Zeinab Hazbavi[1], Seyed Hamidreza Sadeghi[1*] and Mehdi Gholamalifard[1]
[1] Tarbiat Modares University, Tehran, Iran
*** Corresponding author:** sadeghi@modares.ac.ir

DYNAMIC ANALYSIS OF SOIL EROSION-BASED WATERSHED HEALTH

ABSTRACT. Accelerated soil erosion is one of the most important detrimental factors affecting the quality of the watershed health. Due to different environmental pressures and drivers, the effort is needed for ecological health and resilience assessment in regards to erosion changeability. However, this important subject has not been adequately studied yet. Towards this, in the present research, an innovative approach was developed for conceptualizing the watershed health dynamics in viewpoint of soil erosion. A risk-based study was conducted to quantitatively characterize the spatiotemporal variability of erosion-based health in an industrialized watershed i.e., the Shazand Watershed using the conceptual reliability, resilience and vulnerability ($R_{el}R_{es}V_{ul}$) framework for four node years of 1986, 1998, 2008 and 2014. To this end, the soil erosion was estimated at monthly scale in 24 sub-watersheds by applying the Revised Universal Soil Loss Equation (RUSLE). The $R_{el}R_{es}V_{ul}$ indicators were then computed according to the threshold defined for the study watershed. A geometric mean was used to combine the three risk indicators and the erosion-based watershed health index was ultimately calculated for each study sub-watershed. Additionally, the change detection analysis was conducted over the years of 1986 to 2014. According to the results of erosion-based the $R_{el}R_{es}V_{ul}$ indices, very healthy, healthy, moderately healthy, unhealthy and very un-healthy conditions in the Shazand Watershed were respectively distributed over some 67, 25, zero, zero and eight percent for 1986; 50, 13, eight, zero and 29 % for 1998; 71, eight, 83, zero, zero and eight percent for 2008 and finally 71, zero, 17, zero and 12 % for 2014. The results of change detection revealed an oscillating trend of erosion-based watershed health index during the whole study period (1986 -2014). So that, during periods of 1986-1998, 1986-2008 and 1986-2014, the watershed health decreased at tune of 23, 13 and six percent, respectively. Whilst, the watershed health improved during study periods of 1998-2008 (13 %), 2008-2014 (eight percent) and 1998-2014 (22 %). The results also identified 'hot spots' of the most important index of land degradation and 'bright spots' of land improvement in the Shazand Watershed. The proposed approach would provide a sustainable framework supporting decision makers to comprehend health-related soil erosion targets according to the integrated watershed management plans.

KEY WORDS: Dynamic monitoring, Hydrological responses, Land health, Watershed integrity

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INTRODUCTION

The extent of land degradation in Iran has been recognized as a pressing challenge for the country economy. It is reported that the soil and water degradation and fertilizers application annually costs the country around than USD12.8 billion about four percent of the total gross domestic product (GDP) (Emadodin et al. 2012). Degradation of land health is distinguished as a foremost global problem, but remains poorly quantified (Shepherd et al. 2015; Hazbavi and Sadeghi 2017; van Noordwijk 2017; Hazbavi et al. 2018a). Soil erosion as the most important indicator of land degradation affect the quality of watershed ecosystems. Numerous approaches have been developed for soil erosion prediction. The Universal Soil Loss Equation (USLE) and the Revised USLE (RUSLE) models (Wischmeier and Smith, 1965; 1978; López-Vicente et al. 2008; Golosov et al. 2014; Pietroń et al. 2017; Van der Knijff et al. 2017; Chatrsimab et al. 2019) have been widely used to efficiently predict the soil erosion under different conditions because of their low data demanding and wide applicability at different scales. RUSLE as an empirical method based on functionalities of the soil erosion processes has been then established. In the last decades, RUSLE has been adopted to watershed scale in integration with Geographic Information Systems (GIS) (Fayas et al. 2019).

A variety of watershed health and protection treatments have been proposed to reduce long-term risks to watershed from accelerated soil erosion (Golrang et al. 2013; Sadeghi et al. 2014; Sadeghi and Hazbavi 2017a; Sadeghi et al. 2018a). However, after more than 40 years, due to increasing degradation, it looks that these activities were not successful (Golrang et al. 2013; Spalevic et al. 2016). Hence, it is essential to advance and improve land health surveillance approaches to target sustainable land management interventions (Hazbavi, 2018). Towards this objective, the dynamic monitoring of the watershed health can help to detect trends over time, identify emerging problems, direct efforts to stressor impacts mitigation for areas where they are most needed and ultimately track the response of watersheds to different environmental drivers.

Although different approaches were developed to monitor the conditions of the different ecosystems in regards to different environmental stressors (Sadeghi and Hazbavi 2017a and b; Sadeghi et al. 2017; Hazbavi et al. 2019), a risk-focused watershed health monitoring and assessment, which rests on sustainable watershed management approaches has received much less attention. The reliability (R_{el}), resilience (R_{es}) and vulnerability (V_{ul}) framework is one of the most commonly used approach in water resources management perspectives initially introduced by Hashimoto et al. (1982). The $R_{el}R_{es}V_{ul}$ indicators can be characterized by means of daily, monthly or annual datasets of different determinant factors. This framework simultaneously measures the pressure, state and response of the watershed against to external stressors (Chanda et al. 2014; Hazbavi et al. 2018b and c; Sadeghi et al. 2019). The proficient watershed management would expect improving R_{el} and R_{es} of the watershed whereas decreasing V_{ul} (Alemaw et al. 2016; Hazbavi et al. 2018a and b; Sadeghi et al., 2019). The risk assessment of watershed in the context of health is a topic of great interest to many researches seeking to promote sustainable practices. In this regards, the reliability (R_{el}), resilience (R_{es}) and vulnerability (V_{ul}) framework ($R_{el}R_{es}V_{ul}$) got more attention due to considering the risk-based indicators to mathematically quantify the potential for an entire watershed to fail, the probability of a failed watershed recovering, and the consequences of a watershed lapsing into a failed status (Ahn and Kim 2017; Hazbavi et al. 2018a).

Thereinto, the $R_{el}R_{es}V_{u}l$ framework in regards to watershed health has been applied for social, environmental and biodiversity criteria (Sood and Ritter 2011), drought management index (Maity et al. 2013; Chanda et al. 2014), water quality data (Hoque et al. 2012; Hoque et al. 2014a; Hoque et al. 2014b, Hoque et al. 2016), hydrological criteria (Hazbavi and Sadeghi 2017; Sadeghi and Hazbavi 2017b) and standardized precipitation index (Sadeghi and Hazbavi 2017a). Nevertheless, characterization and quantitative risk assessment of watershed health in viewpoint of soil erosion using the $R_{el}R_{es}V_{ul}$ framework has not been formulated, yet. So, for the present study, a quantitative risk assessment of watershed health with emphasis on soil erosion as an important representative of land degradation was applied to an urbanized and industrialized watershed located in central Iran. Thereinto, the spatiotemporal of watershed health and its change was analyzed during the period of 1986 to 2014.

Recently, the trend of the hydrological health status of the Shazand Watershed has been assessed as un-healthy from 1977 to 2014 (Hazbavi and Sadeghi 2017; Sadeghi et al. 2019; Hazbavi et al. 2019). However, more comprehensive evaluation of determinant index of watershed health is still lacked. The present study has therefore been formulated for better understanding of land degradation situation in the study watershed in time and space hopefully leading to a correct and cost-effective management in the future.

MATERIALS AND METHODS
Study area

The study area is located in the Markazi Province, in the central plateau of Iran (Fig. 1). The watershed with a total area of almost 1740 km2 is composed of nearly 44.85 % alluvial sediments and/or sub-mountain gravels and 50.15 % highlands and hard formations. The climate is moderate semi-arid to cold semi-arid (Bsk) and receives about 420 mm rainfall annually (Mokhtari et al. 2011; Darabi et al. 2014; Davudirad et al. 2016). Since 1973, a rapid industrialization has been taken place in the Shazand Watershed. Consequently, the social and economic development in this area was completely changed (Darabi et al. 2014; Davudirad et al. 2016; Sadeghi et al. 2018).

Soil erosion estimation

The present study used the predictive empirical model of the Revised Universal Soil Loss Equation (RUSLE) as the simplest model for erosion prediction of an area (Wischmeier and Smith, 1965; 1978; Renard

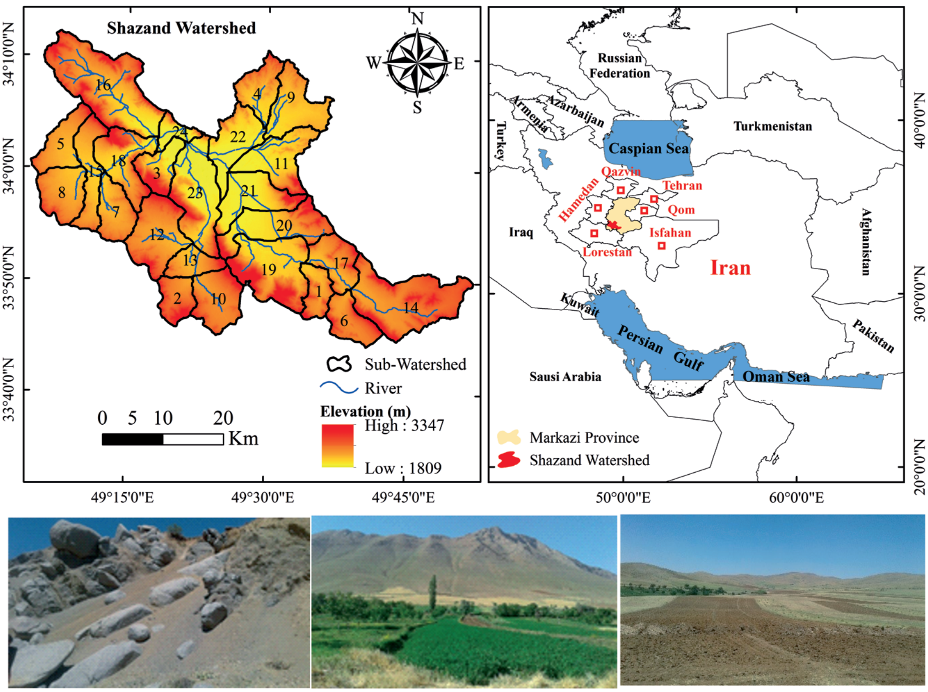

Fig. 1. Location (Upper) and general governing condition (Bottom) of the Shazand Watershed in Markazi Province, Iran

et al. 1997). The RUSLE model was applied based on the following equation (Renard et al. 1997).

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where A is the computed spatial average soil loss over a period selected for R, (t ha^{-1}); R, K, L, S, C and P are rainfall erosivity [(MJ mm) (ha h)$^{-1}$], soil erodibility [(t ha h) (ha MJ mm)$^{-1}$], slope length, slope steepness, land cover management, and conservation practices factors, respectively. All dimensionless factors were normalized with respect to the unit plot conditions as described in Jain et al. (2001) and Dabral et al. (2008), and has been validated by Ganasri et al. (2016). To determine study factors, the RUSLE was integrated in GIS and Remote Sensing (RS) as successfully reported by many researchers (Millward and Mersey 1999; Prasannakumar et al. 2011; Vijith et al. 2012; Asadi et al. 2017; Mohammadi et al. 2018; Chatrsimab et al. 2019) to improve the accuracy and expedite the estimation. The quantitative output of monthly soil erosion was eventually computed by multiplying the R, K, L, S, C and P factors using the Raster Calculator tool in ArcGIS 10.3.

- Rainfall erosivity (r) factor

R factor measures the soil erosion potential caused by rainfall (Wischmeier and Smith 1978; Renard et al. 1997). R factor is often estimated from rainfall intensity if high-resolution of rainfall measurements exist. In the present research, R factor for the Shazand Watershed was estimated on monthly basis according to the calibrated Roose's index developed with reasonable statistical performance (Sadeghi and Tavangar 2015). The primary formula of Roose's model is as follows (Roose 1977).

$$Rfactor = \left[0.5 + 0.05P\right] \quad (2)$$

where R factor and P are rainfall erosivity index [(MJ mm) (ha h)$^{-1}$] and mean monthly rainfall (mm), respectively.

- Soil erodibility (k) factor

The soil susceptibility to erosion could be measured through K factor. The resistance of the soil to particle detachment and soil ability to absorb rainfall affect K factor. For the present study, K factor was computed using data of the soil types distribution of the study area according to the tables supposed by the USDA (1978).

- Topographic (ls) factor

LS factor quantifies the combined impact of slope length (L) and steepness (S) on the soil loss. As the slope length and steepness increase, the progressive runoff accumulation in the downslope direction and runoff velocity and erosivity increase. Thence, the amount of soil loss increases. LS factor was determined using the following approach (Prasannakumar et al. 2011; Vijith et al. 2012) that is verified for Iranian conditions, too (Mohammadi et al. 2018). Flow accumulation denotes the accumulated upslope contributing area for a given cell. The

$$LS = (FlowAccumulation \times \frac{CellSize}{22.13})^{0.4} (\frac{Sin(Slope) \times 0.01745}{0.0896})^{1.3} \quad (3)$$

cell size is the size of the grid cell used for the study and sin (slope) is the sine of the slope angle in degrees. The flow accumulation was obtained with the help of the Digital Elevation Model (DEM) of the study area with a cell size of 30 m. The maps were derived using ArcGIS 10.3 Spatial analyst plus. The following flowchart (Fig. 2) shows different stages of calculation of LS factor.

- Land cover management (c) factor

C factor reflects the protective impact of ground covers against the erosive action of rainfall on reducing soil loss. To estimate C factor, the most widely used index of vegetation of Normalized Difference Vegetation Index (NDVI) was applied according to the following formula (Lin 1997) which is approved for Iranian conditions by Mohammadi et al. (2018).

$$C = \left[\frac{(-NDVI + 1)}{2}\right] \quad (4)$$

$$NDVI = \frac{(NIR - RED)}{(NIR - RED)} \quad (5)$$

where NDVI is the mean values of Normalized Difference Vegetation Index derived at monthly scale, NIR and RED stand for the spectral reflectance measurements acquired in the near-infrared and visible regions, respectively. All calculation of NDVI were conducted in Terr-

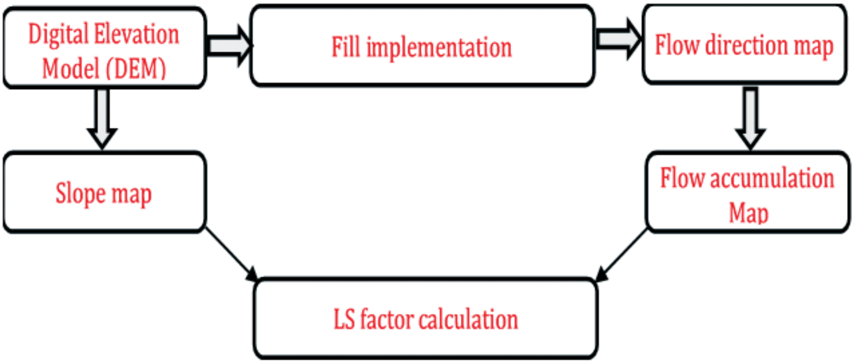

Fig. 2. Different stages of derivation of topographic (LS) factor (Teh, 2011) for the Shazand Watershed, Iran

Set 18.21 Software. Forty Landsat TM, ETM+ and OLI images acquired during the years of 1986, 1987, 1998 and 2014 with a spatial resolution of 30 m were used to create NDVI images as detailed in Sadeghi et al. (2019).

- Conservation practices (*p*) factor

P factor is defined as the ratio of soil loss by a conservation practices to that of straight-row farming up and down the slope (Yuan et al. 2016). In the same vein, P factor accounts for the supporting effects of control practices that reduce the erosion potential of runoff. Accordingly, the efficiency of conservation supporting practices depends on slope and land use pattern (Lakkad 2017). Towards this, the P factor of the Shazand Watershed (Table 1) was determined according to tables proposed by Li et al. (2010), Lu (2011), Yu et al. (2011) and Yuan et al. (2016). Accordingly, the slope map (%) was prepared by DEM and it was merged with land use data using overlay analysis in ArcGIS.

$R_{EL}R_{ES}V_{UL}$ framework conceptualization

A quantitative methodology of reliability, resilience and vulnerability ($R_{el}R_{es}V_{ul}$) initially proposed by Hashimoto et al. (1982) in context of water resources systems was developed for assessing the long term watershed health. The $R_{el}R_{es}V_{ul}$I framework was conceptualized to an important index of degradation i.e., generated soil erosion in the Shazand Watershed allowing

Table 1. Used P factor values according to different land use/cover types and slope percentages (Yuan et al. 2016) for the Shazand Watershed, Iran

Land use/cover	Slope (%)	P factor
Water bodies	0~330	0.00
Irrigated croplands	0~330	0.05
Arable lands	0~5	0.11
	5~10	0.12
	10~20	0.14
	20~30	0.19
	30~50	0.25
	>50	0.33
Forest lands	0~330	0.80
Others	0~330	1.00

conclusions to be drawn for the health analysis of the study watershed.

The $R_{el}R_{es}V_{ul}$ framework is applicable for different time scales. For the present research, the data were analyzed at monthly scale for soil erosion-based the $R_{el}R_{es}V_{ul}$ index. The mathematical definitions of reliability, resilience and vulnerability concepts in the $R_{el}R_{es}V_{ul}$ framework were presented using following formulae. where M is the number of un-satisfactory

$$Reliability(R_{el}) = 1 - \frac{\sum_{j=1}^{M} d(j)}{T} \quad (6)$$

$$Resilience(R_{es}) = \left\{ \frac{1}{M} \sum_{j=1}^{M} d(j) \right\}^{-1} \quad (7)$$

$$Vulnerability(V_{ul}) = \frac{1}{M} \sum_{i=1}^{T} \left\{ \left[\frac{S_{RUSLE}(i) - S_{std}(i)}{S_{std}(i)} \right] H\left[S_{RUSLE}(i) - S_{std}(i) \right] \right\} \quad (8)$$

events, d(j) is the duration (the number of months that soil erosion amount exceeds the threshold) of the j^{th} un-satisfactory event, and T is the total number of events (here 12). In the context of soil erosion, a satisfactory event was defined beyond a certain threshold of permissible soil erosion for the study watershed as five t ha^{-1} y^{-1} (Hosseini and Ghorbani 2005) and the period under consideration. $S_{RUSLE}(i)$ is the estimated soil erosion at the i^{th} time step, $S_{std}(i)$ is the corresponding compliance standard, and H[ ] is the Heaviside Function, which ensures that only failure events are involved in the vulnerability calculation in Eq. (8). The mathematical and discontinuous Heaviside Function was supposed zero and one for negative and positive arguments, respectively. R_{el} is controlled by *d* and *T*. This implies that the duration of failure events was the only factor affecting R_{el} of watersheds for soil erosion. Whilst, R_{es} indicator was influenced by *d* and *M*. Thereafter, interaction of these two factors forms R_{es} of watersheds against soil erosion process.

The above mentioned concepts were then articulated to describe the performance of the Shazand Watershed against soil erosion long term variations in result of industrial development in the region. The computed $R_{el}R_{es}V_{ul}$ indicators values were standardized between zero and one (Loucks 1997; Zhao et al. 2006; Wiegand et al. 2013; Hazbavi and Sadeghi 2017) using Eqs. (9) and (10) respectively applied for positively and negatively affected indicators of R_{el} and Res and V_{ul}.

$$C_S = \frac{C_i - C_{min}}{C_{max} - C_{min}} \quad (9)$$

$$C_S = \frac{C_{max} - C_i}{C_{max} - C_{min}} \quad (10)$$

where C_S is the standardized value of each individual indicator; C_i is the indicators under consideration; and C_{min} and C_{max} are the minimum and maximum indicator values respectively.

Then, the soil erosion-based $R_{el}R_{es}V_{ul}$ index (G_A) was then computed using geometric mean by the following formula.

$$G_A = \sqrt[3]{standardizedR_{el} \times standardizedR_{es} \times standardizedV_{ul}} \quad (11)$$

The erosion-based $R_{el}R_{es}V_{ul}$I index was ranked into five classes of I (0.81-1.00), II (0.61-0.80), III (0.41-0.60), IV (0.21-0.40) and V (0.00-0.20) specified as very healthy, healthy, moderately healthy, un-healthy and very un-healthy watersheds respectively.

Watershed health change analysis

Assessments of watershed health change in viewpoint of soil erosion was done through the elementary watershed health index (EWHI) during two time nodes of t and t+1 of the study period given by Salvati et al. (2014) and Smiraglia et al. (2016) as given below.

$$EWHI_{(t:t+1)} = \frac{EWHI_{t+1} - EWHI_t}{EWHI_t} \times 100 \quad (12)$$

RESULTS AND DISCUSSION

The results of the soil erosion characteristics and $R_{el}R_{es}V_{ul}$ indicators in the study sub-watersheds and node years have been respectively presented in Tables 2 and 3. The raw data and corresponding calculations of soil erosion for each sub-watershed of the Shazand Watershed have been also presented as supplementary information. The standardized $R_{el}R_{es}V_{ul}$ indicators for all sub-watersheds and four study years were calculated and the erosion-based $R_{el}R_{es}V_{ul}$ index was obtained as depicted in Fig. 3. The spatiotemporal maps and the percentage distribution of different categories of soil erosion-based RelResVul index were also presented in Fig. 4.

The minimum soil erosion-based RelResVul values were 0.50, 0.67 and 12.84 for 1986; 0.58, 0.60 and 11.94 for 1998; 0.58, 0.80 and 0.35 for 2008, and 0.50, 0.67 and 10.71 for 2014. Additionally, the maximum soil erosion-based $R_{el}R_{es}V_{ul}$ values were obtained 0.67, 1.00 and 1958.47 for 1986; 0.75, 1.00 and 1155.46 for 1998; 0.75, 1.00 and 169.37 for 2008 as well as 0.75, 1.00 and 6985.09 for 2014. The best state of erosion-based $R_{el}R_{es}V_{ul}$ indicators at all study node years were observed in sub-watershed 9 and the worst situation was obtained for sub-watersheds 7 and 24 (Table 3).

As seen from Table 3, the reliability and resilience indicators are in the good level for most of the study sub-watersheds. It is indicated that the duration of failure of events (*d*) in the Shazand Watershed was short. So that, the maximum duration under failure conditions for the watershed was six months of a year. In addition, these durations were not happening continuously. It was observed that the minimum number of failure events (*M*) was four. It meant that the six-months failure event was happened in six intervals. This status indicated the high potential of the Shazand Watershed in reliability and resilience. In fact, it can be concluded that the study watershed had a fast reaction to return to a satisfactory state.

The interactions of these indicators resulted in low vulnerability of the Shazand Watershed. According to Fig. 3, the high geometric values of the final index also proved the low vulnerability of the Shazand Watershed to soil erosion process, but the variability of vulnerability was higher than other two study risk indicators, because the vulnerability in addition to "*M*" was influenced by the high variability of soil erosion rates. It is in line with the results obtained for SPI-$R_{el}R_{es}V_{ul}$ index characterization of the same watershed (Sadeghi and Hazbavi 2017b; Hazbavi et al. 2018a). This finding proved the efficiency of soil erosion from climatic variables. Besides that, the long-term measured sediment concentration of the Shazand Watershed characterized by $R_{el}R_{es}V_{ul}$ (Hazbavi and Sadeghi 2017) reported the consistent results.

Table 2. Descriptive statistics of soil erosion for different Shazand Sub-watersheds in the study node years

Year	Statistical criteria	Soil erosion (t ha^{-1} y^{-1})
1986	Mean	128.25
	Standard deviation	46.17
	Minimum	27.89
	Maximum	219.26
1998	Mean	58.89
	Standard deviation	30.44
	Minimum	17.33
	Maximum	126.04
2008	Mean	28.98
	Standard deviation	12.45
	Minimum	4.98
	Maximum	52.73
2014	Mean	141.65
	Standard deviation	103.94
	Minimum	12.22
	Maximum	360.05

Table 3. Un-standardized R_{el}, R_{es} and V_{ul} indicators for the different Shazand Sub-watersheds in the study node years

Year	1986			1998			2008			2014		
Indicator Sub-watershed	R_{el}	R_{es}	V_{ul}	R_{el}	R_{es}	V_{ul}	R_{el}	R_{es}	V_{ul}	R_{el}	R_{es}	V_{ul}
1	0.67	1.00	134.23	0.75	1.00	25.27	0.67	1.00	4.62	0.75	1.00	637.53
2	0.67	1.00	99.92	0.75	1.00	254.85	0.67	1.00	19.65	0.75	1.00	36.12
3	0.67	1.00	68.91	0.75	1.00	57.01	0.75	1.00	3.56	0.75	1.00	188.70
4	0.67	1.00	68.43	0.75	1.00	69.46	0.67	1.00	2.55	0.75	1.00	67.23
5	0.58	1.00	380.73	0.58	0.60	27.93	0.67	1.00	17.45	0.67	1.00	5630.44
6	0.67	1.00	248.62	0.75	1.00	80.67	0.67	1.00	10.36	0.75	1.00	778.74
7	0.50	0.67	1958.47	0.58	0.60	1155.46	0.58	0.80	169.37	0.50	0.67	6985.09
8	0.58	1.00	418.03	0.58	0.60	25.85	0.67	1.00	24.57	0.67	1.00	6036.30
9	0.67	1.00	12.84	0.75	1.00	11.94	0.75	1.00	0.35	0.75	1.00	10.71
10	0.67	1.00	235.61	0.75	1.00	441.41	0.67	1.00	30.08	0.75	1.00	260.81
11	0.67	1.00	30.39	0.75	1.00	82.32	0.67	1.00	0.93	0.75	1.00	24.42
12	0.67	1.00	702.32	0.67	1.00	770.73	0.67	1.00	92.72	0.58	0.80	305.10
13	0.67	1.00	283.40	0.75	1.00	619.02	0.67	1.00	55.62	0.75	1.00	48.75
14	0.67	1.00	73.87	0.75	1.00	28.00	0.67	1.00	2.15	0.75	1.00	128.49
15	0.58	1.00	360.65	0.67	0.75	61.24	0.67	1.00	25.04	0.67	1.00	5407.43
16	0.58	1.00	260.23	0.58	0.60	99.54	0.67	1.00	15.42	0.75	1.00	1923.18
17	0.58	1.00	234.71	0.58	0.60	41.95	0.67	1.00	7.33	0.75	1.00	1077.56
18	0.58	1.00	401.19	0.58	0.60	147.77	0.67	1.00	34.44	0.58	0.60	5980.47
19	0.67	1.00	158.87	0.75	1.00	107.20	0.67	1.00	10.86	0.75	1.00	446.11
20	0.67	1.00	82.43	0.75	1.00	48.26	0.67	1.00	3.15	0.75	1.00	187.50
21	0.67	1.00	19.14	0.75	1.00	71.93	0.67	1.00	0.84	0.75	1.00	16.93
22	0.67	1.00	39.42	0.67	1.00	102.03	0.67	1.00	4.72	0.75	1.00	122.55
23	0.67	1.00	209.66	0.75	1.00	394.42	0.67	1.00	26.87	0.75	1.00	84.76
24	0.50	0.67	988.09	0.58	0.60	931.81	0.58	0.80	79.36	0.50	0.67	2487.68

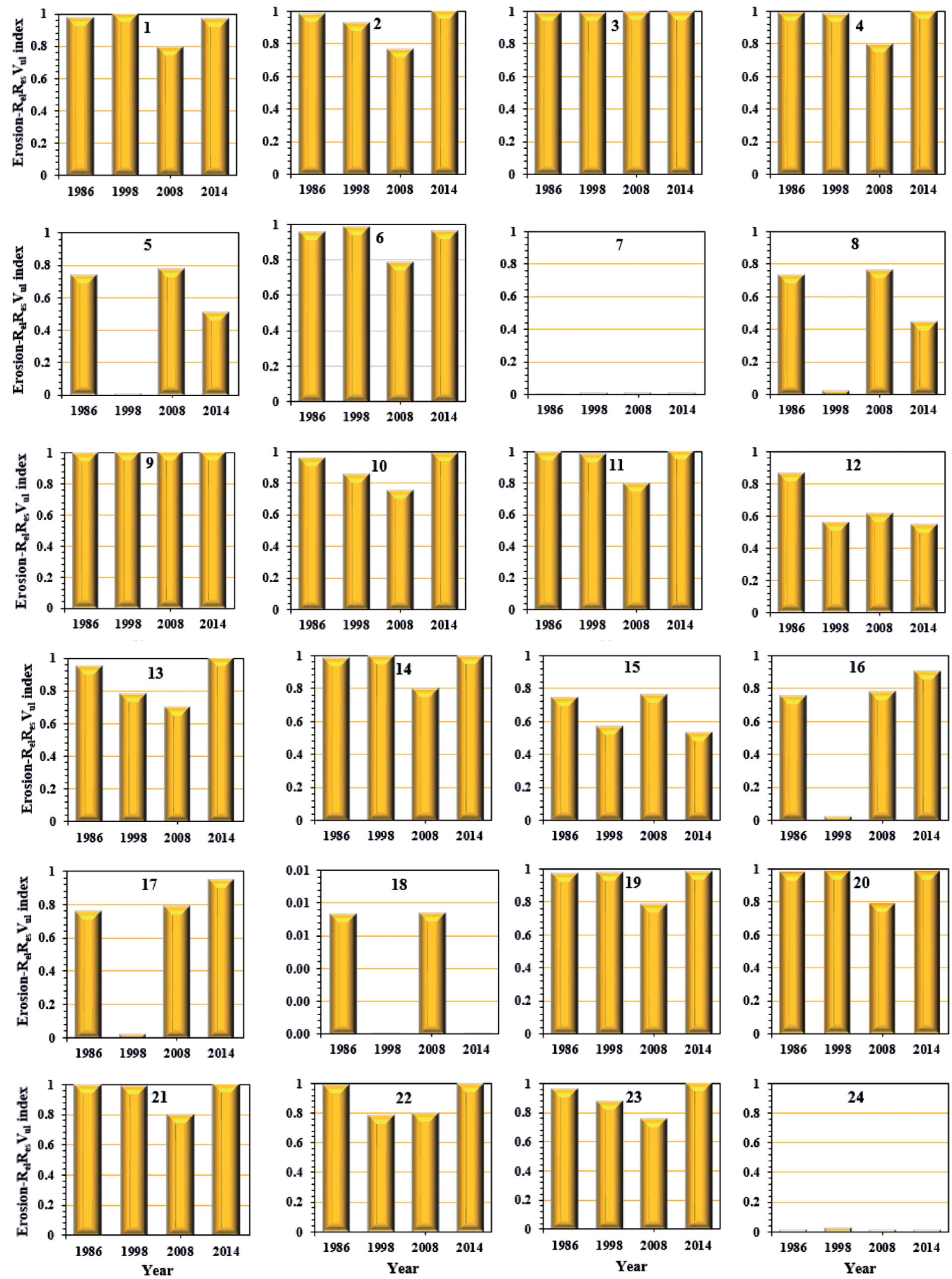

Fig. 3. Soil erosion-based $R_{el}R_{es}V_{ul}$ index for the different Shazand sub-watersheds (as numbered) in the study node years

Analysis of the application of the $R_{el}R_{es}V_{ul}$-framework also revealed that the distribution of sub-watersheds in viewpoint of soil erosion-based $R_{el}R_{es}V_{ul}$ index for different status of very healthy (1.00–0.81), healthy (0.80-0.61), moderately healthy (0.60-0.41), and very un-healthy (0.20-0.00) were 67, 25, zero and eight percent for 1986; 50, 13, eight and 29 % for 1998; eight, 84, zero and eight percent for 2008 and ultimately 71, zero, 17 and 12 % for 2014, respectively, as shown in Fig. 4. No un-healthy (0.40-0.21) condition of soil erosion-based RelResVul index was found for the Shazand Watershed (Fig. 4). Hereinto, the interchange of RelResVul have also been summarized in Fig. 5.

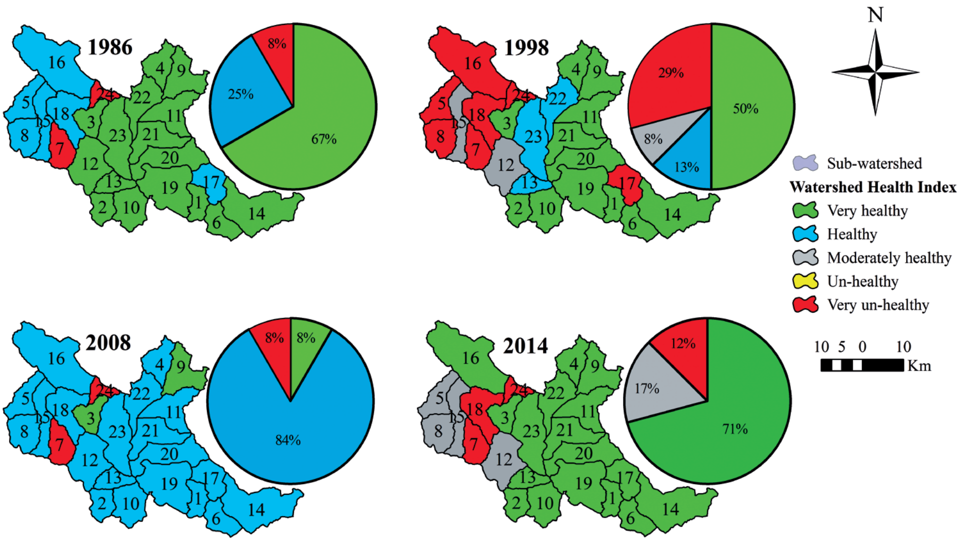

Fig. 4. Spatial distribution of the erosion-based watershed health index for the different Shazand sub-watersheds in the study node years

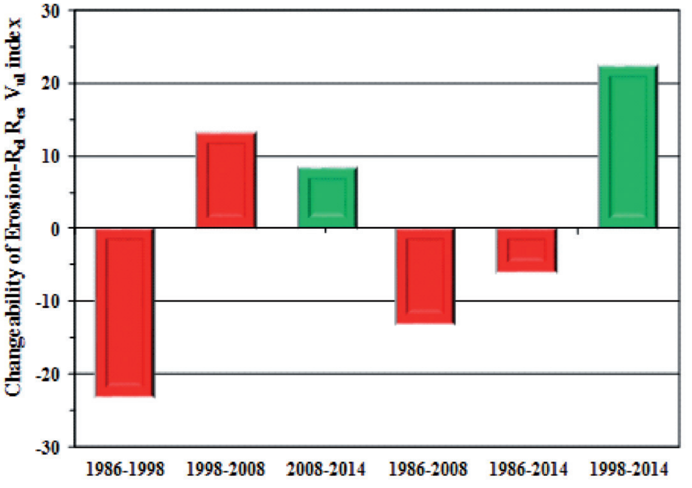

Fig. 5. Change detection of the erosion-based watershed health index in the Shazand Watershed

The sub-watersheds 7 and 24 were found as 'hot spots' of land degradation, since they could not recover their ability against soil erosion process in all study node years. This result showed that the soil loss of this sub-watershed was always more than permissible threshold (5 t ha^{-1} y^{-1}). Similar health conditions were verified in the previous researches using other criteria. So that, Hazbavi et al. (2018c) with characterizing the $R_{el}R_{es}V_{ul}$ framework stated a land cover based watershed health index of 0.36 for sub-watershed 24 indicating an un-healthy state. In addition, the climatic drought state of sub-watershed 24 was quantified less than 0.35 (un-heathy state) according to the $R_{el}R_{es}V_{ul}$ framework by Sadeghi et al. (2018). Sadeghi et al. (2019) and also reported an un-healthy state during node years of 1986 and 2008 as well as very un-healthy state during 1998 and 2014 for sub-watershed 24 with the help of an integrated watershed health index (IWHI) based on the $R_{el}R_{es}V_{ul}$ framework. Recently, Hazbavi et al. (2019) also estimated an un-healthy state for this sub-watershed during all study node-years using pressure–state–response (PSR) framework. Accordingly, they recommended to adapt the immediate managerial measurements to improve and restore the health condition of sub-watersheds located in the north and northeast including the sub-watershed 24. The sub-watershed 18 was also under stress more than other sub-watersheds due to un-stable state during the study period (1986 to 2014). This sub-watershed with land cover based watershed health index of 0.31 for 2014 (Hazbavi et al. 2018c), flow discharge based watershed health index less than 0.40 (Sadeghi and Hazbavi 2017a), climatic drought based watershed health index less than 0.32 (Sadeghi et al. 2018) and IWHI less than 0.40 (Sadeghi et al. 2019) was classified in un-healthy and very un-healthy states. In this context, it is essential to plan the land management strategies and enhance the riparian vegetation.

The sub-watersheds 5, 8, 16 and 17 were in the relatively bad status but they were finally classified in a better status rather than at the end of the study period. These results were in line with Sadeghi et al. (2018) findings who noted that the mentioned sub-watersheds were classified in the fragile and critical classes of Environmental Sensitive Area Index (ESAI) computed for the whole Shazand Watershed. Whilst, Sadeghi et al. (2019) reported a relatively constant state for the mentioned sub-watersheds which could be associated with influence of combination of soil erosion criterion with other criteria of standardized precipitation index, NDVI, and low and high flow discharges in integrated watershed health assessment.

According to the results (Table 3; Fig. 4), sub-watersheds 1, 2, 3, 4, 6, 9, 10, 11, 12, 13, 14, 19, 20, 21, 22 and 23 almost had healthy and very healthy state in terms of the soil erosion-based $R_{el}R_{es}V_{ul}$ index during study node years. This result reflected a high potential of the stated sub-watersheds in viewpoint of R_{el} and R_{es} indicators and their low V_{ul} to soil erosion. The high soil erosion-based $R_{el}R_{es}V_{ul}$ index value meant that the sub-watersheds are not prone to soil erosion. However, the state of these sub-watersheds in viewpoint of land cover (Hazbavi et al. 2018c), climatic drought (Sadeghi and Hazbavi 2017b), hydrology (Sadeghi and Hazbavi, 2017a) and integrated watershed health assessment was classified as moderately healthy (0.41-0.60) or un-healthy (0.21-0.40). In overall, Sadeghi et al. (2019) with considering interactive impacts of climatic, hydrologic and anthropogenic activities on watershed health verified a better state of the above mentioned sub-watersheds.

Results of change detection (Fig. 5) revealed that during the study period (1986 -2014), the Shazand Watershed has experienced different condition changes. So that, the rates of changes were not uniform over the study period. The decreasing health trend was found during 1986-1998 (-23 %), 1986-2008 (-13 %) and 1986-2014 (-6%), whilst, the increasing health trend was obtained for periods of 1998-2008 (13 %), 2008-2014 (8%) and 1998-2014 (22 %). As seen in Fig. 5, unpleasant changes in the Shazand Watershed health happened during the periods of 1986-1998, 1986-2008 and 1986-2014. In this regard, Sadeghi et al. (2018) reported an increasing trend in the process of land degradation in the study region. According to their finding, 17, 33, 42, 42 and 50 % of the study area in five year nodes of 1986, 1998, 2008 and 2014, respectively, were in critical condition of land degradation in viewpoint of ESAI. The main factor of land degradation in the Shazand Watershed is vegetation land use change resulted from anthropogenic and managerial factors (Sadeghi et al. 2018). Sadeghi et al. (2019) who assessed the integrated health of the Shazand Watershed noted a deteriorating trend for 1986–1998 and 1986–2008 periods owing to industrialization and urban development.

CONCLUSION

A novel soil erosion risk assessment-based $R_{el}R_{es}V_{ul}$ framework was successfully applied in the industrialized and urbanized Shazand Watershed, Central Iran, to map watershed health and to detect changes during node years of 1986, 1998, 2008 and 2014. According to the results, the sub-watersheds 7, 18 and 24 were found un-healthy in viewpoint of erosion. The emergency managerial strategy is therefore needed to be adopted. However, for major part of other sub-watersheds, the reliability, resilience and vulnerability were in the healthy or moderately healthy status. During the time, the sub-watersheds status was in change. Based on the results, the erosion-based watershed health index in periods of 1986-1998, 1986-2008 and 1986-2014 had decreasing trend of 23, 13 and 6%. The applied technique and conceptualized strategy would provide a sustainable framework supporting decision making to realize health-related soil and water conservation targets and plans towards the 17 United Nations Sustainable Development Goals (SDGs) from 2015 to 2030. Of course, more research and monitoring programs are required for better understanding of the scale and immediacy of the threating drivers of soil erosion such as human interventions and climate change to watershed health and to act within a much larger and more comprehensive framework.

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