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Early-Warning System for Desertification Based on Climatic and Hydrologic Criteria

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Abstract

The United Nations' convention on desertification encourages the participating countries to introduce criteria for developing Early-Warning Systems (EWS) in order to monitor and assess desertification. The objective of the present study was to establish an EWS for desertification assessment in Kashan plain, Iran, using the methodology of practical and general applicability. Designing EWS requires a model to identify the influential criteria and areas vulnerable to desertification. The Kashan Plain's EWS relies on the Iranian Model for Desertification Potential Assessment (IMDPA) to establish desertification thresholds and generate desertification maps with Geographic Information Systems (GIS). The EWS of Kashan plain was designed to calculate hydrologic (groundwater level and electric conductivity of groundwater indices) and climatic (precipitation, Transeau aridity, and drought indices) criteria and assess the degree of regional desertification. Afterwards, the desertification intensity maps of criteria and indices were produced and overlapped. The EWS was developed in areas most bound to be threatened by desertification. EWS quantifies desertification data and thresholds to issue desertification assessments and warnings for management purposes. In the next step, Client–Server program was designed based on an algorithm defined by Java programming language and implemented as a data collection, analysis, and response management system. Whenever the thresholds exceed the defined limits, warning messages can be sent via SMS or internet to relevant system managers for appropriate action.

Keywords: Desertification, Drought, Early-Warning System, Groundwater, Precipitation, GIS

1. Introduction

As noted by Stocking and Murnaghan (2001), desertification or land degradation refers to the decline in the quality and productivity of land, which involves processes affecting not only the soil, but also water and vegetation. Indicators of land degradation include soil erosion (wind and water erosion), reduced soil fertility, declining groundwater levels, vegetation loss or reduction and paucity of biodiversity. Some of these processes are deemed irreversible and attributed to human actions (Mortimore, 2005). According to the United Nations, desertification threatens the livelihood of two billion people in the world's drylands and even non-dryland areas; therefore, it is one of the world's most pressing environmental issues today.

Desertification is divided into creeping and slow-onset that, if ignored, may cause a great number of losses (UNEP, 2012). In Iran, an arid and semi-arid country, there are no monitoring systems such as EWS for the real-time assessment of desertification. This hinders the country's ability to detect changing desertification and act against the ensued risks in real time. By providing information, an EWS reduces economic losses and helps people protect their properties (UNEP, 2012). Several other countries vulnerable to desertification lack EWS. One of the main purposes of an early warning system (EWS) for desertification is to deploy a technology capable of detecting evolving

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conditions as they occur and issue warnings to respond to those conditions based on factual evidence. A sound EWS must be based on appropriate criteria to evaluate desertification conditions, make assessments, and transmit warnings to responsible parties for action. The severity of drought condition and its consequences such as famine, is increasing in various regions of the world. Accordingly, in response to the impacts of drought, the majority of early warning systems are designed to ensure timely and appropriate decisions and measures. An EWS requires models to recognize the areas vulnerable to desertification (Singh and Ajai, 2015) and the effective indicators. Therefore, The Iranian Model for Desertification Potential Assessment (IMDPA) was employed as an approach to evaluating desertification potential in Iran. This model was introduced by the country's Forest, Rangeland, and Watershed Management Services (Ahmadi *et al*., 2004; see Appendix A for details about the IMDPA).

Several studies have been conducted worldwide dealing with EWS for drought. Different types of drought require different descriptive criteria (De Pauw, 2000). For instance, in a study carried out on an EWS for drought in North Africa and West Asia, biological and meteorological criteria were selected as the main indicators (De Pauw, 2000). A study conducted in India reported that a soil-moisture index including the data of daily rainfall and estimated pearl millet yield improved the drought early warning system (Boken, 2009). The Nigerian Department of Meteorological Services (NDMS) employed the Standardized Precipitation Index (SPI, McKee *et al*., 1993), NDMS Prediction Schemes, and Sea Surface Temperature (SST) prediction schemes to implement a meteorological early warning system (Akeh, et.al, 2000).

The Turkish State Meteorological Service (TSMS) has adopted a network of radars to implement a climate warning system to assist with drought management in Turkey. To predict drought, the TSMS applies the SPI index in the analysis and estimation of precipitation (UNCCD, 2005).

Although the idea of deploying early warning systems for desertification was introduced years ago, there have been few studies published concerning early warning systems for desertification. In many countries, there have been a few pilot projects tackling the basic principles of early warning systems for desertification. One such example is the Japanese government's pilot studies to develop an EWS for desertification in north-eastern Asia (United Nations Convention to Combat Desertification (UNCCD, 2005)).

In another study in India, desertification vulnerability index (DVI) was obtained using climate, land use, vegetation, soil and socio-economic factors. Thereafter, the studied area was classified based on DVI values into regions of no vulnerability to high vulnerability. Identifying vulnerable areas was their first step towards early warning for desertification. Their results indicated the necessity of monitoring and surveying any further degradation in the entire area, high vulnerability areas in particular(Singh and Ajai, 2015)

Han *et al*. (2017) performed desertification monitoring and early warning during land consolidation project in Kezuohouqi, China, where there is sandy land. To achieve desertification monitoring and early warning system, the decision tree classification method and PSR (pressure-state-response) model were respectively employed.

Also, an intelligent model of desertification forewarning was utilized in China by Meng *et al*.(2018). Climate, remote sensing, land surface, and human factors were used in their study. This model showed the distribution of desertification degree in the selected study period. The trend of desertification was predicted under two conditions of "intermittent water conveyance" and "no water conveyance". Their results revealed that intermittent water conveyance plays an important role in combating desertification.

The IMDPA relies on nine criteria and 36 indices for desertification assessment (Ahmadi *et al*., 2004), which classifies desertification intensity within a EWS (Appendix A). In the present study's EWS, the IMDPA was employed to identify alert desertification thresholds, albeit with a simpler scheme for determining desertification thresholds. The IMDPA was applied using geology-geomorphology, soil, and wind erosion criteria to assess the desertification status in the region of Abuzeid Abad, Iran; it was concluded that the desertification status (DS) for that area equaled 2.7, which is a high level of desertification severity (Mesbahzadeh, 2007). Another IMDPA application was based on hydrologic and soil criteria to generate a desertification map for the mentioned criteria in the Kashan region; in this research, a hydrologic criteria with a geometric average of 3.59, implying a very high level of desertification severity, was recognized as the major problem in the studied area (Khosravi *et al*., 2014).

Vesali (2008), Raeesi (2008), Kamali (2011), and Rafiee (2012) applied the IMPDA in the assessment and monitoring of desertification in different cities of Iran.

Our literature review revealed that most early warning systems (EWSs) created to date have addressed natural disasters such as drought, floods, and earthquakes. Other EWSs have been tailored for human-induced calamities such as pollution of drinking water sources (Hou *et al*. 2003) or hazards of mixed origin, including online global early warning system for wildland fires. However, there have not been any reports on the development and application of desertification EWSs.

The current study identifies key controlling factors of desertification intensity in Kashan plain, Iran, and develops an EWSs for desertification assessment based on the measurements of hydrologic and climatic variables. The proposed EWS is a novel tool for monitoring and assessing desertification. In addition, the present research proposes recommendations for future studies involving desertification EWSs. This is the first attempt at the implementation of a desertification EWS in Iran, specifically Kashan plain. The method developed in this work aims at practicality and generality in the assessment of desertification with EWSs to broaden its potential use to arid realms beyond Kashan plain. Its assessment capacity offers potential benefits to those concerned with the assessment of desertification in other parts of the world.

2. Materials and Methods

2.1. The Case Study Area

Kashan plain is located in the alluvial fan of the Karkas Mountains, on the edge of the central desert of Iran, about 240 km south of Tehran, Iran. This region is located between 50° 54’ 10” and 52° 6’ 2” of longitude and between 33° 37’ and 34° 31’ of geographical latitude. With an area of 1474 km^2, this plain encompasses the cities of Kashan and Aran Bidgol and the surrounding agricultural lands (Figure 1). Kashan Plain is known as one of the most arid areas in Iran. Because it is located next to a desert far from the sea, it receives less than 150 mm of annual precipitation.

The climate of Kashan plain is classified according to the de Martonne's aridity index (de Martonne, 1926; see Thornthwaite, 1948, for a review of De Martonne’s and other aridity indices) as having a 4.8 aridity coefficient. Therefore, it is an arid region with high desertification intensity (Water Balance Framework, Ministry of Engineering Water And Energy Resources Studies, 1999). The Kashan watershed covers parts of the Karkas Mountains, hence its geological division by two mountainous regions.

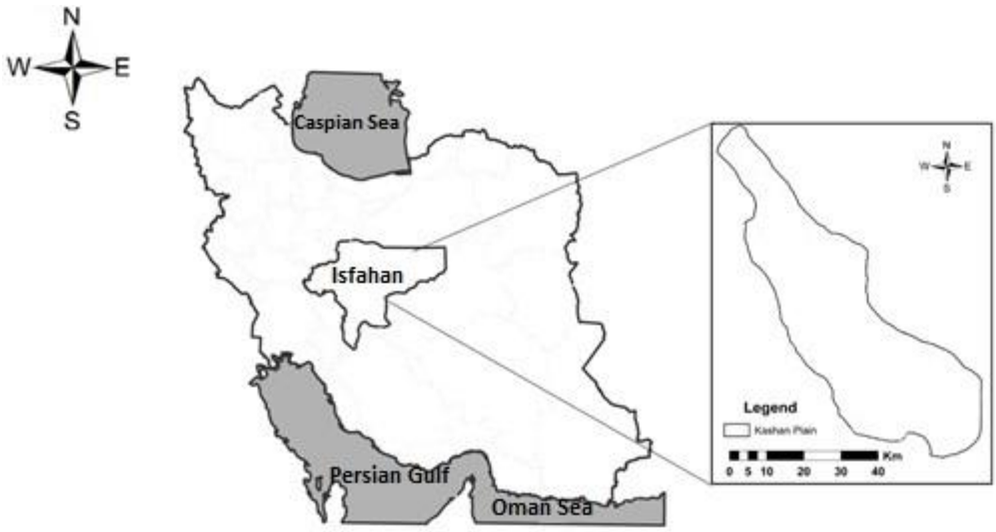

Fig. 1. Geographical location of Kashan plain in Iran

2.2. Methodology

An effective EWS comprises four components: risk knowledge, monitoring and warning services, dissemination and communication, and response capability (UNCCD, 2007). The main steps involved in the development of an EWS are as follows: (1) defining relevant criteria and indices adopted from the IMDPA model, which must be measured in the case study region; (2) defining thresholds for different indices (each index’s threshold may vary by locality); (3) selecting sites based on desertification intensity to install and operate the EWS's monitoring devices for data collection; (4) developing a software for monitoring indices and data collection within the studied region; (5) determining the devices required for data collection and recording; (6) calculating the desertification criteria and issue desertification warnings in the region of study; and (7) establishing a communication between the EWS management unit and other relevant devices.

Each EWS is to be organized according to the characteristics of the region under study (UNCCD, 2007). In this study, two desertification criteria were used, one for climate and the other for hydrology. These two criteria were determined to be the two most important variables for desertification assessment during the data collection period (between 1991 and 2013) in Kashan plain. The climatic and hydrologic criteria were selected based on expert opinion, field investigations, and the study of critical factors in Kashan region.

The climatic criterion involves three indices, namely annual precipitation, the Transeau aridity index (see Transeau, 1905, Thornthwaite, 1948, and Steila, 1983, for a review of the Transeau Aridity Index), and the drought index (Ahmadi, *et al*. 2004). Precipitation and temperature data were collected from climatic stations located within the study region. There are four climatic stations in Kashan region. Drought is a temporary phenomenon which differs from dryness, which is endemic to regions with low precipitation and a permanent climatic feature. Drought is a complex natural hazard, simply defined as a deficit (shortage) of water in comparison with normal conditions (Van Loon, 2015; Sheffield and Wood, 2011). The drought index includes two sub-indices: the SPI (Standard Precipitation Index) (Masoudi, 2011, World Meteorological Organization (WMO), 2012, and Khosravi *et al*., 2017) and the drought extension index (the maximum duration of the drought (year)) (Ahmadi, *et al*. 2004). The decline in groundwater level and the electric conductivity (EC) of groundwater were selected as indices for the hydrologic criterion in the EWS.

Statistical data from 53 piezometers over a 19-year period (1991-2013) were used in the groundwater assessment. One of the main methods for calculating the average hydraulic head of an aquifer is to draw a hydrograph of its groundwater level using Thiessen polygons. The polygons of the case study area were derived in the first phase of the method based on the piezometers' data. All required calculations were made to generate the hydrograph of Kashan plain. The main purpose associated with this hydrograph was to specify the changes in the groundwater level across the study region. The Thiessen method was applied to cover particular areas described by a set of piezometers. The groundwater index was assigned according to the depletion of the groundwater level using the scheme presented in Table B.6 of Appendix B. Lastly; the average drop of the groundwater level was calculated for the period 1991-2013.

The selected indices were utilized for the quantification of the criteria's values according to the IMDPA procedure. Weighing values of 1 to 4 were assigned to each cited index depending on (1) their impacts on desertification severity and (2) the expert opinion.

The numerical value of each criterion equals the geometric mean of its indices. For the climatic criterion, this is accomplished with the following equation:

$$CC = (P \cdot TAI \cdot DI)^{\frac{1}{3}}$$
$$CC = (P \cdot TAI \cdot DI)^{\frac{1}{3}} \quad (1)$$

In which *CC* = climatic criterion, P = annual precipitation index, *TAI* = Transeau aridity index, and *DI* = drought index. The drought index is calculated as follows:

$$Drought\ index = DI = (Drought\ extension\ index \cdot SPI)^{1/2}$$
$$Drought\ index = DI = (Drought\ extension\ index \cdot SPI)^{1/2} \quad (2)$$

The drought extension index is tabulated in Table B.5 of Appendix B.
The equation used for the hydrologic criterion is:

$$HC = (GL \cdot EC)^{\frac{1}{2}} HC = (GL \cdot EC)^{\frac{1}{2}} \quad (3)$$

where *HC* = hydrologic criterion, *GL* = groundwater level depletion, and *EC* = electric conductivity of groundwater.

The numerical value of the desertification status (*DS*) is calculated by the geometric mean of the climatic criterion (*CC*) and the hydrologic criterion (*HC*), as shown in Eq. (4).

$$DS = (CC \cdot HC)^{\frac{1}{2}} DS = (CC \cdot HC)^{\frac{1}{2}} \quad (4)$$

The desertification intensity (DS) is then classified according to Table 1, which lists the five categories of desertification intensity adopted in this study (Vesali, 2008).

Table 1. Classification of desertification intensity

Numerical value	Classification of desertification intensity
0.0001 to 1	Negligible
1.1 to 1.5	Low
1.6 to 2.5	medium
2.6 to 3.5	High
3.6 to 4	Very high

Appendix B contains information about the indices and sub-indices applied in this work. Appendix C presents equations for the Transeau aridity index and SPI implemented in this research. Maps of desertification intensity for all analysis periods were created using the calculated and georeferenced values of desertification criteria (climatic and hydrologic in this case) and the processing of those values with Geographic Information Systems (GIS). The maps of each of the two criteria (climatic and hydrologic) or their indices could be generated if so desired. Climatic and hydrologic data for the period (1999-2013) were used to calculate and prepare the desertification intensity maps. The desertification intensity maps of each criterion and index identify the most suitable sites for deploying the EWS. The sites and thresholds with most evident trends of desertification were identified in the prepared maps. Afterwards, remote-sensing analysis was carried out to monitor the most influential indices causing desertification in the region. Monitoring instruments were installed within the region for this purpose (see the Discussion session for monitoring instruments).

3. Results and Discussion

3.1. A map of desertification

The results obtained from the climatic criterion (using Eq. (1)) indicated that the Transeau aridity index played a critical role in the assessment of desertification in Kashan plain. Table 2 lists the calculated indices and sub-indices influencing the climatic criterion (Eq.(1) and appendix B).

The calculated indices for the hydrologic criterion (Eq. (3) and appendix B) are listed in Table 3.

Table 2. The calculated indices for the climatic criterion

Index or sub-index	Numerical value	Classification of desertification intensity
Precipitation (P)	2.73	Very high
Transeau aridityTranseau aridity (TAI)	3.01	high
SPI	1.92	Medium
Drought extension	0.60	Negligible

Table 3. The calculated indices for the hydrologic criterion

Index	Numerical value	Classification of desertification intensity
Groundwater level depletion	3.82	Very high
Groundwater conductivity	3.04	high

As shown in Figure. 2, the calculated climatic and hydrologic criteria values were employed to prepare a desertification map for Kashan plain (Eq. (4)). Figure 2 shows that Kashan plain exhibited desertification intensities equal to medium and high in approximately 60 and 40% of its areas, respectively.

3.2 Classification of regions by the intensity of desertification

The GIS layers (the maps of criteria and indices) were overlapped. The EWS is deployed in areas most susceptible to desertification. The regions that are most threatened by desertification comprise three groups whose maps were prepared with GIS. The desertification groups are defined as follows:

3.2.1 Regions classified as having high desertification intensity and being slightly above the medium intensity threshold (2.6 <Numerical value<2.7). In these regions, conditions can be improved through monitoring and controlling the groundwater withdrawal (Figure 3).

3.2.2 Regions with medium desertification intensity and numerical values (2.4<Numerical value <2.6) close to high desertification intensity thresholds; in the absence of controlled groundwater withdrawal or water quality status, regions of such ilk are prone to becoming highly degraded (Figure 4).

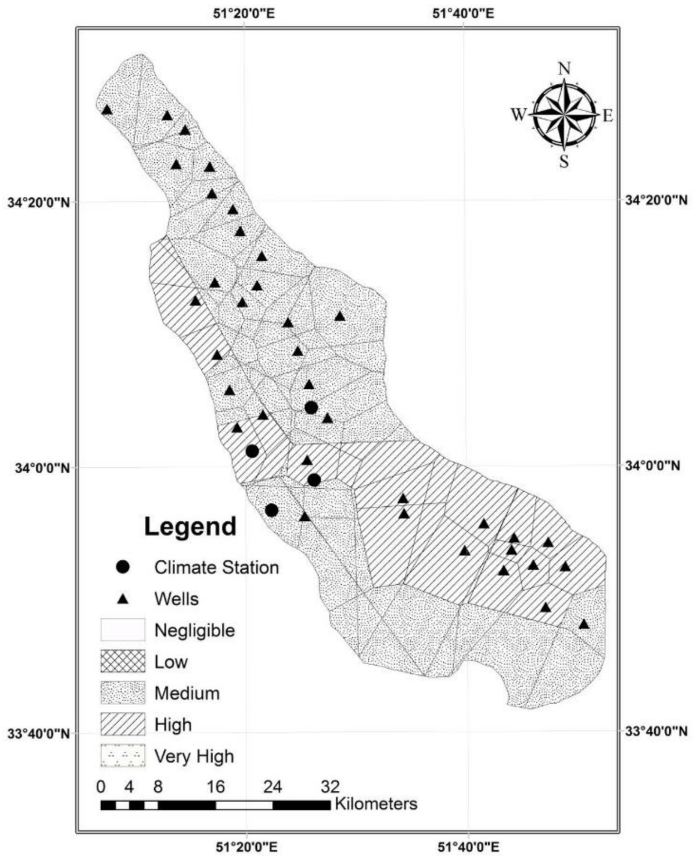

Fig. 2. The desertification map of Kashan plain, Iran, for the 19-year period (1991-2013). The numerical ranges of the desertification categories are listed in Table 1

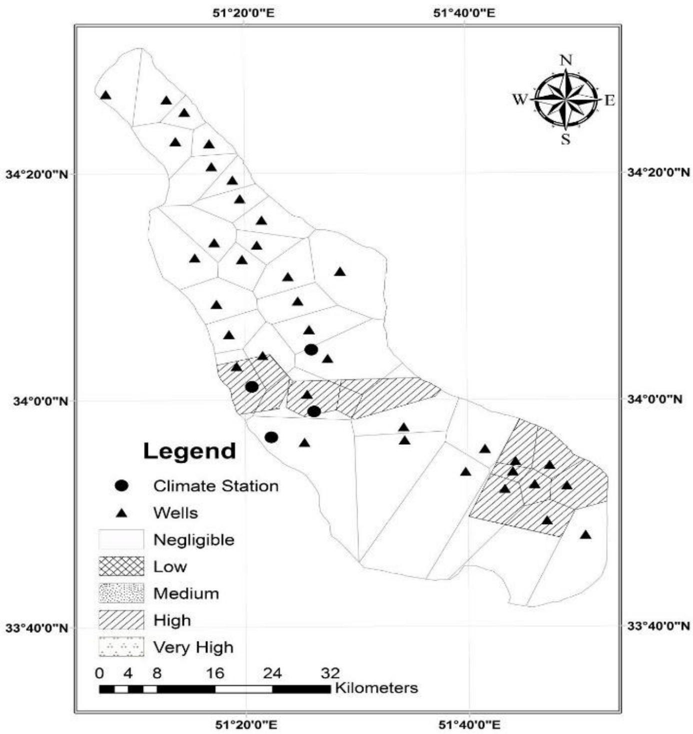

Fig. 3. The regions with high desertification intensity. The numerical ranges of desertification categories are listed in Table 1

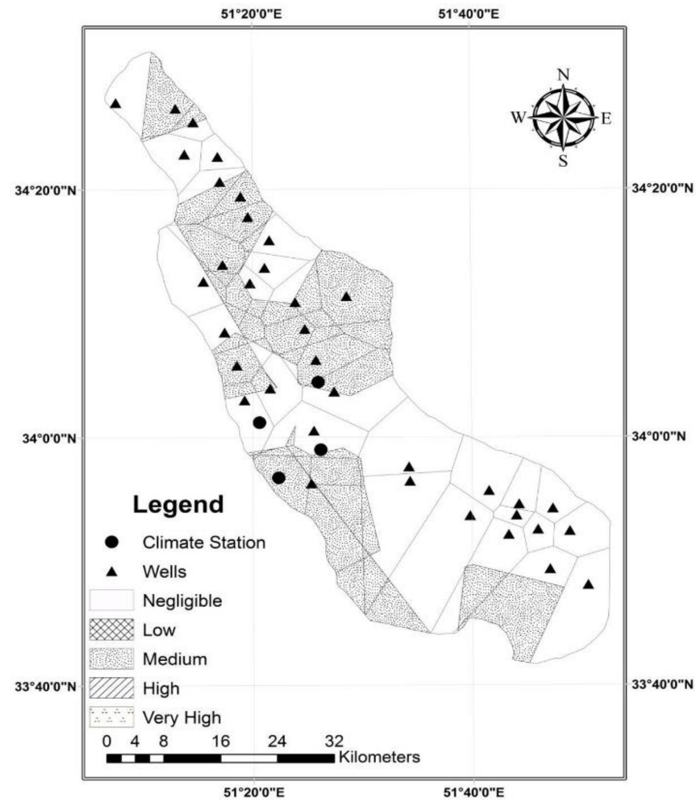

Fig. 4. The regions with medium desertification intensity. The numerical ranges of desertification categories are listed in Table 1

3.2.3 Regions with the highest numerical value of desertification intensity (Numerical value>2.7). Severe degradation has been observed in these areas based on the results obtained from the monitoring of groundwater levels. The lands are portrayed in Figure 5.

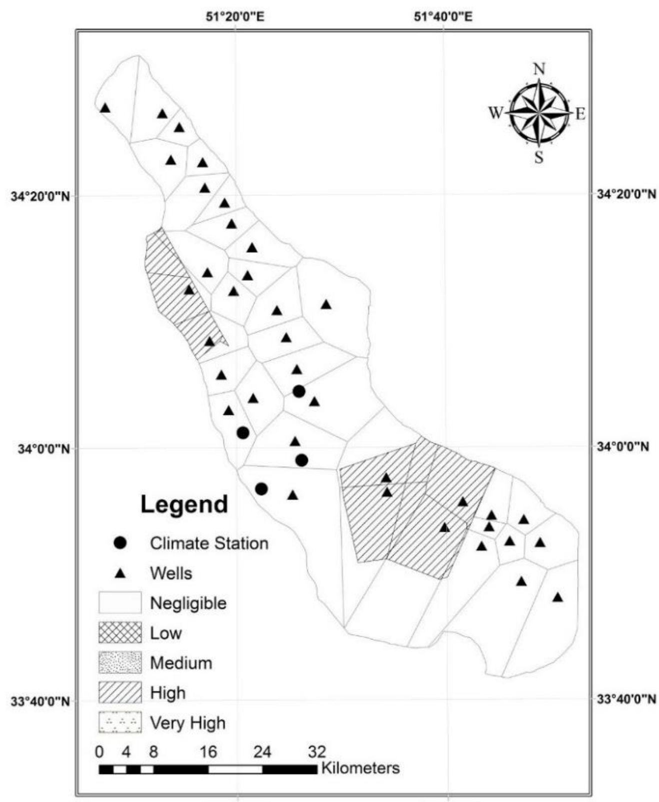

Fig. 5. The regions with the highest desertification intensity. The numerical ranges of desertification categories are listed in Table 1

The indices of groundwater level decline, groundwater electric conductivity, and Transeau aridity, with (average) numerical values of 3.82, 3.04, and 3, respectively, had the highest impact on desertification in Kashan plain. Furthermore, the sub-indices of extended drought and SPI had (averages) values of 0.60 and 1.92, respectively. As depicted in Figure 6, these sub-indices, together with an (average) annual precipitation index of 2.73, were found to have the least impacts on desertification trends.

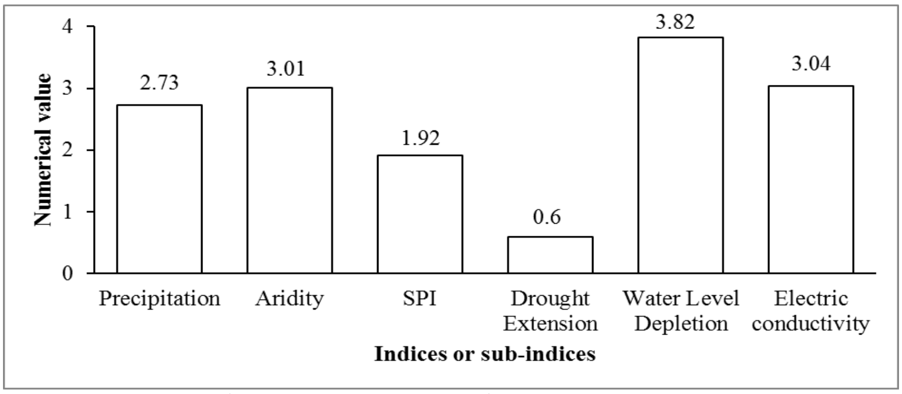

Fig. 6. The values of the indices and sub-indices of the hydrologic and climatic criteria

The hydrologic criterion with a value equal to 3.36 (calculated with Eq. (3)) was determined to be the dominant desertification factor. This value corresponds to a desertification intensity category equal to High based on Table 1. The climatic criterion, with an average value of 1.89 (calculated with Eq.(1)), was the second most influential factor of desertification. Its value corresponds to a desertification intensity category equal to Medium in Table 1.

The previous results showed that the Transeau aridity index and groundwater decline index were the most influential factors of desertification in Kashan plain. The EWS and a Client-Server program (depicted in Figure 7) were designed based on these two indices and implemented as a data collection, analysis, and response management system. The application was written by Java programming language based on the defined algorithm; a part of the software interface is illustrated in Figure 8.

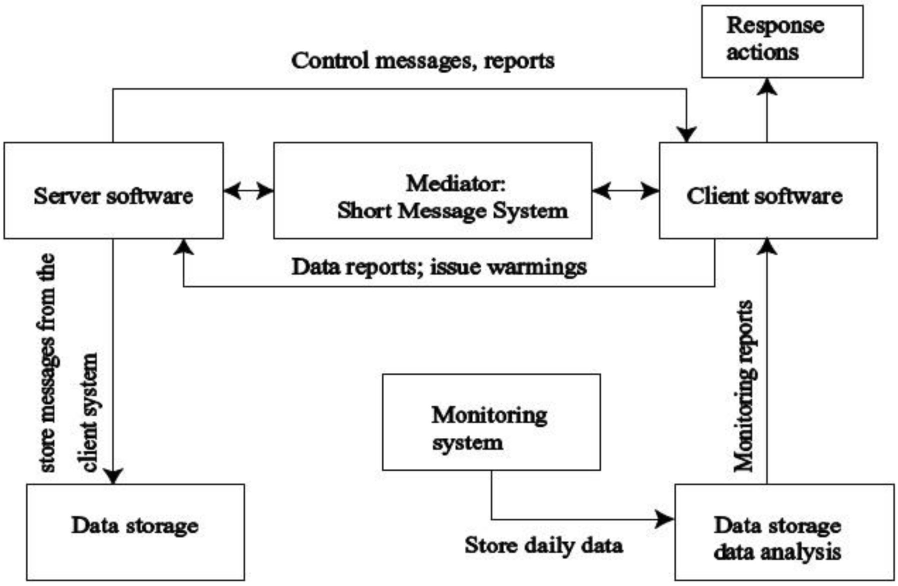

Fig. 7. Generic diagram of the Client-Server program

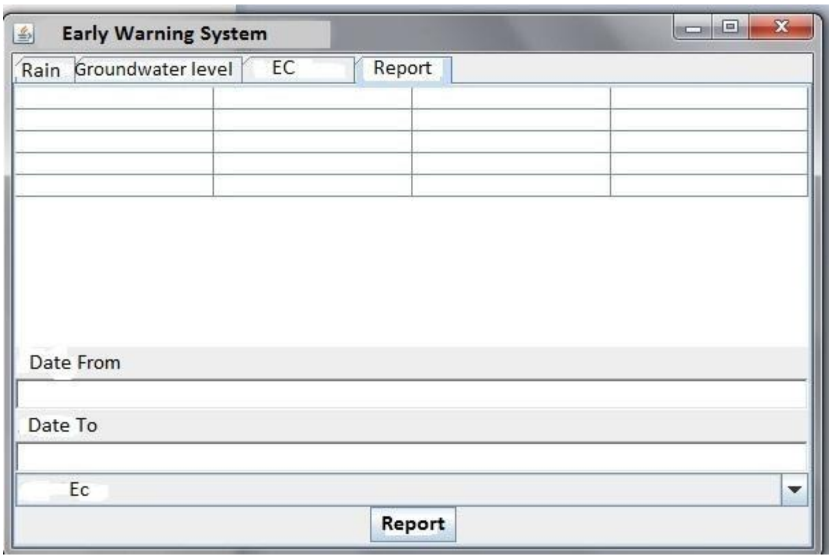

Fig. 8. Software interface

3.3. Client-Server Program

Designed as a Client-Server interactive tool, this program is an online system that involves remote sensing. The Server handles request messages, stores data, and receives reports from Clients. The Client module receives control messages, executes requests from the Server system, stores data, and sends warnings and reports to the Server. The Client and Server interact with one another via a Short Message System (SMS) (see Figure 7). The SMS was chosen based on the fact that the majority of wells' groundwater levels are monitored in rural areas not reached by internet facilities. The use of the Internet does not seem feasible due to the restrictions inherent to the Client system; however, in regions with internet access and more advanced facilities, using Internet can be a potential alternative.

The Client-Server program sends control messages from the Server system to the Client system. The control messages include thresholds of the desertification indices. The Server system determines the circumstances in which the controller device installed in the Client system sends warning messages and specifies the time the controller system must send warning messages based on measured parameters received by the controller device.

3.3.1. Data Storage

The Server system stores all the messages received from the Client system. These data are included in the submitted reports together with the occurrence time of the events. In addition to the data storage by the Server system, each client (the client refers to the wells and different sites instruments are or will be installed) saves its data separately and locally.

3.3.2. Reception of Reports

Reports are received from all clients and classified by the Server. The Client can communicate with the controller device through the provided communication medium. This communication enables the Client system to make changes to the thresholds of different parameters and apply these modifications to the system settings.

3.3.3. Sending Reports

The Client can issue desertification reports on a regular basis (daily, weekly, and so forth) or whenever necessary. The central system prepares the reports and sends them to the Server system. The reports contain warnings about the groundwater level status in the region, its threshold, and other factors.

4. Conclusion

The results of this research revealed that over the past two decades or so, Kashan plain has persistently experienced a decline in groundwater levels. About 27.11% of Kashan plain is in a very severe groundwater decline category. Most of the groundwater declined has occurred in the southern parts of the plain where agricultural lands are concentrated. The electrical conductivity of groundwater has increased with the reduction in groundwater levels. This indicates the increased amount of dissolved solids in groundwater and the associated degradation of groundwater quality in areas with significant groundwater withdrawals. According to the obtained results, the desertification intensity of Kashan plain was 2.4, implying a medium desertification intensity category (Table 1). This value is consistent with the findings of other studies in this region (Abdi, 2007, Mesbahzade, 2007, and Vesali, 2008).

Warning thresholds for the groundwater level index (slightly over 50 centimetres of decline annually), the electric conductivity (in the range 2250 – 5000 (μmohs/cm) (μmohs/cm)), and the Transeau aridity index (in the range 0.05 - 0.2) were identified. The EWS was designed to issue desertification warnings based on the identified thresholds

Regions threatened by desertification were mapped (Figures. 3, 4, 5). Recommendations were made for the installation of monitoring devices to measure the variables contained in the desertification. Rain gage stations and evaporation meters are recommended to be installed in localities to monitor the Transeau index. To monitor the groundwater levels, water level meters are recommended for installation in wells. The designed EWS will process the monitoring data and issue warning messages in real time whenever desertification indices exceed the established thresholds. Warning messages can be sent via SMS or Internet to the pertinent system managers for appropriate action. The features of the designed EWS's include:

1. Access to remote areas to collect monthly or online data;
2. Groundwater level monitoring devices in wells;
3. Lower costs of field data collection in comparison with other monitoring and assessment schemes;
4. Prevention of desertification trends and their consequences in the studied region;
5. Flexible design to allow modifications and additions as required.

The developed desertification monitoring and analysis system most have uniformity in terms of measurement locations to allow for the identification of long-term patterns. Due to the future changes in conditions, it may be necessary to re-establish the desertification assessment criteria and their corresponding thresholds over time. In this manner, the EWS will remain current and effective in its objective, which is to timely diagnose the desertification conditions. The EWS constitutes an innovative approach to informing water and resources managers of the evolving conditions, which helps prevent adverse environmental impacts through appropriate measures.

Appendix A. Summary of the Iranian Model for Desertification Potential Assessment (IMDPA)

The development of the IMDPA model is based on the MEDALUS (Mediterranean Desertification and Land Use) model funded by the European Commission in 1999. The IMDPA, in its most complete form, uses 9 criteria and 36 indices to assess desertification in Iran. Table A.1 lists the IMDPA's criteria and indices.

Table A.1. The IMDPA's criteria and indices

Criterion	Sub-criterion	Index
Water		irrigation system, decline of groundwater level, electric conductivity, SAR (sodium adsorption ratio)
Geomorphology and Geology		physiography, rock composition, exploitation condition
Erosion	Wind erosion	emergence of erosion, denudation, non-vegetated cover, vegetated cover, the number of days with dust-storm index
	Water erosion	type and degree of water erosion, vegetated cover, land use type
Vegetation cover		vegetation cover status, vegetated cover exploitation, vegetation cover recovery
Soil		texture, granular percentage, soil depth, electric conductivity
Climatic		precipitation, aridity index, drought index
Agricultural		crop type and pattern, crop production and water requirement, agricultural inputs and machinery
Social-Economic		(population, poverty, legal, law) factors Socio-cultural factors, awareness and experience, indigenous knowledge
Technology and Urban Development		Road and mine density, land use change from farming to industrial and residential

Appendix B. Tables of values for the selected indices and sub-indices

Table B.1. Classification of the annual precipitation (mm) index values

Annual Precipitation (mm)	Numerical value	Classification of desertification intensity
>= 600	0.0001 to 1	Negligible
280-600	1.1 to 1.5	Low
150-280	1.6 to 2.5	Medium
75-150	2.6 to 3.5	High
< 75	3.6 to 4	Very high

Table B.2. Classification of the Transeau aridity index values

Transeau Aridity Index	Numerical value	Classification of desertification intensity
>0.65	0.0001 to 1	Negligible
0.45-0.65	1.1 to 1.5	Low
0.2-0.45	1.6 to 2.5	Medium
0.05-0.2	2.6 to 3.5	High
<0.05	3.6 to 4	Very high

Table B.3. Classification of the SPI (sub-index) values

SPI code	Numerical value	Classification of desertification intensity
7	0.0001 to 1	Negligible
6,5	1.1 to 1.5	Low
4	1.6 to 2.5	Medium
2,3	2.6 to 3.5	High
1	3.6 to 4	Very high

Table B.4. Classification of the electric conductivity index values

Electric conductivity (μmohs/cm)	Numerical value	Classification of desertification intensity
<250	0.0001 to 1	Negligible
250-750	1.1 to 1.5	Low
750-2250	1.6 to 2.5	Medium
2250-5000	2.6 to 3.5	High
>5000	3.6 to 4	Very high

Table B.5. Classification of the drought extension sub-index values

The maximum duration of the drought(year)	Numerical value	Classification of desertification intensity
<3	0.0001 to 1	Negligible
3-4	1.1 to 1.5	Low
5-6	1.6 to 2.5	Medium
6-7	2.6 to 3.5	High
>7	3.6 to 4	Very high

Table B.6. Classification of the ground water depletion index values

Groundwater level depletion(cm per year)	Numerical value	Classification of desertification intensity
0-10	0.0001 to 1	Negligible
10-20	1.1 to 1.5	Low
20-30	1.6 to 2.5	Medium
30-50	2.6 to 3.5	High
> 50	3.6 to 4	Very high

Appendix C. Equations for the Transeau Aridity Index, Potential Evapotranspiration, and the SPI

C.1 The Transeau Aridity Index Equation

$$I = \frac{P}{PET}$$

$$I = \frac{P}{PET}$$

(C.1)

In which:
P: Annual Precipitation (mm)
PET: Annual Potential Evapotranspiration (mm) (Thornthwaite, 1948)

C.2. The Potential Evapotranspiration Equation

$$PET = 16.2(\frac{10\,T_i}{I})^{\alpha}$$

$$PET = 16.2(\frac{10\,T_i}{I})^{\alpha}$$

(C.2)

T_i: average monthly temperature (^{0}C)
I = Annual Heat Index, including the sum of monthly heat indices

$$I = \sum_{i=1}^{12}(\frac{T_i}{5})\ \sum_{i=1}^{12}(\frac{T_i}{5})\ 1/514 \qquad (C.3)$$

$$\alpha = (0.675\,I^3 - 77.1\,I^2 + 17920\,I + 492390)\,10^{-6} \text{ or } \alpha = 0.016\,I + 0.5 \qquad (C.4)$$

The potential evaporation equation is adjusted for location with the calibrated adjustment factors.

C.3. The SPI Equation

A drought period occurs whenever the SPI has been constantly negative at or less than -1. The drought period ends when the SPI reaches a positive value. The cumulative values of SPI represent the volume and severity of the drought. SPI values are classified according to Table C.1.

$$SPI = \frac{Pik - Pi}{\sigma i} SPI = \frac{Pik - Pi}{\sigma i} \qquad (C.5)$$

SPI: Standardized Precipitation Index
P_{ik}: The precipitation rate in station (i) within a year (k) in millimetres
$\overline{P}i$: The long average precipitation rate in station (i) in millimeters
σi: Standard deviation in the precipitation data of station (i)

Table C.1. Standard Precipitation Index (SPI) values

category	extremely wet	very wet	moderately wet	near normal	moderately dry	severely dry	extremely dry
SPI values	>2.0+	1.5 to 1.99	1.0 to 1.49	-.99 to .99	-1.0 to -1.49	-1.5 to -1.99	<-2
code	7	6	5	4	3	2	1

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