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Drought indices supporting drought management in transboundary watersheds subject to climate alterations

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Abstract

There is growing concern in Iraq about the inefficiency of reactive drought management practices. Corresponding actions are largely characterized as emergency-based responses that treat the symptoms of drought rather than consider the vulnerability components associated with impacts. The Diyala watershed shared between Iraq and Iran has been used as an example transboundary river basin marked by ineffectiveness of drought management. The standardized precipitation index and the reconnaissance drought index were used to determine the historical meteorological drought episodes and analysis indicated climate change-induced alterations in the area. Spatiotemporal drought maps were drawn, which can be used for the identification of drought prone areas and assist with proactive planning. This paper discusses the underlying causes of the impairments of drought management policies, and the challenges and difficulties accompanying the governance of drought in Iraq. Given the influence of climate change and the upstream anthropogenic pressures, the time has come to adopt a gradual nation-wide transition step to drought risk planning incorporating a management approach at the transboundary scale. Moreover, the institutional and technical water vulnerability components associated with drought management should be considered in an integrated manner. The paper presents a generic technical template to support decision-makers in drought risk management.

Keywords: Climate change; Crisis drought management; Drought risk management; Iran; Iraq; Reconnaissance drought index; Shared river basin; Standardized precipitation index

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1. Introduction

1.1. Background

A substantial proportion of water resources in Iraq originate outside its territory, from rivers entering Iraq mainly from Turkey and Iran. There are a number of transboundary river basins shared with Turkey (i.e., Euphrates, Tigris, Khabour and the Greater Zab) and Iran (i.e., the Lesser Zab, Diyala, Teeb, Dwairej, Kerkhe and Karun river basins). Iraq is the lower riparian country of all of these shared rivers, which makes its water resources management highly vulnerable to upstream water exploitation schemes, water storage projects and political interests. Turkey controls the headwaters of the Euphrates and a major proportion of the Tigris, Khabour and the Greater Zab, while Iran controls the headwaters of all shared river basins with Iraq.

Climate change is likely to put further pressure on water resources and exacerbate the level of vulnerability (Krysanova *et al.*, 2008). The Intergovernmental Panel on Climate Change (IPCC) (2007, 2014) suggested that global climate models have provided two main predictions which are linked to droughts: increase in temperature and decrease in precipitation regarding some regions.

Since 1999, Iraq has witnessed severe and frequent nation-wide droughts, which adversely affected water-using sectors and local communities (UNESCO, 2014). The spells of drought considerably affected the agriculture sector and vulnerable communities such as those who live in rural areas. Some initial attempts (Rasheed, 2010; UNESCO, 2014) have been carried out to assess the historical spells of drought using the standardized precipitation index (SPI). However, further investigations that are more detailed are needed.

In Iraq, drought management strategies have often been reactive and response-oriented through disaster management actions (UNESCO, 2014). This has led to critical shortcomings of various interventions in both time and space. Wilhite & Pulwarty (2005) have stated that a reactive management approach is generally costly, subject to inappropriate interpretations, poorly coordinated and suffers from the delay in taking proper and timely actions on different spatial scales. Given the adverse impacts of recent episodes of drought, the development of a national integrated drought risk management (DRM) plan to moderate the effects of water shortages and adequately address drought impacts is important.

Understanding the historical frequency, duration and spatial extent of drought episodes and identification of the most vulnerable water-using sectors assists researchers, decision-makers and drought planners in minimizing the implications of the use of crisis-based management strategies (Quiroga *et al.*, 2011; Wilhite, 2011; Estrela & Vargas, 2012). Moreover, it eases the gradual transition to risk planning at transboundary scale, where there is an increased need for the co-riparian states to communicate, coordinate and cooperate (Milman *et al.*, 2013). The development of a timely and adequate basin-wide drought management plan makes it necessary to use a representative transboundary river basin as an example to highlight and subsequently address the challenges.

In this paper, the Diyala watershed shared between Iraq and Iran was selected as an example case study to address the above objectives. The lower riparian country, Iraq, has been experiencing considerable challenges in managing the shared water resources since 1999 (particularly during droughts). The accelerated growth of water exploitation and water diversion in the upstream country, Iran, and the absence of mechanisms for cooperative actions is a major challenge. Al-Faraj & Scholz (2014a, b) have stated that upstream human interventions, damming and excessive water withdrawals have largely altered the flow of the Diyala river and significantly reduced the flow entering Iraq, and thus have exacerbated the consequences of droughts. Moreover, handling of droughts in Iraq lacks an effective drought management methodology.

1.2. Aims, contribution and structure

This study aimed to explore the dynamics of the historical meteorological drought episodes in the transboundary Diyala river basin through reconstruction of historical drought incidences. Moreover, the authors assessed the significance of temporal trends in the annual time series of precipitation, air temperature and potential evapotranspiration (PET) over a period of 30 water years (1981–2010).

The findings were expected to bridge the knowledge gap between the drought impact and nation-wide policy formulation, assisting decision-makers and planners in the Diyala basin and other similar transboundary watersheds to develop water resources management strategies in the context of drought. Outcomes should support water managers, particularly in the lower riparian country, to improve water allocations in time and space during drought periods. Moreover, this paper contributes to the knowledge base on functional drought management policy at transboundary scale.

The structure of the paper consists of five main sections: (1) scientific and policy background, (2) current processes and flaws associated with drought management in Iraq, (3) proposed methodology, (4) discussion of key findings, and (5) conclusions and recommendations.

2. Fragility of drought management in Iraq

2.1. Challenges and constraints for drought mitigation in Iraq

Since 2010, concern has grown in Iraq about the fragility of handling the recent droughts and the inadequacy of current drought management practices, which are predominantly based on emergency relief assistance. Droughts have singular features (e.g., unpredictability, slow and progressive onset, wide and blurred distribution both in time and space, nonstructural and diffuse impacts), which have favored a reactive post-disaster crisis response (Do Ó, 2012). The current water policy is largely confined to treating the symptoms of droughts rather than taking proactive measures to decrease the vulnerability of water systems. The key factors contributing to the increased system vulnerability include: (a) the possible impact of climate change, (b) deficiency of appropriate and timely needed precipitation, (c) growing water demand at national level, (d) significant reduction in annual flow volume entering Iraq from upstream riparian states, (e) deterioration of water quality due to both discharges of untreated hazardous industrial wastes and return flows from irrigation projects into rivers, and (f) lack of efficient water use and management.

Recognizing the urgent need to comprehensively tackle the situation, the Government of Iraq has thus called on the United Nations to provide support in formulating a national framework for integrated DRM (UNDP, 2013a, b, c). The objectives are to support Iraq to implement a series of technical assessments of present DRM measurements and weaknesses, and perform a series of consultations and consensus-building activities to shape a nation-wide strategy for mitigating drought impacts and risk management processes.

The current drought management policy in Iraq seems flawed in terms of the timing for action to take place and the range of spatial coverage. Effective management actions often follow drought periods.

Relief measures are commonly delayed well beyond the time span when the assistance would have been most needed in addressing the symptoms of drought. The obstacles concerning the establishment of short- to long-term risk drought management strategies in Iraq are plentiful and diverse:

- There is a lack of knowledge and common understanding of pre-emptive short- to long-term drought planning and management associated with multiple scenarios.
- Deficiencies exist in institutional and technical capacities at the operational and strategic levels to respond to drought. Moreover, there is an absence of consensus among governmental institutions on issues related to drought management.
- There is a deficit in reliable data on historical drought consequences on various sectors. Furthermore, there is also little transparency in exchange of the data, which are disseminated by institutional stakeholders such as the Ministry of Water Resources, Ministry of Agriculture, Ministry of Environment, Ministry of Planning, Ministry of Municipalities and Public Works, and Ministry of Agriculture and Water Resources in the Kurdistan region of Iraq. Large differences in the capacity and willingness of various groups to provide or to handle information exist. Data, if available, are in different formats, often partly incomplete and not regularly updated.
- Responsibilities, coordination and actions regarding DRM are fragmented, and commonly inconsistently administered among governmental bodies and their local departments.
- Drought remedies are biased towards relief measures in the form of reactive assistance programmes in an attempt to accelerate the pace of the recovery process through provision of money or other specific types of support (e.g., livestock feed, distribution of water via water tanks, food provision and rapid deep well extraction license approvals) to those experiencing the most severe impacts of the drought (FAO, 2008). The government often acts after the onset of symptoms of drought and their activity usually wanes when precipitation returns to normal.
- Recent occurrences of recurrent episodes of drought coincide with dramatic reductions in annual flow volumes of the rivers in Iraq. A considerable proportion of Iraq's water resources originate outside its territory (UNESCO, 2014), which makes it considerably vulnerable to the upstream level of water exploitation and development.
- The upward trends in temperature and PET, and the downward tendency in precipitation are likely to continue and therefore require addressing (UNESCO, 2014). The impact of drought is exacerbated by the lack of precipitation, high demand for water, and increasing human activities. Both the incidence and effects of drought could change in the near future because of climatic alterations and changing vulnerabilities brought on by growing populations and water-using bodies competing over limited water resources (FAO, 2008).
- Decades of conflict and related unstable political, economic and security conditions have considerably weakened and delayed appropriate stakeholder responses.

2.2. Diyala basin

The Diyala basin is situated between latitudes 33.216°N and 35.833°N, and longitudes 44.500°E and 46.833°E (Figure 1). The Diyala river stretches 384 km before flowing into the Tigris river south of Baghdad draining about 32,600 km^2, of which 43% lies in Iraq. The climate of the basin is characterized by cool and wet winters, and hot and dry summers. Precipitation usually occurs from October to May.

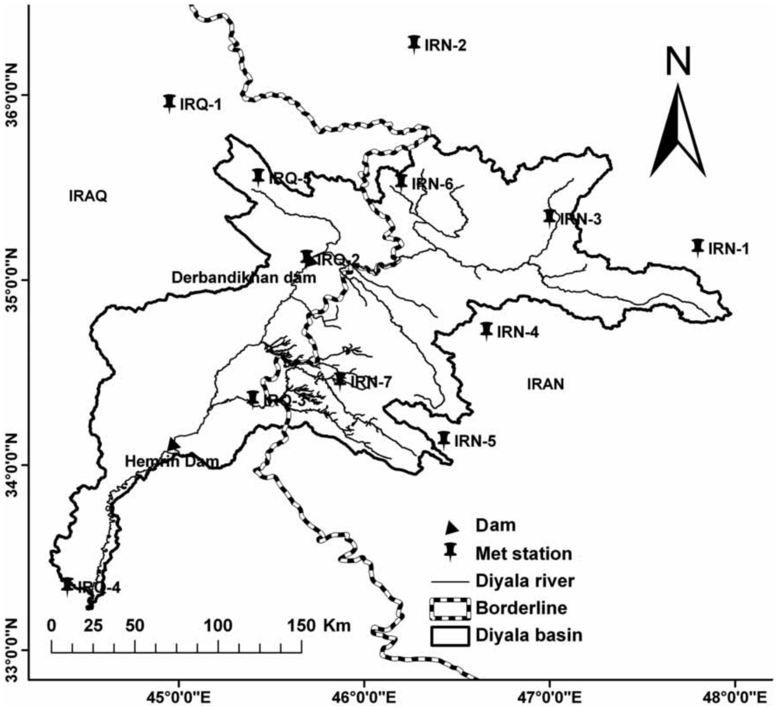

Fig. 1. Diyala transboundary river basin and the locations of the meteorological stations.

Most of the precipitation falls between November and April. The dry season is typically between June and September.

The water management system in the Diyala basin is divided into three segments. The upper segment occupies an area of about 17,900 km^2, which is located mainly in the upper riparian country, Iran, and utilizes the river for water storage schemes, irrigation projects, water diversions and inter-basin water transfer systems (Al-Faraj & Scholz, 2014a, b). In the lower riparian nation, Iraq, the upper segment is controlled by the Derbandikhan dam.

The middle segment of the basin covers the reach between Derbandikhan dam and Hemrin dam (Figure 1), which drains a transboundary area of about 11,900 km^2. The middle Diyala reach receives discharges from three rivers (Havasan, Qaratu and Alwand) originating in Iran. Some seasonal wadis located on the right bank of the river (e.g., Narin Chai servicing the Hemrin reservoir) in Iraq share these contributions. The three rivers are controlled by dams in the upper state, and serve mainly irrigation projects and fish farms. Irrigation projects exist also along the banks of the river in Iraq. These irrigation projects are directly supplied from the middle reach of the river by either gravity irrigation canals or irrigation pumps (MoWR, 2010).

The lower segment forms the water distribution system where the main irrigation projects are located. Key barrages and main regulators exist in the middle and lower parts of the water management system. The lower segment of about 2,800 km^2 is controlled by the Diyala weir, which is a fully controlled barrage across the head of the lower Diyala reach. This complex system ensures two-way water diversions for irrigation serving the combined canal (As Sader Al-Mushtarak canal) on the right bank and the

Al-Khalis canal on the left bank (MoWR, 2010). Water is abstracted from the Tigris river via irrigation pumps located on the left bank to augment water shortages in this reach.

In the early 1960s, a plan was developed to augment the Diyala basin from the Lesser Zab river basin via the Lesser Zab-Diyala link canal, which has a varying capacity between 30 and 55 m^3/s (Harza and Binnie-Main Report, 1963). The recommended mean annual flow volume was estimated to be 945.4 million m^3, which represents 30 m^3/s (MoWR, 1982). However, the recommended Lesser Zab-Diyala link canal has not been implemented, yet.

3. Methodology

3.1. Justification

The proposed methodology presents a clear analytical platform aimed at formulating action plans to counter potential risks of possible drought events in the near future. Moreover, it will help Iraq to effectively improve the current hydro-meteorological monitoring networks and prepare programmes to improve technical and institutional performances, and capacities. Furthermore, the methodology can be regarded as a technical benchmark index to be applied for the assessment of the dynamics of droughts at different scales for other countries as well. The proposed method is presented in the following subsections.

3.2. Data processing and manipulation

The monthly precipitation and the mean air temperature data between the hydrologic years 1981 and 2010 were analyzed. Twelve meteorological stations (Table 1), which are located either within or in close proximity to the examined basin, were investigated. The selection of the stations was made according to the availability (mainly precipitation and mean air temperature over a minimum of 30 years), homogeneity and consistency of meteorological data. Mean air temperature data at Sulaymaniyah station in Iraq were not made available. Therefore, the analysis for this station was limited to precipitation data. Since precipitation plays a substantial role in estimating the drought indices such as the SPI and the reconnaissance drought index (RDI), and temperature is crucial in estimating the RDI, the analysis of precipitation, temperature and PET data have been presented in this paper. The RDI incorporates the PET, which is estimated from the monthly mean air temperature.

The locations of the meteorological stations are shown in Figure 1. The altitudes of these stations ranged from 32 to 1,906 m above sea level (Table 1).

The Kolmogorov-Smirnov (K-S) and Shapiro-Wilk (S-W) tests ($P > 0.05$), visual inspection, normal Q-Q plot and Z-scores for skewness and kurtosis ($-/+$ 1.96) were applied to test the normality of the precipitation data. The software package SPSS IBM-20 was used to perform the entire statistical analysis.

The homogeneity test and double-mass curve analysis (Eris & Agiralioglu, 2012) were applied as essential tools to account for changes in data collection procedures (or other local conditions) and examine the consistency of the precipitation data available at the investigated meteorological stations. The detection of trends in precipitation, temperature and PET time series was performed using the non-parametric Mann–Kendall (M–K) test at 5% significance level. The software XLSTAT 2013.5 was

Table 1. Minimum, maximum, mean and standard deviation for precipitation (*P*), temperature (*T*) and potential evapotranspiration (PET).

					P (mm)				*T*°C				PET (mm)			
ID	Station	Latitude	Longitude	Altitude	Min	Max	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max	Mean	Stdev
IRN-1	Ghorveh	35.17	47.80	1,906	165.7	569.7	383.5	103.7	8.5	13.4	11.2	1.1	931.1	1,256.3	1,107.2	69.7
IRN-2	Saghez	36.27	46.27	1,523	148.5	736.0	461.8	157.1	7.9	15.5	11.5	1.8	897.8	1,342.0	1,126.1	101.5
IRN-3	Sanandaj	35.33	47.00	1,373	170.0	720.0	435.5	134.3	11.1	15.5	13.7	1.0	1,062.8	1,336.5	1,249.2	63.3
IRN-4	Ravansar	34.72	46.66	1,363	197.9	888.4	572.3	162.4	12.5	16.3	14.8	0.9	1,134.0	1,364.1	1,286.5	53.7
IRN-5	Eslamabad	34.13	46.43	1,346	201.6	788.3	521.8	150.2	11.4	14.9	13.5	0.8	1,097.3	1,306.3	1,240.6	51.3
IRN-6	Marivan	35.52	46.20	1,287	446.4	1,605.6	963.4	281.6	10.0	14.6	12.6	1.0	1,034.7	1,299.4	1,182.8	60.5
IRN-7	Sarpolzahab	34.45	45.87	545	169.8	7,84.3	454.5	145.0	18.3	24.8	20.4	1.3	1,444.9	1,689.6	1,525.6	51.3
IRQ-1	Dokan	35.95	44.95	499	240.5	1,346.2	714.4	264.0	18.0	22.8	20.1	1.1	1,440.5	1,620.4	1,518.6	38.9
IRQ-2	Derbandikhan	35.11	45.69	481	207.3	1,083.8	623.4	225.9	18.8	23.1	20.9	1.1	1,467.0	1,632.1	1,546.5	42.0
IRQ-3	Khanaqin	34.35	45.40	202	89.7	507.3	289.3	100.0	21.4	24.5	22.8	0.8	1,571.8	1,689.0	1,628.0	31.2
IRQ-4	Baghdad	33.34	44.40	32	36.6	220.2	109.7	43.4	21.4	24.0	22.9	0.6	1,574.8	1,670.1	1,629.9	23.1
IRQ-5	Sulaymaniya	35.55	45.43	824	230.1	1,252.2	714.4	221.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

used to accomplish the analysis. The M–K test is superior in detecting both linear and nonlinear trends (Hisdal *et al.*, 2001; Wu *et al.*, 2008) and has been applied in many previous studies (Kahya & Kalayci, 2004; Gadgil & Dhorde, 2005; Li *et al.*, 2008; Yaning *et al.*, 2009).

3.3. Estimation of PET

The limited access to a wide range of meteorological data such as minimum and maximum air temperature, minimum and maximum relative humidity, solar radiation, and wind speed has led to the use of a temperature-based method (Blaney–Criddle (B–C)) for estimating the PET. Moreover, the use of the B–C method is appropriate for the calculation of RDI (Vangelis *et al.*, 2013). The application of the B–C procedure has also been proven to be a reliable method for both different locations and climates of the world (Fooladmand & Ahmadi, 2009; Benli *et al.*, 2010; Mohawesh, 2010; Razzaghi & Sepaskhah, 2010; Fooladmand, 2011). The DrinC software (Tigkas *et al.*, 2013a, 2014) was utilized to determine the PET. A default value (average of 0.85) for the crop coefficient was used in the computation process.

3.4. Drought analysis and assessment

Conventionally, droughts are characterized by the determinants studied and are categorized as meteorological, hydrological, agricultural and socioeconomic (Tsakiris *et al.*, 2007b). A long list of drought indices, which range from single index parameters such as the SPI to more data demanding and time consuming ones such as the Palmer drought severity index, have been discussed by the Institute for Environment and Sustainability (IES, 2008). No single index is universally suitable. Therefore, in most cases, it is necessary to consider more than one index (Morid *et al.*, 2006). In this paper, historical episodes of droughts were investigated using two meteorological drought indices with low data requirements: the SPI and the RDI.

The SPI is a precipitation-based index, which has often been applied in many countries over recent years (Vincente-Serrano *et al.*, 2004; Wilhite *et al.*, 2005; Wu *et al.*, 2006; Khadr *et al.*, 2009; Rasheed, 2010; Karavitis *et al.*, 2011; Al-Timimi & Al-Jiboori, 2013; Palchaudhuri & Biswas, 2013; UNESCO, 2014). Following the Lincoln Declaration on Drought Indices, the experts of the World Meteorological Organization (WMO) (2009) reported that the SPI should be used to characterize meteorological droughts by all national meteorological and hydrological services around the world. The SPI was developed by McKee *et al.* (1993). Detailed descriptions of the SPI can be found in the literature (Vincente-Serrano *et al.*, 2004; Wilhite *et al.*, 2005; Wu *et al.*, 2006; Karavitis *et al.*, 2011; Palchaudhuri & Biswas, 2013; UNESCO, 2014).

The RDI is initially based on the ratio of aggregated precipitation to PET for a certain period (Tsakiris & Vangelis, 2005; Tsakiris *et al.*, 2007a). Vangelis *et al.* (2011) have indicated that the RDI is more suitable than the SPI for drought severity detection subject to a climate change scenario, because it incorporates precipitation and PET, and it can be used to assess rationally any drought episode. The latter index is directly related to temperature. The application of the RDI covers a significant part of many studies that have been conducted to examine historical droughts in many countries such as Greece (Tigkas, 2008), Cyprus (Pashiardis & Michaelides, 2008), Malta (Borg, 2009) and Iran (Khalili *et al.*, 2011). The RDI can be expressed in three forms: the initial form (α_k), the normalized form (RDI_n) and the standardized form (RDI_{st}) according to Tigkas *et al.* (2013b). Detailed descriptions of the RDI can be found in the literature (Taskiris & Vangelis, 2005; Tigkas, 2008; Elagib & Elhag, 2011; Zarch *et al.*, 2011).

The SPI and the RDI_{st} indices have been categorized, previously (Zarch *et al.*, 2011): extremely wet conditions prevail when both SPI and RDI_{st} are greater than or equal to 2.00, and extremely dry conditions occur when both SPI and RDI_{st} are less than -2.00. The severity classifications are very wet ($1.5 \leq \text{SPI and RDI}_{st} < 2.00$), moderately wet ($1.00 \leq \text{SPI and RDI}_{st} < 1.50$), near normal ($-1.00 < \text{SPI and RDI}_{st} < 1.00$), moderately dry ($-1.50 < \text{SPI and RDI}_{st} \leq -1.00$) and severely dry ($-2.00 < \text{SPI and RDI}_{st} \leq -1.50$).

In this study, the analyses were performed using the DrinC software (version 1.5). DrinC has been used in several studies for drought assessment and monitoring, predominantly in arid and semi-arid areas. The SPI and RDI indices were calculated for four time intervals per each water year from 1981 to 2010. The four timeframes are October–December, October–March, October–June and October–September (entire hydrologic year). The precipitation data were fitted to the two-parameter Gamma distribution function in the computation process to obtain the SPI and the RDI indices. Drought characteristics of the 3, 6 and 9 months, and annual, SPI and RDI time series were generated. For each drought index, four time series were produced corresponding to the four reference periods of 3, 6, 9 and 12 months, respectively.

A Free and Open Source Geographic Information System (QGis version 2.2; http://www.qgis.org/en/site/) was utilized to provide spatial distribution representation maps of historical droughts. The calculated SPI and RDI values for the four reference time intervals were first converted to a geo-referenced database. A deterministic interpolator called the inverse distance weighted methodology (Chen & Liu, 2012) was applied for the computation of the value of a location that was not sampled. The inverse distance weighted method uses information concerning the spatial structure of the data by giving relatively large weights to data close to the interpolation point, while those far away exert little influence.

4. Results and discussion

The K-S and the S-W tests of normality ($P > 0.05$), skewness Z-score, kurtosis Z-score, visual inspections of histograms and normal Q-Q plots showed that the monthly precipitation data observed at all examined stations are not normally distributed. The skewness and kurtosis values ranged from 1.101 to 2.147 and from 0.906 to 6.767, respectively. The skewness Z-scores and kurtosis Z-scores extended from 8.53 to 1.64 and from 3.54 to 26.43, respectively. The standard errors of the skewness and the kurtosis were 0.129 and 0.256, respectively.

With regard to the homogeneity test, the application of the double-mass curve analysis revealed no changes in instrumentation, observation procedures, gauge locations and other boundary conditions. This implies that the precipitation data of the 12 assessed meteorological stations are consistent and homogeneous.

4.1. Characteristics of precipitation, temperature and PET

Table 1 shows the coordinates and altitudes of the examined stations, and summarizes the descriptive statistics for the annual time series of precipitation, temperature and PET. The annual long-term minimum, maximum and mean precipitation for the period 1981–2010 were between 37 and 447 mm, between 220 and 1,606 mm, and between 110 and 964 mm, respectively. The corresponding temperatures were between 7.9 and 21.4 °C, between 13.4 and 24.8 °C, and between 11.2 and 22.9 °C in that order. The PET values were between 931 and 1,575 mm, between 1,256 and 1,690 mm, and between 1,107 and 1,630 mm, correspondingly.

The ratios expressed as percentages of the long-term mean monthly precipitation to the long-term mean annual precipitations for the water years 1981–2010 are summarized in Table 2. Results reveal that the aggregated precipitation over the wet months (October–May) contributes about 99% of the total annual precipitation. Accumulated rainfall over the dry season (June–September) accounts for only 1% of the total annually. The proportion of precipitation between November and April represents about 90%. The ratio of precipitation in October and May accounts for about 5%.

Temperature and PET rate rises, and precipitation decreases were more pronounced over the time horizon 1998–2010 in comparison to the time period between 1981 and 1997 (Table 3). Findings regarding precipitation declines were confirmed by UNESCO (2014). Between 1998 and 2012, the reduction in total annual hydroelectric production in the Kurdish region of Iraq coincides with a fall in precipitation.

The proportions of increase in the rates of temperature and PET ranged from 4 to 14% and from 2 to 7%, respectively. The rates of reduction in precipitation fell between 16 and 31%. The average increase in temperature and PET rates over the entire basin were 8 and 4%, respectively. By contrast, the average drop in precipitation was 23%. The fractions of increase in PET rate exemplify about 48–60% of those detected in temperature, indicating an average of about 53%. The reduction in precipitation and increases in temperature and PET have widened the gap between precipitation and water demand, mainly for the agriculture sector.

Overall, findings suggest that the Diyala basin has been experiencing climatically-induced changes. Climate change-induced alterations in temperature, PET and precipitation within the Diyala basin are likely to lead to a further reduction in annual flow volume entering the lower riparian country. The

Table 2. Ratios of long-term mean monthly to long-term mean annual precipitation.

		% of long-term annual precipitation											
ID	Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
IRN-1	Ghorveh	6.1	14.1	10.5	10.4	12.2	19.1	15.9	8.7	0.9	1.1	0.4	0.5
IRN-2	Saghez	6.2	13.7	12.0	12.3	13.7	15.9	15.0	8.3	1.1	1.0	0.5	0.3
IRN-3	Sanandaj	6.5	14.1	12.4	12.4	14.3	17.1	15.4	6.6	0.5	0.4	0.0	0.3
IRN-4	Ravansar	1.9	13.6	13.7	12.9	16.6	17.1	14.8	8.3	0.6	0.1	0.0	0.3
IRN-5	Eslamabad	4.6	15.5	14.6	16.5	16.2	17.3	10.8	3.6	0.2	0.2	0.0	0.3
IRN-6	Marivan	4.3	13.4	14.8	15.0	18.1	17.2	11.7	4.9	0.2	0.1	0.0	0.2
IRN-7	Sarpolzahab	2.6	12.9	16.0	17.8	15.2	18.7	11.5	5.2	0.1	0.1	0.0	0.1
IRQ-1	Dokan	4.6	12.0	16.7	17.7	18.4	16.6	10.3	3.1	0.2	0.1	0.1	0.2
IRQ-2	Derbandikhan	3.9	11.6	16.3	19.4	19.7	16.4	9.3	3.1	0.1	0.0	0.0	0.2
IRQ-3	Khanaqin	4.6	13.7	16.3	20.6	16.1	17.4	9.5	1.8	0.0	0.0	0.0	0.0
IRQ-4	Baghdad	3.4	14.5	15.7	21.9	13.3	16.2	12.1	2.8	0.1	0.0	0.0	0.0
IRQ-5	Sulaymaniya	4.9	12.5	15.2	17.1	17.5	15.2	11.9	5.4	0.2	0.0	0.0	0.2
Mean		4.5	13.5	14.5	16.2	15.9	17.0	12.3	5.1	0.4	0.3	0.1	0.2

Table 3. Increase in temperature and potential evapotranspiration and reduction in precipitation. A comparison between 1981–1997 and 1998–2010.

Station	Temperature increase (%)	Potential evapotranspiration increase (%)	Precipitation reduction (%)
Ghorveh	13.00	7.00	22.25
Saghez	13.90	6.77	30.95
Sanandaj	10.70	5.29	26.66
Ravansar	6.24	3.50	20.30
Eslamabad	8.20	4.30	24.50
Marivan	10.00	5.00	20.14
Sarpolzahab	5.02	2.66	27.60
Dokan	6.50	3.20	25.60
Derbandikhan	8.30	4.00	16.00
Khanaqin	3.60	2.14	25.50
Baghdad	3.54	2.13	15.80
Sulaymaniya	X	X	18.30

reduction in precipitation and the increase in temperature and PET rates have widened the gap between available water and water demand, particularly in the agriculture sector.

It is worth noting that the reduction in precipitation, and the increase in temperature and PET may give a pretext to an upstream country to exploit more water, and build additional dams to store water in order to address the growing demand for water in its territorial boundaries. This may lead to additional burdens and challenges facing water managers and decision-makers in a corresponding downstream country.

4.2. Drought characteristics and temporal-spatial dynamics

Comparability analyses were performed to assess differences between the SPI and the RDI_{st}. Results show that both indices have often comparable trends and respond in a similar manner. Robust coefficients of determination (r^2) were obtained between both indices for the four reference time intervals (3–12 months) regarding all investigated meteorological stations. The r^2 ranged from 0.71 to 0.99. The corresponding means were 0.984, 0.901, 0.967 and 0.984 for 3, 6, 9 and 12 months, respectively. This suggests that both SPI and RDI respond in a similar manner, and thus can be applied effectively to explore and analyse droughts for various time intervals. However, it is important to mention that the lower values of r^2 are observed for the 6-month interval, for which the low temperature of the winter months plays an important role in the analysis. Therefore, RDI seems to depict in more detail the drought conditions, especially during winter months, due to the utilization of the PET.

Results from the M–K test of SPI for the 3-, 6-, 9- and 12-month time intervals (Table 4) indicate that the significant downward trend at the 5% level of significance has developed from 25% of the investigated meteorological stations for the 3-month time window to 75% for the 6-month time span aggregated precipitation, and remained steady for the 9- and 12-month time scales cumulative precipitation. Marivan station in Iran and Suleymaniya, and Baghdad station in Iraq were not associated with a significant trend for the four overlapped periods. A comparison between the results of the M–K trend test of precipitation (Table 5) with the M–K trend test of SPI (Table 4) demonstrates that there was a

Table 4. The Mann–Kendall trend analysis of the standardized precipitation index for four time intervals.

		3-month SPI			6-month SPI		
ID	Name	Kendall's tau	*P*-value	Trend at 5%	Kendall's tau	*P*-value	Trend at 5%
IRN-1	Ghorveh	−0.237	0.069	Insignificant	−0.411	0.001	Significant
IRN-2	Saghez	−0.207	0.112	Insignificant	−0.331	0.011	Significant
IRN-3	Sanandaj	−0.186	0.155	Insignificant	−0.370	0.004	Significant
IRN-4	Ravansar	−0.182	0.166	Insignificant	−0.297	0.022	Significant
IRN-5	Eslamabad	−0.237	0.069	Insignificant	−0.411	0.001	Significant
IRN-6	Marivan	−0.205	0.117	Insignificant	−0.223	0.087	Insignificant
IRN-7	Sarpolzahab	−0.347	0.007	Significant	−0.499	<0.0001	Significant
IRQ-1	Dokan	−0.269	0.038	Significant	−0.292	0.024	Significant
IRQ-2	Derbandikhan	−0.283	0.029	Significant	−0.306	0.018	Significant
IRQ-3	Khanaqin	−0.246	0.058	Insignificant	−0.356	0.005	Significant
IRQ-4	Baghdad	−0.186	0.155	Insignificant	−0.207	0.112	Insignificant
IRQ-5	Sulaymaniya	−0.177	0.177	Insignificant	−0.154	0.242	Insignificant
		9-month SPI			12-month SPI		
ID	Name	Kendall's tau	*P*-value	Trend at 5%	Kendall's tau	*P*-value	Trend at 5%
IRN-1	Ghorveh	−0.448	0.000	Significant	−0.444	0.000	Significant
IRN-2	Saghez	−0.375	0.003	Significant	−0.375	0.003	Significant
IRN-3	Sanandaj	−0.320	0.013	Significant	−0.320	0.014	Significant
IRN-4	Ravansar	−0.292	0.024	Significant	−0.292	0.024	Significant
IRN-5	Eslamabad	−0.448	0.000	Significant	−0.444	0.000	Significant
IRN-6	Marivan	−0.191	0.145	Insignificant	−0.182	0.166	Insignificant
IRN-7	Sarpolzahab	−0.393	0.002	Significant	−0.393	0.002	Significant
IRQ-1	Dokan	−0.255	0.049	Significant	−0.264	0.041	Significant
IRQ-2	Derbandikhan	−0.287	0.026	Significant	−0.287	0.026	Significant
IRQ-3	Khanaqin	−0.338	0.008	Significant	−0.338	0.008	Significant
IRQ-4	Baghdad	−0.145	0.272	Insignificant	−0.145	0.272	Insignificant
IRQ-5	Sulaymaniya	−0.131	0.321	Insignificant	−0.131	0.321	Insignificant

100% match for three time intervals (6, 9 and 12 months). Ghorveh station showed a mismatch for the 3-month time scale.

Correspondingly, the RDI (Table 6) findings indicate that the M–K trend has grown from about 27% of the studied stations for the 3-month time interval to nearly 91% of the considered stations for the 6-month period. For the 9- and 12-month time domain, the proportion was approximately 64 and 73%, respectively. Baghdad station in Iraq demonstrated no significant trend for the four aggregated time frames. Marivan and Saghez stations in Iran displayed significant trends for the 6-month time scale only. A comparison between the results of the M–K trend test of PET (Table 7) with the M–K trend test of RDI (Table 6) determined that there were differences for three of the time horizons (3, 6 and 9 months). The corresponding proportions of PET and RDI were 36, 45 and 82%, and 27, 91, and 64%, respectively. A 100% match was observed for the 12-month time domain. The differences could be attributed to the influence of precipitation in computing RDI.

The differences between the SPI and RDI M–K trend results could be attributed to (a) the unavailability of sufficient mean air temperature data observed at Suleymaniya station, and the fact that RDI was not obtained, resulting in a reduction of the number of stations for RDI computation from 12 to

Table 5. The Mann–Kendall trend analysis of the precipitation (*P*) for four time intervals.

		3-month P			6-month P		
ID	Name	Kendall's tau	*P*-value	Trend at 5%	Kendall's tau	*P*-value	Trend at 5%
IRN-1	Ghorveh	−0.262	0.044	Significant	−0.425	0.001	Significant
IRN-2	Saghez	−0.207	0.112	Insignificant	−0.331	0.011	Significant
IRN-3	Sanandaj	−0.186	0.155	Insignificant	−0.370	0.004	Significant
IRN-4	Ravansar	−0.182	0.166	Insignificant	−0.297	0.022	Significant
IRN-5	Eslamabad	−0.237	0.069	Insignificant	−0.411	0.001	Significant
IRN-6	Marivan	−0.205	0.117	Insignificant	−0.223	0.087	Insignificant
IRN-7	Sarpolzahab	−0.347	0.007	Significant	−0.499	<0.0001	Significant
IRQ-1	Dokan	−0.269	0.038	Significant	−0.292	0.024	Significant
IRQ-2	Derbandikhan	−0.283	0.029	Significant	−0.306	0.018	Significant
IRQ-3	Khanaqin	−0.246	0.058	Insignificant	−0.356	0.005	Significant
IRQ-4	Baghdad	−0.184	0.159	Insignificant	−0.205	0.117	Insignificant
IRQ-5	Sulaymaniya	−0.177	0.177	Insignificant	−0.154	0.242	Insignificant
		9-month P			12-month P		
ID	Name	Kendall's tau	*P*-value	Trend at 5%	Kendall's tau	*P*-value	Trend at 5%
IRN-1	Ghorveh	−0.366	0.004	Significant	−0.343	0.008	Significant
IRN-2	Saghez	−0.375	0.003	Significant	−0.375	0.003	Significant
IRN-3	Sanandaj	−0.320	0.013	Significant	−0.320	0.013	Significant
IRN-4	Ravansar	−0.292	0.024	Significant	−0.292	0.024	Significant
IRN-5	Eslamabad	−0.448	0.000	Significant	−0.444	0.000	Significant
IRN-6	Marivan	−0.191	0.145	Insignificant	−0.182	0.166	Insignificant
IRN-7	Sarpolzahab	−0.393	0.002	Significant	−0.393	0.002	Significant
IRQ-1	Dokan	−0.255	0.049	Significant	−0.264	0.041	Significant
IRQ-2	Derbandikhan	−0.287	0.026	Significant	−0.287	0.026	Significant
IRQ-3	Khanaqin	−0.338	0.008	Significant	−0.338	0.008	Significant
IRQ-4	Baghdad	−0.147	0.261	Insignificant	−0.147	0.261	Insignificant
IRQ-5	Sulaymaniya	−0.131	0.321	Insignificant	−0.131	0.321	Insignificant

11 (compared to 12 stations for SPI), and (b) the influence of the mean air temperature and, correspondingly, the PET on RDI development.

A close screening of Figures 2 and 3 suggest that the most severe drought spells took place during the water years 1999–2001 and the hydrologic years between 2008 and 2009. This complies with what was reported by UNESCO (2014). During the drought between 2007 and 2009, cropland throughout Iraq experienced reduced coverage, and livestock was decimated. The situation in 2009 caused a significant number of rural inhabitants to relocate in search of more sustainable access to drinking water and livelihoods.

Findings also show that the basin has suffered from the most significant drought events in 1999, 2000 and 2008. Results suggest that in 2008 both annual SPI and RDI indices indicated that nearly the entire basin was under extreme drought condition, while a small proportion experienced moderate drought patterns. Indicatively, a temporal-spatial map pattern for the drought of the water year 2008 for the four time intervals of SPI and RDI (3, 6, 9 and 12 months) is shown in Figure 4. In 2000, the annual SPI and RDI reported similar drought tendencies, where the upper and lower parts of the basin suffered from moderate droughts, while the remaining areas witnessed extreme drought conditions. For SPI,

Table 6. The Mann–Kendall trend analysis of the reconnaissance drought index for four time intervals.

		3-month RDI			6-month RDI		
ID	Name	Kendall's tau	*P*-value	Trend at 5%	Kendall's tau	*P*-value	Trend at 5%
IRN-1	Ghorveh	−0.203	0.120	Insignificant	−0.503	<0.0001	Significant
IRN-2	Saghez	−0.195	0.135	Insignificant	−0.320	0.013	Significant
IRN-3	Sanandaj	−0.223	0.087	Insignificant	−0.398	0.002	Significant
IRN-4	Ravansar	−0.191	0.145	Insignificant	−0.352	0.006	Significant
IRN-5	Eslamabad	−0.246	0.058	Insignificant	−0.398	0.002	Significant
IRN-6	Marivan	−0.200	0.126	Insignificant	−0.297	0.022	Significant
IRN-7	Sarpolzahab	−0.375	0.003	Significant	−0.503	<0.0001	Significant
IRQ-1	Dokan	−0.292	0.024	Significant	−0.329	0.011	Significant
IRQ-2	Derbandikhan	−0.306	0.018	Significant	−0.333	0.009	Significant
IRQ-3	Khanaqin	−0.237	0.069	Insignificant	−0.366	0.004	Significant
IRQ-4	Baghdad	−0.182	0.166	Insignificant	−0.223	0.087	Insignificant
IRQ-5	Sulaymaniya	N/A	N/A	N/A	N/A	N/A	N/A
		9-month RDI			12-month RDI		
ID	Name	Kendall's tau	*P*-value	Trend at 5%	Kendall's tau	*P*-value	Trend at 5%
IRN-1	Ghorveh	−0.389	0.002	Significant	−0.490	< 0.0001	Significant
IRN-2	Saghez	−0.343	0.008	Insignificant	−0.338	0.008	Insignificant
IRN-3	Sanandaj	−0.407	0.001	Significant	−0.398	0.002	Significant
IRN-4	Ravansar	−0.356	0.005	Significant	−0.343	0.008	Significant
IRN-5	Eslamabad	−0.471	0.000	Significant	−0.490	< 0.0001	Significant
IRN-6	Marivan	−0.241	0.063	Insignificant	−0.223	0.087	Insignificant
IRN-7	Sarpolzahab	−0.393	0.002	Significant	−0.398	0.002	Significant
IRQ-1	Dokan	−0.292	0.024	Significant	−0.278	0.032	Significant
IRQ-2	Derbandikhan	−0.310	0.016	Significant	−0.292	0.024	Significant
IRQ-3	Khanaqin	−0.352	0.006	Insignificant	−0.361	0.005	Significant
IRQ-4	Baghdad	−0.177	0.177	Insignificant	−0.172	0.189	Insignificant
IRQ-5	Sulaymaniya	N/A	N/A	N/A	N/A	N/A	N/A

the year 1999 had impressively similar drought patterns to the year 2000. Although similar drought patterns between SPI and RDI were observed for the lower segment of the basin, dissimilarity was observed for the middle and upper areas.

4.3. Human intervention and drought management plans

Al-Faraj & Scholz (2014a, b) have highlighted that anthropogenic perturbations such as land use changes, dam operations and overexploiting water resources in the upstream country Iran have extremely altered the flow regime of the lower riparian state Iraq, in particular during basin-wide drought episodes. Human interventions coupled with droughts would adversely intensify the impact on socio-economic and environmental systems of the downstream country and impair their resilience. The effect is especially noticeable in heavily irrigated watersheds such as the Diyala river basin.

The collective impact of man-made activities and droughts is likely to considerably increase when the Nosoud inter-basin water transfer tunnel (annual transfer of about 1,378 million m^3 from the Diyala basin to other basins) of 48 km length and the Daryan dam will be in operation in 2018 (Al-Faraj &

Table 7. The Mann–Kendall trend analysis of the potential evapotranspiration for four time intervals.

		3-month PET			6-month PET		
ID	Name	Kendall's tau	*P*-value	Trend at 5%	Kendall's tau	*P*-value	Trend at 5%
IRN-1	Ghorveh	0.246	0.058	Insignificant	0.361	0.005	Significant
IRN-2	Saghez	0.108	0.416	Insignificant	0.168	0.201	Insignificant
IRN-3	Sanandaj	0.310	0.016	Significant	0.297	0.022	Significant
IRN-4	Ravansar	0.209	0.109	Insignificant	0.228	0.081	Insignificant
IRN-5	Eslamabad	0.260	0.045	Significant	0.301	0.020	Significant
IRN-6	Marivan	0.237	0.069	Insignificant	0.246	0.058	Insignificant
IRN-7	Sarpolzahab	0.172	0.189	Insignificant	0.094	0.479	Insignificant
IRQ-1	Dokan	0.255	0.049	Significant	0.237	0.069	Insignificant
IRQ-2	Derbandikhan	0.315	0.014	Significant	0.375	0.003	Significant
IRQ-3	Khanaqin	0.110	0.402	Insignificant	0.209	0.109	Insignificant
IRQ-4	Baghdad	0.200	0.126	Insignificant	0.347	0.007	Significant
IRQ-5	Sulaymaniya	N/A	N/A	N/A	N/A	N/A	N/A
		9-month PET			12-month PET		
ID	Name	Kendall's tau	*P*-value	Trend at 5%	Kendall's tau	*P*-value	Trend at 5%
IRN-1	Ghorveh	0.425	0.001	Significant	0.434	0.001	Significant
IRN-2	Saghez	0.195	0.135	Insignificant	0.205	0.117	Insignificant
IRN-3	Sanandaj	0.407	0.001	Significant	0.416	0.001	Significant
IRN-4	Ravansar	0.264	0.041	Significant	0.251	0.054	Insignificant
IRN-5	Eslamabad	0.389	0.002	Significant	0.421	0.001	Significant
IRN-6	Marivan	0.274	0.035	Significant	0.301	0.020	Significant
IRN-7	Sarpolzahab	0.080	0.548	Insignificant	0.117	0.376	Insignificant
IRQ-1	Dokan	0.361	0.005	Significant	0.444	0.000	Significant
IRQ-2	Derbandikhan	0.476	0.000	Significant	0.462	0.000	Significant
IRQ-3	Khanaqin	0.338	0.008	Significant	0.320	0.013	Significant
IRQ-4	Baghdad	0.499	<0.0001	Significant	0.531	<0.0001	Significant
IRQ-5	Sulaymaniya	N/A	N/A	N/A	N/A	N/A	N/A

Scholz, 2014a, b). The growing human demand for freshwater in both riparian states, degraded and mismanaged (in an unsustainable manner) water resources systems in the lower state, and the threat of successive severe drought episodes at transboundary scale confirm the need for proactive water supply and drought management plans. Therefore, an increase in communication, collaboration and coordination, an improvement of the quality of information, refinement of the planning process, and identification and engagement of stakeholders are urgently required at the transboundary level. The following key components need to be considered: (a) provisions for efficient and effective hydro-meteorologic monitoring and early warning systems; (b) risk and impact assessments; (c) response and attenuation strategies; (d) timely and transparent exchange of information and corresponding access to data; (e) high level of synergies between related stakeholders; and (f) public awareness campaigns.

4.4. Importance of drought analysis and indices in supporting drought management

Historical drought analysis and the establishment of drought indices support the development of a set of water supply reduction objectives and the formulation of action plans for various drought conditions.

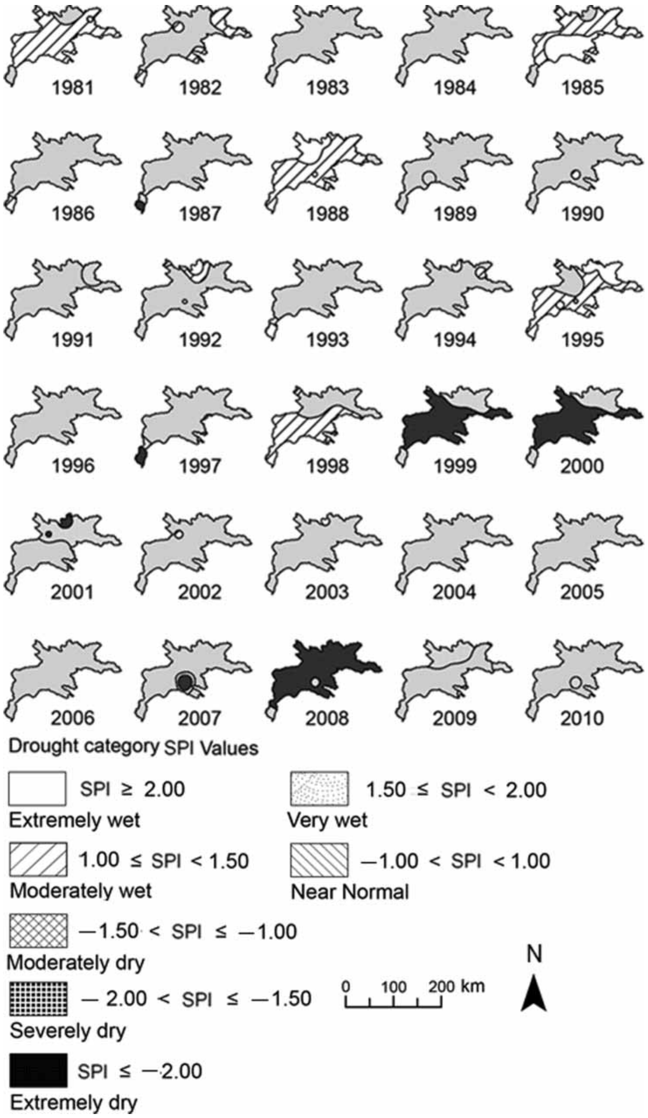

Fig. 2. Spatial distribution of the annual SPI between 1981 and 2010.

Drought contingency plans can be based on the rational evaluation of alternatives for drought consequences taking into account short- and long-term criteria (Tsakiris *et al.*, 2014). A set of water management actions can be designed whereby a particular action becomes operational when a certain drought condition is evident. When a witnessed drought condition activates the application of the corresponding water management plan, multi-water users and the public should be notified. The report needs to guarantee information about the provisions to curtail use of water. A system of priorities of water use categories needs to be in place before droughts occur, so that each user knows, in advance of a drought, in what order water limitations will be applied. If beneficiaries know, in advance of a

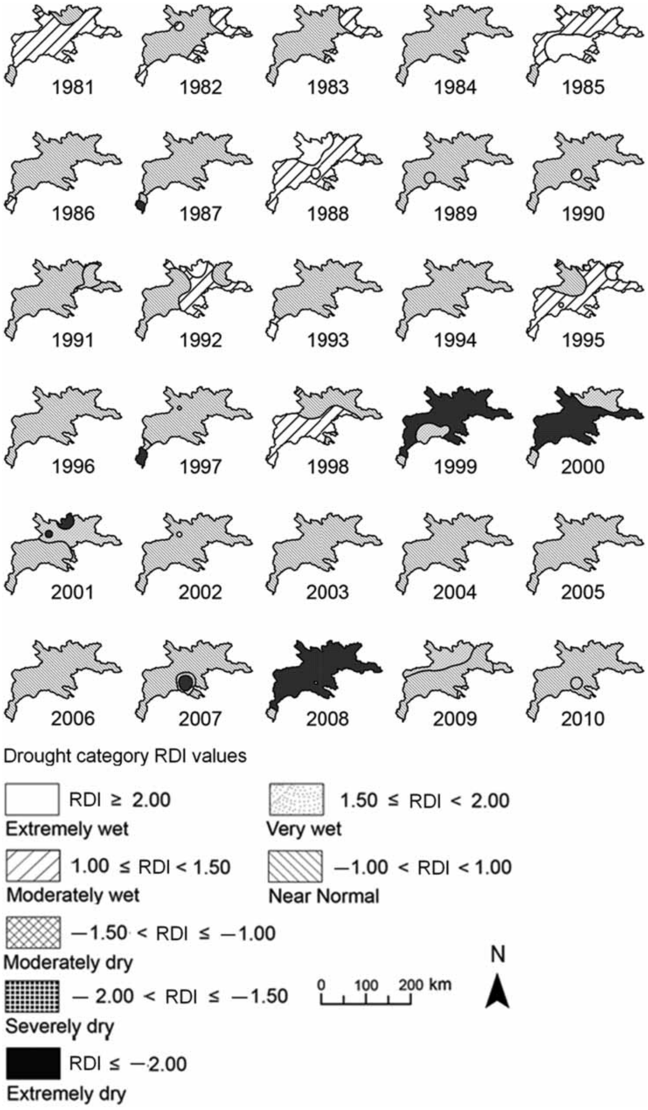

Fig. 3. Spatial distribution of the annual RDI between 1981 and 2010.

drought, the transactions to be followed in reducing water use, they can establish their own contingency plans for those reductions and arrange for alternatives.

The nation-wide plan is directed at providing water managers and other related stakeholders at various levels with effective and systematic means of assessing drought conditions, developing mitigation actions and programmes to reduce risk in advance of drought, and developing response options that minimize economic stress, environmental losses and social hardships during drought. Furthermore, constraints to the planning process and to the activation of the plan in response to a developing drought will be identified. These constraints may be physical, financial, legal or political. The costs associated with the development of a plan must be weighed against the losses that will likely result if no plan is in place.

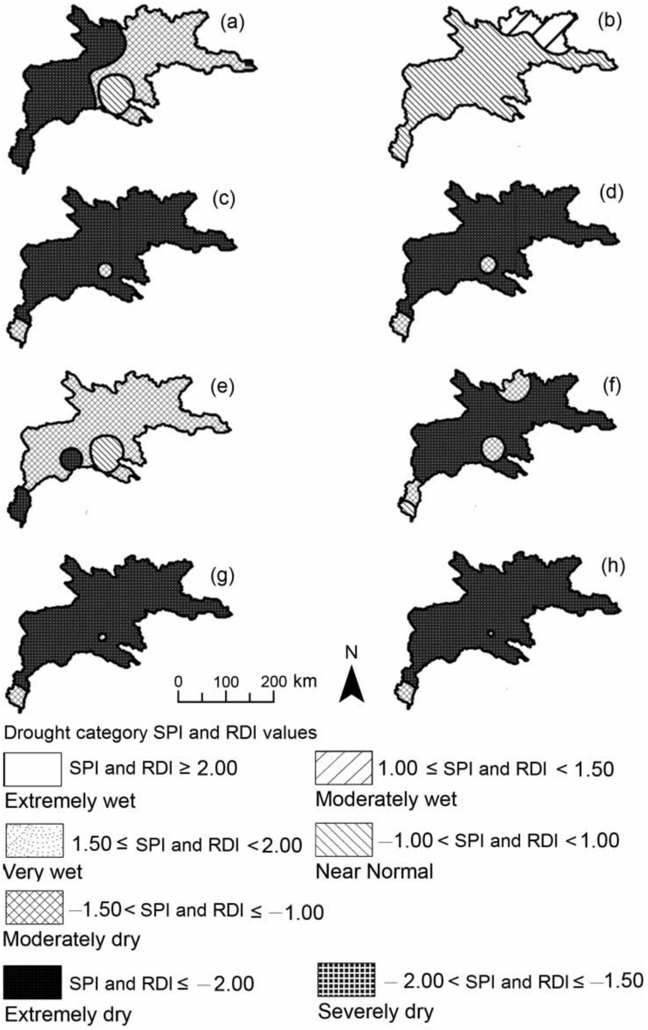

Fig. 4. The SPI and the RDI for four time intervals in 2008: (a) SPI for 3 months; (b) SPI for 6 months; (c) SPI for 9 months; (d) SPI for 12 months; (e) RDI for 3 months; (f) RDI for 6 months; (g) RDI for 9 months; and (h) RDI for 12 months.

For the Diyala basin, the agriculture sector bears the most direct adverse impact of drought. Wells may run dry, crops may fail and forage for livestock may be scarce.

Spatial and temporal drought analyses support identification of high risk areas of the state and the most vulnerable economic and social sector. Moreover, a reliable assessment of water availability and its outlook for the short- and long-term is valuable information during dry periods. Drought indices assimilate a tremendous amount of data on precipitation, temperature, PET, streamflow, water level and other water supply indicators. The assessment of previous reactions in time and space to diverse drought conditions is a good planning aid, whereby weaknesses or problems caused or not covered can be distinguished and addressed. Decision-makers and water managers find it useful to consult one or more drought indices before making decisions for water allocation, temporally and spatially. Drought analysis helps in establishing drought management zoning and regionalization, whereby the country can be divided into regions according to climatic characteristics, available water resources, socioeconomic condition as well as other means such as vulnerability to drought.

5. Conclusions and recommendations

This paper proposes a technical platform analysis for drought management in countries such as Iraq, supporting decision-makers in DRM. The recommended novel platform should be embedded within a framework covering both national drought plans and policies that all relevant stakeholders can follow in order to shift from the emergency mode to a risk-based management paradigm. The platform may lead to a more accurate vulnerability assessment. Therefore, appropriate mitigation measures can be taken to minimize the vulnerability of the system, and build resilience in case of future episodes of drought worsened by climate change.

Given projections of climate change impact, it is essential to move toward a more risk-based approach to drought management. However, even if the drought patterns do not noticeably change in the future in terms of frequency, severity and duration, the current difficulties of coping with most droughts strongly suggest the need for a risk management mode.

The lower riparian country as well as other similar downstream riparian states can gain potential benefits from the presented generic technical template to improve its preparedness level, while maintaining goals of decreasing vulnerabilities to droughts. The paper also highlights a risk management approach and the adoption of proper mitigation actions. However, the development of a national drought policy should be viewed as a continuous process.

It is noteworthy to highlight that the reduction in precipitation and the rise in temperature and PET rates may give a strong excuse to the upstream country to exploit more water and build additional water storage projects to address the growing demand for water in its territorial boundaries. In this context, the water managers and decision-makers of the downstream country will face additional challenges to find practical and resilient solutions.

Drought management in Iraq calls for greater and robust coordination between stakeholders. Policy coordination also requires institutional change and management of possible conflicts among different governmental bodies. Coordination and cooperation between stakeholders is vital for achieving an integrated water resources management. Without a harmonized national drought strategy and institutional flexibility, which includes wide-ranging meteorological monitoring networks, early warning and information systems, impact assessment procedures, risk-based management measures and drought preparedness plans, Iraq will continue to respond to drought in a relief crisis-based management mode.

The authors encourage the creation of a new nation-wide culture in terms of water consumption that supports and fosters the rational use of water resources and avoids a wasteful attitude by all consumers. The proposed development of a national drought policy for climate alterations should support sustainable water resources planning.

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