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Integrated Index for Assessment of Vulnerability to Drought, Case Study: Zayandehrood River Basin, Iran

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Abstract Drought is an extended period of deficient precipitation that causes damage to crops and reducing their performance, causes temporary scarcity of water for human/livestock consumption. Over the years, various indices have been proposed to identify onset, characterize and quantify the attributes of meteorological, hydrological and agricultural drought by various researchers. Because of the spatial and temporal variability and multiple impacts of drought, it is necessary to develop an integrated index for assessment of vulnerability of this natural phenomenon. The aim of this paper is presenting an integrated index for assessment of vulnerability to drought using multiple factors which includes hydrological, meteorological, land use and other factors. Spatial information of various factors was categorized in to various sub-classes and maps were prepared in spatial domain using Geographic Information System (GIS). This study has been carried out in the Zayandehrood River basin located in west-central Iran with semi-arid region. Due to continue droughts at recent decade, this area has been chosen as a case study. The long-term climate data (1991–2011) used for assessment. The results show that Zayandehrood River basin has experienced 11 dry years, 4 normal years, and 6 wet years in the 21 years. The results have been validated with intensive field surveys.

Keywords Drought · Vulnerability · Integrated index · Assessment · Zayandehrood River basin

1 Introduction

Drought is categorized as a natural disaster that unpredictable but in recent years has been experienced with higher severity levels. Drought affects all climatic regions and more people than any other natural hazards (Wilhite 2000). More than 50 % of the earth is susceptible to drought each year (Kogan 1997). Due to population growth and expansion of agricultural zones, the demand for water has increased; hence assessment of droughts is of great importance in water resources planning and management.

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The effective of a drought plan depends on its indicators and triggers. Indicators are variables for characterizing drought conditions, and triggers are specific values of indicators for activating drought responses. Together, they form the linchpin of a drought plan, linking drought conditions with drought responses (Steinemann and Cavalcanti 2006).

By implementing an operational definition of drought, three main physical drought types were established: meteorological, agricultural and hydrological drought. Meteorological drought occurs directly from climate variation, a decrease in precipitation. The results of the meteorological drought lead to an agricultural drought. A decrease in the availability of water causes soil moisture to decrease and vegetation stress to increase. This in term leads to a hydrological drought. During a hydrological drought the effects of drought can be seen on the surface water (Smith and Maidment 2008). Several methodologies for drought characterization exist; using drought indices is prevalent (Tsakiris et al. 2007). Commonly, drought indices are categorized based on the type of impacts they relate to. On the other hand, Niemeyer (2008) adds three categories to this list: comprehensive, combined and remote-sensing-based drought indices.

Over the year, various drought index have been proposed to identify onset, characterize and quantify the attributes of meteorological, hydrological, agricultural, comprehensive, combined and remote-sensing-based by various researchers like Palmer (1965), Keetch and Byram (1968), Shafer and Dezman (1982), Hardisky et al. (1983), McKee et al. (1993), Kogan (1995), Gao (1996), Byun and Wilhite (1999), Stahl (2001), Tsakiris and Vangelis (2004), Keyantash and Dracup (2004), Narasimhan and Srinivasan (2005), Tsakiris and Vangelis (2005), Wang and Qu (2007), Ghulam et al. (2007), Brown et al. (2008), Karamouz et al. (2009), Vicente-Serrano et al. (2010).

Most of drought indices specifically reflect one type of drought like meteorological, hydrological, agriculture drought indices, while a few of them like comprehensive and combined drought indices, can be configured to correspond to varying impacts and thus drought type. For example indices such as SPI (Standardized Precipitation Index), (McKee et al. 1993), PDSI (Palmer Drought Severity Index), (Palmer 1965), and SWSI (Surface Water Supply Index) (Shafer and Dezman 1982) suggested for evaluating drought, which based on a variety of meteorological, hydrological and agricultural drought. So, an integrated drought index includes various factors such as meteorological, hydrological, agricultural, socio-economic and environmental drought. Social vulnerability to drought is complex and reflected by society's capacity to anticipate, cope with and respond (Tsakiris and Pangalou 2009). Several integrated drought indicators are proposed by various researchers like Smith and Maidment (2008), Karamouz et al. (2009). The concept of derivation of drought vulnerability map was originally describe in the "AVD" methodology by Pandey et al. (2010, 2012) by using geoinformation for drought hazard assessment.

This paper presents a methodology for integrated assessment of vulnerability to drought in time and space domain using geographic information system (GIS). The integrated index is composed of features that can be broken in to two groups: static and dynamic indicators. Static indicators do not change. These indicators include land use, slope and soil type. Dynamic indicators contain features that have data attached to them changes through time. These indicators include precipitation, evapotranspiration, temperature, surface water storage, groundwater levels, and environmental needs. Different layers of above independent static and dynamic indicators have been integrated using numerical weighing scheme to evaluate assessment vulnerability to drought of the classes within each factor.

This study was taken up in the Zayandehrood River basin located in west-central Iran with semi-arid region. The long-term climate data (1991–2011) used for assessment of vulnerability to drought hazards.

2 Study Area

The Zayandehrood River basin covers an area of 26,917 Km^2 located between latitudes 31° 15′ and 33° 45′ north and longitudes 50° 02′ and 53° 20′ east in west-central Iran (Fig. 1). The total precipitation in the basin varies between 1,500 mm in the west and 50 mm in the east of the basin with an average annual value of 140 mm, the mean annual temperature is 14.5 °C, the lowest was −12.5 °C in January, and the highest was 42 °C in July, ranking the basin in semi-arid regions. The potential annual evapotranspiration in the region is 1,900 mm. The Zayandehrood River, having an average natural flow of about 900 MCM, is the most important river in the basin that originates in the eastern slopes of the Zagross Mountain Range. In addition to the Zayandehrood surface flow, groundwater is one of the most reliable water resources in the basin. The thickness of the unconfined aquifers in the basin varies from 20 to 300 m. The storage coefficient and transmissivity of the aquifers range from 1 to 15 % and 40 to 4,000 m^2/day, respectively (Rezaei et al. 2012).

In recent decade, water has become increasingly scarce and the Zayandehrood basin has shown signs of salinization of agricultural land and increased pollution in the lower reaches of the river. Furthermore, drought is a current phenomenon affecting various parts of the Zayandehrood River basin. The goal of this paper is presenting an integrated index for assessment of vulnerability to drought using multiple factors which includes hydrological, meteorological, land use, slope and soil type, and for this purpose we have used the long-term climate data (1991–2011) for assessment.

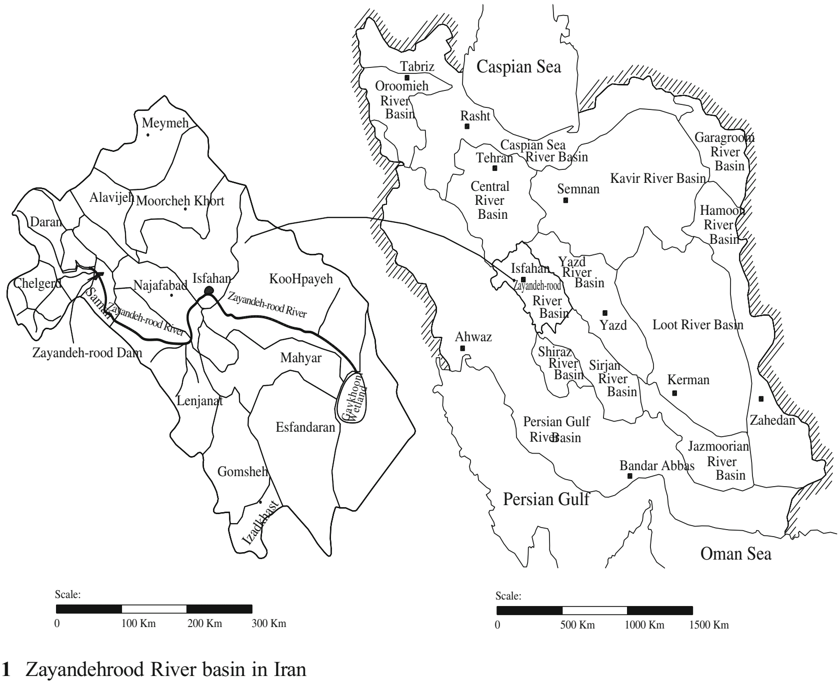

Fig. 1 Zayandehrood River basin in Iran

3 Methodology

3.1 Identification of Drought Vulnerability Factors

Severity of drought depends on numerous factors. An integrated drought index includes various causes such as meteorological, hydrological, agricultural, socio-economic and environmental factors. The integrated drought index is designed in an attempt to overcome some of the ambiguities in drought indices. It is unique because incorporates information from so many disparate types of drought information resources. The integrated index is composed of features that can be broken in to two categories: static and dynamic features. Static features do not change with time. The static layers are the backdrop geographic to the whole system. The static layers don't actually contain any drought information; however, their existence gives a base to interpret drought factors. The static layers are typically including: land use, slope and soil type. The dynamic layers are depending to time and linked to time series data. Space-time or

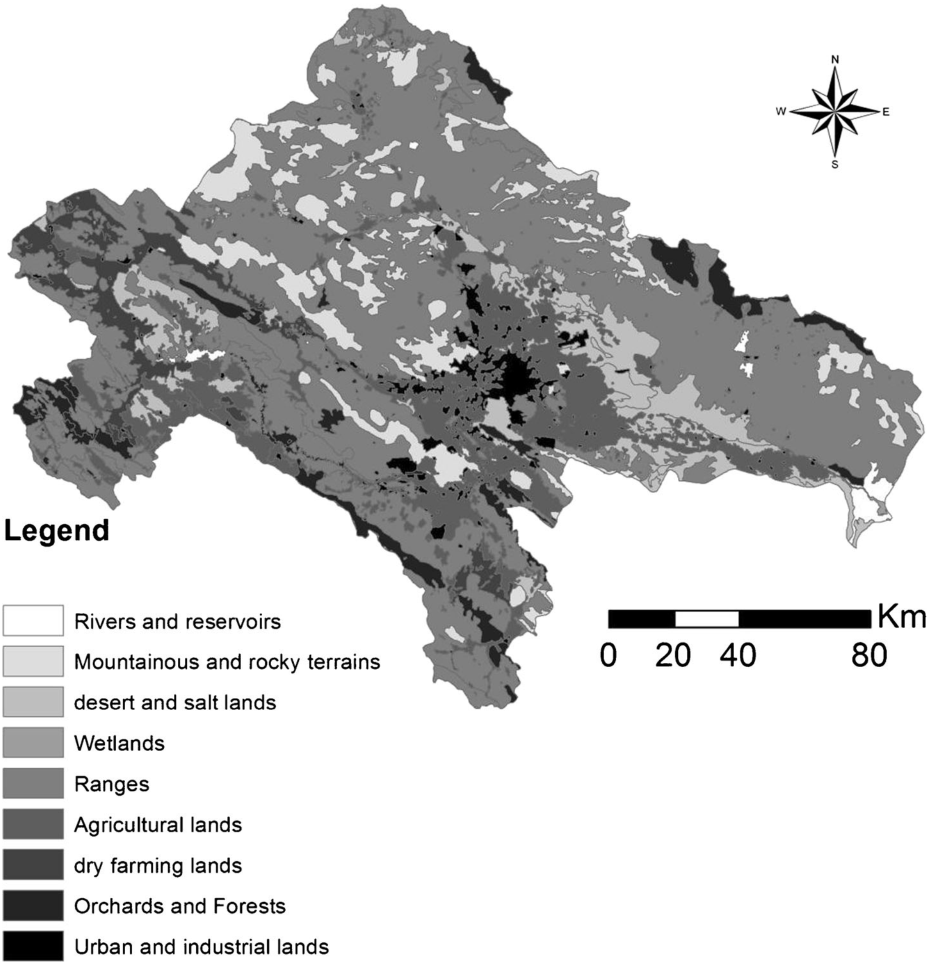

Fig. 2 Land use categories in Zayandehrood River basin

dynamic layers including: precipitations, evapotranspiration, mean temperature, groundwater levels, surface water storage, and environmental needs.

In this paper, we have used various collateral data to produce spatial maps pertaining to nine factors or layers. The study presented the spatial integration of large number of factors using GIS resulted in exact assessment of drought vulnerability in the Zayandehrood River basin. Although understanding of other physical and climate factors like soil moisture, soil temperature, relief, drainage density, humidity, etc., are also important for drought vulnerability prediction.

In the present study, we used dynamic data of 21 years from 1991 to 2011 recorded by Isfahan Regional Water Company and Chaharmahal va Bakhtiary Water Company in Iran. For introducing an integrated drought index or integrated drought map for Zayandehrood River basin, various layers representing static and dynamic layers of different parameters were prepared using GIS software. It should be noted that static layers are fixed for each year and dynamic layers are variable. Static layers representing land use, slope and soil type, and dynamic layers representing precipitation, evapotranspiration, mean temperature, groundwater levels, surface water storage, and environmental needs that prepared by GIS software.

Land Use The land use is one of the static layers and a significant factor for water use. Land use map in the basin was categorized into urban and industrial zones, orchards and forests, dry farming lands, agricultural lands, ranges, wetlands, desert and salt lands, mountainous and rocky terrains, rivers, and reservoirs. The land use layer and land use categories in the Zayandehrood River basin is shown in Fig. 2. As drought affects primarily the habitation, therefore, all urban and industrial zones are considered to be highly vulnerable to drought.

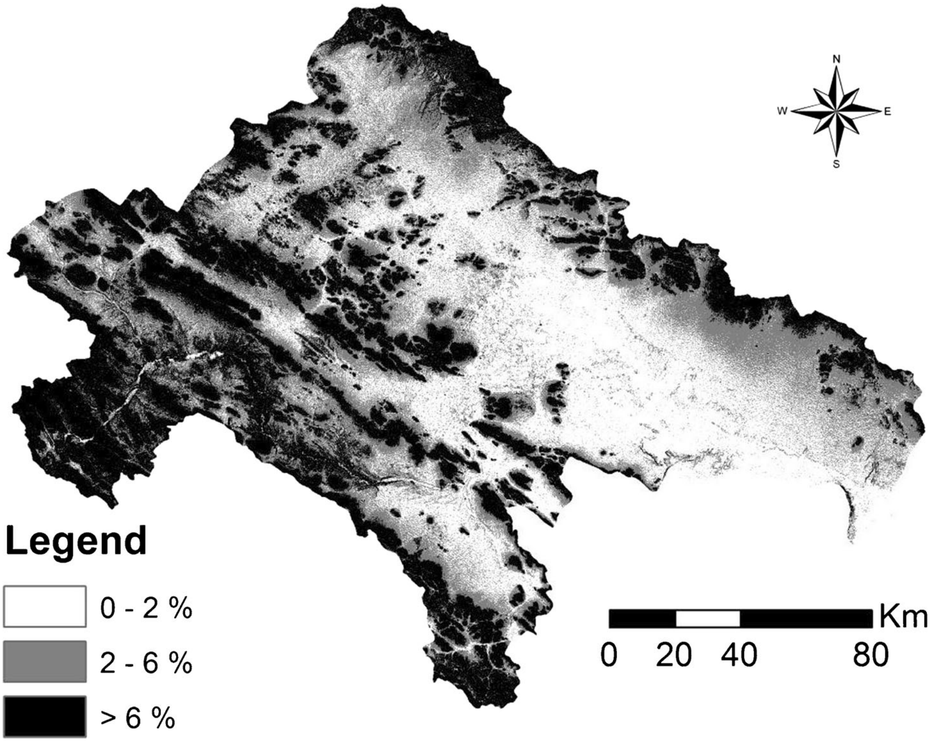

Fig. 3 Slope categories in Zayandehrood River basin

Orchards and forests are considered next most vulnerable compared to urban and industrial zones. Dry farming lands, agricultural lands and ranges after orchards and forests considered as mean vulnerability to drought. On the other hand, other land use, like desert and salty lands, mountainous and rocky terrains encompass rare economic and social activities, and therefore are least sensitive to drought.

Slope The slope is another static layer. Slope map was prepared based on slope function using GIS software. The terrain was classified into three sub-classes viz. upper reach basin terrain (hilly terrain), middle reach basin terrain (undulating terrain), and lower reach basin terrain (flat area). The upper, middle and lower reach basin terrain have been delineated considering topographic features and stream orders. The upper reach basin terrains refer to residual hill and structuro-denudational hill areas with average slops >6 % and having stream orders 1 and 2. The middle reach basin terrains refer to pediment inselberg complex areas with average slopes between 2 and 6 % and having stream orders 3 and 4. The lower reach basin terrains are defined as alluvial plain, flood plain, pediplain, and valley with average slopes <2 % and stream orders more than 4 (Pandey et al. 2010). The slope layer and slope categories in the Zayandehrood River basin are shown in Fig. 3. The hilly terrain of basin mainly comprising the runoff zone over the steeply sloping land and get less time for water storage, while the

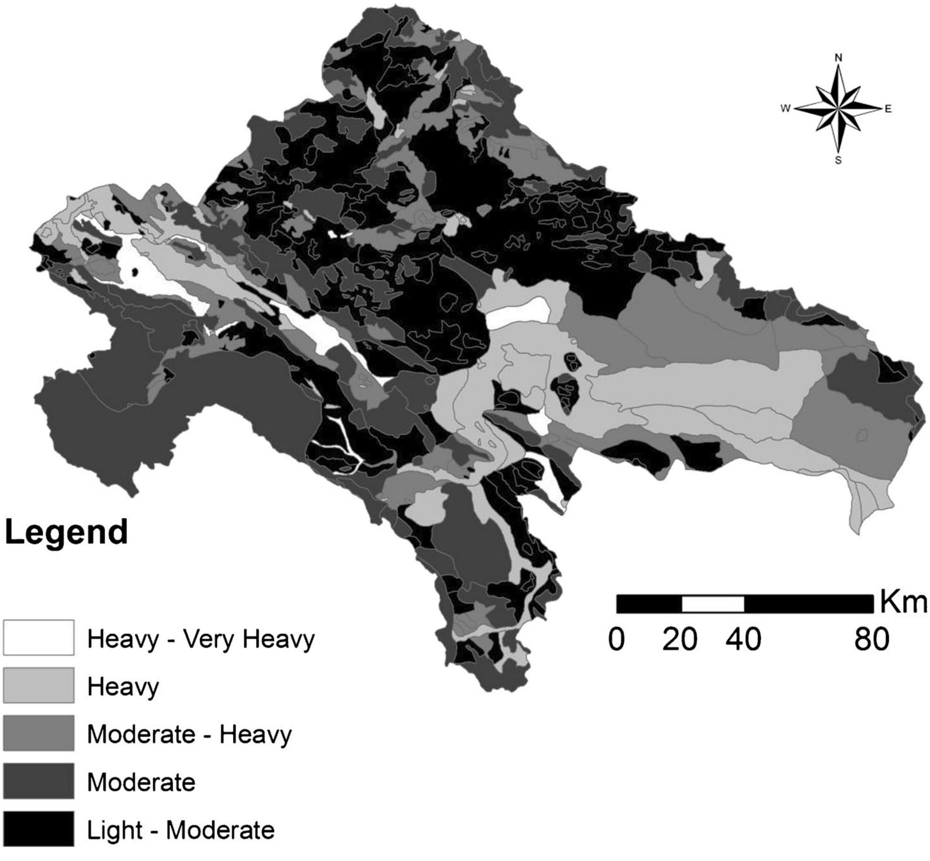

Fig. 4 Soil type categories in Zayandehrood River basin

lower reach of basin get more time for water storage. Thus, hilly terrains of basin have been considered highly prone to drought followed by undulating terrain and flat area.

Soil Type The soil texture is the last static layer. Soils in the Zayandehrood River basin have been categories into five sub-classes vis. light–moderate, moderate, moderate–heavy, heavy and heavy–very heavy soils. The light soils due to high porosity and less water holding capacity are result in faster loss of soil moisture. On the other hand, light soils are considered most vulnerable to drought because they are suitable for agricultural activities. Heavy soils are considered least vulnerable to drought. Accordingly, areas with lighter soils are considered relatively more vulnerable than heavy soil regions. Therefore, heavy and very heavy soils are relatively less vulnerable to drought as compared to moderate and light soils (Pandey et al. 2010). The soil type layer and soil type categories in the basin are shown in Fig. 4.

Precipitation The precipitation is one of the dynamic layers and is the main factor for drought vulnerability. In the present study, daily precipitation data of 21 years from 1991 to 2011 recorded by Isfahan Regional Water Company and Chaharmahal va Bakhtiary Water Company in Iran were used to derive 21-year average annual data for all of stations in the study area. The average precipitation was spatially interpolated using krigging interpolation method using ArcGIS to derive average precipitation range map for each years. Then the precipitation contour was drown spatially using krigging map and contour method using ArcGIS to derive contour map for each years. As an example, precipitation contour map for 2009 in the Zayandehrood River basin is shown in Fig. 5. It is clear that regions with lower precipitation are generally more prone to drought than other regions with higher amount of precipitation.

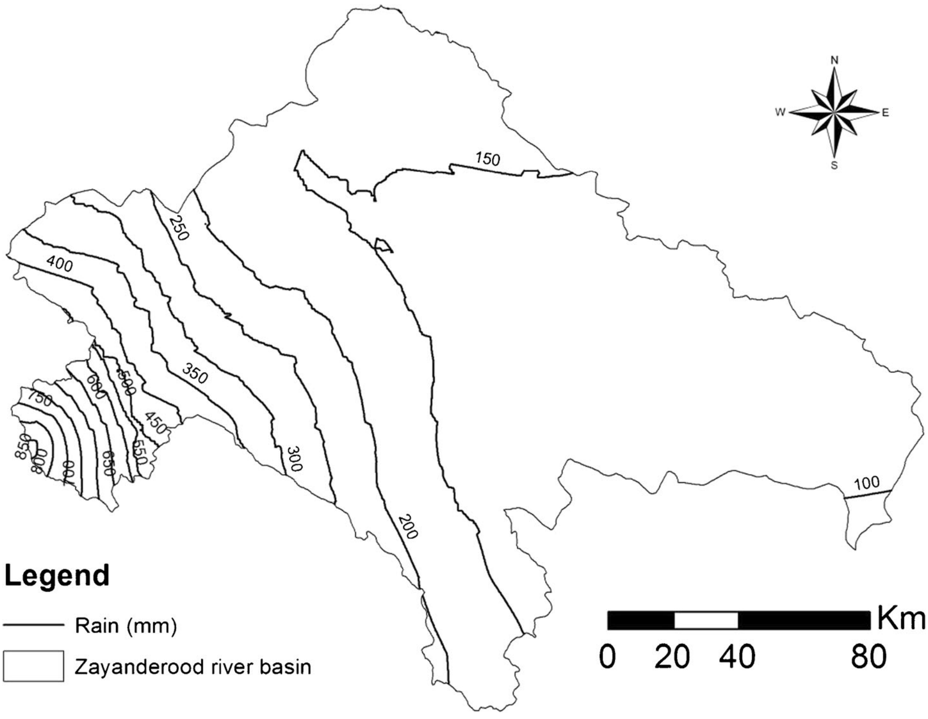

Fig. 5 Precipitation map for 2009 in Zayandehrood River basin

Evapotranspiration The evapotranspiration is another dynamic layer for assessment of drought vulnerability. In this study, daily evapotranspiration data of 21 years from 1991 to 2011 recorded by Isfahan Regional Water Company in Iran were used for preparation of monthly evapotranspiration data. By using this data set, the monthly evapotranspiration data were used to derive 21-year average annual data for all of stations in the Zayandehrood River basin. The average evapotranspiration was spatially interpolated using krigging interpolation method using ArcGIS to derive average evapotranspiration range map for each year. Then, evapotranspiration contour was drowning spatially using krigging map and contour method using ArcGIS to derive contour map for each year. As an example, evapotranspiration contour map for 2009 in the study area is shown in Fig. 6. It is clear that regions with higher potential of evapotranspiration are generally more prone to drought than other regions that have lower potential of evapotranspiration.

Mean Temperature The mean temperature is another dynamic layer for assessment of drought vulnerability. In this study, daily mean temperature data of 21 years from 1991 to 2011 recorded by Isfahan Regional Water Company were used for the preparation of monthly mean temperature data. Based on this data set, the monthly mean temperatures were used to derive 21-year average annual data for all of stations in the Zayandehrood River basin. The average of mean temperature was spatially interpolated using krigging interpolation method using ArcGIS to derive average mean temperature range map for each years. Then the mean temperature contours were drown spatially using krigging map and contour method using ArcGIS to derive contour map for each year. As an example mean temperature map for 2010 in the basin is shown in Fig. 7.

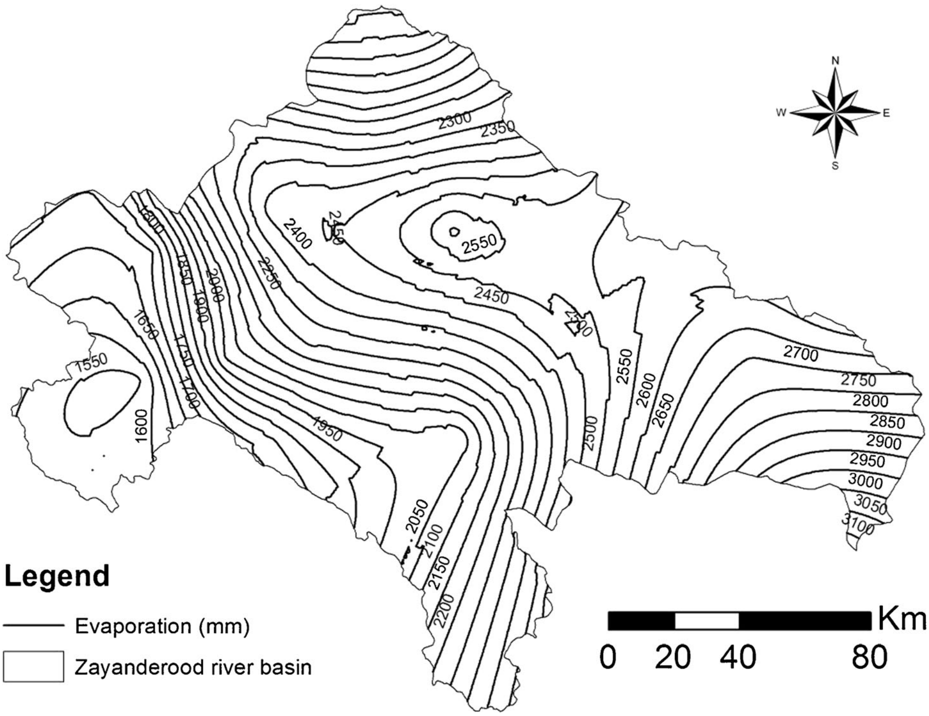

Fig. 6 Potential of evapotranspiration map for 2009 in Zayandehrood River basin

Groundwater Level The groundwater level is another dynamic layer for assessment of drought hazard. In this study, monthly depth of groundwater table at observation wells recorded by Isfahan Regional Water Company for a period of 21 years (1991–2011) were used to derive annul groundwater level. As an example, groundwater level map for 2011 is shown in Fig. 8. Regions with shallow groundwater levels are less vulnerable to drought compared to the regions with deeper groundwater levels.

Surface Water Storage The surface water storage is another dynamic layer for assessment of drought vulnerability. The Zayandehrood River is controlled by Zayandehrood Dan at upstream of the basin. Hence the volume of water storage of this dam very important for supplying to users especially in drought condition. Daily volume of reservoir storage of the Zayandehrood Dam is recorded by Water Resources Management Company in Iran and for a period of 21 years (1991–2011) were used to derive average annual volume. It is clear that whenever the volume of storage is low, therefore vulnerability to drought is high. The volume of water storage for period of 21 years (1991–2011) for the Zayandehrood Dam is shown in Table. 1.

Environmental Needs The environmental need is the last dynamic layer for assessment of drought hazard. Because of the Zayandehrood River basin is a closed basin and Zayandehrood river ended to Gavkhoni wetland as a protected wetland in Iran, this wetland has a water right as environmental need equal to 160 (MCM) per year. The total volume of water entered to Gavkhoni wetland for a period of 21 years (1991–2011) is shown in Table 2.

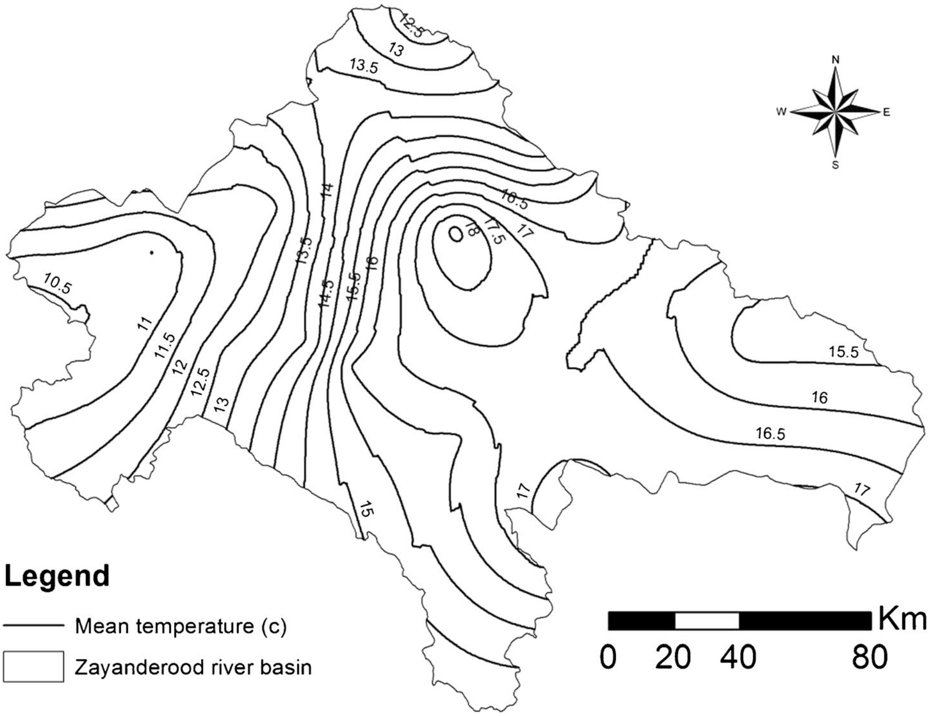

Fig. 7 Mean temperature map for 2009 in Zayandehrood River basin

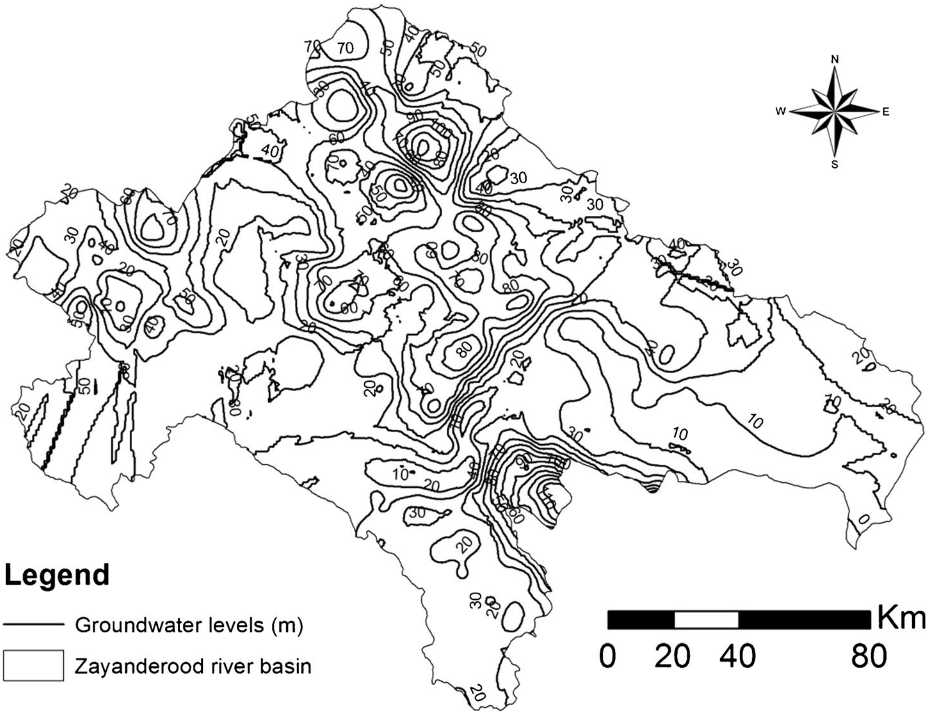

Fig. 8 Groundwater depth map for 2009 in Zayandehrood River basin

3.2 Weighing Scheme for the Derivation of Integrated Drought Vulnerability map

The integrated drought index is composed of features that can be broken in to two groups: static and dynamic features. The static and dynamic factors considered in this study are land use, slope and soil type (static), precipitation, evapotranspiration, mean temperature, groundwater levels, surface water storage, and environmental needs (dynamic). Rainfall, evapotranspiration and mean temperature were considered for meteorological drought assessment, slope and soil type for agricultural drought assessment, groundwater levels and surface water storage for hydrological drought assessment, land use for socio-economic drought assessment and

Table 1 Volume of water storage in the Zayandehrood Dam for a period of 21 years (1991–2011)

Year	Water storage (MCM)	Year	Water storage (MCM)	Year	Water storage (MCM)
1991	842.7	1998	779.9	2005	713.2
1992	926.2	1999	618.2	2006	857.5
1993	1,189.8	2000	278.8	2007	996.2
1994	1,035.3	2001	268.6	2008	647.6
1995	1,143.4	2002	619.9	2009	429.3
1996	1,158.3	2003	785.5	2010	464.1
1997	881.7	2004	726	2011	377.1

Table 2 Volume of water entered to the Gavkhoni wetland for a period of 21 years (1991–2011)

Year	Water entry wetland (MCM)	Year	Water entry wetland (MCM)	Year	Water entry wetland (MCM)
1991	44.5	1998	46.5	2005	16.5
1992	117.9	1999	9.8	2006	70.4
1993	941.8	2000	4.8	2007	77.2
1994	391.5	2001	1.2	2008	35.7
1995	67.4	2002	1.7	2009	4.3
1996	104.3	2003	5.1	2010	4.8
1997	87.8	2004	10.2	2011	0.8

environmental needs for environmental drought assessment. Each of the static and dynamic factors has been categorized in to various sub-classes to distinguish their degree of assessment vulnerability to drought. The following numerical weighting scheme has been proposed to assessment of vulnerability to drought. On the other hand, a numerical weighting scheme was used to assess the relative drought hazard of each factor. Each class of nine vulnerability factors have been assigned a relative weight as 1, 2, 3, ..., and 10 with 1 being considered least vulnerability in regards to assessment drought and 10 being considered most vulnerability. Each sub-class of vulnerability factors has been assigned a relative numeric weight between 1 and 10. Weighting was performed based on an informed assumption on relative contribution of each factor to drought assessment. The value of weight depends on the relevance of attributes of a given sub-class in aggravation of vulnerability to drought assessment. The weight value of 1 indicates that the subclass of a given factor is least vulnerable to drought and a weight value of 10 indicates that the sub-class is highly vulnerable to drought assessment. On the other hand, it may be explained that more weight value is assigned to the factor which is more vulnerable. The weights assigned to various sub-classes of factors are given in Table 3. Weights assigned to static layers are fixed for a period of 21 years but weights assigned to dynamic layers are variable for a period of 21 years. For each year, static layers are fixed and dynamic layers are variable. To produce integrated drought index map in Zayandehrood River basin, the various drought layers were combined among five types of drought considered for analysis through the 'union' mathematical function in ArcGIS.

In a drought plan for Zayandehrood River basin, indicators and triggers are linked with drought categories and drought responses. Triggers, which are values of indicators, then determine the timing and degree of drought responses associated with drought categories.

To obtain drought triggers in this study, all of layers except precipitation (other eight layers), have uniform weighting equal to 1, but precipitation layer has weighing equal 2, because precipitation is the main factor for drought assessment. Thus summation of weights assigned to each factors in Zayandehrood River basin are a value between 0 and 100. The proposed integrated drought index is validated using physical surveys conducted at study area. Due to drought experiences in Zayandehrood River basin, these values are divided into nine categories vis. very extreme wet, extreme wet, moderate wet, negligible wet, normal, negligible drought, moderate drought, extreme drought and very extreme drought. Triggers of integrated drought index are given in Table 4.

To produce an integrated drought map comprising static and dynamic layers in Zayandehrood River basin, the various drought vulnerability factors were combined among five types of drought considered for analysis through the 'union' mathematical function in ArcGIS. The weighted maps were cumulated in GIS by using the parameters selected for each

Table 3 Weights assigned to various sub-classes of drought factors

Sl no.	Factors	Sub-class name	Weightage
1	Land use	Rivers and reservoirs	2
		Mountainous and rocky terrains	3
		Desert and salt lands	4
		Wetlands	5
		Ranges	6
		Agricultural lands	7
		Dry farming lands	8
		Orchards and Forests	9
		Urban and industrial lands	10
2	Slope	Flat area	1
		Undulating terrain	5
		Hilly terrain	10
3	Soil Type	Heavy-very heavy	1
		Heavy	3
		Moderate-heavy	5
		Moderate	7
		Light-moderate	10
4	Precipitation	>−10 %	0
		−10 % to −15 %	2
		−15 % to −25 %	4
		−25 % to −35 %	6
		−35 % to −50 %	8
		<−50 %	10
5	Evapotranspiration	<2 %	0
		2 % to 4 %	2
		4 % to 6 %	4
		6 % to 8 %	6
		8 % to 10 %	8
		>10 %	10
6	Mean temperature	<2 %	0
		2 % to 4 %	2
		4 % to 6 %	4
		6 % to 8 %	6
		8 % to 10 %	8
		>10 %	10
7	Groundwater level	<4 %	0
		4 % to 8 %	2
		8 % to 12 %	4
		12 % to 16 %	6
		16 % to 20 %	8
		>20 %	10
8	Surface water storage	>−10 %	2
		−10 % to −20 %	4
		−20 % to −30 %	6

Table 3 (continued)

Sl no.	Factors	Sub-class name	Weightage
		−30 % to −40 %	8
		<−40 %	10
9	Environmental needs	>160 MCM	0
		150 MCM to 160 MCM	1
		140 MCM to 150 MCM	2
		130 MCM to 140 MCM	3
		120 MCM to 130 MCM	4
		110 MCM to 120 MCM	5
		100 MCM to 110 MCM	6
		90 MCM to 100 MCM	7
		80 MCM to 90 MCM	8
		70 MCM to 80 MCM	9
		<70 MCM	10

types of drought. The resulting map was reclassified into nine classes, identifying geographic areas with 'very extreme wet', 'extreme wet', 'moderate wet', 'negligible wet', 'normal', 'negligible drought', 'moderate drought', 'extreme drought' and 'very extreme drought' hazard using superposition method. Integrated drought map was computed for each year in the study area. Further, the classified static and dynamic layers were aggregated in GIS to develop an integrated drought vulnerability map.

4 Results and Discussion

To produce integrated drought vulnerability map both in spatial and temporal dimension, the composite map of static layers have been combined with dynamic layers using ArcGIS software for each years. The result maps showing integrated vulnerability to drought for a period of 21 years (1991–2011). The average of drought factors and summation of factors and area statistics under various drought factors in Zayandehrood River basin for this period are shown in Table 5. Table 5 shows that Zayandehrood basin has experienced 11 dry years, 4

Table 4 Triggers for integrated drought index

Sl no.	Triggers	Type	Value
1	Drought	Very extreme	70–100
		Extreme	50–70
		Moderate	40–50
		Negligible	35–40
2	Normal		30–35
3	Wet	Negligible	25–30
		Moderate	20–25
		Extreme	15–20
		Very extreme	0–15

Table 5 Average of ranks and summation of factors

Year	Rank of land use	Rank of slope	Rank of soil type	Rank of precipitation	Rank of evapotranspiration	Rank of mean temperature	Rank of groundwater level	Rank of surface water storage	Rank of environmental needs	Total
1991	6.01	6.13	6.68	6	2	0	0	0	10	42.8
1992	6.01	6.13	6.68	0	0	0	0	0	5	23.8
1993	6.01	6.13	6.68	0	0	0	0	0	0	18.8
1994	6.01	6.13	6.68	4	0	2	0	0	0	28.8
1995	6.01	6.13	6.68	0	0	0	0	0	10	28.8
1996	6.01	6.13	6.68	0	0	0	0	0	6	24.8
1997	6.01	6.13	6.68	6	0	0	0	0	8	38.8
1998	6.01	6.13	6.68	0	2	0	0	0	10	30.8
1999	6.01	6.13	6.68	4	4	8	0	4	10	52.8
2000	6.01	6.13	6.68	8	8	4	4	10	10	70.8
2001	6.01	6.13	6.68	4	2	2	2	10	10	52.8
2002	6.01	6.13	6.68	0	2	2	2	4	10	38.8
2003	6.01	6.13	6.68	0	0	0	4	0	10	32.8
2004	6.01	6.13	6.68	0	0	0	2	2	10	32.8
2005	6.01	6.13	6.68	0	0	0	2	2	10	32.8
2006	6.01	6.13	6.68	0	6	0	2	0	9	35.8
2007	6.01	6.13	6.68	0	0	0	0	0	9	27.8
2008	6.01	6.13	6.68	10	6	0	0	4	10	58.8
2009	6.01	6.13	6.68	0	0	0	4	10	10	42.8
2010	6.01	6.13	6.68	0	4	4	6	8	10	50.8
2011	6.01	6.13	6.68	6	2	0	8	10	10	60.8

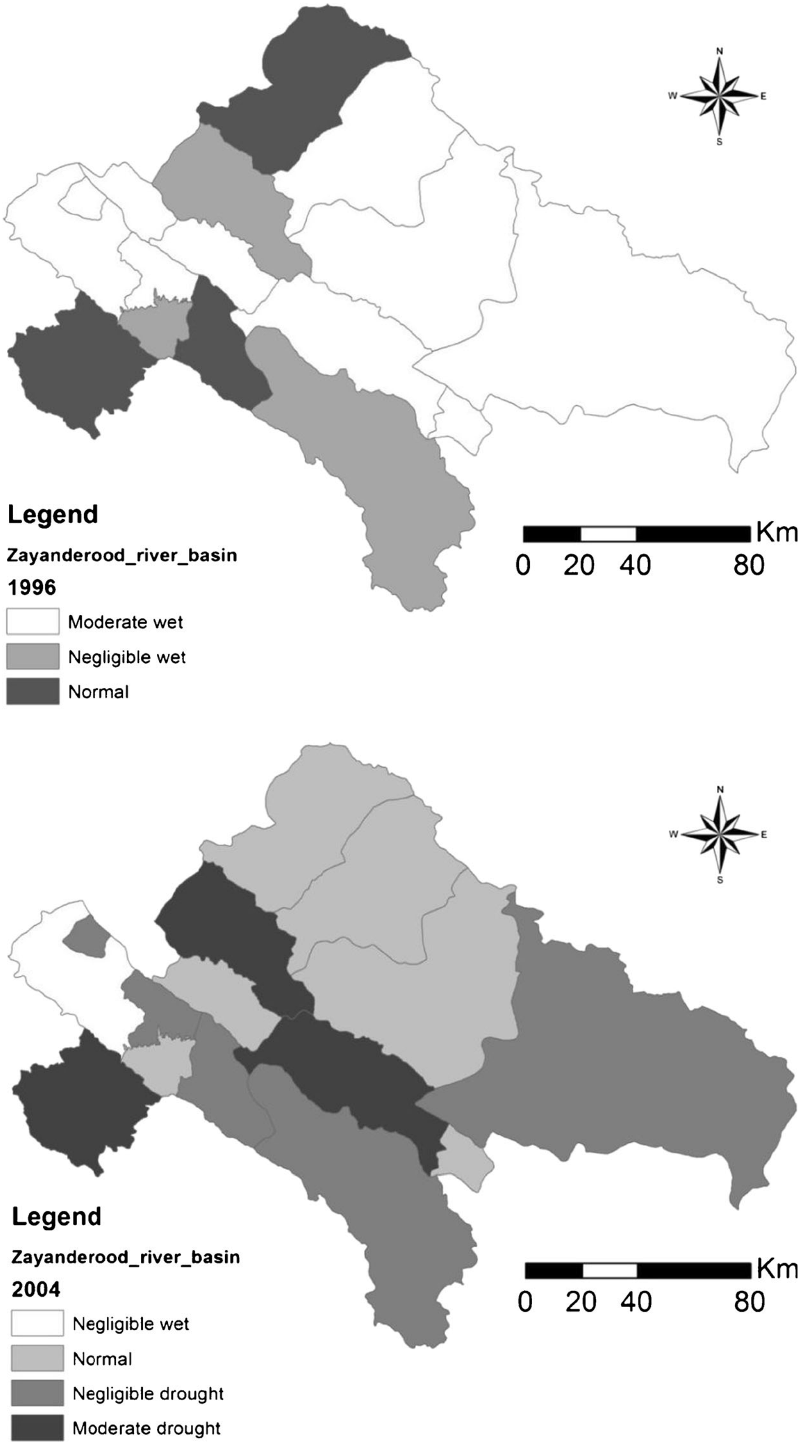

Fig. 9 Integrated drought vulnerability maps for 1996 and 2004

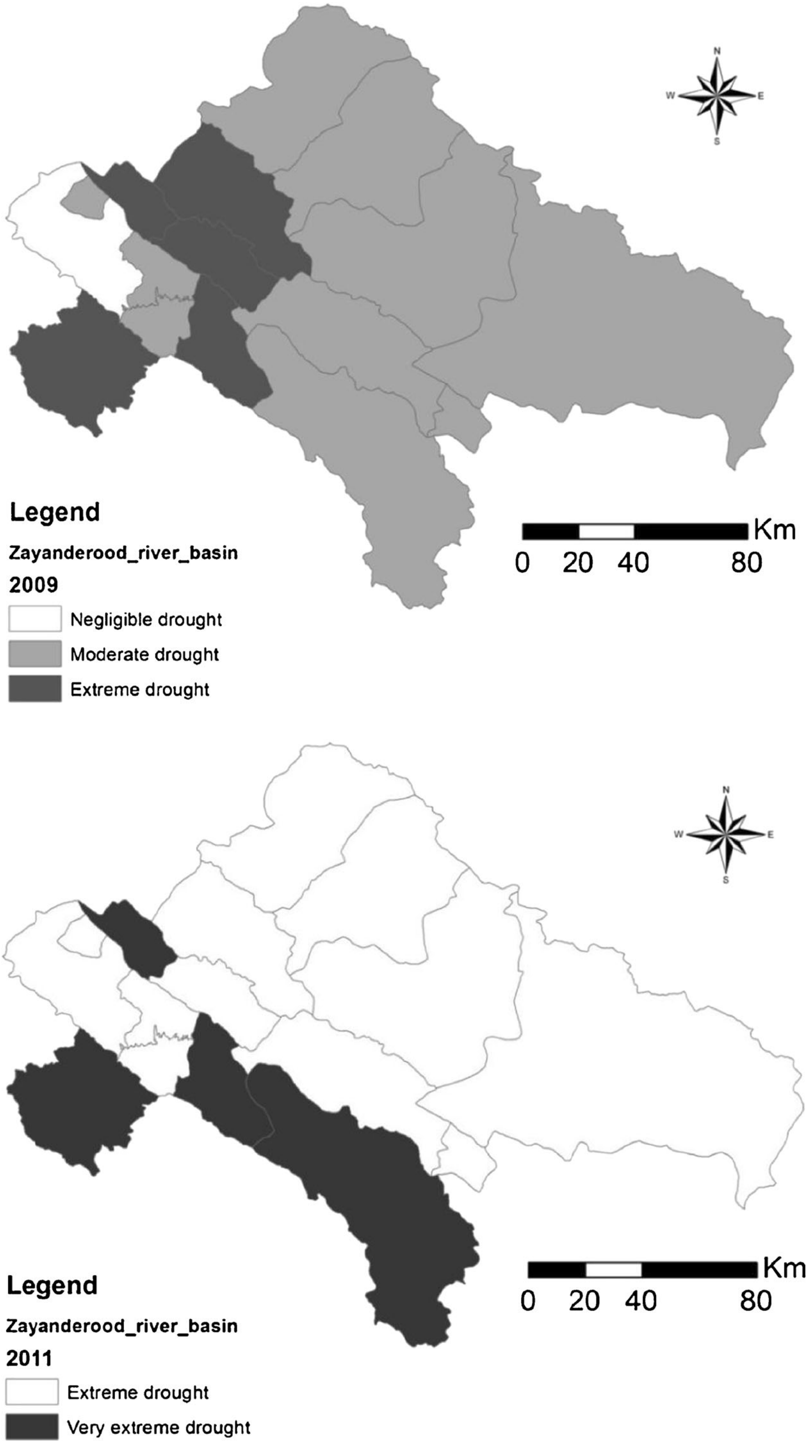

Fig. 10 Integrated drought vulnerability maps for 2009 and 2011

normal years and 6 wet years in the period of 21 years. In this period, 1994 was as the most wet year and 2001 was the most dry year in the basin. For example, integrated drought vulnerability maps were obtained for 1996, 2004, 2009, and 2011 are shown in Figs. 9 and 10.

5 Conclusion

In this paper, an integrated drought index is developed based on nine different types of factors that affected to drought. This integrated drought index is composed of features that can be broken in to two groups: static and dynamic features. The space-time features of the integrated index are the dynamic layers. The map of integrated drought synthesized a variety of data and serves as an indicator of areas deserving a detailed drought hazard and risk evaluation. The structure of integrated index is not more complex, but it is capable of showing in advance the drought vulnerability. In the present study, we used dynamic data of 21 years from 1991 to 2011 in Zayandehrood River basin in Iran.

The methodology proposed in this study provides an integrated drought index in spatial and temporal domain. This method was identified the drought vulnerabilities in space and time that can lead to effective response for drought monitoring. The authors recognize that limitations in acquisition and representation of spatial and temporal data did not allow inclusion of all factors of drought vulnerability in this assessment. This integrated index could help the decision makers to study the drought severity according to the special meteorological, hydrological, agricultural, socio-economical, and environmental characteristics of the study regions.

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