensively. It can be stated that the conceptual framework of PSR, by organizing the criteria in the form of comprehensive indicators of pressure, state and response, has been able to determine the health in terms of all the conditions governing a system (Hazbavi, Sadeghi, and Gholamalifard 2018c). In the PSR conceptual framework, P refers to the pressures on the environment imposed on a watershed through human activities and natural factors. S describes the current state of the natural environment and watershed performance. R also expresses the degree of community response or different watershed outcomes to the driving forces imposed on the watershed system (Liang, Liming, and Guijie 2010; Hazbavi and Sadeghi 2017; Hazbavi, Sadeghi, and Gholamalifard 2018c). The PSR conceptual framework was first proposed by Rapport and Friend in 1979. It was developed in 1992 following an agreement between the Netherlands, Norway and the United States, and other Organization for Economic Cooperation and Development (OECD) member countries on environmental performance. This framework is based on the concept of causality. According to the governing concepts, any human activity or natural driving force inserts some pressures on the ecosystems (P) and puts the quantity and quality of natural resources in a specific state (S). Therefore, ecosystems will show a kind of response (R) to the pressure. Ultimately, the combined algorithm (PSR) mirror the health condition of the system, which can be used as a sound basis for the proper management of the prioritized areas (Hazbavi and Sadeghi 2016, 2017; Sadeghi and Hazbavi 2017; Asadiliwan et al. 2018; Sadeghi, Hazbavi, and Gholamalifard 2019b; Sadeghi et al. 2020b).

Regarding assessing ecological potential based on watershed health analysis and experiences of using the PSR framework, various studies have been conducted with different objectives of maintaining the health of the river, urban, and wetland ecosystems worldwide. In this vein, Yang et al. (2015) investigated the effect of remediation operations on the health of the Yellow River Delta Wetland in China by analyzing the PSR framework. Using hierarchical analysis, some 27 criteria were combined into a comprehensive PSR evaluation framework. The results showed that the wetland with a health index of 0.59 was moderately healthy. Alliou et al. (2019) evaluated the watershed health using the Fuzzy-ANP approach, taking geo-environmental and topo-hydrological criteria into account. In this study, an analytical network process (ANP) and fuzzy theory were used to investigate the relationships between the
geo-environmental factors and the classification and ranking of the health of each watershed. Wang, Li, and Li (2019) also assessed the sustainability of the Beijing water resources in China during 2012–2016 using the PSR framework. This study defined 24 indices from economic, social, and environmental factors. The results showed that in 2012, the stability of water resources was in relatively low productivity. The stability of water resources efficiency in 2016 was also relatively low. Momenian et al. (2019) prioritized the sub-watersheds of the Qoturchay Watershed in West Azerbaijan Province, Iran, based on the degree of watershed health. The prioritization of indicators showed that the health status of all sub-watersheds was moderate. Then, the cause of the decline in health conditions in each sub-watershed was investigated, and associated solutions were proposed to improve the health status. Sadeghi et al. (2019a) compiled a strategic and problem-based plan for the comprehensive management of the Asyabrood and Barrarud Watersheds in Chalous Township, northern Iran. Hazbavi et al. (2020) applied the conceptual PSR framework of the watershed health in the Shazand Watershed, Iran, for four target years of 1986, 1998, 2008, and 2014.

The health condition of the Shazand Watershed was found relatively unhealthy with temporal variations during the study span. In another study, Sadeghi, Hazbavi, and Gholamalifard (2020a) evaluated the current health status and effectiveness of watershed management measures in changing the Safarood Watershed health condition using the PSR conceptual framework. The results showed the relative difference in the indicators during the study periods and verified the difference in the type and extent of the influential factors on the health status of the study watershed. Zhang et al. (2020) also assessed water cycle health status based on the cloud model in 13 cities in China. Four characteristics of ecology, quality, quantity, and water consumption, were examined. The results showed that the water cycle health in the study area varied from unhealthy to a healthy condition. Mosaffaie et al. (2021) focused on analyzing the main environmental problems for the Gorganroud Watershed health in Iran using the Driving force-Pressure-State-Impact-Response (DPSIR) framework. The results showed that the health of the Gorganroud Watershed becomes worse over time due to the socio-economic activities and related pressures. In Taiwan and its outlying islands, Tsai, Lin, and Chen (2021) examined the health of seven sub-watersheds by analyzing data from 95 public water stores, power generation, and irrigation reservoirs. Health index standards were evaluated, and each sub-watershed was prioritized in terms of health index. Results showed that management strategy should be determined following the type of watershed. Recently, Mirchooli et al. (2021) assessed the sustainability of the Shazand Watershed in Iran with the help of an innovative barometer developed based on various social, economic, environmental, and policy dimensions. In general, the results of this study showed that the proposed sustainability barometer facilitated the understanding of dimensional and comprehensive sustainability of the study watershed and provided a practical reference for the proper policy-making and management at the watershed scale.

Besides watershed health and sustainability concepts, ecological security is when an ecosystem maintains its stability under external stresses (Huang et al. 2020). Studies on ecological security have been mainly considered during the current decade (Yu et al. 2009; Liu et al. 2018; Peng et al. 2018). Accordingly, Chang and Zhang (2014) investigated the ecological security of the Shuleh River, China. Also identified the leading indicators of the landscape pattern affecting the ecological security of the Shuleh Watershed. Zhang et al. (2020) investigated land-use/cover predictions incorporating ecological security for China’s Yangtze River region. They provided fundamental scientific guidance Davudi for spatial land planning given an ecological security premise. Huang et al. (2020) studied the declines in global ecological security under climate change. They showed a severe decline in ecological security in dry-lands expanded into surrounding regions over the past 60 years. They further reported that the response of ecological security to global warming and human activities is projected to be stronger.

The pressure-state (situation)-response (PSR) model objectively expresses the complex relationship between human economic activities, resource systems, and environmental systems. It further reflects the mechanism of reciprocal feedback between different evaluation indicators effectively. Hence, it is widely used in health and ecological security and ecological vulnerability assessment (Liao et al. 2018; Zhao et al. 2019; Sadeghi, Hazbavi, and Gholamalifard 2019b; Sadeghi et al. 2020c; Wang et al. 2021). The lack of a comprehensive conceptual framework for assessing watershed health and related ecological security and the necessity of operational guidelines for the proper management of the watersheds justifies insight research (Hazbavi and Sadeghi 2017; Sadeghi, Hazbavi, and Gholamalifard 2019b; Sadeghi and Hazbavi 2019). The current study was formulated to evaluate and prepare a health and ecological security map for the Pishkuh Watershed in Yazd Province, central Iran since it has been recently subjected to climatic, hydrological, and human stresses in recent years and has created natural, economic-social, and political challenges. Nonetheless, the conceptual framework has been rarely developed on the basis of existing issues and problems in the areas under consideration.
Therefore, in the current endeavor, the Pressure-State-Response (PSR) framework was systematically employed to assess the health and ecological security at sub-watershed scale and focusing issues and problems diagnosed in the region. The findings of the present study would provide an appropriate platform to assess health and ecological security conditions at regional and national levels. The results of the present study complement and enrich the theory of health and ecological safety evaluation to which less attention has been practically paid at the watershed scale. It further provides the scientific basis for the early warning to managers and decision makers in the world or Iran and responding to the health security risks of watersheds. Hopefully, the study results will provide an appropriate framework to show how watershed health-based assessment and monitoring would facilitate better resources management and policy-making at the watershed scale. Although the current study results are watershed specific, the methodology and the introduced framework can be practically employed for the sound management of the other watersheds worldwide. The results of the current watershed health assessment study facilitate a change in the mind-sets of decision makers, managers, and experts to efficiently adopt appropriate measures by concentrating on hotspots of the watershed. As a result, the most effective and balanced strategy may be used to minimize existing issues, prevent hasty actions, and guide society toward long-term stability.

Material and methods

Study area

The present study was conducted for the Pishkhu Watershed in Taft City, Yazd Province, Iran (Ca. 95,000 ha). Today, lack of proper land management and land-use changes, unlawful expansion of gardens and residential lands, mounding urban wastes in rangelands and along with local roads, digging illegal wells and uncontrolled abstraction of groundwater resources, as well as droughts and flash floods, have led to many problems in the region. Without the understanding of the health status of large, and highly human-induced watersheds like the Pishkhu Watershed in Central Iran, management activities and choices can lead to ineffective management and worsen issues in the region. It mainly consisted of one hydrologically delineated area with 18 sub-watersheds and one anthropogenically induced region in the north most (i.e., 519). It wholly lies between 53° 72’ 52” to 54° 23’ 41”E and 31° 55’ 32” to 31° 90’ 2”N. The mean annual precipitation is 191.18 mm. The mean weighted elevation is 2623 m above the mean sea level, and the mean slope is 24.99%. Geologically, the greatest extent is allocated to permeable rocks of the Shirkuh granite and then to sediments and alluvial deposits at mid-elevation areas of the watershed. The sediments mainly belong to granite arenas resulting from physical and chemical weathering of the Shirkuh granite mainly covered the central parts of the watershed. A general view and associated sub-watersheds of the Pishkhu Watershed are shown in Figure 1.

Identification of the issues of the Pishkhu Watershed

To better identify the Pishkhu Watershed, several visits were made to the region. The opinion of natural resource experts and stakeholders of the Pishkhu Watershed was very influential in field visits. The study team was surveyed the study area for a few days. Adequate brainstorming with local experts and stockholders was also taken into account. The condition of the sub-watersheds in terms of hydrological, climatic, and anthropogenic factors showed many issues in the region. The issues of each sub-watershed documented through field studies were found different according to the prevailing conditions. Nevertheless, the whole watershed has involved specific problems due to proper planning and management. However, the main issues of the Pishkhu Watershed were summarized as shown in Table 1 based on numerous expert discussions, various interviews, and intensive visits to the region.

Development of the PSR conceptual framework

The present study was accordingly conducted for the health assessment of the Pishkhu Watershed in Yazd Province, Iran, using the PSR conceptual framework. The conceptual model of PSR refers to the pressure–state–response model, which is an extension of the pressure-response model. Then, it was formally proposed as an ecological assessment model by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (UNEP) (Walz 2000; Li, Chen, and Zhao 2020). The conceptual model of PSR is a tool for modeling natural and human systems, and by extracting the indicators of pressure, state, and response, the cause-and-effect relationships between environmental, economic, and social factors can be determined. The compatibility of the PSR conceptual model with the conditions governing natural resources and its problem-orientation and the ease of use and availability of the required data is among the most important reasons for choosing this model in this study. The watershed health assessment is being conducted using different methods. However, in this
Figure 1. A general view and the location of the Pishkuh Watershed in Taft City, Yazd Province, Iran.

Table 1. The main issues in different sub-watersheds of the Pishkuh Watershed, Yazd Province, Iran.

| Sub-watershed No. | Sub-watershed name | Input/ driving force | Outcomes/ response |
|-------------------|--------------------|----------------------|--------------------|
| S1 to S19         | All Sub-watersheds | Disruption of the drainage system due to construction activities (960 points) | Demolition of constructed civil structures (e.g., roads and bridges) |
| S8                | Sanij              | Encroachment to the main river prohibitive zones | Hydrological disturbances |
| S8                | Sanij              | Lack of maintenance of constructed watershed management structures | Demolition and mal-functioning of soil and water conservation structures |
| S9                | Aliabad            | Encroachment to natural resources and expansion of agricultural lands and gardens | Drilling illegal wells and overexploitation of water resources |
| S6, S19, S8, and S15 | Nasrabad, Ko-Kase, Sanij, Mazrae akhond | Disposing construction waste | Landscape degradation |
| S15               | Mazrae Akhond      | Harvesting and destructing topsoil and vegetation cover | Soil, landscape and vegetation cover degradation |
| S15               | Mazrae Akhond      | Over-exploitation of groundwater resources | Sinkholes and land subsidence |
| S15               | Mazrae Akhond      | Reduction in water resources, changes in precipitation patterns and increasing pests | Drying gardens |
| S18               | Daregahan          | Lack of systematic organization for using ecosystem services | Un-supervised management, missing ecotourism capabilities, and motivating firing potentials |
| S19               | Ko-Kase            | Disproportionate harvesting of sand mines | Land degradation, high water demand, river bed degradation, and destruction of traditional water systems |
study, the PSR framework was examined to prepare a conceptual model for the health and ecological security assessment at the sub-watershed scale based on recognized and prioritized issues and problems in the region, which seems to be a novel approach in terms of the integrated watershed management. The PSR conceptual model was used in the current study due to easiness in application and accessibility of input data to model natural and human systems’ interactions. Accordingly, Continuous and extensive records of study variables, proxied by relevant factors, were collected for all sub-watersheds across the study area with different characteristics. The climatic factors were obtained from data collected for 26 meteorological stations distributed in Taft, Yazd, Mehriz, and Abarkooh from 1986 to 2015. To analyze the hydrological components, appropriate models were employed to the data collected from the hydrometric stations in the region. Due to the need to update information and analyze the trend of changes in watershed characteristics, remote sensing was also used as one of the applied tools to extract essential and practical information about land surface changes resulting from anthropogenic activities. All P, S, and R indices and associated factors and criteria extracted based on the cause and effect concept have been summarized in Table 2.

**Watershed health assessment**

The required data to analyze the problems of the Pishkuh Watershed was collected in different ways hinged on the previous studies conducted by the General Department of Natural Resources and the Regional Water Company of Yazd Province, Iran. The standardization of the study variables was then performed to diminish the difference in the magnitudes and dimensions of the study data. Equations (1) and (2) were respectively used to standardize the criteria with positive and negative impacts on the watershed health (Hazbavi et al. 2018b; Hazbavi 2018, 2019). These equations, $X_s$, $X_a$, $X_{min}$ and $X_{max}$ represent the study variables’ standardized, actual, minimum, and maximum values in these equations.

\[
X_s = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad \text{Eq.(1)}
\]

\[
X_a = \frac{X_{max} - X_i}{X_{max} - X_{min}} \quad \text{Eq.(2)}
\]

Then, pressure, state, and response indices were calculated based on the arithmetic mean of standardized values of the studied criteria. Eventually, the final health status of the study watershed was determined and categorized by taking the geometric mean of pressure, state, and response indices at sub-watershed scale using Eq. (3) (Hazbavi and Sadeghi 2017; Hazbavi et al. 2018a, 2018b; Hazbavi, Sadeghi, and Gholamalifard 2018c, 2019). In this equation, $\prod_{n=1}^{k} X_n$ and $k$ are the product and the number of the indices, respectively.

\[
\text{Health Index} = \left( \prod_{n=1}^{k} X_n \right)^{\frac{1}{k}} \quad \text{Eq.(3)}
\]

The P, S, R, and health indices were initially classified into five categories from zero to one with a significant equal step of 0.2. The necessary subclassifications were also made with a minor step of 0.1 shown in negative and positive signs to understand better the governing conditions and practical use of local managers. According to the regression analysis, the contribution of each criterion to the pressure, state, and response indices and the final status of the watershed health was also evaluated (Dai et al. 2007; Sadeghi, Hazbavi, and Gholamalifard 2019b; Sadeghi et al. 2020b).

Finally, the health status of the watershed was categorized as healthy (0.8–1.0), relatively healthy (0.6–0.8), moderately healthy (0.4–0.6), relatively unhealthy (0.2–0.4), and unhealthy (0.0–0.2). The health status of the Pishkuh Watershed was also mapped using ArcGIS 10.4 software.

**Ecological security assessment**

To assess the ecological security, a comprehensive index resulting from the pressure, state, and response indices were applied using Eq. (4) as proposed by Xia et al. (2014). The ecological security was also classified into poor (0.0–0.3), relatively poor (0.3–0.4), intermediate (0.4–0.5), relatively good (0.5–0.6), good (0.6–1), and very good (>1) statuses.

\[
\text{Ecological security index} = \frac{S \times R}{P} \quad \text{Eq.(4)}
\]

**Results**

**The customized PSR conceptual approach**

The numerical values of each climatic, hydrological and anthropogenic factor associated with pressure, state, and response indices were calculated. Considering a large number of conceptual framework variables in the three indices of pressure, state, response, and also the presence of 19 sub-watersheds in the study area, a determination coefficient of 0.47 at a significant level of 5% and degree of freedom of 18 was used in STATISTICA software with the help of Correlation Matrix subroutine to remove auto-correlated variables. The
| Index          | Factor                | Criteria                                                                 | References or calculation method                                                                 |
|---------------|-----------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Pressure      | Hydrology             | Flow peak discharge (m³ s⁻¹)                                              | Statistical analysis of three hydrometric stations in Islamiye, Taft and Feyzabad and using the Fuller method for the maximum available data from 1991 to 2011 |
|               |                       | Annual mean flow (m³ s⁻¹)                                                | Statistical analysis of three hydrometric stations in Islamiye, Taft and Feyzabad and using the Fuller method for the maximum available data from 1991 to 2011 |
|               |                       | Slope (%)                                                                | Physiographic report of Saedabad-Aliaab Taft watershed (General Department of Natural Resources and Watershed Management of Yazd Province, 2020) |
|               |                       | Time of Concentration (h)                                                | Physiographic report of Saedabad-Aliaab Taft watershed (General Department of Natural Resources and Watershed Management of Yazd Province, 2020) |
|               |                       | Human encroachment to the river bed (Length ratio)                       | Analysis of current land-use map and field observations                                           |
|               |                       | Runoff coefficient (%)                                                  | Precipitation-runoff data analyses                                                                 |
|               |                       | Centroid of impermeable areas to the main outlet (km)                    | Using land-use map                                                                                  |
|               |                       | The relative area of the mountains to the alluvium                      | Extent of rock outcrops extracted from Google Earth images                                          |
| Anthropogenic | Moving population density (Person km⁻²)                               | Statistics and information of Yazd Management and Planning Organization for the statistical period available in 1390 and 1395 |
|               | Inhabited population density (Person km⁻²)                            | Census of Yazd Management and Planning Organization for the maximum available period 2011 and 2016 |
|               | Population pyramid      | Census of Yazd Management and Planning Organization for the maximum available period 2011 and 2016 |
|               | Area of cultivation of non-native plants (km²)                        | Annual data of Agricultural Jihad Organization in Yazd Province (2020)                             |
|               | Area of human intervention such as mining and other forms of destruction (km²) | Industry and mining statistics and information along with field visits and Google Earth image analysis |
|               | Abundance of illegal wells                                          | Statistics and information from Yazd Regional Water Company and changes in the area under land cultivation during different years |
|               | Disruption of the natural drainage system (Number and length)         | Google Earth Image Analysis                                                                        |
|               | Environmental sensitive areas index (ESA)                             | Compiling climatic, geologic, vegetation, and anthropogenic and managerial factors (Davoudi Rad et al., 2016) |
|               | Mean distance between destruction center and the main outlet (km)      | Using land-use map                                                                                  |
|               | Relative area of disposed areas of construction waste                 | Google Earth image analysis and data of Yazd Natural Resources Department using land-use map       |
|               | Relative area of agricultural lands and gardens (km²)                 |                                                                                                        |
| Pressure      | Anthropogenic          | Number of livestock uses rangelands according to grazing license (mm)     | Annual data from Agricultural Jihad Organization in Yazd Province (2020)                          |
| Climates      |                       | Mean annual precipitation (mm)                                           | Data from 26 meteorological stations from Taft, Yazd, Mehriz, Abarkooh cities for the statistical period available from 1986 to 2015 |
|               |                       | Mean annual temperature (°C)                                             | Data from 26 meteorological stations from Taft, Yazd, Mehriz, Abarkooh cities for the statistical period available from 1986 to 2015 |
|               |                       | Mean annual evaporation (mm)                                             | Data from 26 meteorological stations from Taft, Yazd, Mehriz, Abarkooh cities for the statistical period available from 1986 to 2015 |
|               |                       | Standardized Precipitation Index (SPI)                                  | Data from 26 meteorological stations from Taft, Yazd, Mehriz, Abarkooh cities for the statistical period available from 1986 to 2015 |
|               |                       | Length of dry period (Month)                                            | Data from 26 meteorological stations from Taft, Yazd, Mehriz, Abarkooh cities for the statistical period available from 1986 to 2015 |
Table 2. (Continued).

| Index | Factor                  | Criteria                                                                 | References or calculation method                                                                 |
|-------|-------------------------|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
| State | Hydrology               | Groundwater level decline (m)                                            | Data on well extraction from Yazd Regional Water Company (2009)                                      |
|       |                         | Flood index                                                              | Data from three hydrometric stations of Islamia, Taft and Feyzabad for the statistical period available from 1991 to 2011 |
|       |                         | Mean annual runoff coefficient                                           | Data from three hydrometric stations of Islamia, Taft and Feyzabad for the statistical period available from 1991 to 2011 |
|       | Anthropogenic           | Landscape diversity                                                      | Using land-use maps and preparing land features                                                      |
|       |                         | The ratio of the degraded area to natural landscapes                     | Analysis of Google Earth images and locate damaged during field visits                                |
|       |                         | Non-local manpower (Number)                                              | Field data along with a survey through a questionnaire                                              |
|       |                         | Lack of fodder and feed for livestock and poultry (t)                    | Annual data of Agricultural Jihad Organization in Yazd province (2020) and interviews to watershed residents |
| State | Anthropogenic           | Normalized difference vegetation index (NDVI)                            | Product MOD13A2 MODIS sensor (2000–2020)                                                           |
|       | Climatic                | The ratio of mean annual evapotranspiration to mean annual precipitation | Data from 26 meteorological stations from Taft, Yazd, Mehriz, Abarkooh cities for the statistical period available from 1986 to 2015 |
|       | Response                | Hydrology Drainage density (km km$^{-2}$)                                | Drainage system analysis                                                                             |
|       |                         | Specific flow discharge (m$^3$ s$^{-1}$ km$^{-2}$)                       | Statistical analysis of watershed hydrometric stations for the statistical period available from 1991 to 2011 |
|       |                         | Ratio of annual low flow discharge to high flow discharge                | Statistical analysis of watershed hydrometric stations for the statistical period available from 1991 to 2011 |
|       | Anthropogenic           | Area of abandoned land (km$^2$)                                          | Comparison of land-use maps for the period 2000 to 2020                                              |
|       |                         | Soil erosion (t ha$^{-1}$)                                               | General Department of Natural Resources and Watershed Management, and Faculty of Natural Resources of Yazd University and Tarbiat Modares, and field visits |
|       |                         | Landscape fragmentation                                                  | Using land-use map and landscape metrics                                                             |
|       |                         | Immigration rate                                                         | Census from Yazd Management and Planning Organization for the available statistical period of 2011 and 2016, and questionnaire |
|       |                         | Unemployment rate                                                        | Census from Yazd Management and Planning Organization for the available statistical period of 2011 and 2016, and questionnaire |
|       |                         | Economic productivity                                                    | Census from Yazd Management and Planning Organization for the available statistical period of 2011 and 2016, and questionnaire |
Table 3. Determinant factors in assessing pressure, state and response indices for health assessment of Pishkuh Watershed, Yazd Province, Iran.

| Index          | Climatic                                      | Hydrology                                      | Anthropogenic                                          |
|----------------|-----------------------------------------------|-----------------------------------------------|--------------------------------------------------------|
| Pressure       | Mean annual precipitation (mm)                | Mean annual flow (m$^3$ s$^{-1}$)              | Environmentally sensitive index                         |
|                | Standardized annual rainfall index            | Flood volume (m$^3$)                          | Land-use change to agriculture (km$^2$ km$^{-2}$)     |
|                |                                               | Slope (%)                                     | Number of livestock exploiting pastures (number km$^{-2}$) |
|                |                                               | Runoff coefficient                           |                                                        |
|                |                                               | Drainage system disruption (number km$^{-2}$)  |                                                        |
|                |                                               | Rock protrusion area ratio                    |                                                        |
| State          | The mean annual evapotranspiration ratio to precipitation | Flood index                                  | Annual NDVI                                            |
| Response       |                                               | Stream density (km km$^{-2}$)                 | Naturalism Evaluation Index                            |
|                |                                               | Flow Discharge special moment (m$^3$ s$^{-1}$ km$^{-2}$) | Unemployed number (person)                             |
|                |                                               |                                               | Number of landscape spots                              |
|                |                                               |                                               | The area of the spots protrudes from the rock          |
|                |                                               |                                               | The area of the spots is poor pasture                   |
|                |                                               |                                               | Number of spots is weak pasture                         |
|                |                                               |                                               | The perimeter to area of Poor rangeland landscape      |
|                |                                               |                                               | (km km$^{-2}$)                                          |
|                |                                               |                                               | Area of spots in the garden (km$^{2}$)                  |
|                |                                               |                                               | The area of the spots is agriculture (km$^{2}$)         |
|                |                                               |                                               | The area of the spots is water (km$^{2}$)               |
|                |                                               |                                               | The area of the spots is residential (km$^{2}$)         |
|                |                                               |                                               | The area of the spots is industrial (km$^{2}$)           |
|                |                                               |                                               | The area of the spots is a intermediate rangeland       |
|                |                                               |                                               | The ratio of the area of the largest spot to the total landscape of the intermediate rangeland |
|                |                                               |                                               | The area of the spots is a good pasture area (km$^{2}$) |
|                |                                               |                                               | Mining area (km$^{2}$)                                  |

Determinant factors of pressure, state, and response indices, as shown in Table 3, were finally used in the health assessment of the Pishkuh Watershed.

**Pressure index**

Out of many initially selected factors affecting the pressure index, a few final determinant factors non-autocorrelated to other factors were selected. The pressure index was classified into four classes: low, negative intermediate, positive intermediate, and relatively high, as mapped at the sub-watershed scale in Figure 2.

The results of the health assessment of the Pishkuh Watershed (Figure 2 and Table 4) showed that the mean and standard deviation of the pressure index in the watershed were 0.499 and 0.074, respectively. The lowest pressure index was 0.43 related to sub-watershed 19, and the highest pressure index was 0.63 related to sub-watershed 3. The pressure index in low, negative intermediate, positive intermediate and relatively high categories covered some 7.17, 40.61, 48.63, and 3.58% of the total watershed. In general, among the criteria used to calculate the pressure index in the Pishkuh Watershed, flood volume with 14.43%, area with the number of livestock under grazing license with 13.66%, and mean annual precipitation with 10.08% had the highest percentage of contribution to the pressure index. The main pressures on the Pishkuh ecosystem were anthropogenic and hydrological factors (i.e., >28%).

**State index**

Based on statistical analyses, flood index, naturalness index, the ratio of annual evapotranspiration to precipitation, and annual NDVI were finalized to assess the state index of the study watershed. The status index was classified into three categories: desirable, moderately desirable, and relatively undesirable, as shown in Figure 2.

Concerning the state index, the Pishkuh Watershed was in relatively unfavorable, relatively favorable, moderately favorable, and favorable categories with relative coverage of 15.70, 29.55, 45.86, and 8.89%, respectively. The highest and the lowest state index with 0.86 and 0.24 were allotted to sub-watershed 3 (Shokrabad) and sub-watershed 2 (Menark region in Nasrabad), respectively. The flood index, annual NDVI, and the ratio of mean annual evapotranspiration to precipitation were also recognized as the most effective criteria on the state index in the Pishkuh Watershed.

**Response index**

After statistical analysis, the non-autocorrelated effective criteria on the response index were similarly finalized. Likewise, the spatial zoning of response index at sub-watershed scale for the Pishkuh Watershed was conducted as shown in Figure 2. The response index status of the Pishkuh Watershed was divided into three categories: relatively low, intermediate, and high.

In terms of response index, in general, 48.04% of the whole region was in a relatively positive low situation, and 31.49, 18.12, and 2.34% had the negative relatively
low, moderate, and low situation. In the Pishkuh Watershed, sub-watershed 6 (i.e., Glicheh area in Nasrabad sub-watershed) with 0.77, and sub-watershed 19 (i.e., Koh-Kase) with 0.28 had the best and the worst response index, respectively. The stream density, the area of stains in the mining region, were evaluated as the most effective criteria on the response index in the Pishkuh Watershed.

**Watershed health assessment**

The overall health index of the Pishkuh Watershed resulted from the geometric mean of pressure, state, and response indices were about 0.50, classified into relatively healthy, moderately healthy, and relatively unhealthy conditions. The numerical value of watershed health varied from zero (i.e., unhealthiest) to one (i.e., healthiest) according to the environmental conditions of each region. So that the highest health index with a value of 0.75 was reported for sub-watershed 1 (i.e., Nasrabad plain), and the lowest index with a value of 0.35 belonged to sub-watershed 19 (i.e., Koh-Kase). The results showed that some 90.60% of the watershed area belonged to the moderate class. According to the watershed health atlas, it could be explained that the Pishkuh Watershed was in a moderate condition in terms of health and ecological potential.

Based on the results of the Pishkuh Watershed health index, it could be concluded that watershed management measures are necessary by observing

### Table 4. Descriptive features extracted from the indicators of the PSR conceptual framework at sub-watershed scale to assess the health of the Pishkuh Watershed, Taft City, Yazd Province, Iran.

| Index   | Minimum | Maximum | Mean | Standard deviation | Change coefficient (%) |
|---------|---------|---------|------|--------------------|------------------------|
| Pressure| 0.34    | 0.67    | 0.49 | 0.07               | 14.82                  |
| State   | 0.24    | 0.86    | 0.50 | 0.17               | 34.38                  |
| Response| 0.28    | 0.77    | 0.64 | 0.11               | 17.91                  |
| Health  | 0.35    | 0.75    | 0.53 | 0.09               | 16.91                  |

Figure 2. Zoning of pressure, state, response, and health index of the Pishkuh Watershed, Taft City, Yazd Province, Iran.
the necessary prioritization and applying the correct management approaches. Accordingly, sub-watersheds 1, 2, and 4 (in the main sub-watershed of Nasrabad and Mazre Akhund), 5 and 7 (in the main sub-watershed of Sadeghabad and Aliabad), 9 (in the sub-watershed of Aliabad), and 19 (Koh-Kase sub-watershed) with health indices between 0.35 and 0.48 had the highest priority for executive watershed management measures.

The contribution of pressure index to the study watershed health was found at 30.23%. The flood volume with a contribution of 14.43% had the most significant effect on the pressure index. The mean annual discharge also had the minuscule contribution of 0.20% to the pressure index compared to other criteria assigned to sub-watersheds 2, 3, 12, 14, 15, 16, and 17.

The contribution rate of the state index to the health status of the Pishkuh watershed was 30.86%. According to the multivariate regression analyses, the naturalness index with a mean relative contribution of 15.41% had the lowest impact on the state index. The minimum contribution was estimated to be 0.63% associated with sub-watershed 19, whereas the maximum contribution of 31.36% was reported for sub-watershed 16.

The results of analyses verified that the response index had the highest contribution of 38.90% to the health status of the study watershed. Out of affective criteria on the response index, the stream density criterion had the highest mean contribution of 8.22%, varying from 0.32 to 3.37 km km⁻² associated with sub-watersheds 18 and 19, respectively. The criterion of the number of outcrops per 100 ha had the lowest contribution (i.e., 1.08%) to the response index.

The overall contributions of pressure, state, and response indices to the watershed health index were found at 38.90, 30.86, and 30.24%, respectively. The Pishkuh Watershed was evaluated as having a moderate status of health index in general due to its appropriate relative capacity and relative flexibility against relatively uniform spatial pressures following available statistics and information. However, the variability of the condition of different parts of the watershed was not similar to the input pressures and had led to the output of large states and then different relative responses. This indicates the role of anthropogenic interventions in managing the behavior of the study watershed system.

### Ecological security index

In addition to assessing the watershed’s health, the ecological security index of the watershed was also examined using Eq. (4) at the sub-watershed scale. The calculations, corresponding categorization results, and pictorial presentations have been summarized in Table 5 and Figure 3. It varied from 0.28 to 1.55 associated with sub-watersheds 1 and 12, respectively. It is implied from the results that the ecological safety index with 8.10, 40.58, 12.00, 9.01, 24.87, 5.42% of the whole area fell in categories I, II, III, IV, V, and VI. The results obtained from Tables 3 to 5 and Figure 3 verified different contributions of selected factors, criteria, and leading indices to the health status of the Pishkuh Watershed.

### Discussion

The present study was successfully conducted for a highly-interfered human watershed in central Iran. The successful application of the PSR framework in watershed health assessment has also been confirmed

| Sub-watershed | P   | S   | R   | Healthindex | Healthcondition | EcologicalSecurity | Ecological Security condition |
|---------------|-----|-----|-----|-------------|-----------------|--------------------|-------------------------------|
| S1            | 0.57| 0.25| 0.66| 0.45        | Moderately healthy | 0.29               | I                             |
| S2            | 0.58| 0.24| 0.76| 0.48        | Moderately healthy | 0.32               | II                            |
| S3            | 0.68| 0.86| 0.72| 0.75        | Relatively healthy | 0.92               | V                             |
| S4            | 0.46| 0.31| 0.58| 0.44        | Moderately healthy | 0.39               | II                            |
| S5            | 0.48| 0.39| 0.55| 0.47        | Moderately healthy | 0.44               | III                           |
| S6            | 0.56| 0.46| 0.77| 0.58        | Moderately healthy | 0.65               | V                             |
| S7            | 0.48| 0.32| 0.51| 0.43        | Moderately healthy | 0.34               | II                            |
| S8            | 0.54| 0.50| 0.62| 0.55        | Moderately healthy | 0.58               | IV                            |
| S9            | 0.43| 0.42| 0.61| 0.48        | Moderately healthy | 0.59               | IV                            |
| S10           | 0.42| 0.75| 0.71| 0.60        | Moderately healthy | 1.28               | VI                            |
| S11           | 0.47| 0.48| 0.64| 0.53        | Moderately healthy | 0.65               | V                             |
| S12           | 0.42| 0.77| 0.63| 0.59        | Moderately healthy | 1.15               | VI                            |
| S13           | 0.48| 0.65| 0.58| 0.56        | Moderately healthy | 0.79               | V                             |
| S14           | 0.49| 0.46| 0.77| 0.55        | Moderately healthy | 0.72               | V                             |
| S15           | 0.49| 0.58| 0.71| 0.59        | Moderately healthy | 0.84               | V                             |
| S16           | 0.56| 0.69| 0.71| 0.65        | Moderately healthy | 0.87               | V                             |
| S17           | 0.51| 0.59| 0.69| 0.59        | Moderately healthy | 0.80               | V                             |
| S18           | 0.53| 0.49| 0.71| 0.57        | Moderately healthy | 0.65               | V                             |
| S19           | 0.34| 0.46| 0.29| 0.35        | Relatively unhealthy | 0.38              | II                            |
by Hazbavi and Sadeghi (2016), Hazbavi and Sadeghi (2016), and Wang, Li, and Li (2019). The conceptual model of PSR is based on the problems of the region. The watersheds’ types and amount of problems are not the same. However, after standardization, the indicators will show their effect on health assessment. The numerical value of watershed health varied from zero (i.e., unhealthiest) to one (i.e., healthiest) according to the environmental conditions of each region. Accordingly, the health index of 0.5 or something similar would assign to the sub-watershed with a moderate health condition. Analysis of the results showed (Figure 3 and Table 5) that only the sub-watershed 19 is in relatively unhealthy status, in this sub-watershed, specific flow discharge (m³·s⁻¹·km⁻²), disruption of the natural drainage system (number and length), the ratio of mean annual evapotranspiration to mean annual precipitation, landscape fragmentation, flood index are involved in assessing the relatively unhealthy condition of the sub-watershed 19 (Sadeghi et al. 2020b). However, it is recommended to make managerial decisions to stop or control the negative trend and improve the conditions governing the sub-watershed health 19. The health status of the Pishkuh Watershed has been mainly influenced by anthropogenic factors, which will lead to long-term recovery. The results of this study are consistent with the findings of Ahn and Kim (2019), (Sadeghi, Hazbavi, and Gholamalifard 2019b), and Xu et al. (2004) on the effect of unnatural factors on health status. Although the health status of the Pishkuh Watershed was found moderate, in the future, if the pressures are not uploaded, the health status of the watershed will certainly decrease (Sadeghi et al. 2020b).

On the other hand, the results of the ecological security assessment of the Pishkuh Watershed (Figure 3 and Table 5) showed that it would have different statuses according to the status of pressure, state, and response indicators of each sub-watershed. In addition, sub-watershed 1 had the lowest ecological security index and flood volume, mean annual runoff coefficient, environmental sensitive areas index (ESAI), a set of land-use measures, naturalness assessment index, and NDVI had the most significant impact than other study factors. Also, sub-watershed 10 had the best ecological security status due to the low-pressure index. Therefore, the simultaneous assessment of the health and ecological security of the watershed would lead to appropriate decisions in executive actions to be commensurate with the watershed conditions (Tsai, Lin, and Chen 2021). The most crucial approach in watershed management is to assess its health status and sustainability (Sadeghi, Sharifi Moghadam, and Mohseni Saravi 2019c).

Conclusion

The watershed health and ecological security assessment framework were compatible with the Pishkuh Watershed in Yazd Province, Iran. This study showed that watershed health and ecological security indices were moderate and good. The Pishkuh Watershed has the appropriate relative capability and flexibility with relatively uniform spatial pressures. The higher importance of anthropogenic on watershed health and ecological security compared to hydrological and climatic criteria was also verified. Due to the importance of applied management of the watershed, the affective factors on the watershed health and ecological security index (i.e., pressure, state, and response) were different in the study sub-watersheds. Eventually, the executive managerial measures will differ in each part of the Pishkuh watershed. Toward that, prioritization of various sub-watersheds based on the integrated approach would greatly help managers and decision-makers. In this study, we have tried to use all available data in accordance with the problems existing in the region to assess the present health condition of the study watershed using the most updated data and information at a sub-watershed basis. It means no temporal comparison has been examined or studied in the current research. In contrast, studying changes in dynamic watershed health and ecological security is vital and has to be materialized through periodic studies. Because natural resources are so complicated, a problem-solving
approach can lead to more integrated solutions. In watersheds, every action has both direct and indirect impacts. The identification of climatic, hydrological, and anthropogenic concerns led to a detailed evaluation in this study, allowing us to characterize the region's circumstances in detail. The dynamic and periodical monitoring of the watershed health and ecological security and assessment of watershed management measures are strongly recommended based on health promotion for future research.

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Disclosure statement

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ORCID

Seyed Hamidreza Sadeghi http://orcid.org/0000-0002-5419-8062
Abdulvahed Khaledi Darvishan http://orcid.org/0000-0002-5596-5411

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