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Assessment of Drought Conditions and their Impacts on the Environment of the Udhaim River Basin, Iraq

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Słowa kluczowe: susze, SPEI, degradacja środowiska, zlewnia rzeki Udhaim, Irak

Keywords: droughts, SPEI, land degradation, Udhaim River basin, Iraq

Abstract

This research addresses selected key issues related to the occurrence of droughts and their impacts on the environment in the mesoscale basin of the Udhaim River, the left tributary of the Tigris River, Iraq. It highlights the importance of water resources, which are dependent on the climate and human activity, as well as exposed to drought hazard. The Standardized Precipitation-Evapotranspiration Index was applied to analyze drought development over the period 1980-2010. Trends in the SPEI time series in the years 1980-2010 were analyzed. Following this, the impacts of drought on land degradation, water discharge and water quality were investigated. The study results may help develop sustainable water management strategies important in mitigating water shortage.They can be used as a baseline for further research on improving water management in the region. The main contributions of this research include: (1) multi-year analysis of drought development of variable duration in the mesoscale basin; (2) extended understanding of drying trends explained by using the statistical tests; (3) broadened knowledge on the scale of land degradation, through remote sensing data sets and application of advanced GIS techniques; (4) improved understanding of water quality changes and their links with the magnitude of the revenue of water resources.

Title of the PhD thesis in Polish

Ocena występowania susz oraz ich wpływu na środowisko
w zlewni rzeki Udhaim w Iraku

DEDICATION

To our martyrs in paradise,

My brother, Hassib

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CHAPTE ONE:

1. INTRODUCTION

1.1. Background

1.1.1. The importance of drought

Drought is a complex phenomenon considered to be a natural hazard causing several environmental, societal, and economic problems (Tallaksen & Van Lanen, 2004; Van Loon, 2015). Its impact on global life in the last decades is very clear. That is, the impact is due to climate change resulting from global warming which is dangerous to wide areas of the Earth. Changes in climate characteristics significantly affect the Earth's hydrological cycle. This situation leads to the prevalence of famine in many countries, especially in Asia and Africa. It is a worldwide problem the negative impacts of which occur not only in limited areas within single country, but can spread to the entire territory of a country and to large areas across political borders (Rasheed, 2009). According to the Global Report on Food Crises (GRFC, 2017), is Iraq the among countries, where widespread food insecurity is likely to persist. Besides extreme weather events resulting in the occurrence of droughts occurrence, livelihoods, lack of employment, and bad humanitarian situation since the beginning of the conflicts (GRFC, 2017).

Drought as a recurring climate and periodic phenomenon occurs as the result of precipitation decrease below its common average for a long or short period of time. Thus, it leads to the reduction of groundwater recharge and the soil water resources and, in consequence, the reduction of vegetation activity and growth declining land productivity (e.g. Vicente-Serrano et al., 2013). This is one of the problems prevailing in most of the world regions with humid, semi-humid, dry and semi-dry conditions. Iraq is one of these regions.

Although the recurrence of drought and climate changes can stimulate the process of desertification, they are not the only drivers of land degradation. Human activities greatly contribute to the development of desertification (Bauer & Stringer, 2009; Sun et al., 2005). Both population growth and economic development increase pressure on land use, especially in vulnerable environments. Desertification undermines

the productive potential of land and contributes to poverty. According to the UNCCD (United Nations Convention to Combat Desertification), desertification is a worldwide phenomenon which affects about 40% of the Earth's land area (Holtz, 2003).

Almost 70%, of all dry areas, are hit by desertification and underdeveloped countries are severely affected by this detrimental process Iraq among them. Desertification affects 75% of Iraq's total land area, in particular the arable land (Al-Saidi & Al-Juaiali, 2013).

Climate elements such as rainfall, temperature, sunlight, wind, and human activities like the intensive use of land, overgrazing, over-lumbering, and logging can lead to changes in land surface conditions during desertification processes (Sivakumar, 2007; Zeidler et al., 2002). Vegetation conditions in the arid, semi-arid and dry sub-humid environments have greatly changed due to climate variations and human activities that cause desertification. Such changes include the decrease in vegetation cover, density and biomass. They are also characterized by structural configurations of vegetation types and landscape patterns (Li et al., 2006; Sivakumar, 2007; Wu & Ci, 2002).

Since geography deals with issues related to people and their life activities, investigating drought is of a great significance. It attracts the attention of geographers who wish to investigate the impacts of such phenomena on human beings, their environment and activities, as well as finding suitable solutions to reducing these impacts. That is, the issue at hand is one of the world problems which negatively influence the environment in the affected regions. Hence, it leads to the reduction of natural resources in these areas. It is thus of great importance to improve our understanding of drought timing and severity under past and current climate conditions. One of the greatest difficulties in advancing the current knowledge in this scope is that in many regions of the world, including the territory of Iraq, ground-based observations are limited in time and space. However, the increasing availability of satellite data which serve as a source of spatial information gives us the opportunity to fill this gap. As Iraq suffers from droughts due to the exposure to climate conditions, the identification of wetness conditions and their impact on the environment is a challenging issue.

1.1.2. Definitions of drought and drought indices

The term 'drought' not always associated with the occurrence of desertification, nor does drought occur only in the dry regions of the world. However, the term signifies the decrease of precipitation in a specific region to a level which is lower than the common average in that area. For instance, if the precipitation average is 1000 mm in a particular region, then if it goes down to 800 mm, that fact might be considered as an indication of drought in that region even though 800 mm are considered enough for cultivation and keeping vegetation in that region.

(Wilhite, & Glantz, 1985) classified droughts into four types: meteorological, agricultural, hydrological, and socio-economic. The classification of meteorological drought depends on the degree of dryness (normal, medium or very high) and on the duration of the dryness period dependent on climate characteristics related to the specific location or region. Rain plays a major role in that process. A decrease in rainfall causes a decrease in the agricultural production in these regions in effect causing agricultural drought. Most impacts on agricultural activity are caused by the decrease of soil water and the diminishing of ground water levels as well as impacts on the biological characteristics of plants during the growth phase. Hence, any definition of agricultural drought should explain how strongly plants and crops are affected during the different phases of growth. The term drought refers also to extreme hydrological phenomena with a direct impact on ecosystems, and human activities (Wilhite, 2000). Hydrological drought refers to shortages in water resources, when river flows, spring yields, and groundwater levels are significantly reduced. It refers also to the reduced amount of surface water stored in reservoirs and fresh water lakes. In consequence of meteorological, agricultural and hydrological drought, socio-economic drought can occur. It takes a place when the demand for economic goods exceeds supply as the result of shortages in the water supply (Falkenmark, 2013). Whereas, when the agricultural production exceeds demand, this signifies that there is no drought, though there might be a deficiency in rainfall in that area.

The definitions of drought are constantly being updated. Several different drought indices have been formulated and used for drought assessment (WMO, 2016). The Standardized Precipitation Index (SPI) developed by McKee, Doesken, and Kleist (McKee et al., 1993) is the most commonly used for the characterization of drought. It is applied for many goals in the field of water resources. It was developed to understand the impact of rain deficit on the characteristics of soil moisture, groundwater and reservoir levels, and river flows. On short time scales (e.g. 3 months), the SPI can be used to characterize meteorological and agricultural (soil) drought due to the close relation of drought to soil moisture (WMO, 2012). On longer time scales (12 or 24 months), the SPI is related to river flows, groundwater levels and reservoir storage, and is applied to characterize hydrological drought. The SPI is widely recognized as the standard index for quantifying dryness or wetness conditions with the sole use of precipitation data. It can be applied across regions with different climates. Despite the widespread acceptance of SPI, it does not account for atmospheric conditions other than precipitation which may affect the evolution and the severity of drought, such as air temperature, wind speed, and humidity.

An improved index, the Standardized Precipitation-Evapotranspiration Index (SPEI) was developed by (Vicente-Serrano et al., 2010a). It is based on the same standardization concept as SPI, but the calculations are based on a difference between the precipitation and potential evapotranspiration. Different estimates of potential evapotranspiration might be applied in the calculation of the SPEI (Stagge et al., 2014). The Global SPEI database, SPEIbase, offers long-time, robust information on drought conditions at the global scale, with a 0.5-degree spatial resolution and a monthly time resolution (Beguería et al., 2010). It provides SPEI data with time scales between 1 and 48 months. The SPEIbase is based on monthly precipitation and potential evapotranspiration from the Climatic Research Unit of the University of East Anglia. The SPEIbase is based on the FAO-56 Penman-Monteith estimation of potential evapotranspiration, so it is considered a superior method, and recommended for most uses including long-term climatological analysis (NCAR/UCAR, 2013). It may express the water supply-demand relation and may accommodate climate change influence (Paulo et al., 2012). It is widely used for ecological, agricultural and hydrological applications (Vicente-Serrano et al., 2012). The drought at 1-, 3-, and 6-month time scales is usually considered to be relevant for agriculture, at 12 months – for hydrology, and at 24 months it has a socioeconomic impact, respectively (Potop et al., 2014). In local conditions, the correlations between hydrological characteristics (river flows and reservoir storage) and drought have been proven to vary (Lorenzo-Lacruz et al., 2010).

1.1.3. Water and environmental problems in Iraq

Among the major challenges faced by Iraq are increasing climatic changes and its readiness to tackle them. Such changes lead to the irregularity of water supplies, the shrinkage of arable lands, drought-related health impacts and the inability to reserve rain water efficiently, migration from the arable lands affected with drought, and the aggravation of discharge in the permanent rivers in Iraq. The dangers also include the shrinkage of marshes, soil deterioration leading to the curbing of soil fertility, an increase of salinity of the Arab gulf and the decline of the level of underground water, particularly in the south of the country,

Furthermore, a decline in surface water flow, the lowering of groundwater levels, the drying up of groundwater wells, and an increase in soil salinity, desertification, the deterioration of agriculture, frequent sand and dust storms resulting in problems with the respiratory system are just some among the prominent effects of drought. In effect, the status of the environment cannot be separated from the status of the economy. Hence, it is clear that economic underdevelopment and environmental deterioration strengthen each other and result in further underdevelopment. This fact demands the restoration of balance between humans and their environment – between the population level, number of population, the available resources and the environment through the appropriate use of resources which can help in alleviating pressure and restoring balance (Gerasimov, 1983).

Precipitation in Iraq is restricted and the major area of the country tends to be arid to semi-arid. Annual precipitation in the hills and mountain ranges north of the country ranges from 300 mm to 1000 mm whereas in the far southern and western parts of the country it ranges from 100 mm to 200 mm. The central alluvial plain relies considerably on the flow of the Tigris and Euphrates rivers and their tributaries. Catchments and groundwater recharge zones are mainly located in the northern and eastern parts of Iraq and the adjacent countries. In the extra arid hilly areas to the east, networks of wadis – seasonal watercourses – supply isolated areas with considerable recharge. Evaporation rates in the arid areas are higher than the precipitation and natural recharge rates, causing the natural salinization of groundwater. Both surface water and groundwater are greatly extracted, with most urban centers serviced by river water extraction and purification plants. As for rural areas, village wells and springs are the principal water sources. Receiving and maintaining the required quantity and quality of water is a significant problem for Iraq.

Climate change and variability degenerate the already water stressed region resulting in more severe water stress conditions, which will have implications in terms of food insecurity and social and political instability. Confirms that “physical water scarcity is partially induced by human behavior as well as being affected by natural phenomena like droughts since there are some empirical evidences that climate change is induced by human lifestyle because of greenhouse gas emissions” (Hashemi, 2012). Across the ‘Arc of Crisis’or in other words from Somalia, Sudan and Egypt in Africa to Yemen, Iraq, and Syria in the Middle East, water shortage has caused drought and famine, the spread of water-borne diseases, the loss of livelihoods, open conflicts, and forced migrations (WANA Forum, 2010). Water shortage is closely related to health and food security, making better water management the main step towards the reduction of poverty.

Both Syria and Iraq, which are the downstream countries of the Euphrates River, are affected by the construction of the Turkish GAP project (South Eastern Anatolian Project). It has been estimated that because of the GAP project, Iraq and Syria have witnessed an 80% and 40% reduction, respectively, of their equitable shares of the Euphrates River water. Such impacts are already clearly seen by the Iraqis and have had extreme effects on the country’s food security, shown by the fact that many Iraqi farmers have abandoned their farms. Furthermore, the damming processes of the Turkish authorities have also focused on the Tigris River water, which has further aggravated the Iraqi water situation to an extent that cannot be tolerated. The serious conditions of water in Iraq destabilize the country’s weak economic growth, and place pressures on the Iraqi government to fulfill the food security challenges (Bigas, 2012).

1.2. The study area: Udhaim River Basin, Iraq

The Udhaim River basin (also known as the Adhaim River basin) has been selected as the study area (Fig. 1.1). The Udhaim River is one of the important left tributaries of the Tigris River with relatively large zones of agricultural development. Although recent inventory of water resources of main tributaries of the Tigris River has been performed recently (UN-ESCWA & BGR, 2013), a detailed study on water resources of the Udhaim River basin has not been included.

With a length of about 230 km, the Udhaim River drains the area of approximately 12495 km^2. The basin is located entirely within Iraqi territory. It is adjacent to the Little Zab (also known as Lesser Zab or Lower Zab) River basin in the north and north-west, and the Diyala River basin in the south-east. The Udhaim River originates from the mountainous regions in northern parts of Iraq, specifically in the southern slopes of the Hamrin Mountains in Sulaymaniyah Governorate, and discharges into the Tigris River south of the Balad city, 80 km north of Baghdad (Fig. 1.1). The major left tributaries of the Udhaim River are Chai Dakuk and Chi-Tuz . The basin is located between latitudes 34^o 00’ and 35^o 45’ North and longitudes 43^o 25’ and 45^o 40’ East. This large latitudinal spread of the basin results in the natural environment of the Udhaim River being very diverse in terms of climate, topography, geology, soil and vegetation. Such a discrepancy has led to a difference in the quality of human activities in various parts of the basin. Some of the major cities in the region are- Kirkuk, Chamchamal and Tuz. Besides, there are many villages located across the whole basin.

The river is controlled by the Udhaim Dam (known also as the Adhaim Dam) which is a multi-purpose embankment dam on the Udhaim River. It is situated 133 km northeast of Baghdad. The purpose of the dam is flood control, hydro-power and irrigation. The dam was constructed in 2000 with only the embankment, the spillway and the intake being operational. The power station and irrigation outlets remain unfinished (Ministry of Water Resources, 2009). The dam is 3800 m long, and 12 m wide and the spillway itself is 562 m long. The Udhaim reservoir has an area of about 120 square kilometers. The capacity of the reservoir is about 2 billion cubic meters. The dam is projected to provide electricity (through a hydropower turbine) an the annual generation output of about 38 MegaWatt Hours (Al-Samawi, 2008).

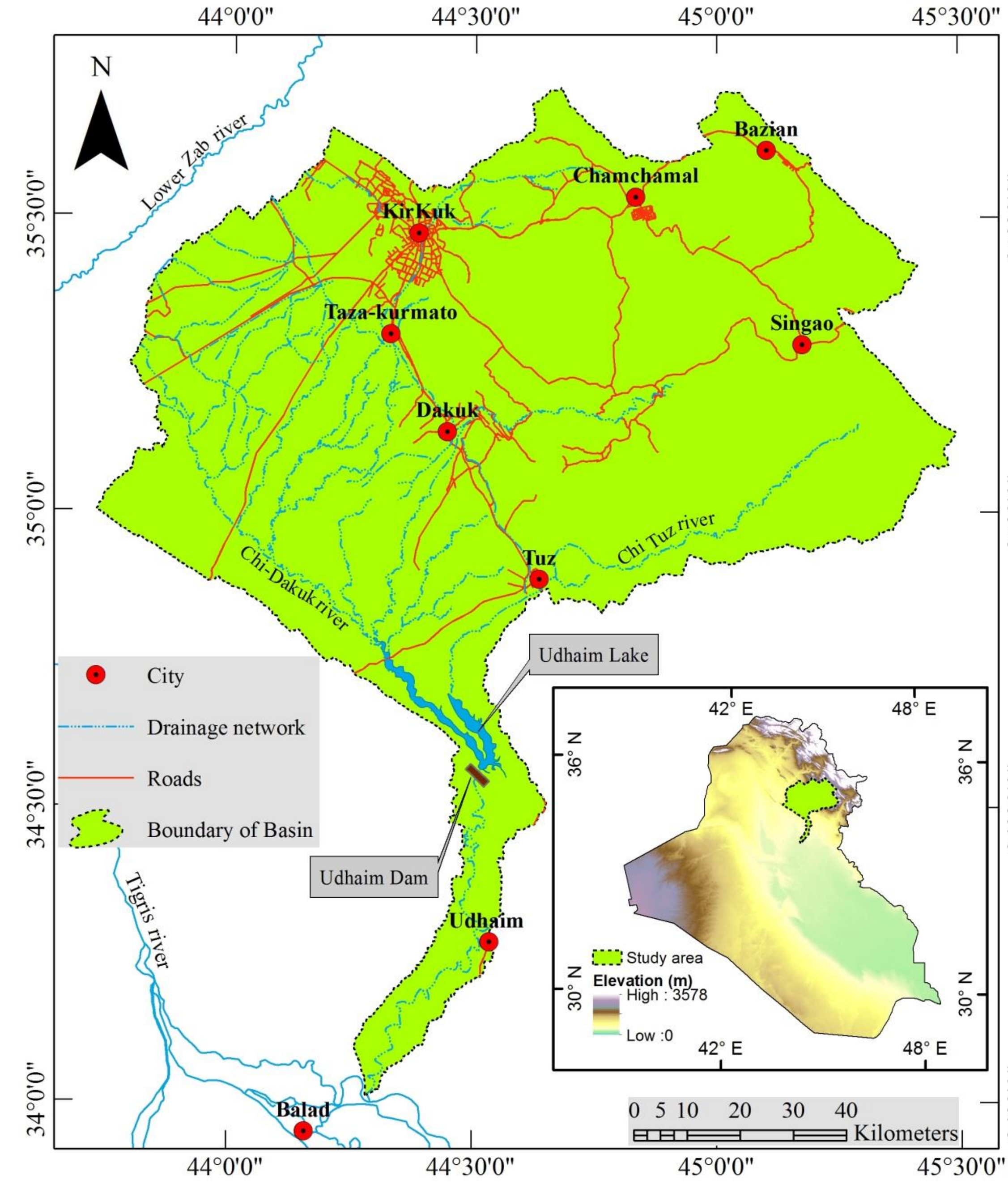


Figure 1.1: Location of the Udhaim River basin (Mail, 2017).
Source: General Commission of Survey 2013, Iraq Governorates Map, Ministry of Water Resources, Baghdad,(**Iraq)**.

The construction of the dam in the southern part of the river basin has led to environmental implications due to the submerging of many agricultural fields and natural pastures located in the valley. While water stored in the reservoir should meet agricultural demands, poorly maintained distribution systems (still not completed) have had negative impact on the surrounding environment. It is revealed through a dramatic increase in the number of wild animals having migrated from nearby areas, causing a deterioration in agricultural activities in downstream agriculture fields. Furthermore, some of the wild animals are predators and thus a threat to local residents and ecosystems. This problem mainly concerns the south-western parts of the basin. In contrast to the south, south-western and central parts of the basin (lowland parts), most of north-eastern parts of the basin is located in a mountainous region and characterized by relatively high precipitation of an order of 700-1000 mm annually. This is the only part of the basin that receives substantial precipitation influencing the environment and human activities.

There is limited, recent scientific literature available on the environment, water resources or management targets concerning the Udhaim River basin. Since the Seventies and Eighties of the 20. Century some scientific reports and dissertations have been published, mainly in Arabic (David, 1974; Kaka & George 1980**a**, 1980**b**; Al-Ansari, N. 1983; Al-Hammadi, 1984). They focus on the topography, soils, vegetation, the hydrographic network and hydrological characteristics of the basin, including physical and chemical characteristics of river water and sediment load. The impact of atmospheric circulation on the amount of rainfall and the resulting river runoff was investigated by (Al-Hathal,1999). Short-term water balance of the Udhaim reservoir, and selected aspects of reservoir impact on the environment and development zone were analyzed by (Al-Jaf, 2002). Most recent research was conducted by (Faris et al., 2011). It concerned the spatial variability of evapotranspiration in the western part of the Udhaim River basin, based on the Surface Energy Balance Algorithm for Land (SEBAL) method, this is as a function of vegetation density, soil conditions and weather conditions i.e. wind speed at different elevations, air temperature and humidity at the time of satellite overpass. The results show daily evapotranspiration values ranging from zero for bare soils and rock outcrops to 9 mm/day for dense vegetation cover and water bodies. The estimated values of evapotranspiration along the area are spatially distributed and related to land use/land cover and soil conditions.

1.2. Thesis objectives and outline

1.2.1. Objectives and hypotheses

The general objective of this research is to increase the understanding of drought evolution in different time scales that occurred in the Udhaim River basin, and to evaluate the drought impacts in terms of the effects on water availability, land degradation, and water quality. In order to fulfill this general objective, five specific objectives have been addressed, which are:

1. To evaluate the spatial and temporal variability of precipitation, air temperature, potential evapotranspiration, and SPEI as a drought index for different time scales.
2. To determine the temporal tendencies in SPEI by using statistical tests.
3. To evaluate vegetation conditions for selected summer conditions using remote sensing techniques, and to determine the rate of land degradation.
4. To detect the impact of drought conditions on river discharge.
5. To detect inter-annual changes in the water quality of the water dam reservoir fed by the inflow from the Udhaim River.

The study has been conducted based on the following hypotheses:

1. There is significant spatial and temporal variability in precipitation, air temperature and potential evapotranspiration within the basin.
2. Droughts assessed by the Standardized Precipitation Evapotranspiration Index (SPEI) for different time scales are becoming more severe in the multiyear period.
3. The territory of the basin undergoes land degradation.
4. The inter-annual variability of SPEI is reflected in variable outflow.
5. The water quality of the water reservoir responds to drought condition.

1.2.2. Outline of the thesis

With the aim of elucidating the problems in the study area, satisfying the objectives, and providing the details of research methods, the dissertation has been divided into six chapters.

Chapter 1 introduces the importance of the occurrence of droughts and their impact on the environment and society. Environmental and water problems in Iraq are synthetically discussed. The main characteristics of the study area are introduced and previous studies are reviewed. General and specific objectives of the thesis are formulated and the main working hypotheses are specified.

Chapter 2 describes selected climatic data (precipitation, air temperature, potential evapotranspiration), drought indices data, runoff and water quality data, and remote sensing data. Following this, methods of analyses and applied techniques are presented.

Chapter 3 focuses on the physical and human characteristics of the study area. Topography, land use and land cover, surface water resources, and human activities related to agriculture are presented.

Chapter 4 discusses the evolution of drought conditions using the Standardized Precipitation Evapotranspiration Index (SPEI).Time series graphs present the temporal variability of drought indices. Drying trends in SPEI series were detected.

In Chapter 5 vegetation characteristics in the summer season are investigated, and land degradation is evaluated.

Finally, Chapter 6 gives conclusions and recommendations based on research results. The main achievements of the research are specified.

CHAPTER TWO

2. DATA AND RESEARCH METHODS

2.1 Research approach

To assess drought conditions in the Udhaim River basin, the temporal variability of selected climate characteristics and drought indices were analyzed over the multiyear period 1980-2010. The gridded CRU TS (time-series) 3.24.01 data on precipitation, air temperature, and potential evapotranspiration (Harris & Jones, 2017) were analyzed. Data from the global SPEIbase v. 2.5 (Vicente-Serrano et al., 2010b; Beguería et al., 2010) provided a base for the analysis of drought indices, namely the Standardized Precipitation-Evapotranspiration Index (SPEI) at different time scales. Trends in the SPEI time series in the years 1980-2010 were analyzed. Following this, the impact of drought on land degradation, water discharge and water quality was investigated. Remote sensing images were acquired to evaluate land degradation through the analysis of selected indices. Then, relation between drought indices and hydrological characteristics were investigated, and the impact of the revenue of the reservoir on water quality was assessed.

The next sections of this chapter briefly present the data used and the methods applied in this research.

2. 2 Data and methods

2.2.1. Topography evaluated from SRTM data

Data from the Shuttle Radar Topography Mission (SRTM) were obtained from the CGIAR-CSI (Consortium for Spatial Information of the Consultative Group for International Agricultural Research) database (Jarvis et al., 2008). The elevation model in version 4 is available at 3 arc spatial resolution, equivalent to about 90 m at the Equator (Farr et al., 2007). It is available in files that contain data for 5-degree tiles. GeoTiff raster files with data representing the area of 30°-40° North and 40°-50° East were acquired, and merged in the ArcGIS software, and then elevation model within the basin's boundary was extracted. The SRTM model was used to characterize the spatial variation of the elevation in the Udhaim River basin.

2.2.2. Climate characteristics computed from CRU datasets

Due to the limited number of weather stations located in the Udhaim River basin, gridded datasets were used to evaluate the spatial and temporal variability of precipitation, air temperature, and potential evapotranspiration over the basin. The CRU TS 3.24.01 datasets prepared by the Climate Research Unit (CRU) at the University of East Anglia were used in the analysis (Harris & Jones, 2017). These are data on high-resolution (0.5x0.5 degree) grids. Monthly time series (TS) were downloaded from the on-line resources of the Centre for Environmental Data Analysis (CEDA) at http://catalogue.ceda.ac.uk/. Time series of climatic characteristics (precipitation, air temperature, potential evapotranspiration) were retrieved at selected grid points over the basin in the period 1980-2010 (Fig. 2.1). This multiyear period was chosen as a baseline in order to fit with discharge data of limited availability. Time series of climatic characteristics comprised the period from October 1979 (start of the 1980 water year) to September 2010 (end of the 2010 water year). Additionally, the CRU TS 3.24.01 datasets were acquired for the year 2015, to characterize weather conditions in the months prior to the date of the satellite image, which was used for the evaluation of land degradation.

The Thiessen polygon method was applied to compute the mean areal values of climate characteristics using grid point location. This is commonly used method applied for large areas although it is unable to catch orographic differences in precipitation distribution (Herschy & Fairbridge, 1998; Shaw et al., 2010). The weights of the grid points in the Udhaim River basin were estimated by their relative areas, which were computed based on the Thiessen polygon network (Fig. 2.1 & Tab. 2.1). Due to negligible area of polygon no. 21, it was included into polygon no. 22. Thiessen-based grid point weight was computed as $W_i=A_i/A$,where A_i – the area of particular Thiessen polygon within the basin, A – the total area of the basin, W_i – the weight of the *i* polygon.

According to the Köppen climate classification (Peel et al., 2007), the climate of the Udhaim River basin varies latitudinally, from warm desert (BWh) in the south, semi-arid (BSh) in the central part to cold semi-arid in the north-east, depending on latitude and elevation. Thus to account for latitudinal diversity in climate characteristics, besides the mean areal values computed over the basin, mean values in the latitudinal bands were analyzed. The multiyear averages were computed for four bands comprising 34.0°-34.5° N, 34.5°-35.0° N, 35.0°-35.5° N, and 35.5°-40.0° N.

Table 2.1: Thiessen-based grid point weights

Grid point number	Geographical Latitude	Geographical Longitude	Weight (W_i)
St7	34.25	44.25	0.03
St8	34.25	44.75	0.01
St11	34.75	43.75	0.02
St12	34.75	44.25	0.11
St13	34.75	44.75	0.07
St14	34.75	45.25	0.02
St16	35.25	43.75	0.07
St17	35.25	44.25	0.20
St18	35.25	44.75	0.20
St19	35.25	45.25	0.15
St22	35.75	44.25	0.03
St23	35.75	44.75	0.05
St24	35.75	45.25	0.03

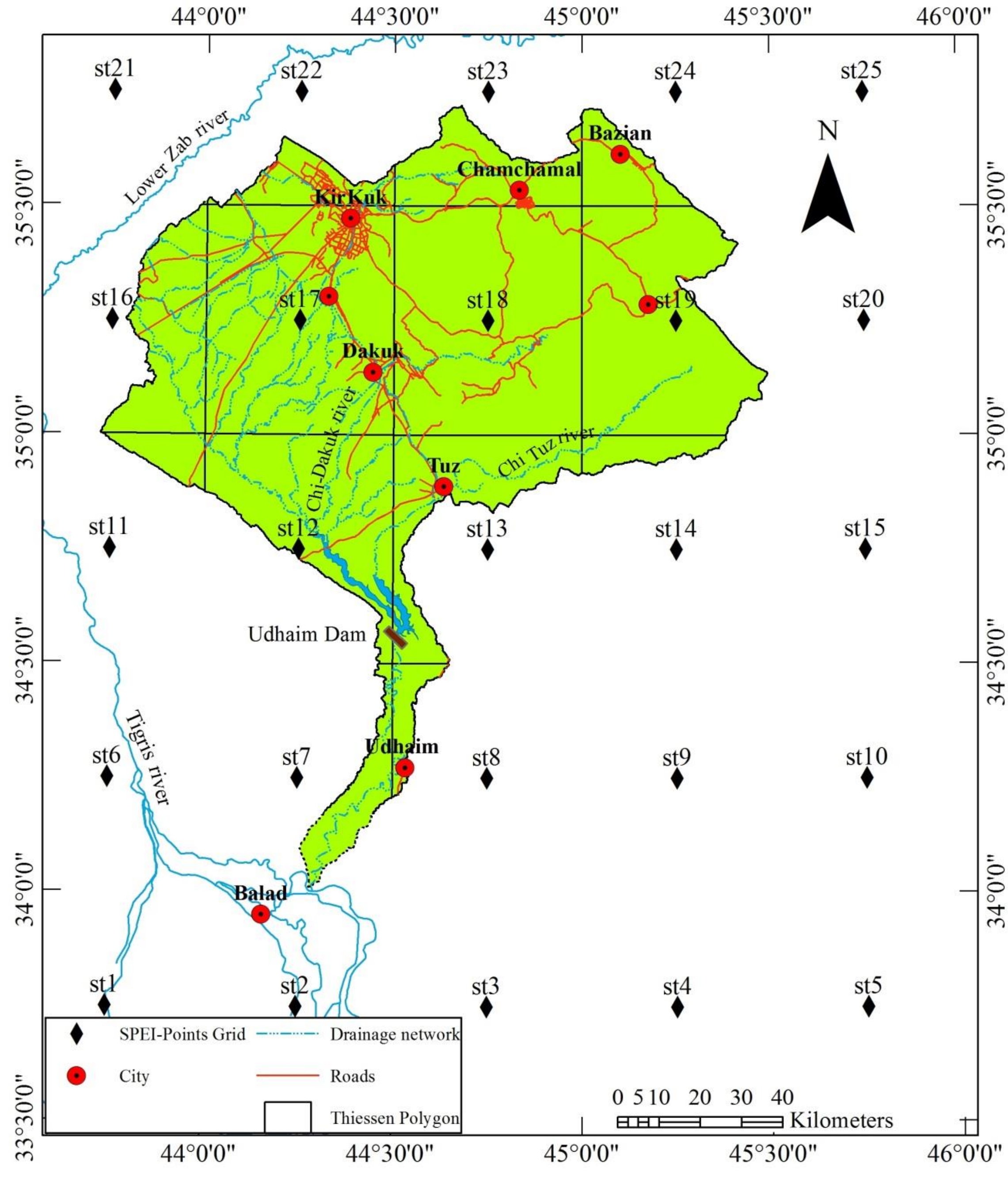


Figure 2.1: The spatial distribution of grid cells from the CRU TS 3.23 database (Harris & Jones, 2017) covering the territory of the Udhaim River basin

2.2.3 Standardized Precipitation-Evapotranspiration Index (SPEI) evaluation

The SPEI data used in this research were acquired from the SPEIbase v2.4, which is based on the CRU TS 3.23 dataset (Beguería et al., 2010). The SPEI time series over the Udhaim River basin have been retrieved from online resources at 13 grid cells (Fig. 2.1) for the period of October 1979 to September 2010 (http://spei.csic.es/database.html).The dataset at the 0.5-degree spatial resolution includes different time scales between 1 and 48 months. In this study four time scales of 3 months, 6 months, 12 months, and 24 months have been selected, representing dryness/wetness conditions relevant to agriculture and hydrology (WMO, 2012). The SPEI-i represents cumulative moisture conditions for the i-month period. For example, a 3-month SPEI at the end of December represents cumulative moisture conditions for October-November-December. Similarly, the SPEI-6, the SPEI-12, and the SPEI-24 represent cumulative wetness conditions for the 6-month, 12-month and 24-month periods respectively. Positive values of the SPEI represent wetter-than-average wetness conditions while negative values represent drier-than-average conditions. Assuming the classification of dryness/wetness conditions proposed by (McKee et al., 1993), which is shown in (Tab. 2. 2), a drought occurs when the SPEI value is less than or equal to −1.

Table 2.2: Categories of dryness/wetness conditions evaluated by SPEI assuming the classification by McKee et al. (1993)

SPEI	Dryness/wetness category
≥ 2.0	Extremely wet
1.50 – 1.99	very wet
1.49 – 1.00	Moderately wet
0.99 - (-0.99)	Near Normal
-1.00 – (-1.49)	Moderately dry (Moderate drought)
-1.5 – (-1.99)	Severely dry (Severe drought)
≤ - 2.00	Extremely dry (Extreme drought)

After acquiring the SPEI datasets for particular grid points, the Thiessen polygon method was applied to compute the mean areal values for each time scale, similarly to the computation conducted for climate characteristics, which was described in chapter 2.2.2.

Besides, latitudinal averages of SPEI were analyzed in four formerly established bands to account for spatial diversity.

2.2.4. Trend detection in time series of SPEI

Time series of SPEI were checked for trends using the non-parametric rank based Mann–Kendall test. This test is often used for trend detection in hydrological and meteorological time series (Radziejewski & Kundzewicz, 2004a). The HYDROSPECT software (Radziejewski & Kundzewicz, 2004b) was used to calculate the Mann-Kendall test statistic and statistical significance. Significance levels of 95% refer to the test statistics of 1.960. The hypothesis that there is a trend is accepted when the value of the test statistic is greater in absolute value than the critical values at a chosen level of significance. Negative values of the test statistic indicate decreasing trends in the SPEI. Statistically significant changes were defined here as those with a significance level equal to or greater than 95%.

2.2.5. Computation of Land Use and Land Cover indices[1]

Changes to Land Use Land Cover (LULC) have been investigated by using remote sensing techniques. Landsat series data may provide long-term and high quality multispectral images for environmental monitoring and assessment useful on regional, national and global scales (Qi & Cai, 2007; Wulder et al., 2008). In this study, Landsat data have been used to assess the desertification rate in the Udhaim River basin.

The spectral characteristics of desertified land vary greatly, from other types of terrain and can thus be captured by satellite sensors. Therefore, satellite images may be fundamental to a quantitative assessment of desertification by means of the indices derived from satellite images (Udelhoven et al., 2003; Lagacherie et al., 2008). Many previous studies have focused on constructing image-based indices to retrieve the vegetation and micrometeorological conditions of the land surface to monitor desertification at different scales (Runnström, 2003; Sun et al., 2005).

[1] Chapter 2.2.5. includes methodology described by the Author (Mail, 2017) in the article titled "Desertification Detected in the Udhaim River Basin, Iraq Based on Spectral Indices Derived from Remote Sensing Images". Miscellanea Geographica – Regional Studies on Development.

The number of attempts to investigate and measure land-degradation and desertification processes has increased substantially in recent decades. The most effective way to assess and monitor desertification is through employing remote sensing data, such as aerial photography and satellite imagery (Tanser & Palmer, 1999; Seixas, 2000; Hostert et al., 2001). The integration of remote sensing with GIS techniques is becoming increasingly important for the assessment of environmental changes to control land desertification (Star et al., 1997; Zhang et al., 2008; Hadeel et al., 2010). Some indices that can reflect environmental changes are being adopted to assess and monitor desertification, such as the Normalized Difference Vegetation Index (NDVI), which is widely used to assess vegetation conditions (Geerken & Ilaiwi, 2004; Liu et al., 2005), the Normalized Difference Water Index (NDWI), used as a complementary index to the NDVI (McFeeters, 1996), the Normalized Difference Build-up Index (NDBI), highlighting the urban areas, the Normalized Difference Bare Land Index (NDBaI), extracting bare land (Zhao & Chen, 2005), the Crust Index (CI), mapping different lithological units (Karnieli 1997) and the Biological Soil Crust Index (BSCI), mapping different BSC types (Chen et al., 2005).

In this study, multi-band Landsat 5 TM imagery data from 1 July 2007 (2 scenes) and Landsat-8 OLI imagery data from 5 June 2015 (2 scenes), with 28.5m spatial resolution, were downloaded from on-line resources (https://earthexplorer.usgs.gov). The path/row of images describing their positions according to WRS-2 (Worldwide Reference System) are 169/035 and 169/036. Data processing was carried out using ERDAS 2014 and ArcGIS 10.2 software packages (Fig. 2.2).

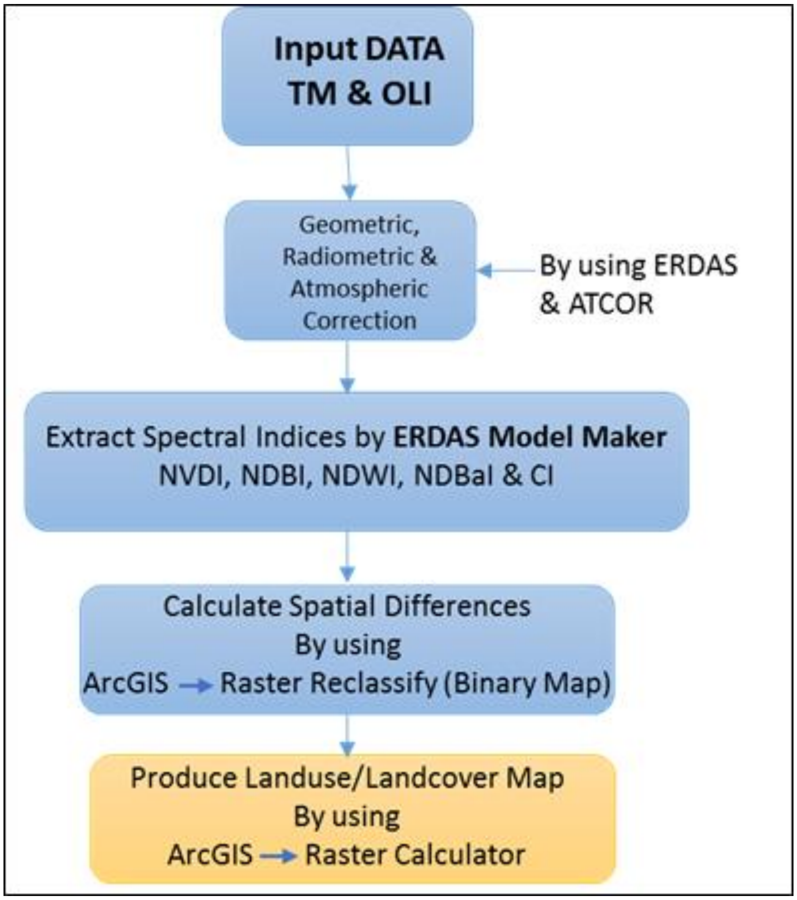


Figure 2.2: Flowchart of remote sensing data extraction and processing (Mail, 2017)

The pre-processing phase began with the geometric correction of the images using ground control points, followed by radiometric calibration, atmospheric correction (using ATCOR software), and mosaicking. A small area to the east of the study area was excluded to avoid problems related to the different acquisition date of the Landsat images. The total size of the study area is 11,169.56 km^2. Based on image processing, five models were designed to extract the spectral indices. The models were processed using ERDAS spatial Modeler Maker. Landsat 5 Thematic Mapper and Landsat 8 OLI data represent the input data for models and the output represents the spectral indices. The Normalized Difference Vegetation Index (NDVI) reflects the state of vegetation growth (Purevdorj et al., 1998) and was calculated as follows:

$$NDVI = (NIR-RED) / (NIR+RED) \qquad (1)$$

where: *NIR* is the reflectance of the near-infrared band and *RED* is the reflectance of the red band.

The Normalized Difference Building Index (NDBI), according to Zha et al. (2003), is sensitive to the built-up area (Zhao & Chen, 2005; Chen et al., 2006) and defined as:

$$NDBI = (MIR - NIR) / (MIR + NIR) \qquad (2)$$

where: *MIR* is the reflectance of mid-infrared band.
The Normalized Difference Water Index (NDWI) (McFeeters, 1996; Chen et al., 2006) is described by the formula :

$$NDWI = (NIR - MIR) / (NIR + MIR) \qquad (3)$$

The Normalized Difference Bareness Index (NDBaI) is used to retrieve bare land area (Zhao & Chen, 2005) according to the following formula:

$$NDBaI = (MIR - TIR) / (MIR + TIR) \qquad (4)$$

where: *TIR* is the thermal infrared band.
A spectral crust index (CI) is also used in this study and defined as follows:

$$CI=1-(RED-BLUE) / (RED+BLUE) \qquad (5)$$

where: RED – red reflectance, BLUE – blue reflectance.

When applying the index to a sand dune environment, it has been shown that the *CI* can be used to detect and to map different lithological and morphological units, such as active sands, crusted interlude areas and playas, from remote sensing imagery (Karnieli, 1997). The *CI* image is much more sensitive to the ground features than the original images (RGB) (Karnieli, 1997). The absence, existence, and distribution of the soil crust are important information sources for desertification and climate change studies (Karnieli, 1997). Chen et al. (2005) have introduced the Biological Soil Crust Index (BSCI), but investigations show that it is only suitable when applied to cold deserts (Chen et al., 2005). Thus, the BSCI was not considered in this study.

NDVI values range between -1 to 1. High positive values indicate dense vegetation cover. NDBI and NDBaI values are between -1 to 1, like NDVI, and they were used to quantify amount of the impervious surface and bare land on the used TM image, respectively.

After implementing the models in the ERDAS software, five binary maps were derived as the results, applying the assumed thresholds. The following thresholds were chosen: NDVI ≥ 0.4, NDBI ≥ 0.1 and NDBI ≤ 0.3 (As-Syakur et al. 2012), NDWI > 0.243 (Xu, 2006), NDBaI > 0 (As-Syakur et al. 2012, Chen et al. 2006) and CI > 0.5 (Karnieli, 1997) (Fig. 2.3). The thresholds vary and differ slightly from one region or area to another, according to the subpixel components (Ji et al., 2009) and the climatic condition of that area (arid, semi-arid and wet regions) (Choi et al., 2013), so the use of spectral data from the spectral library was required for the adjustment of the threshold according to the case study area.

NDVI Map

0.0	0.0	0.1	0.2	0.3
0.1	**0.4**	**0.5**	**0.4**	0.0
0.2	**0.4**	**0.6**	**0.7**	0.0
0.0	**0.4**	0.3	0.2	0.1
0.3	0.0	0.0	0.0	0.2

Binary Map

0.0	0.0	0.0	0.0	0.0
0.0	**1.0**	**1.0**	**1.0**	0.0
0.0	**1.0**	**1.0**	**1.0**	0.0
0.0	**1.0**	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0

Figure 2.3: Converting map of indices ratio to the binary maps using NDVI as an example (Mail, 2017)

Maps were prepared presenting the spatial distribution of the following indices: vegetation area (NDVI), bare land or unused area (NDBaI), water area (NDWI), soil crust area (CI) and built-up area (NDBI), in the two comparative years (2007 and 2015). Following this, the ArcGIS software (Raster Calculator) was used to produce a band combination of five indices for each year and one spectral thematic map for visual interpretation and study of the trends in land use/land cover changes. The procedure was based on multiplying each binary map of indices in (Fig. 2.4 & 2.5) by the selected number using the Raster Calculator and then combining them to produce a LULC map. Based on that, the temporal and spatial changes in the five spectral indices were analyzed. The amount and type of change in each class were quantified, and tabularized.

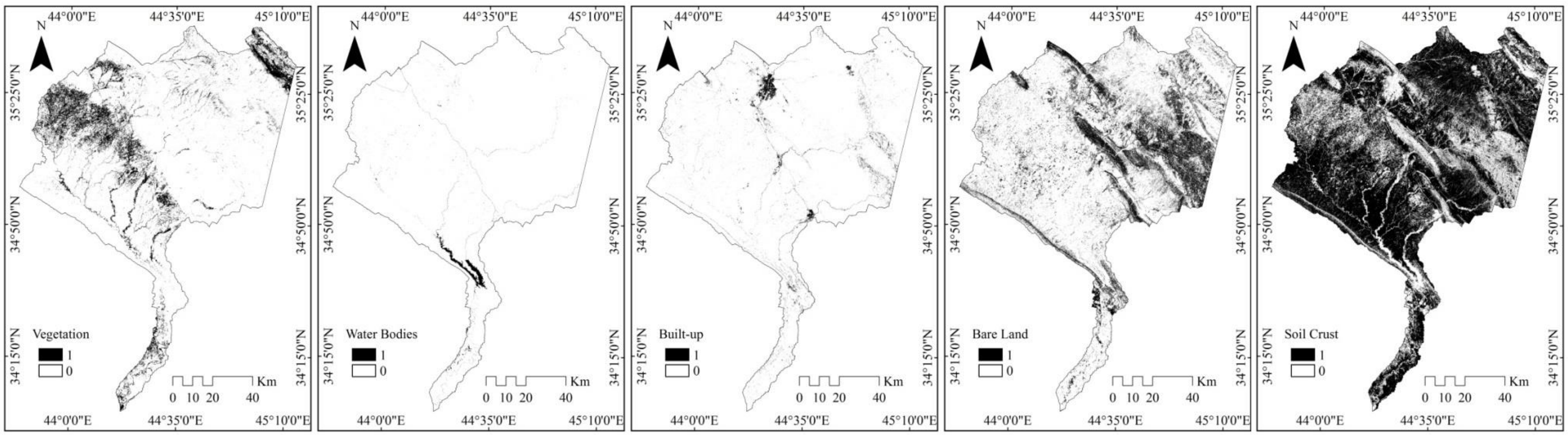


Fig 2.4: Results of five indices (LULC) derived from Landsat-5 TM 2007

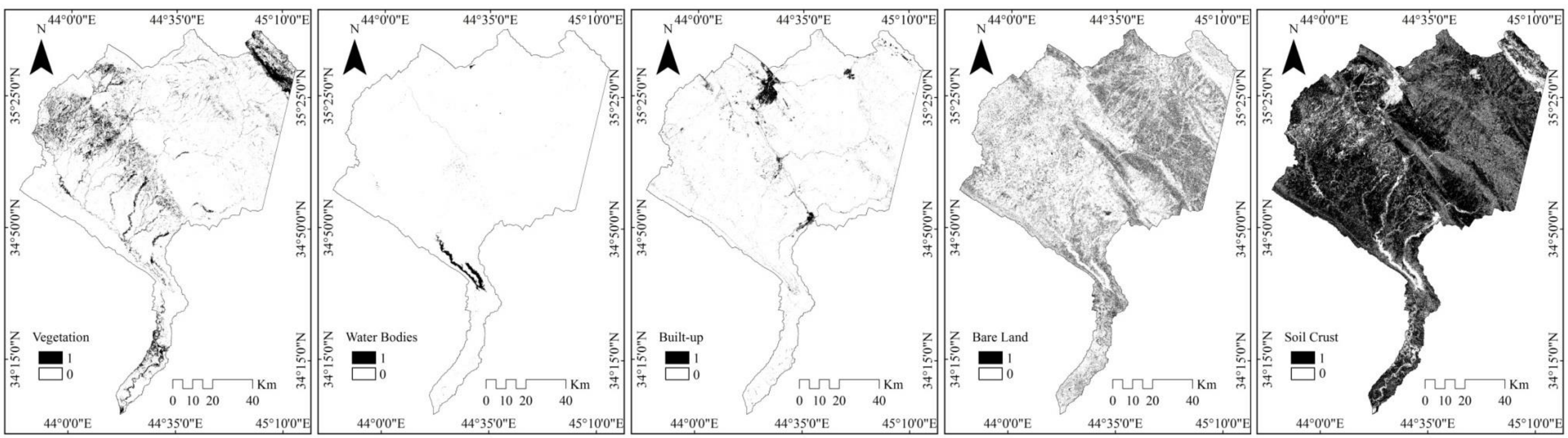


Fig 2.5: Results of five indices (LULC) derived from Landsat-8 OLI 2015

Source: Calculated from USGS (2015) Landsat 5 and Landsat 8 Online available Data, http://earthexplorer.usgs.gov/ by using ERDAS Imagine Software.

2.2.6. River discharge and water quality data analysis

Monthly and annual mean discharge data of the Udhaim River at Udhaim Dam (Fig. 2.6) were provided by the Ministry of Water Resources, Government of Iraq for years 1980-2010 (Tab. 2.3). Relationships between discharges and drought indices have been explored. The utility of drought indices to represent availability of water resources was determined. The drought indices used in the analysis express mean monthly characteristics, thus a monthly time scale was also chosen for the discharge series. The correlations between monthly discharges (dependent variable) and SPEI values (independent variable) were explored using the STATISTICA software, version 13.1.

Besides the quantitative characteristics of the discharge, the water quality in the Udhaim reservoir was evaluated. The assessment of the water quality is essential for the effective management of the reservoir, and in consequence, for securing good quality water for irrigation practices on agricultural fields. The chemical characteristics of irrigation water affect the growth of plant directly by toxicity or deficiency, or indirectly by altering plant availability of nutrients (Ayer & Westcot, 1985; Rowe & Abdel-Magid, 1995). Water quality is determined by the quality of water entering the reservoir, and processes taking place directly in the reservoir, which are susceptible to meteorological and drought conditions.

In this study, Richards's (1954) method has been adopted to calculate the quality of water in the Udhaim reservoir. The calculation was performed for 31 years of available data (Tab.2.4). This method is based on the conductivity of water (EC, expressed in microsiemens per centimeter, μS/cm), and the Sodium Absorption Ratio (SAR).

The conductivity of water is used as an indicator of the water salinity hazard. The higher the EC, the less water is available to plants, even though the soil may appear wet. The availability of soil water for plants decreases with the increase of EC.Thus the assessment of salinity hazard of irrigation water based on EC is being performed according to four distinct water quality classes, C1, C2, C3, and C4 (Tab. 2.5).

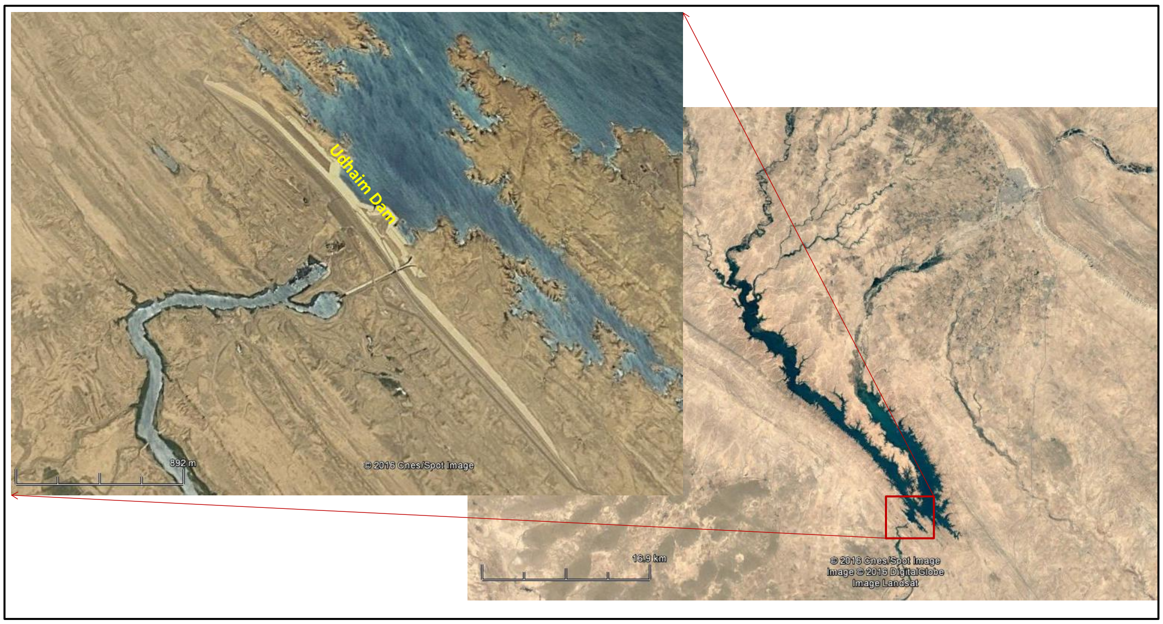


Figure 2.6: Location map of Udhaim Dam

Table 2.3: Monthly and annual mean discharge at a streamflow-gaging station, Udhaim River at Udhaim Dam, Iraq, water years 1980–2010. Unpublished data received from Ministry of Water Resources of the Government of Iraq. From April to July 2003, dam opening took place

Water Year	Oct	Nov	Dec	Jan	Fab	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1980	0.9	4.6	17.6	16.7	28.3	41.4	17.7	4.1	0.4	1.9	1	0.8	11.3
1981	3.1	2.8	48.9	121.4	24.6	75.4	27.7	9.5	4.8	1.1	1.2	2	26.9
1982	20.7	34.5	14.3	154.1	61.2	66.8	72.7	57.4	7.7	3.8	2.7	2	41.5
1983	1.7	2.4	4.2	20	23.5	18.1	16.1	7.6	2	1.5	0.9	0.9	8.2
1984	1.8	94.8	20.5	4.3	4.1	17	19.6	3.7	1.4	4.4	0.2	0.3	14.3
1985	1	3.3	17.5	12.6	69.9	13.1	16.5	3.1	1.7	1	1	1	11.8
1986	2.2	12.5	7.6	4	62.6	5.9	21.5	11.5	1.6	1	1.3	1.5	11.1
1987	10.7	7.3	126.2	2.1	5.5	13	3.9	1.9	1.9	2	2	1	16
1988	9.9	8.8	91.1	73.9	88	288.9	48	38.3	7.1	3.7	3.3	4.1	55.4
1989	5.5	25.5	47.1	22.6	21.5	71.3	25.6	9.8	6.2	8.8	9.3	7.2	21.7
1990	8.4	5.4	5.5	19.4	54.2	42.4	11.1	4.3	6.4	6.8	8.5	8.8	15.1
1991	8.9	21.2	103.6	9.9	59.7	103	13.2	9.7	8.8	3.3	4.2	4.7	29.2
1992	12.4	45.7	138	49.1	159.4	124.5	46.3	27.7	13.4	6	9.7	11.2	53.6
1993	25.3	72.8	49.4	104.4	50	38.6	123.9	57.5	15.9	10.5	11.3	11	47.6
1994	23.5	170.7	52	127.1	50	44.3	21.1	23.9	12.2	10.3	7.8	7.5	45.9
1995	28.5	34.6	41.6	55.6	125.6	44.9	58.9	35.7	17.9	18	21.4	25.7	42.4
1996	1.9	15.8	34	123.4	62.9	58	25.9	16.7	17	9	8.8	6.2	31.6
1997	2	15	34	42.1	16	38.8	27.5	5.7	11	4.7	6	6.4	17.4
1998	15	119	126	160	150	69	48	30	18	9	5	7	63
1999	9	29	40	45	53	31	40	28	14	47	99	19	41.3
2000	7	9	10	18	7	7	6	7	7	6	6	7	8.3
2001	7.7	7.2	13.9	29.5	22.7	21.8	9.8	4.4	6.5	2.3	2.8	3.9	11
2002	6.5	23.3	109.2	65.2	24	44.3	38.9	33.9	38.8	6.5	2.9	3.5	33.1
2003	15	19	49.3	48.5	62	33.1	Dam opening				10.7	14.7	33.3
2004	12.9	26.1	25.6	146	62.9	23.9	11	19.6	16.6	10.3	14.1	8.2	31.4
2005	7.6	15.1	14.9	63.8	77.9	89.8	19.9	31.7	18.1	5.1	15	6.2	30.4
2006	38	34	31	30	25	30	35	35	35	35	35	35	33
2007	35	35	35	25	25	30	30	25	25	25	25	25	28
2008	25	25	25	15	10	9	5	5	5	5	5	5	12
2009	5	5	5	6	6	6	6	6	6	6	6	6	6
2010	6	8	9	14	15	14	16	10	11	15	18	20	13

SAR calculation depends on sodium (Na^{1+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}). It can be calculated through the following formula:

$$\mathrm{SAR} = \frac{Na^{1+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \qquad (6)$$

where sodium, calcium, and magnesium concentrations are expressed in milliequivalents per liter (meq/L). The SAR assesses the potential of the occurrence of infiltration problems due to a sodium imbalance in irrigation water. This problem, which is named “sodicity,” results from the excessive accumulation of sodium in the soil. Sodicity may cause soil swelling and the dispersion of soil clays, and in consequence, the plugging of soil pores. If the soil structure is degraded, it may decrease infiltration into the soil, and limit the availability of water for growing plants. Thus the assessment of the sodium hazard of irrigation water based on SAR is being performed according to four distinct water quality classes, S1, S2, S3, and S4 (Tab. 2.5).

Based on the EC and the SAR, water quality is classified by assigning a water sample to one of six water quality classes (Tab. 2.6). Such a classification was applied to evaluate the water quality of the Udhaim River basin.

Table 2.4: Chemical characteristics of water in the Udhaim reservoir

Year	TDS (Mg/L)	EC (μS/cm)	Ca^{2+} (meq/L)	Mg^{2+} (meq/L)	Na^{1+} (meq/L)
1980	1535	2279	14.61	12.33	16.34
1981	1374	2055	12.98	11.40	13.28
1982	1309	1964	12.32	11.03	12.04
1983	1714	2530	16.43	13.35	19.76
1984	2093	3059	20.27	15.53	26.98
1985	1228	2630	11.51	10.57	10.51
1986	1387	2973	13.11	11.48	13.52
1987	1322	2982	12.46	11.10	12.29
1988	1304	1957	12.27	11.00	11.94
1989	1431	2134	13.56	11.73	14.36
1990	2454	3563	23.93	17.59	33.85
1991	1579	2341	15.06	12.58	17.18
1992	1408	2102	13.32	11.60	13.92
1993	1514	2050	14.40	12.21	15.95
1994	2407	1998	23.46	17.33	32.96
1995	2251	2180	21.88	16.43	30.00
1996	2207	3092	21.43	16.18	29.15
1997	2116	3180	20.51	15.66	27.42
1998	1836	2200	17.67	14.05	22.08
1999	1467	2185	13.93	11.94	15.06
2000	2651	3839	25.93	18.73	37.61
2001	2088	3052	20.22	15.50	26.88
2002	1172	1749	11.53	10.58	10.56
2003	1245	1859	12.24	10.99	11.89
2004	1170	1747	18.06	14.28	22.82
2005	1448	2161	18.11	14.31	22.92
2006	2406	3703	7.80	8.07	6.52
2007	1860	2907	15.60	15.06	5.91
2008	2291	3055	20.80	20.25	8.17
2009	2052	2983	28.80	10.21	8.09
2010	1524	2369	13.40	11.11	7.74

Source: The Iraqi Ministry of Water Resources, SOD and reservoirs, the Udhaim Dam, 2013 (unpublished data). **Explanations**: TDS-Total Dissolved Substance, EC-Electrical connectivity).

Table 2.5: Specification of water-quality criteria based on the Sodium Absorption Ratio (SAR), and conductivity of water (EC) according to Richards (1954)

Class	SAR	Specifications
S1	0 - 10	Low-sodium water that can be used in any soil.
S2	10 -18	Medium-sodium water which is unsuitable for use in soft-tissues soils, which have the ability to ion exchange, but not in the presence of gypsum in the soil, and can be used in coarse-texture soils or membership permeable soils
S3	18 -26	High-sodium water produces influential interchangeable levels in most soils.
S4	> 26	Very high-sodium water, which is unsuitable for irrigation, except in cases where the total amount of salinity, sessile, and calcium available in the soil or use of gypsum.
Class	EC (µs/cm)	Specifications
C1	100 - 250	Low-salinity water and suitable for irrigating most of lands and crops.
C2	251 - 750	Medium- salinity water. It needs to be filtered for irrigating crops sensitive to salinity operations.
C3	751 – 2,250	High-salinity water may not be used continuously without paracentesis
C4	2,251 – 5,000	Very high-salinity water is not suitable for irrigation of crops, but high endurance of salinity and soil require paracentesis continuing operations of large and careful.

Table 2.6: Classification of irrigation water according to Richards (1954)

Water quality	Index
Excellent	C1S1
Good	C1S1, C2S1, C2S2
Permissible	C1S3, C3S1
Marginal	C2S3, C3S2, C3S3
Poor	C1S4, C2S4, C3S4, C4S1, C4S2
Very Poor	C4S3, C4S4

CHAPTER THREE

3. PHYSICAL AND HUMAN CHARACTERISTICS OF THE UDHAIM BASIN

3.1. Topography, Land Use and Land Cover (LULC)

The Udhaim river originates in the Zagros Mountains in Sulaymaniyah Governorate and joins the Tigris river (as its left tributary) after 230 kilometers at 34.002°N 44.293°E, north-east of Balad city. The river network is typically asymmetric and all

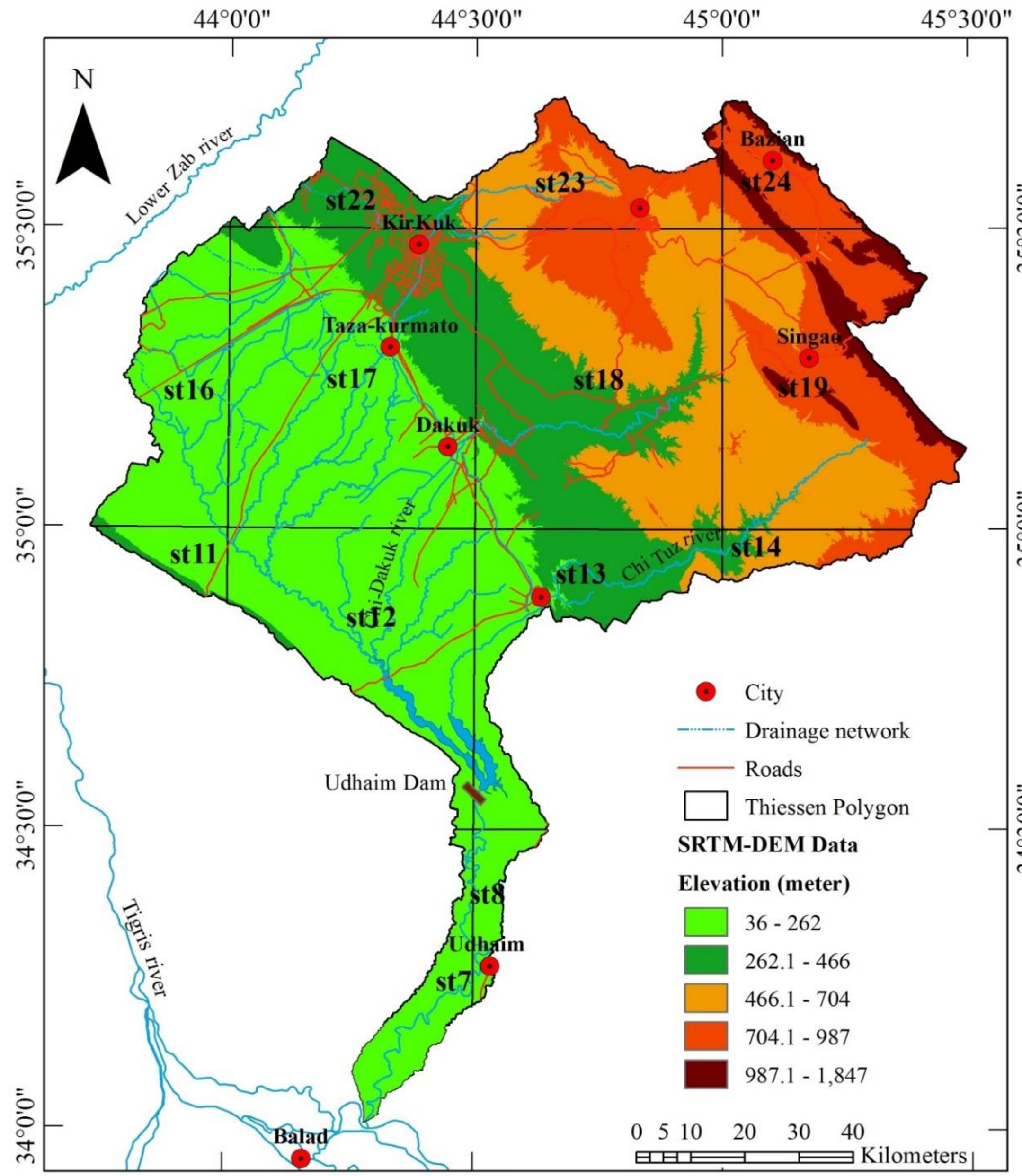


Figure 3.1: The Udhaim River basin's elevation map based on the SRTM (Jarvis et al., 2008)

tributaries are left-bank tributaries originating in the mountainous part of the basin. The Udhaim River basin occupies the area of 12,965 square kilometers, which is approximately 3.5% of the total area of the Tigris River basin.

Elevation in the basin ranges from above 1800 m a.s.l. in the north-east part of the basin to only some 30 m a.s.l. downstream, in the southern part, as evaluated by the SRTM (Fig. 3.1). The highest elevations occur in the north-eastern, mountainous part of the basin, draining the Skrma Dag and the Taslojh Heights (Al-Sammak,1985). The Hamrin Mountains, Hamrin Plain, and Plateau of Kirkuk form the undulating area, with elevations reaching approximately 400 m a.s.l. The most flat area is the alluvial plain which is part of the Mesopotamian plain of Iraq. It borders the Hamrin Mountains chain in the east, and the Tigris River in the west.

Landsat-8 data was used to extract Land use/Land cover in study area by supervised classification method. This process enabled the production of a map with ten classes of Land Use / Land Cover (Fig. 3.2 &Tab. 3.1).

The main class is ‘Agriculture lands’ with 26.3% of total area of the Udhaim River basin. Most of these lands are wheat farms and summer vegetables. These lands are located on the river banks. Bare exposed rock and bare lands occupy 21.8% of the area. Cropland and pasture occur on 20.9% of the area, and mixed range lands – on 18.5%. Those areas are located on the foot-hills of Hamrin anticlines in the east, north-east, and north-west of the basin.

The rest of the Land Use/ Land Cover classes are herbaceous rangeland, bare exposed rock and bare lands, range lands, grass and natural vegetation cover, mixed urban or built-up lands, and reservoirs. All of them occupy 12.5% of the total area. Four built-up areas can be recognized by remote sensing data. They are the Kirkuk, the largest city in Kirkuk province, Tuz, Chamchamal, Bazian and Singao. The only reservoir in the area is the Udaim Lake.

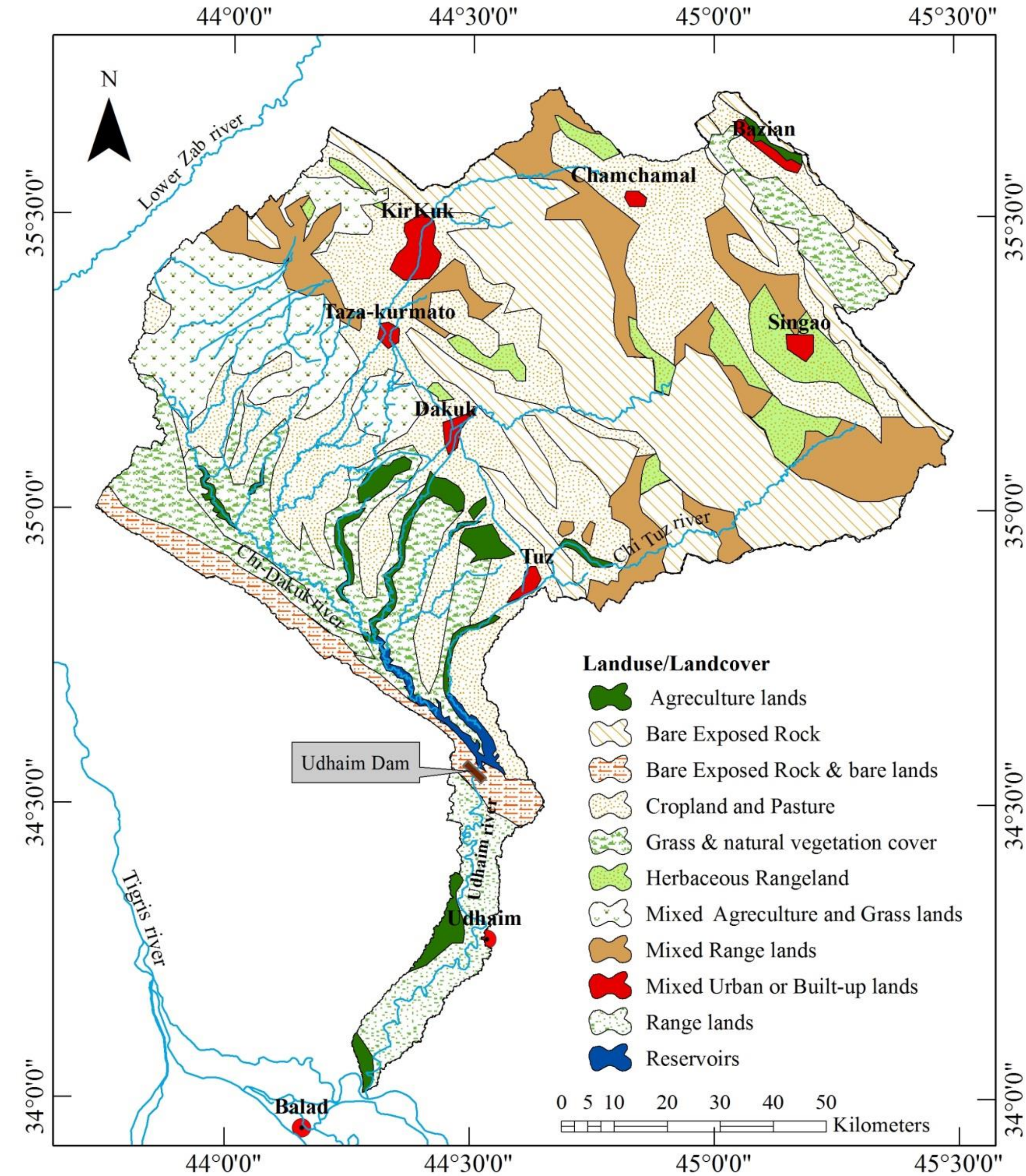


Figure 3.2: Land Use and Land Cover (LULC) in the Udhaim River basin

Table 3.1: Area and percentage of landuse/ landcover in Udhaim River basin

Class name	AREA(m^2)	Area (%)
Agriculture lands	3320169039.3	26.3
Bare Exposed Rock	2753431547.6	21.8
Cropland and Pasture	2644718099.3	20.9
Mixed Range lands	2339026332.8	18.5
Herbaceous Rangeland	566841975.7	4.5
Bare Exposed Rock & bare lands	397686594.2	3.1
Range lands	213069954.9	1.7
Grass & natural vegetation cover	171654689.2	1.4
Mixed Urban or Built-Up lands	148138333.5	1.2
Reservoirs	71289582.4	0.6

3.2. Climate characteristics

Climate plays a major role in influencing the behavior of the hydrological cycle. It is one of the most important factors affecting water resources, soils and in consequence agricultural production. Climate elements, especially precipitation and air temperature, are important factors that directly affect evapotranspiration and runoff – the key hydrological processes. In order to investigate the dependence of surface water resources of the Udhaim River on critical climatic factors, the seasonality of precipitation, air temperature, and potential evapotranspiration were characterized in the multiyear period 1980-2010.

Monthly precipitation over the Udhaim River basin varies spatially. Figure 3.3 provides insight into the monthly mean precipitation, evaluated by data acquired from the CRU TS3.24.01 database. In all four latitudinal zones, the highest monthly mean precipitation begins in October and continues until May, although all zones have different magnitudes. The most north-east part of the basin receives the highest amount of precipitation, which significantly decreases to the south. In the months from June to September, monthly sums are reduced to zero (Fig.3.3c & Fig.3.3d) or do not exceed a few millimeters per month (Fig.3.3a & Fig.3.3b). Thus the main recharge by precipitation takes place from October to May, while the rainless season begins in June and lasts until September. Annual mean precipitation equals 318 mm.

Air temperature in the Udhaim River basin is also characterized by strong seasonality, with maximum daily mean air temperature reaching 35°C in July and August, as evaluated in most of the grid cells (Fig. 3.4). Only in the north-west part of the basin does the daily mean air temperature in these months fall slightly below 35° (Fig. 3.4a & Fig. 3.4b). The lowest daily temperature in all parts of the basin is recorded in January, with temperature below 10°C in the north-east (Fig. 3.4a & Fig. 3.4b), and within the range of 10-12°C in the central and southern parts of the basin (Fig. 3.4c & Fig. 3.4d).

The annual cycle of potential evapotranspiration (PET) shows the suppression of PET during the cold season and the highest PET during the hot and dry season, consistent with seasonality of air temperature and precipitation (Fig. 3.5). The highest PET reaches 10 mm/d in July and August in the south (Fig. 3.5d), while in the central and northern parts of the basin it falls within the range of 6.7-9.6 mm/d (Fig. 3.5a, Fig. 3.5b & Fig. 3.5c).

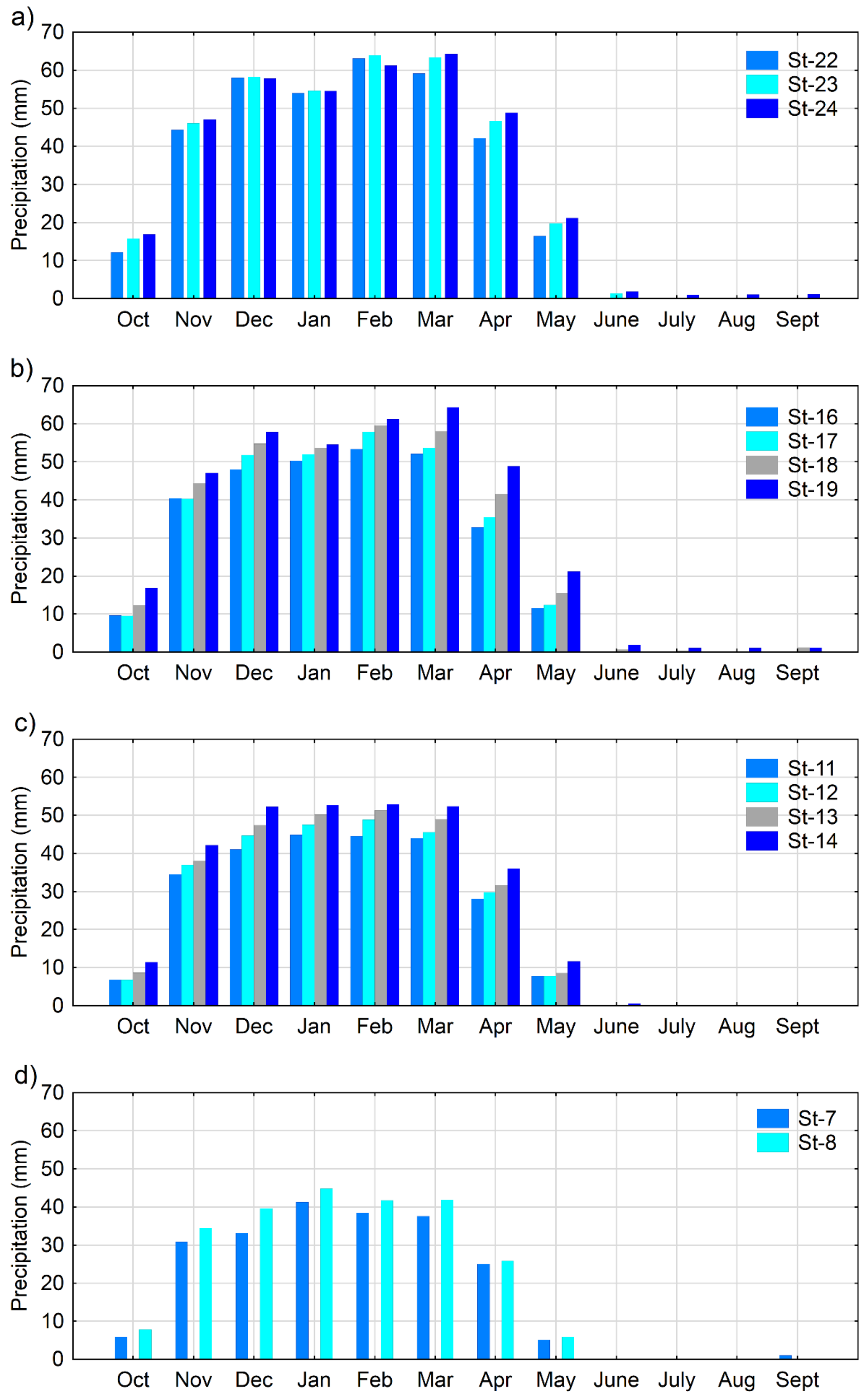


Figure 3.3: Monthly mean precipitation in the years 1980-2010 over the Udhaim River basin evaluated from grid cells no.: a) St22, St23, and St24, b) St16, St17, St18, and St19, c) St11, St12, St13, and St14, and d) St7, and St8.

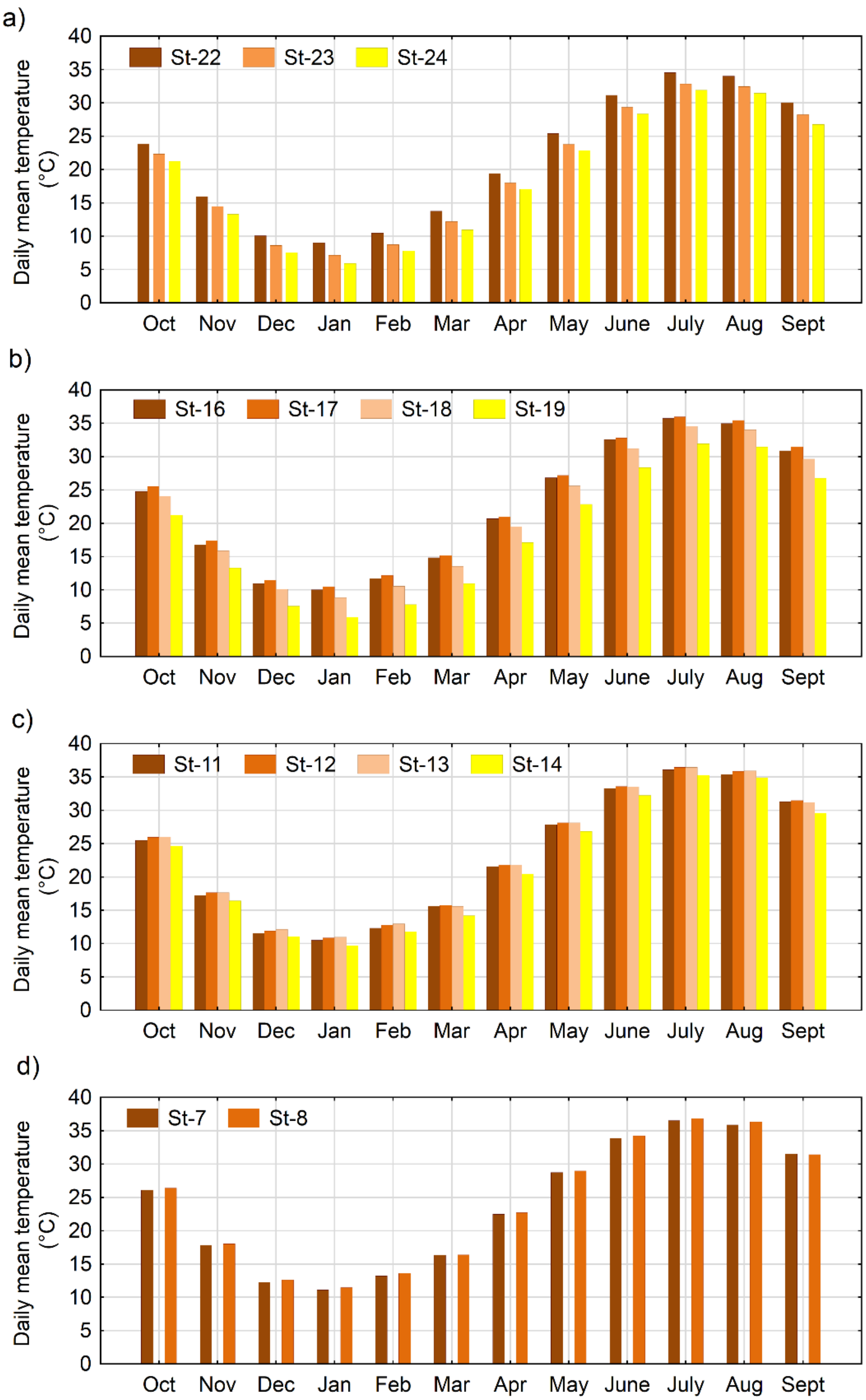


Figure 3.4: Daily mean air temperature in the years 1980-2010 over the Udhaim River basin evaluated from grid cells no.: a) St22, St23, and St24, b) St16, St17, St18, and St19, c) St11, St12, St13, and St14, and d) St7, and St8.

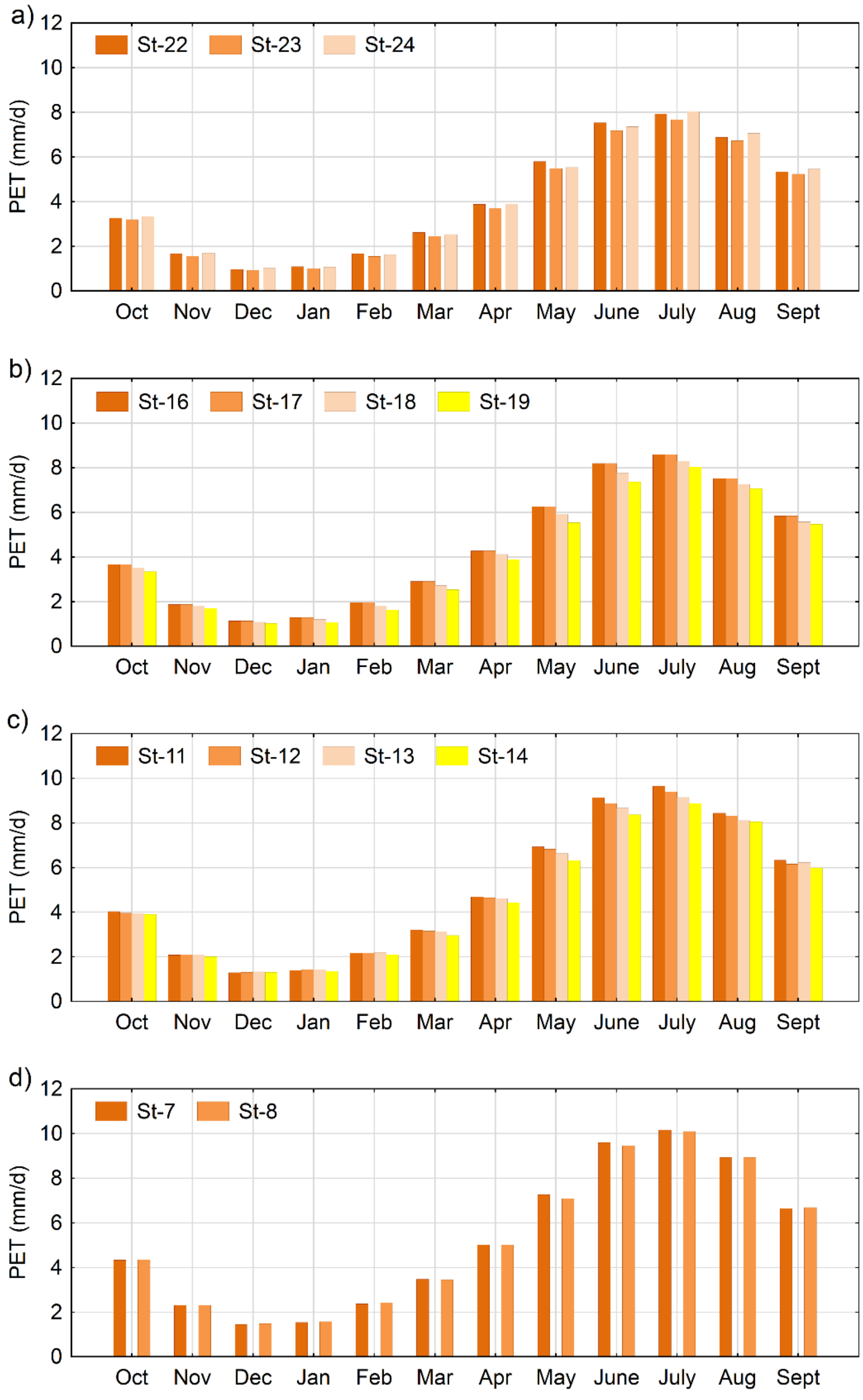


Figure 3.5: Daily mean potential evapotranspiration in the years 1980-2010 over the Udhaim River basin evaluated from grid cells no.: a) St22, St23, and St24, b) St16, St17, St18, and St19, c) St11, St12, St13, and St14, and d) St7, and St8.

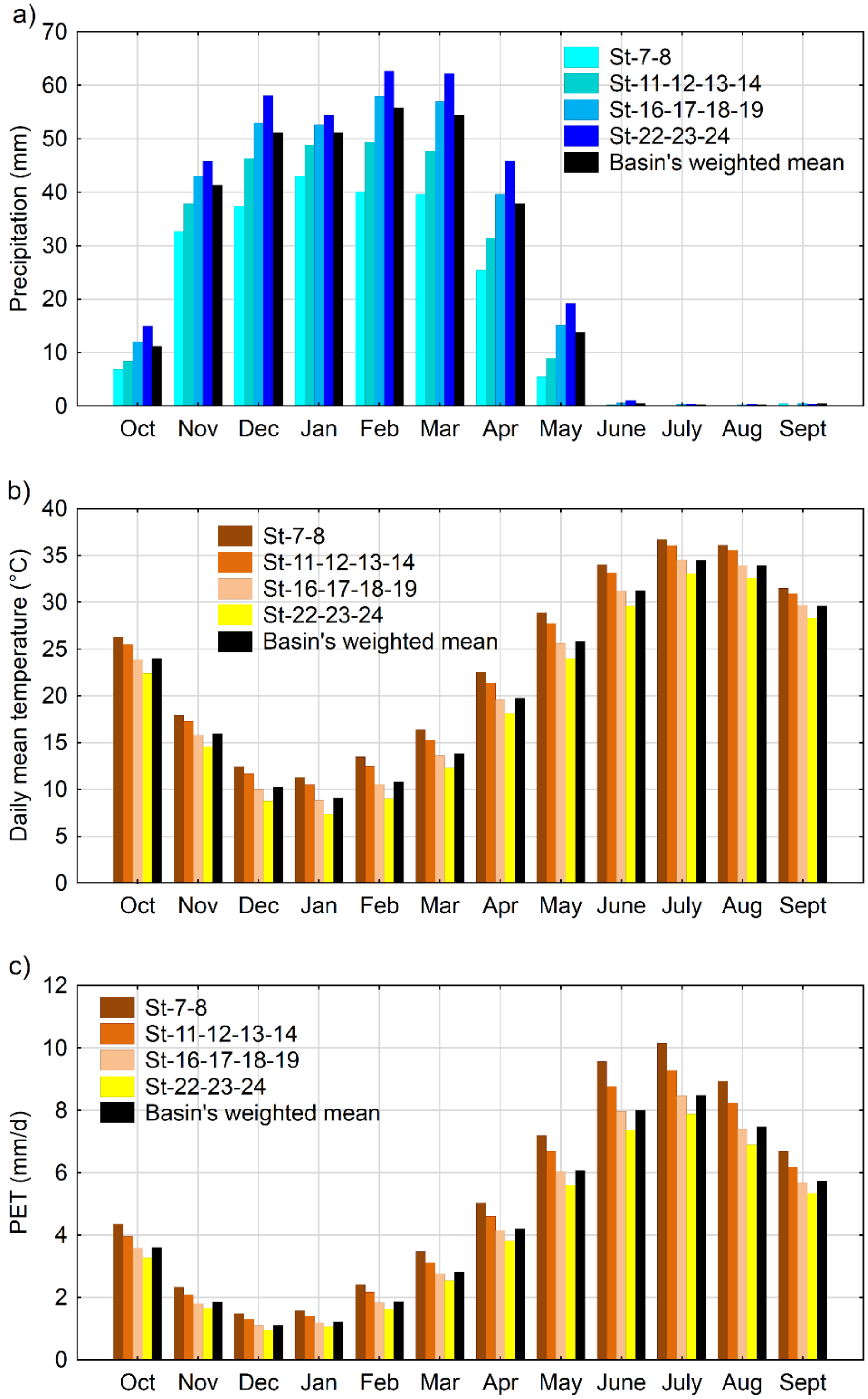


Figure 3.6: Monthly mean precipitation (a), daily mean air temperature (b), and daily mean potential evapotranspiration (c) averaged over the Udhaim River basin in the years 1980-2010

Figure 3.6., Table 3.2, and Annexes 1-3 provide insight into the weighted values of precipitation, air temperature, and PET, averaged over the Udhaim River basin. Multiyear annual potential evapotranspiration exceeds precipitation so the atmospheric demand is much higher thana the recharge by precipitation. Extremely high potential evapotranspiration occurs in the dry months of June, July and August.In December, January, and February, precipitation exceeds potential evapotranspiration, and these are the only months when a surplus of water exists.

Table 3.2: Monthly mean precipitation, daily mean air temperature, and daily mean potential evapotranspiration, with annual values, averaged over the Udhaim River basin in the years 1980-2010

Characteristic	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Annual
Precipitation (mm)	11	41	51	51	56	54	38	14	1	0	0	0	318
Temperature (°C)	24.0	16.0	10.3	9.1	10.8	13.8	19.8	25.8	31.3	34.5	33.9	29.6	21.6
PET (mm/day)	3.6	1.9	1.1	1.2	1.9	2.8	4.2	6.1	8.0	8.5	7.5	5.7	4.4
PET (mm/month)	112	56	35	38	53	87	126	189	240	263	232	172	1602

3.3. Surface water resources

The Udhaim River is the dominant waterbody in the basin, while its principal tributaries, Chi-Tuz and Chi-Dakuk are the only major rivers in the basin. Numerous smaller tributaries flow into these three rivers throughout the basin. There are no large storage reservoirs upstream from the Udhaim Dam. However, there are many small farm ponds. The Udhaim Dam and small ponds have a major impact on the river regime, primarily through changes in the timing, magnitude and frequency of low and high flows. In consequence, the river regime differs significantly from the pre-impoundment natural flow regime.

To assess hydrologic changes associated with dam and influenced by a varying precipitation recharge, mean monthly discharge was computed in pre- and post-dam construction (Fig. 3.7). Discharges in the post-dam construction period (1980-2002) are greatly reduced in months from November to April, and significantly sustained from May to September. However, it has to be mentioned that in the years 1980-2002 the annual mean precipitation was 328 mm exceeding that one in the years 2003-2010, which was 290 mm.

In conclusion, the shift in discharges is caused not only by impoundment but is also associated with variable meteorological conditions.

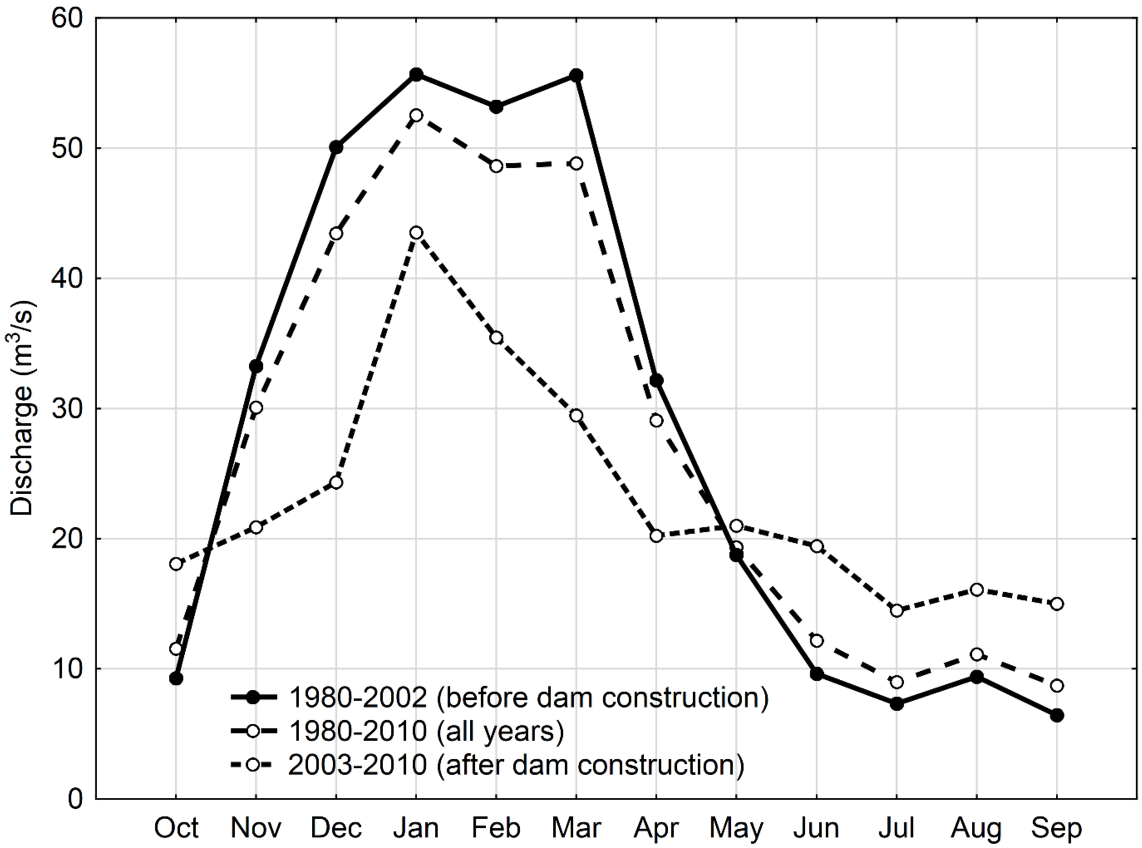


Figure 3.7: Monthly discharge of the Udhaim River at the cross-section of Udhaim Dam, evaluated before and after dam construction

3.4. Settlements and Population

The Udhaim River basin partly covers four provinces: Salah al-Deen, Kirkuk, Diala, and Sulaimaniyah. The main large part of the basin is located in the Salah al-Deen and Kirkuk provinces. The population is concentrated in cities, namely Kirkuk, Chamchamal, Bazian, Dakuk, Tuz, and Udhaim. Besides, there are numerous small villages and scattered houses in the Udhaim basin (Fig. 3.8 & Pic. 3.1). The villages are of different sizes. Some of them have 25 houses with about 100-150 people and some other large ones

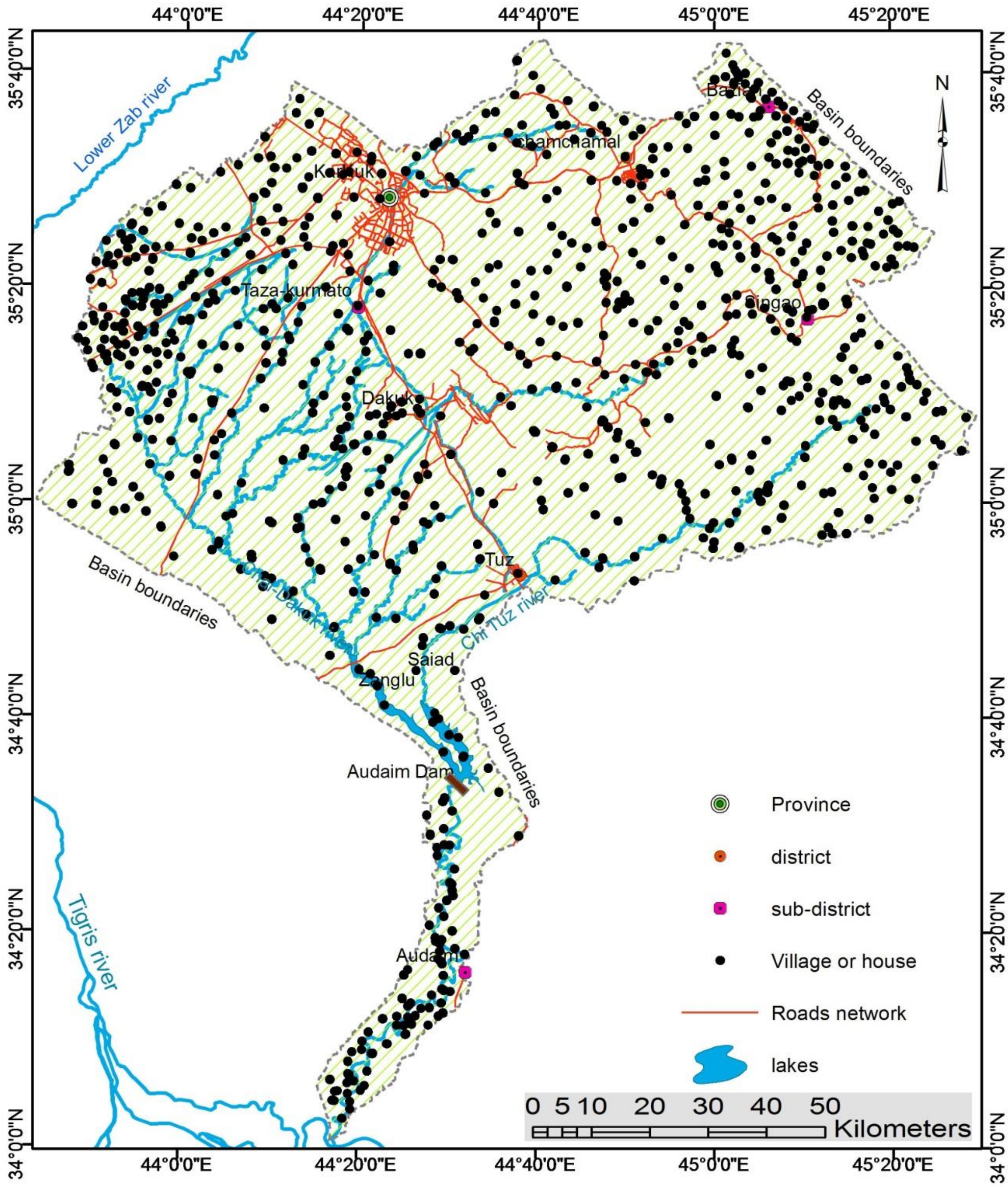


Figure 3.8: Cities and human settlements in the Udhaim River basin
Source: Free data from http://download.geofabrik.de/asia/iraq.html

Picture 3.1: Villages and scattered houses in the Udhaim River basin
Source: Taken by the author on 03.08.2015

have 100 houses with about 500 people. Most of the inhabitants cultivate wheat farms which mainly depend on rain and water wells and they also have herds of sheep and cows (Pic.3.2 & Pic.3.3). The administrative center of those villages and houses is Tuz a small town in the Salah al-Deen province. It had a population of about 64,000 people in 2012. All of the inhabitants of the Udhaim basin send the products of wheat and dairy to Tuz because it is considered to be the economic center of the region.

Picture 3.2: Wheat harvesting in study area
Source: Taken by the author on 03.08.2015

Picture 3.3: Herding of sheep at a bank of the Udhaim River
Source: Taken by the author on 03.08.2015

CHAPTER FOUR

4. THE EVALUATION OF DROUGHT CONDITIONS USING SPEI

4.1. Temporal evolution of SPEI in the years 1980-2010

Figures 4.1- 4.5 provide an insight into the temporal evolution of SPEI at 3-, 6-, 9-, 12-, and 24-month time scales at selected grid cells covering the territory of the Udhaim River basin. A drought is considered to occur when the SPEI value is less than or equal to −1. Annexes 4-8 show monthly SPEI values, averaged over the basin. It can be observed that the occurrence of months in which drought is detected in all severity classes within the range 82-109 and corresponds to about 22-29% of the entire time under analysis (Tab. 4.1).

Table 4.1: Characteristics of drought events for different timescales in the Udhaim basin, based onSPEI values in the years 1980-2010

Time scale (months)	3	6	9	12	24
Number of months with drought in 1980-2010	89	82	87	93	109
Percent of the entire time	24	22	23	25	29

The most severe and extreme droughts of 3- to 24-month duration were recorded in all grid cells in two periods, namely in the years 1998-1999, and 2007-2010 (Fig. 4.1- 4.5). The correlation between SPEI at different grid cells is statistically significant at $p<0.05$ as evaluated by the Pearson correlation coefficient (Annexes 9-13). Thus, It is characteristic, that similar wetness conditions, as evaluated by SPEI, occur over the basin simultaneously.

The most extreme 3-month drought occurred in February and March 2008 (Fig. 4.6a). According to the SPEI-6, the main drought episodes occurred from July 2007 to March 2008 (Fig. 4.6b). The SPEI-9 identified the most extreme drought episodes from May 2007 to February 2008, and from May to December 2008 (Fig. 4.6c). According to the SPEI-12, extreme drought occurred from April 2007 to September 2008 (Fig. 4.7a), and according to the SPEI-24 – from May 2006 to April 2008 (Fig. 4.7b). The results indicate that drought indices respond to high variability in precipitation. Annual basin's precipitation recorded in 2008 was the lowest observed in the whole period of the analysis (139 mm, Annex 1). As inter-annual variability in air temperature is relatively low, precipitation deficit seems to be the main factor responsible for extreme drought development.

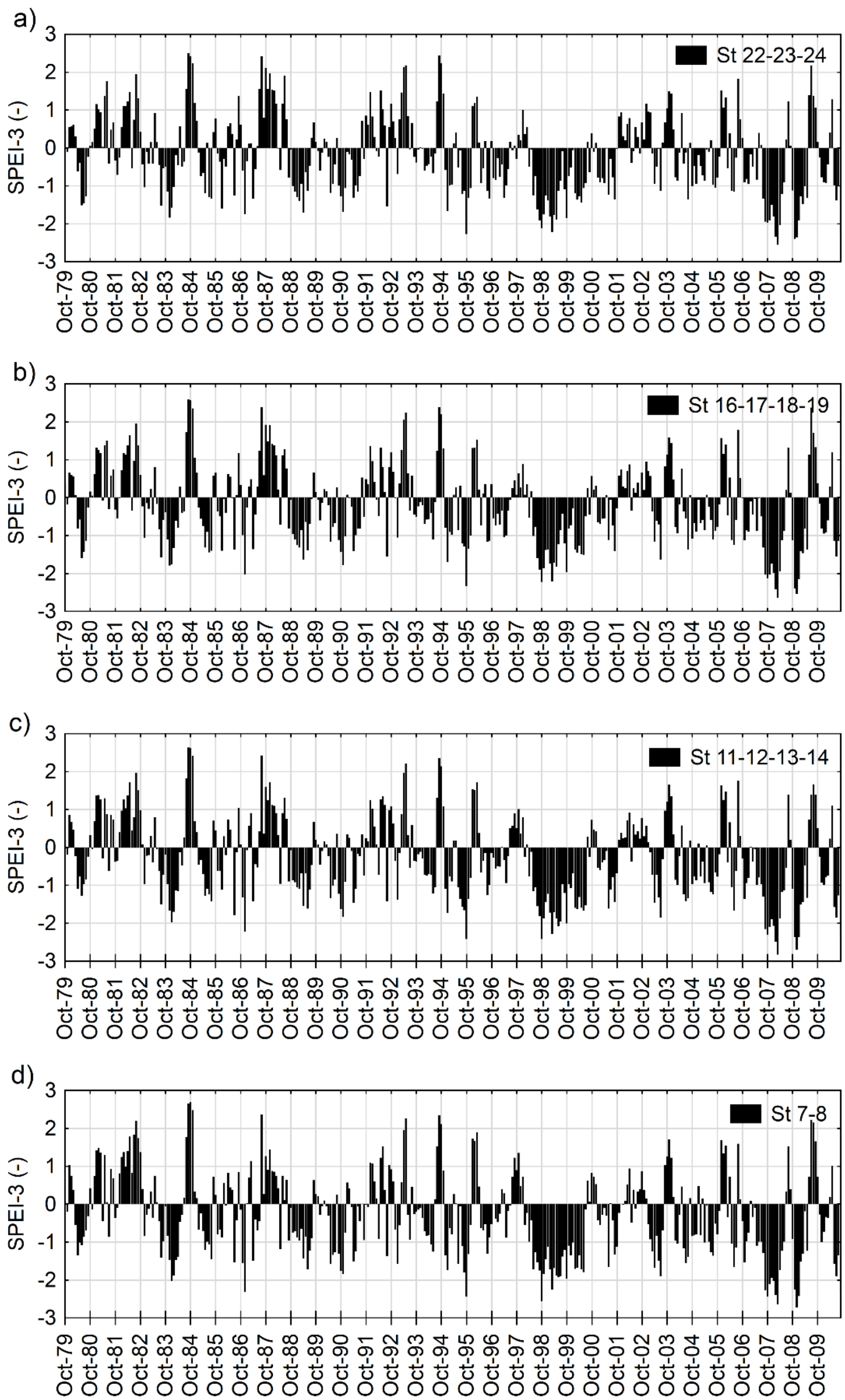


Figure 4.1: Temporal evolution of SPEI-3 in the years 1980-2010

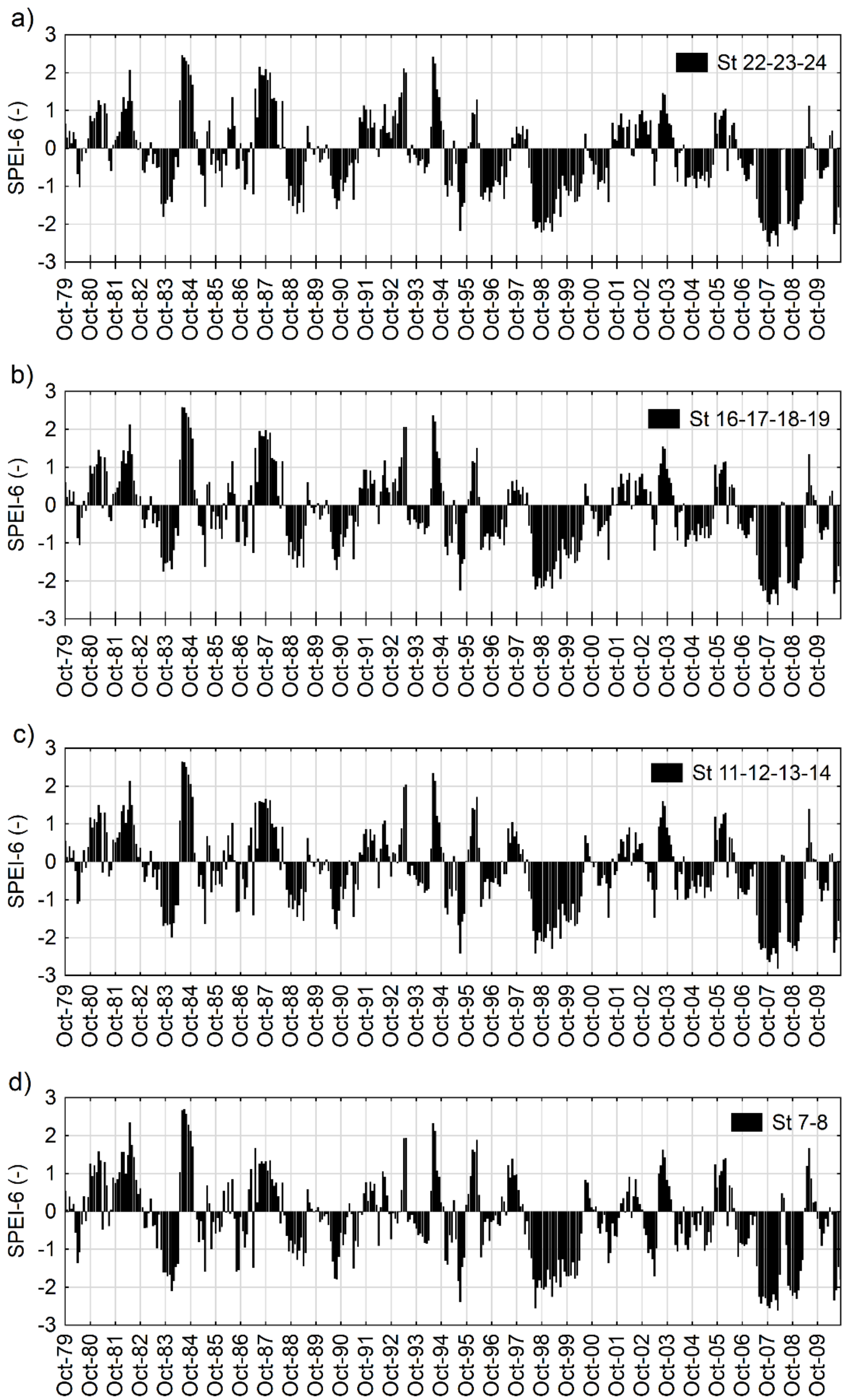


Figure 4.2: Temporal evolution of SPEI-6 in the years 1980-2010

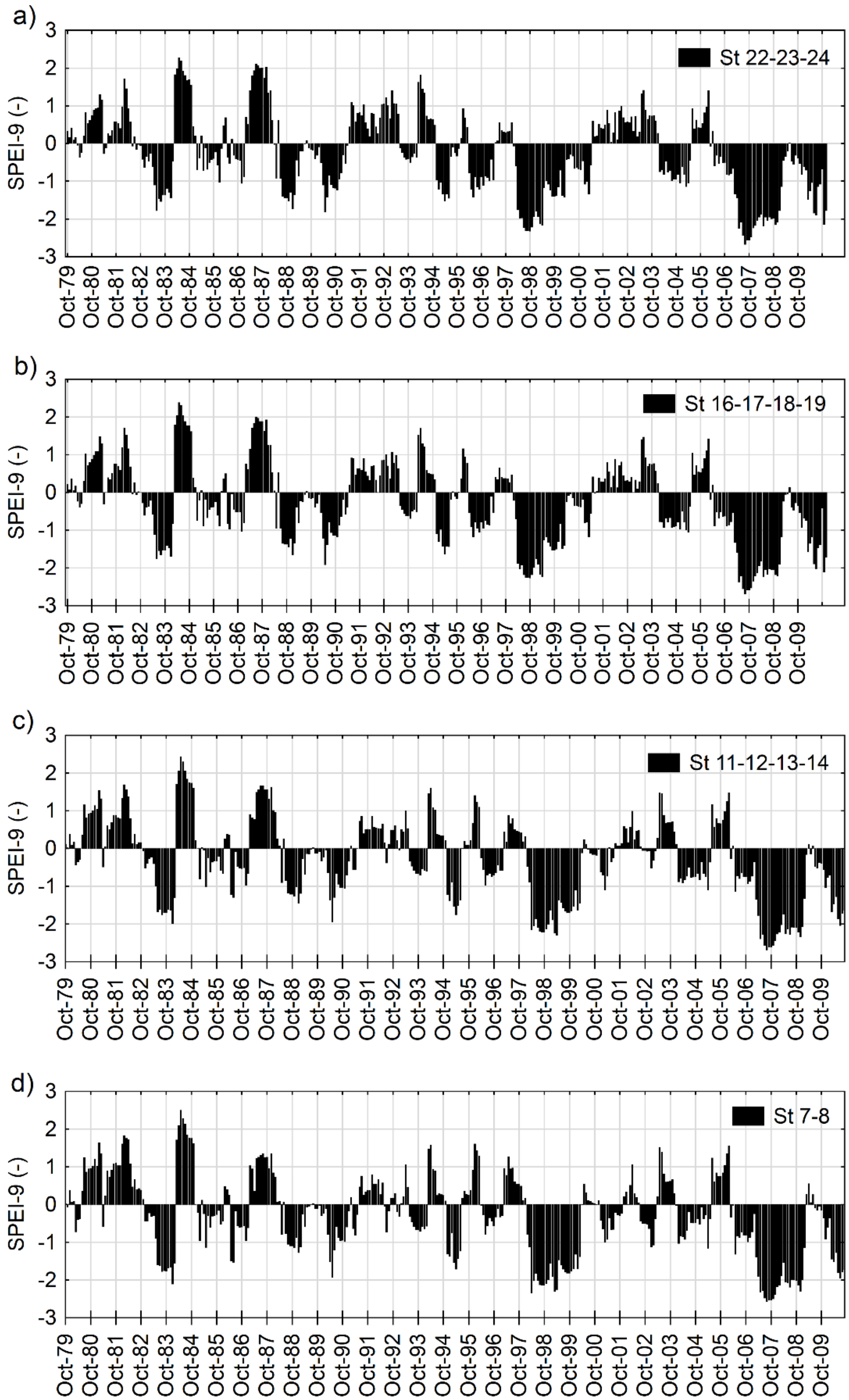


Figure 4.3: Temporal evolution of SPEI-9 in the years 1980-2010

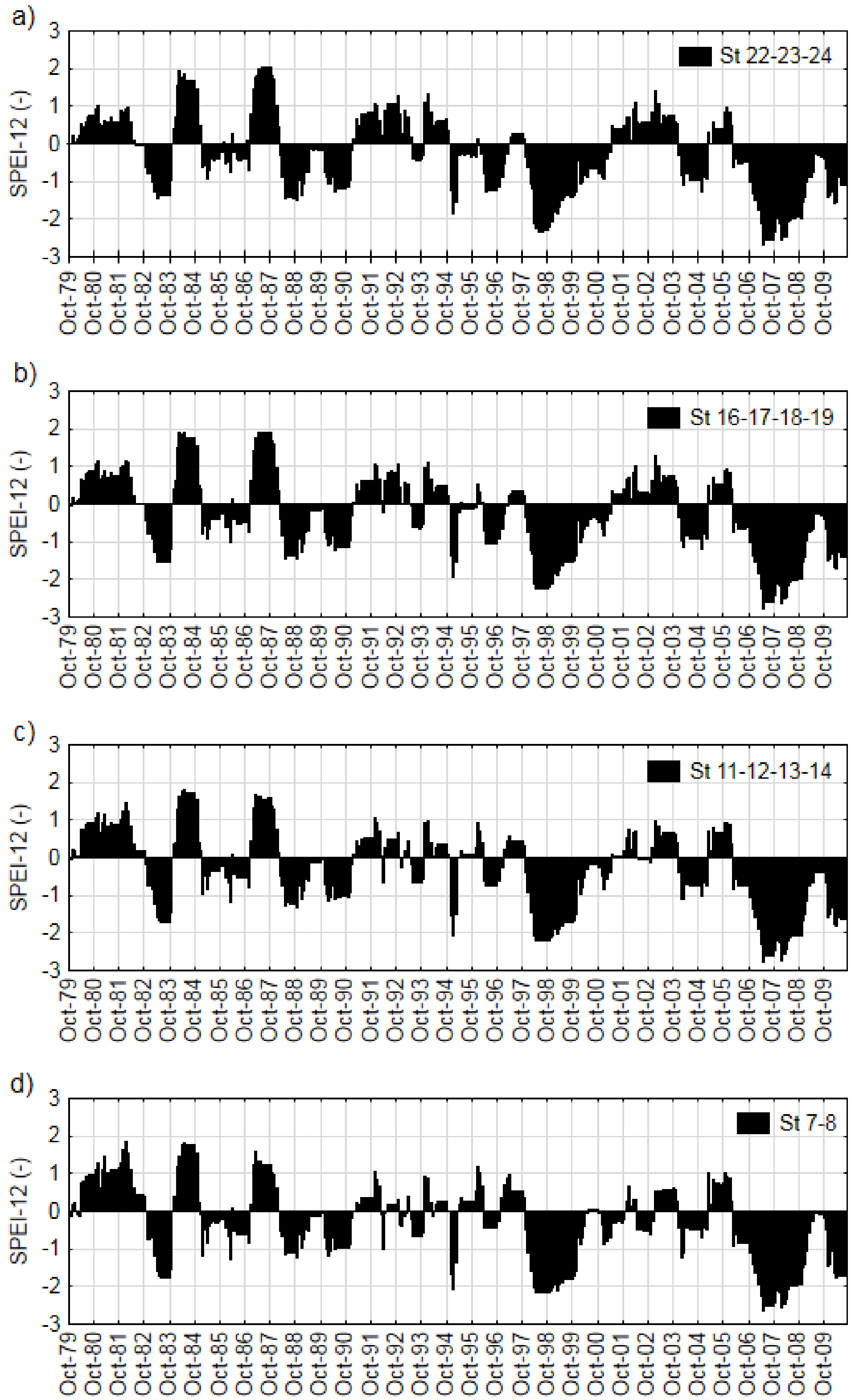


Figure 4.4: Temporal evolution of SPEI-12 in the years 1980-2010

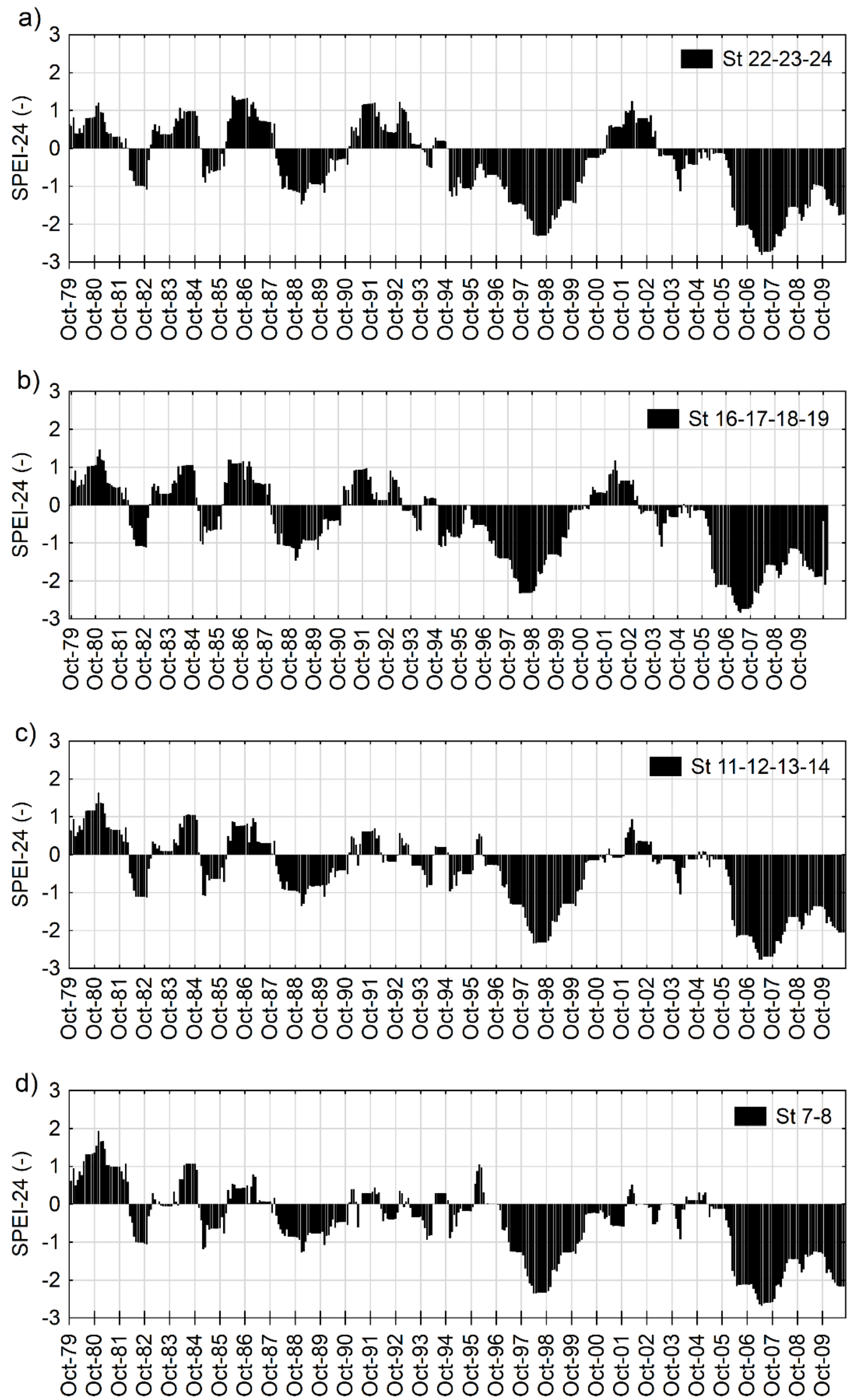


Figure 4.5: Temporal evolution of SPEI-24 in the years 1980-2010

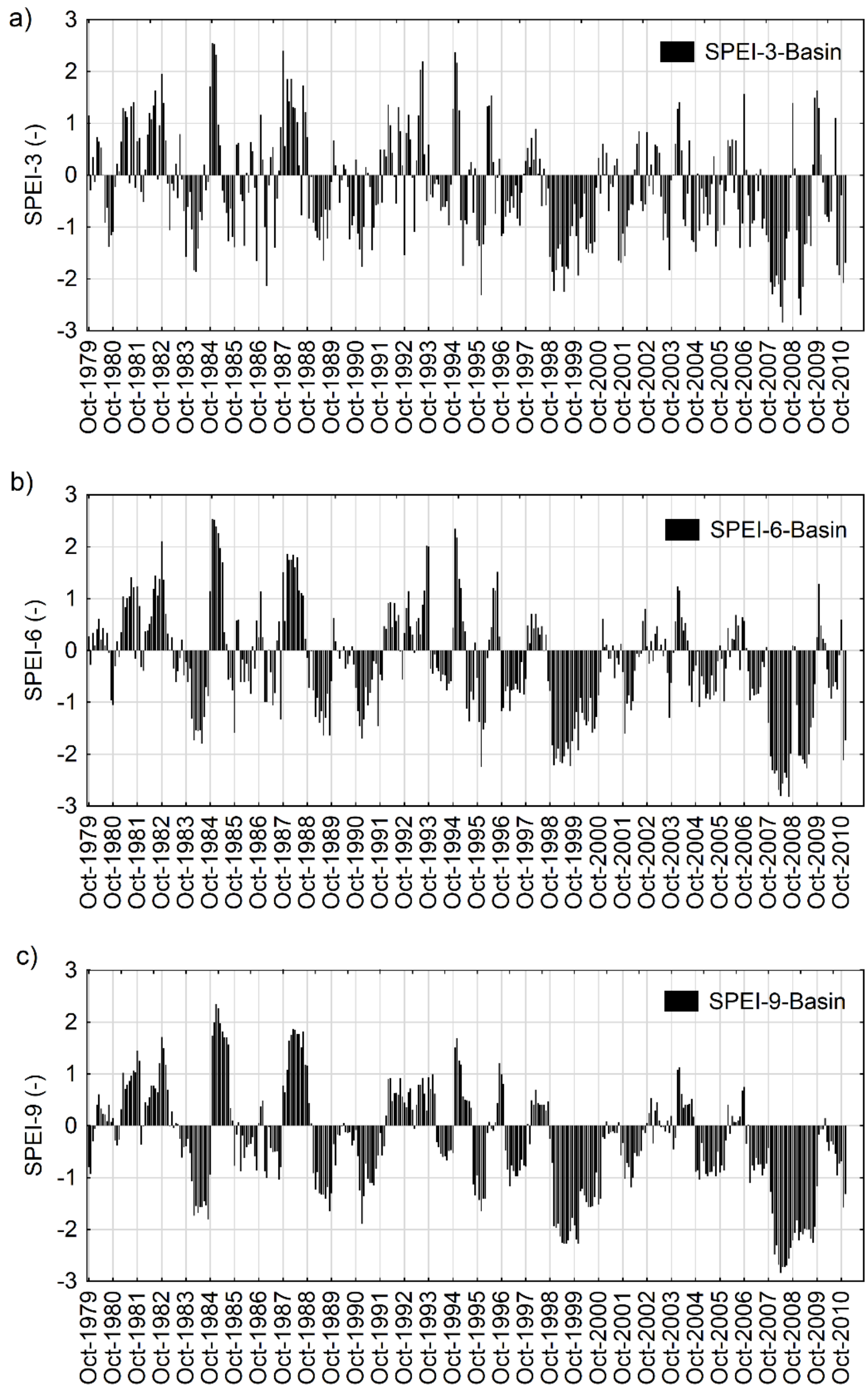
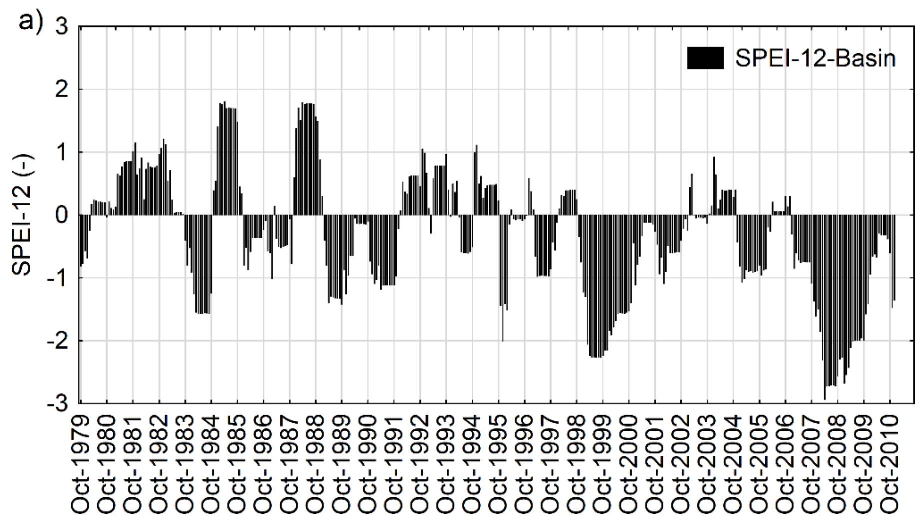


Figure 4.6: Temporal evolution of SPEI-3, SPEI-6, and SPEI-9 in the years 1980-2010. Values weighted over the Udhaim river basin



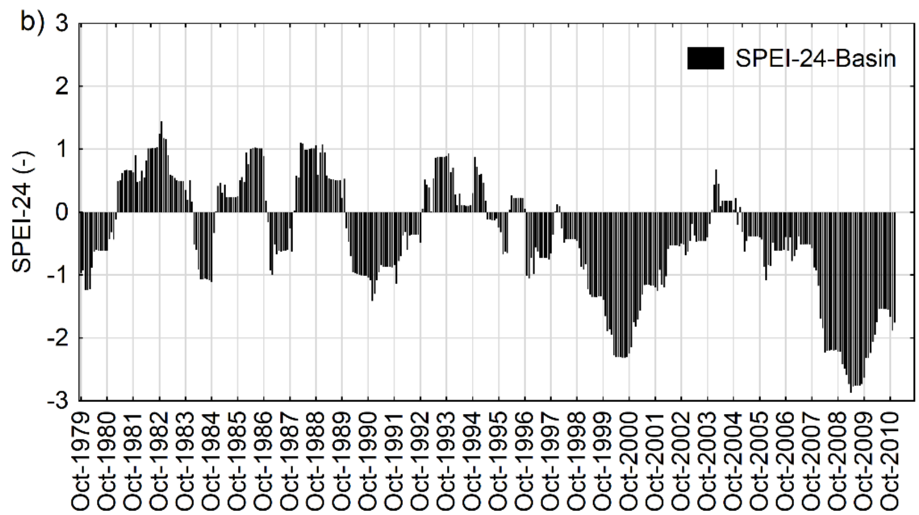


Figure 4.7: Temporal evolution of SPEI-12, and SPEI-24 in the years 1980-2010. Values weighted over the Udhaim River basin

4.2. Monthly and annual extremes of wetness conditions

Figure 4.8 show extreme and mean values of SPEI or different time scales, weighted over the basin. It is worth mentioning that values below -1 (drought conditions) occur in all months, at all investigated time scales (Fig.4.8a - 4.8e). Mean annual minimum SPEI values fall within the range from -1.5 for SPEI-3 (Fig. 4.8f) to -2.5 for SPEI-24 (Fig. 4.8).

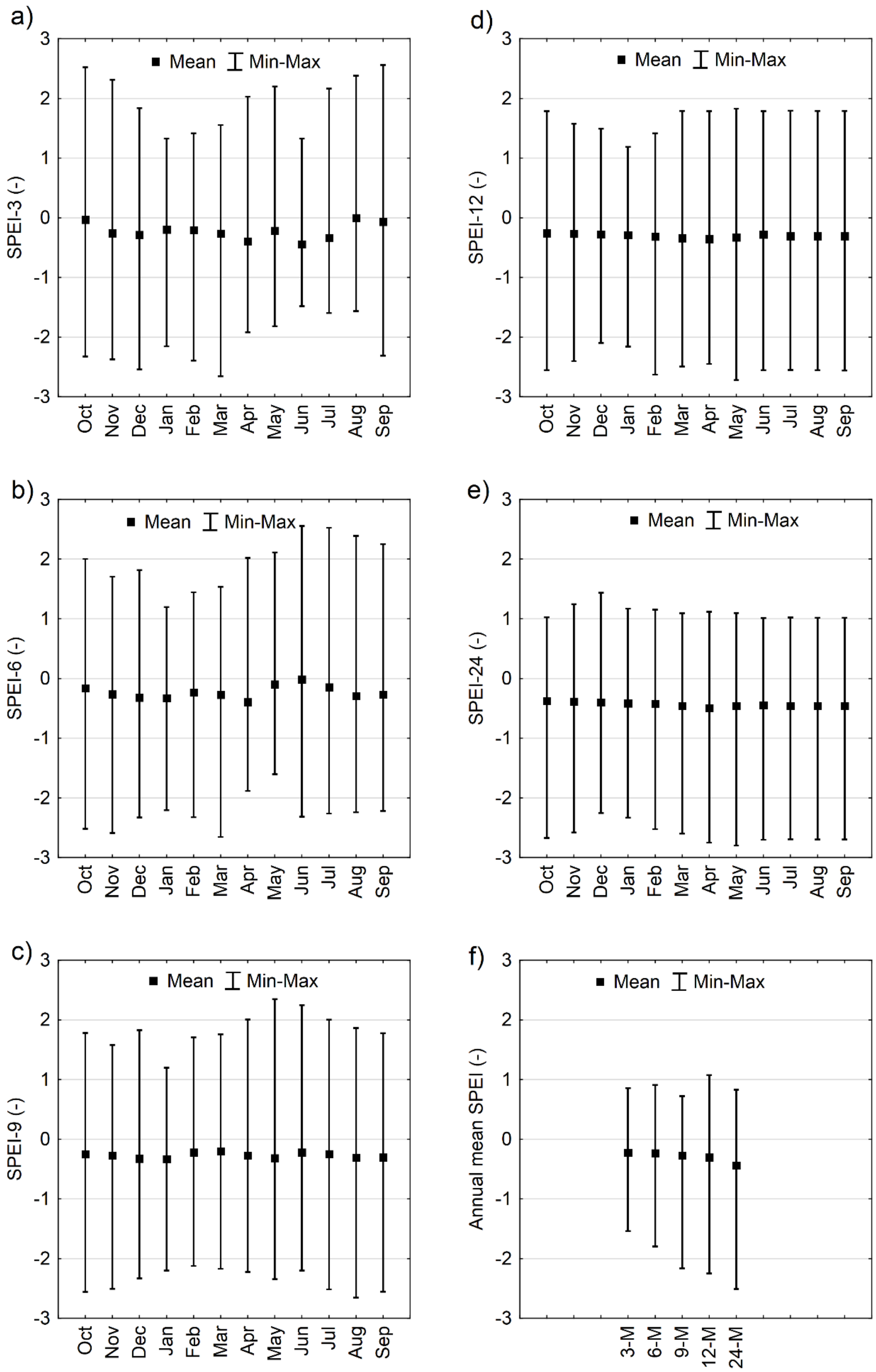


Figure 4.8: Mean and extreme (maximum and minimum) SPEI values at different time scales in the years 1980-2010. Values weighted over the Udhaim River basin

4.3. Drying trends detected in the SPEI time series

In order to check if there is a trend in the SPEI values, 31-element series of SPEI-3, SPEI-6, SPEI-9, SPEI-12, and SPEI-24 were prepared for the Udhaim River basin, for each month. Besides, a 31-element time series was prepared consisting of annual mean values of SPEI of different time scales. Then, the Mann-Kendall test was used the results of which are presented in (Tab. 4.2). In the SPEI-3 monthly series, a drying trend occurred only in March, while in time series representing longer time scales a decreasing trend is marked in considerably larger number of months. This especially concerns SPEI-12 and SPEI-24. Series of annual mean values of SPEI-9, SPEI-12, and SPEI-24 also show a statistically significant drying trend. It is worth mentioning that drying signals (negative values of Z Statistic) are detected in the case of the remaining series. Thus, results show that in all of the analyzed time series either drying trends or drying signals are detected.

Table 4.2: Summary statistics of the Mann-Kendall test applied to monthly SPEI series in the Udhaim River basin in the water years 1980-2010. Bold color indicates a drying trend

SPEI-3													
	Oct	Nov	Dec	Jan	Feb	**Mar**	Apr	May	Jun	Jul	Aug	Sep	Annual
Mann-Kendall Z Statistic	-1.619	-1.201	0.441	-0.491	-1.386	**-2.567**	-0.968	-1.465	-1.010	0.086	-0.237	-1.914	-1.367
Significance (%)	89.5	77.4	34.1	37.7	83.4	**99.0**	66.7	85.7	68.8	6.8	18.8	94.4	82.8
SPEI-6													
	Oct	Nov	Dec	Jan	Feb	**Mar**	Apr	May	Jun	**Jul**	Aug	Sep	Annual
Mann-Kendall Z Statistic	**-2.335**	-1.367	-0.944	-1.225	-1.386	**-2.567**	-0.968	-1.384	-1.903	**-2.062**	-1.172	-1.041	-1.938
Significance (%)	**98.4**	82.8	65.5	78.0	83.4	**99.0**	66.7	83.4	94.3	**96.8**	75.9	70.2	94.7
SPEI-9													
	Oct	Nov	Dec	Jan	**Feb**	**Mar**	**Apr**	May	Jun	**Jul**	Aug	Sep	**Annual**
Mann-Kendall Z Statistic	-1.367	-1.367	-1.325	-1.225	**-2.010**	**-3.136**	**-2.747**	-1.563	-1.262	**-2.668**	-1.632	-1.632	**-2.617**
Significance (%)	82.8	82.8	81.5	78.0	**95.6**	**99.8**	**99.4**	88.2	79.3	**99.2**	89.7	89.7	**99.1**
SPEI-12													
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	Mar	**Apr**	May	**Jun**	Jul	Aug	Sep	**Annual**
Mann-Kendall Z Statistic	-1.241	**-2.009**	**-3.643**	**-2.567**	**-2.730**	-1.801	**-2.247**	-1.632	**-1.966**	-1.632	-1.632	-1.632	**1.993**
Significance (%)	78.5	**95.5**	**100.0**	**99.0**	**99.4**	92.8	**97.5**	89.7	**95.6**	89.7	89.7	89.7	**95.4**
SPEI-24													
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Mann-Kendall Z Statistic	**-2.760**	**-2.571**	**-2.720**	**-2.873**	**-3.311**	**-2.144**	**-3.360**	**-3.450**	**-3.071**	**-2.937**	**-2.937**	**-2.937**	**-3.056**
Significance (%)	**99.4**	**99.0**	**99.3**	**99.6**	**99.9**	**96.8**	**99.9**	**99.9**	**99.8**	**99.7**	**99.7**	**99.7**	**99.8**

CHAPTER FIVE:

5. IMPACT OF DROUGHT CONDITIONS ON THE ENVIRONMENT

5.1. Land degradation evaluated by remote sensing techniques[2]

This chapter investigates the temporal and spatial changes of Land Use and Land Cover (LULC). LULC has been studied by a using remote sensing technique and Landsat data described in Chapter 2.2.5. Five classes of LULC have been distinguished for the years 2007 and 2015, namely soil crust, bare land, built-up areas, water bodies, and vegetation (Fig.5.1 & Fig.5.2). Based on that, LULC changes between the years 2007 and 2015 have been quantified (Tab.5.1).

The percentage of the vegetated land area decreased from 11.27% to 8.43% between 2007 and 2015, with an annual rate of change of -3.6% of the vegetated area. Water bodies have shrunk from 0.9% in 2007 to 0.68% in 2015, with a mean annual change of -3.37% of the water body areas (Tab.5.1, Fig.5.3 & Fig.5.4). The main water body in the area is the Udhaim dam reservoir (Pic.5.1 & Pic.5.2).

Table 5.1: Temporal variation of Land-use/Land cover

Classes	2007 (km^2)	2007 %	2015 (km^2)	2015 %	Changing area (km^2)*	Changing %**	Annual Changing %/yr***
Soil Crust	7414.66	66.38	7749.61	69.38	334.95	4.52	0.65
Bare Land	2154.22	19.29	2093.72	18.74	-60.51	-2.81	-0.40
Built-up	241.43	2.16	308.30	2.76	66.87	27.70	3.96
Water Bodies	100.14	0.90	76.51	0.68	-23.63	-23.60	-3.37
Vegetation	1259.10	11.27	941.42	8.43	-317.68	-25.23	-3.60
Total	11169.56	100.00	11169.56	100.00			

Explanations: changing area (km^2), changing area (percentage) and annual changing area (percentage) were calculated as follows:

***Changing area (km^2) = (area in 2015 – area in 2007),**

**** Changing (%) = (area/area in 2007)*100,**

*****Annual changing (%/yr) = (Changing % / 7).**

[2] Chapter 5.1. includes results that have been published by Mail (2017) in the article titled "Desertification Detected in the Udhaim River Basin, Iraq Based on Spectral Indices Derived from Remote Sensing Images". Miscellanea Geographica – Regional Studies on Development.

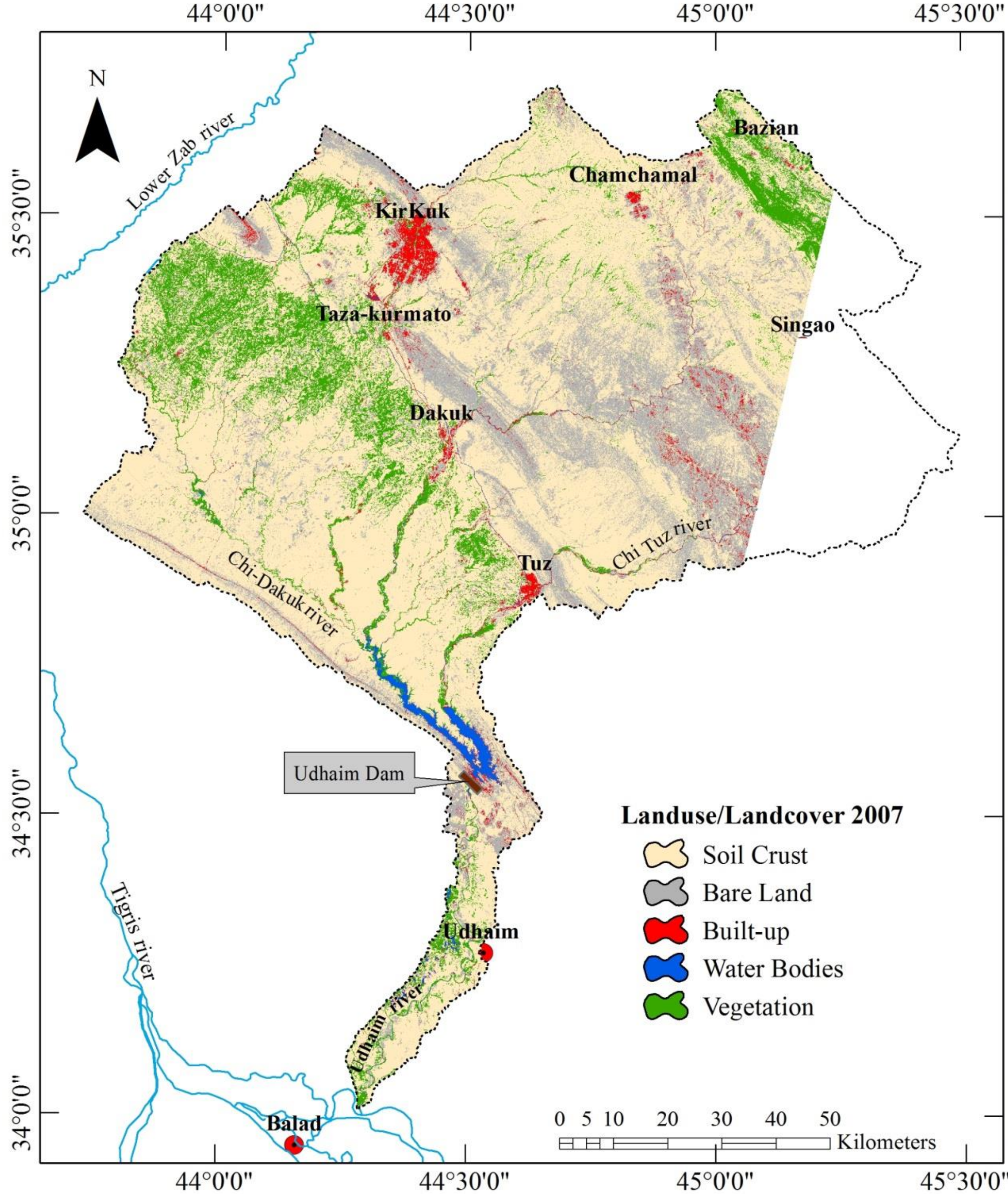


Figure 5.1: LULC in 2007

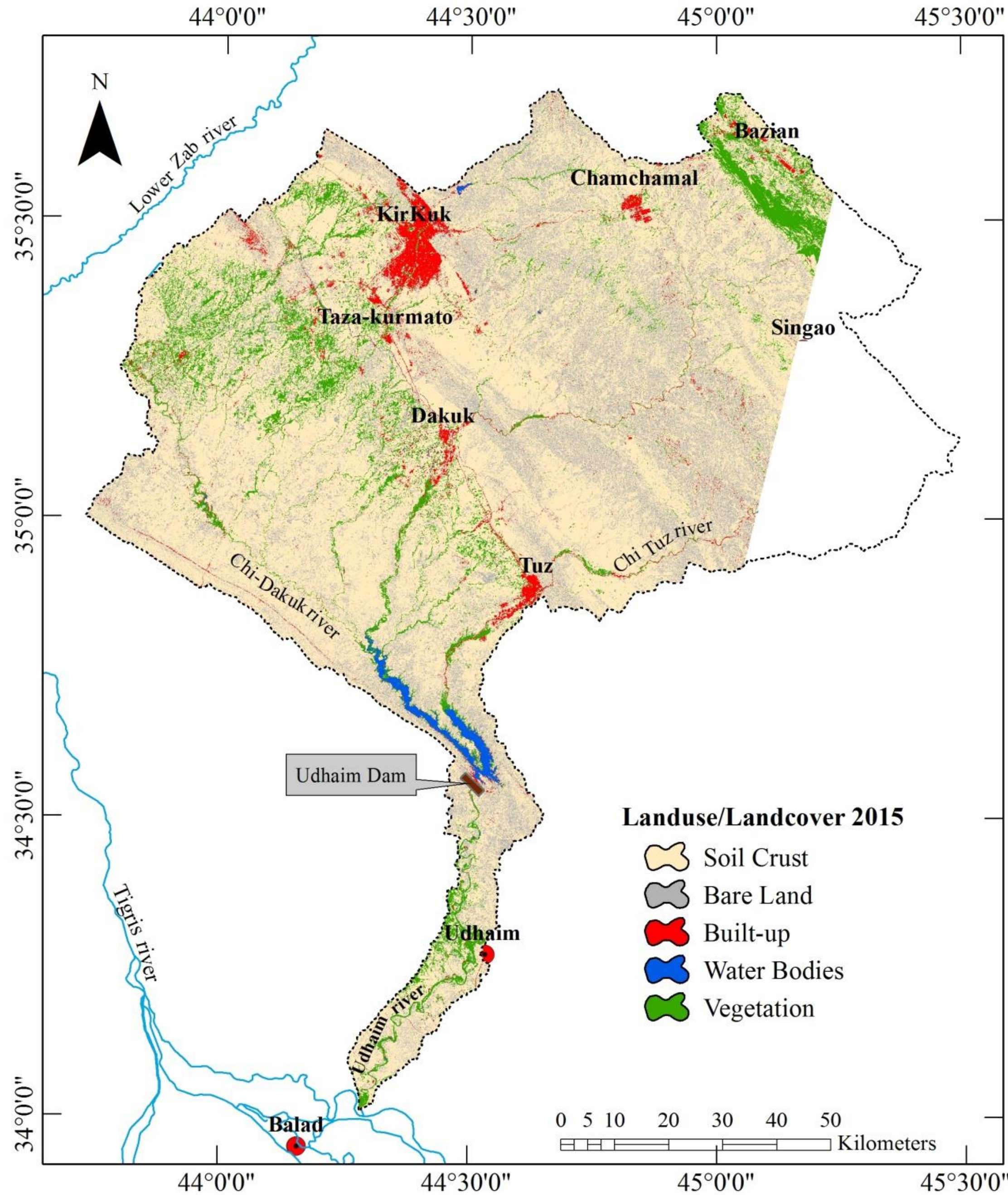


Figure 5.2: LULC in 2015

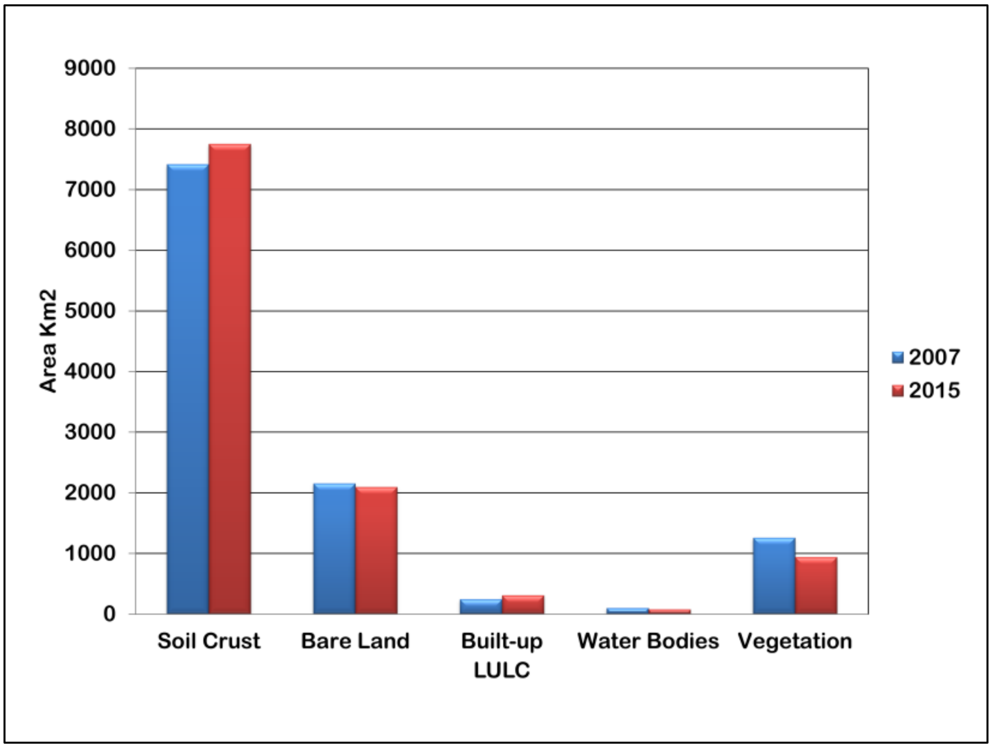


Figure 5.3: Temporal variations of LULC as estimated by five spectral indices

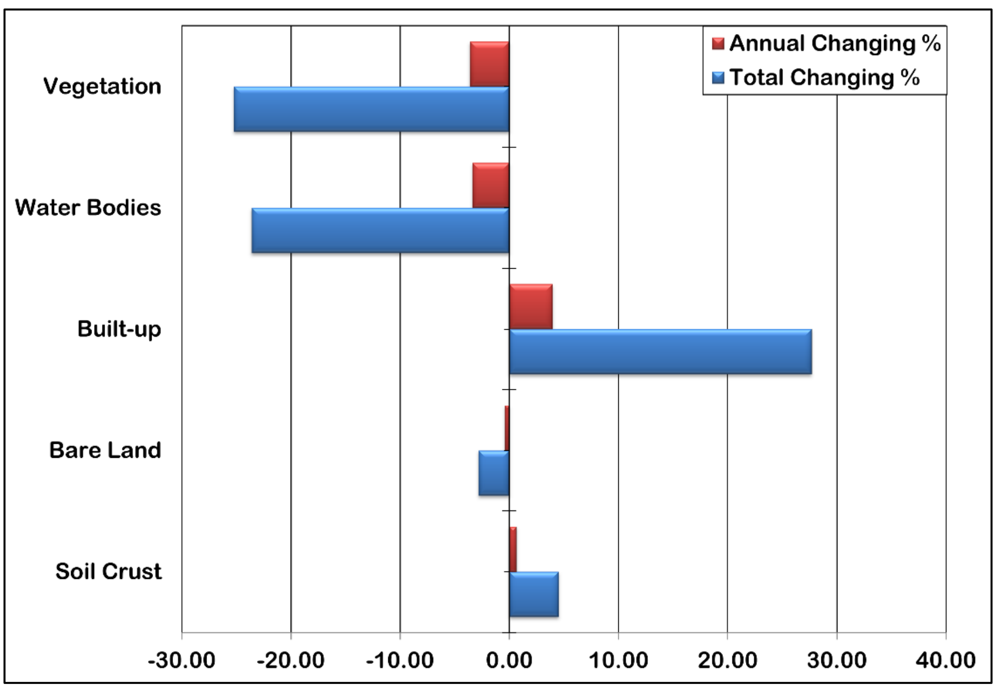


Figure 5.4: Changes in LULC between 2007 and 2015

Picture 5.1: The Udhaim Dam spillway.
Taken on 09.03.2014

Picture 5.2: The Udhaim Dam Reservoir.
Taken on 09.03.2014

Picture 5.3: Ruined village due to Military operations. Taken on 05.04.2014

Picture 5.4: Barley farm abandoned due to the forced displacement of farmers. Taken on 05.04.2014

Picture 5.5: Water well abandoned due to forced displacement of farmers

Taken on 05.04.2014

It is worth mentioning that antecedent meteorological conditions for July 2007 differ from those for June 2015. 3-month, 6-month, 9-month, 12-month, and 24-month precipitation, air temperature and potential evapotranspiration (PET), are presented in Table 5.2. Thus in June 2015, it was much more dry and hot than in July 2007, due to limited recharge by precipitation, higher air temperature, and higher atmospheric demand.

Table 5.2: Antecedent meteorological conditions in the Udhaim River basin

Antecedent Precipitation (mm)					
	3-Month	6-Month	9-Month	12-Month	24-Month
July 2007	59	192	292	292	665
June 2015	1	49	118	183	460
Antecedent mean daily air temperature (°C)					
	3-Month	6-Month	9-Month	12-Month	24-Month
July 2007	25.9	18.3	17.2	21.1	21.6
June 2015	35.1	28.1	22.7	22.7	22.4
Antecedent PET (mm/d)					
	3-Month	6-Month	9-Month	12-Month	24-Month
July 2007	5.9	3.9	3.3	4.2	4.3
June 2015	8.1	6.4	4.8	4.4	4.4

Picture 5.6: Sand dunes in the study area
Taken on 18.08.2015

The vegetated area, water body area, and bare land area (Pic.5.6) decreased, while the built-up and soil crust areas increased. The growth of the population in the main cities such as Kirkuk and an increase in economic activity have led to the quick expansion of the built-up areas into neighboring lands. The percentage of urban areas or built-up areas increased from 2.16% to 2.76% of the investigated area, with an annual increase rate of 3.96%. The soil crust area has increased from 66.38% to 69.38% of the total investigated area. The increase in the soil crust area is caused by the degradation of vegetation and water bodies in this territory.

The degradation of the vegetated area has obviously been impacted by extreme weather events, deficit in water import, abusive land-Use, and the security situation in the area. Since 10 June 2014, most of the villages have been occupied by ISIS and became battle fields (Pic. 5.3), and most of the people and farmers in the villages had fled to Kirkuk, Baghdad, and Erbil. All of the farms have been abandoned due to military activity (Pic.5.4 & Pic.5.5). Meanwhile, the shrinkage of the Udhaim dam reservoir in the area is due to decrease in precipitation and water received from the valleys. Thus, dynamic changes of

Land Use and Land Cover during past 8 years should be attributed to a net result of the variability of climatic driving forces and human impact.

The land use change in the Udhaim River basin caused distinct landscape effects, such as desertification, and a decline in environmental quality. The degraded lands of vegetation areas should be restored as cultivated areas by using new irrigation methods and precise agricultural techniques. This issue might be solved by introducing the governmental, sustainable development program (Aliyas, 2016).

5.2. Impact of drought conditions on river discharge

The water-year discharge of the Udhaim river at the Udhaim Dam reservoir was examined from 1980 to 2010 given the importance of surface water availability in the region. The discharges fluctuate from year to year and are mainly dependent on the rainfall amounts and snow thaw in the far north eastern parts of the basin. It has to be underlined that available discharge data concern the river influenced by human activities and the Udhaim reservoir operation. The river regime is impacted and regulated to meet local water demands. Thus the utility of drought indices to track hydrologic metrics is limited given the increasing vulnerability of water resources. Nonetheless, given the importance of water problems in the semi-arid environment of the Udhaim River basin, the integrated response of a hydrologic system to climate forcing and human impact was investigated.

Correlation coefficients (r) between monthly discharges and SPEI values or different time scales for the months October-September are shown in Annexes 14-18. The results illustrate that the strongest correlation is observed between SPEI-3 and SPEI-6 ending and discharging in April, Respectively. Correlation coefficients for these two time scales equal 0.655, thus coefficients of determination (r^2) equal 0.43. This means that only 43% of the total variation in discharge can be explained by the linear relationship between discharges for April and SPEI-3 (Fig. 5.5a) and SPEI-6 (Fig. 5.5b). The remaining 57% of the total variation in discharge remains unexplained. The wet season starts in November and extends into April. Thus, SPEI-3 and SPEI-6 for April encompass the vast majority of months with precipitation. In general, correlations were higher in the winter months, when the highest monthly precipitation occurs. A significant degradation of coefficient of determination for longer time scales of SPEI suggests that summer precipitation and potential evapotranspiration used for calculating SPEI had a negligible relationship to the discharges.

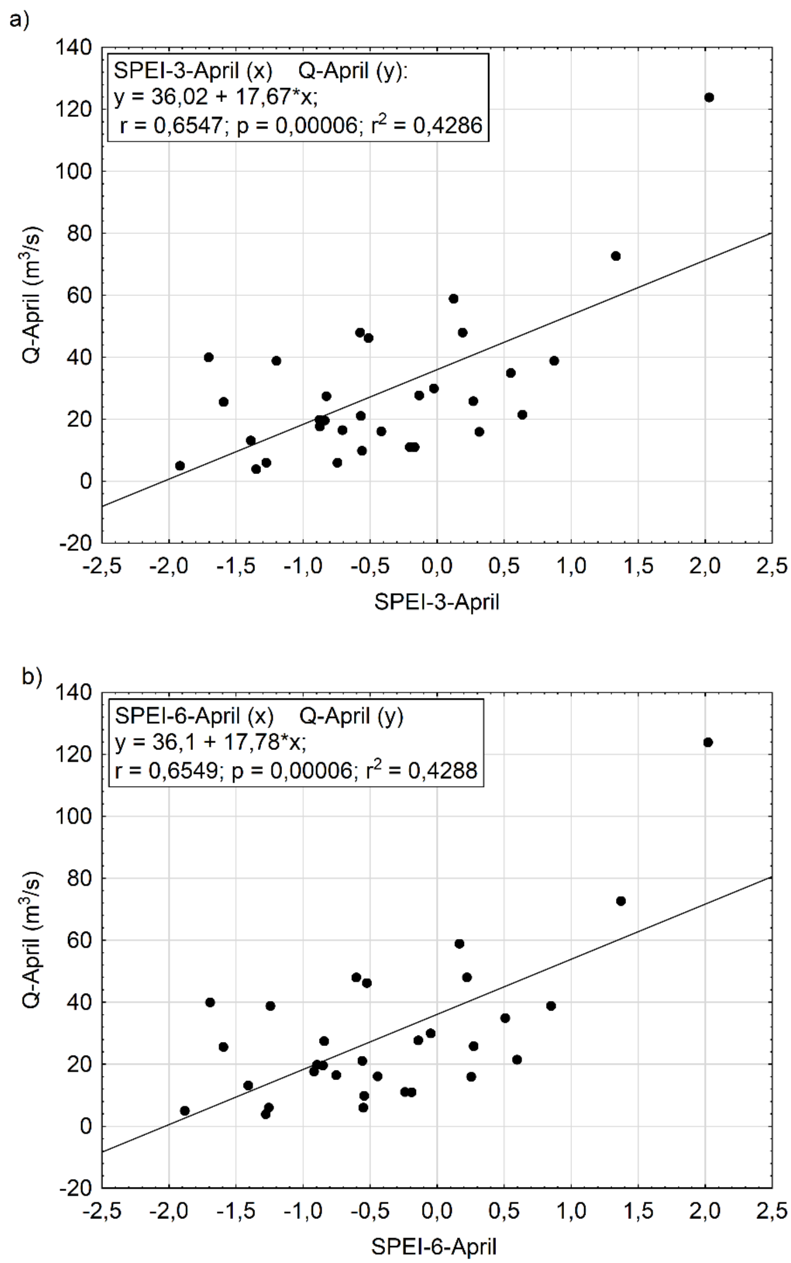


Figure. 5.5: Relationship between (a) SPEI-3 and discharge for April, (b) SPEI-6 and discharge for April

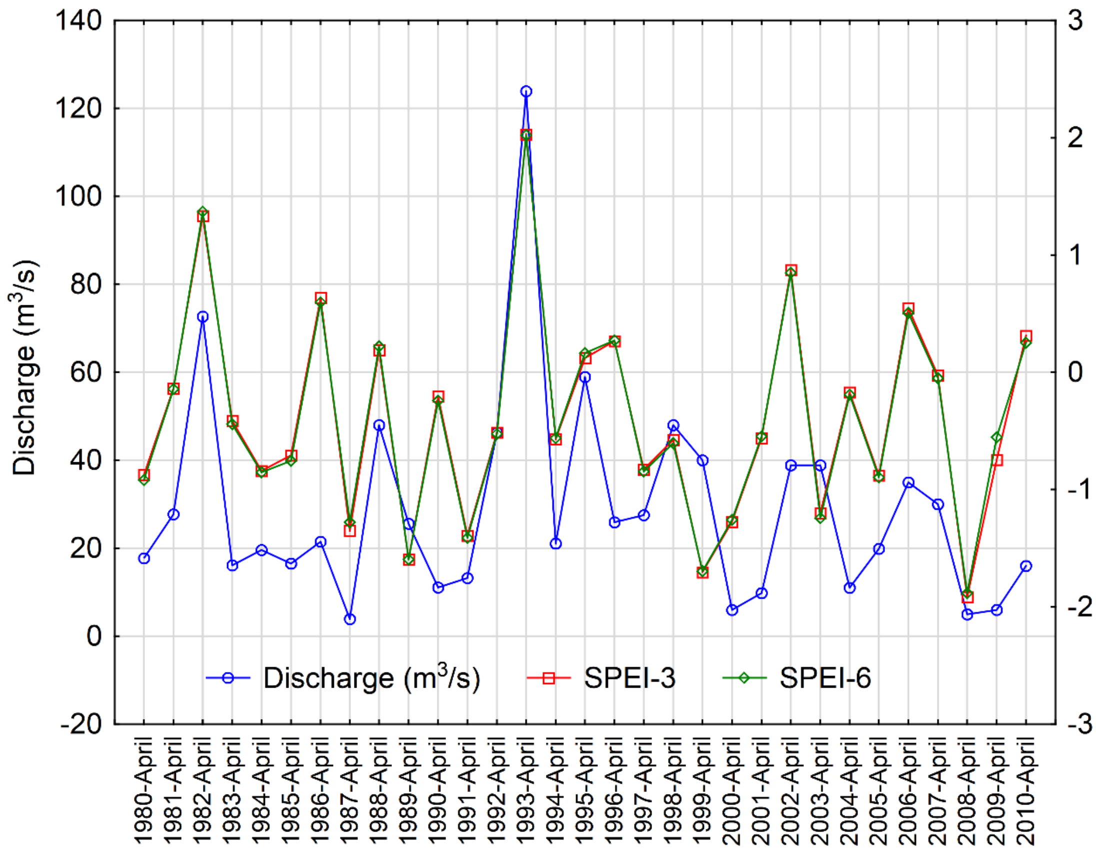


Figure 5.6: Time series of monthly discharge (Q), SPEI-3, and SPEI-6 for April in the years 1980-2010

In general, monthly discharge for April follows the course of SPEI-3 and SPEI-6. Significantly low values of SPEI, below -1, occurred in the years 1987, 1989, 1991, 1999, 2003, and 2008 (Fig. 5.6). In these years, relatively low discharges occurred even lasting for the next year. To summarize, SPEI-3 and SPEI-6 for April capture drought conditions that are reflected in low discharges. Low discharges can have many negative effects such as a change in water quality, decline in the value of agricultural land, destruction of habitats and biodiversity, and increased dust storms, salinization and waterlogging.

5.3. The impact of drought conditions on the water quality of reservoir

This section focuses on the quality of water used for irrigation. Irrigation water quality has direct effects on soils and crops. Good crops can be produced by using water of excellent quality. The quality of irrigation water depends mainly on lithology and climate. The chemical characteristics of irrigation water can a fect plant growth directly by toxicity or deficiency, or indirectly by altering the plant availability of nutrients (Ayer & Westcot, 1985; Rowe & Abdel-Magid, 1995).

The results of water quality analysis indicate that the water samples show poor or permissible categories, and only this last category is suitable for irrigation (Tab. 5.3). Long period of poor water quality occurred in the years 1983-1987 and 2006-2010. According to annual revenue data (Tab. 5.4), the inflow to the reservoir in these two periods was considered to be low or moderate (Fig. 5.7). In the years 1992-1995 and 2002-2005, the revenues were high or moderate, and water was of permissible quality. Results confirm that the poor quality of water is connected with the low water inflow, whereas permissible water occur in years with high water inflow to the reservoir. Water quality in the years 2006 and 2007 was poor although the annual revenue was very close to the ones in 2002 or 2005. This may be due to the stability of water inflow at a medium to low level (close to 1 billion cubic meters), and the stability rate of solubility of salt from gypsiferous and carboniferous soils and rocks.

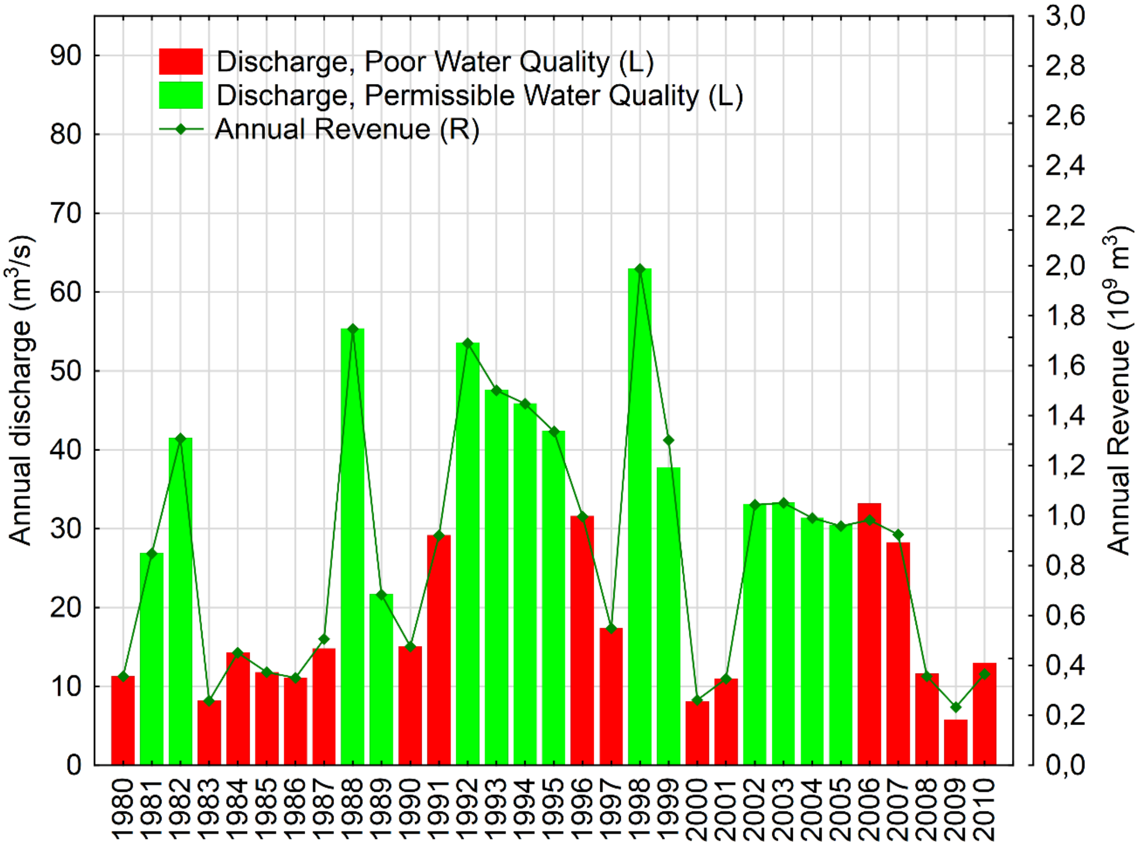


Figure 5.7: Water quality of the Udhaim Dam reservoir in the years 1980-2010, at a background of annual revenue and river discharge

Table 5.3: Water quality in the study area (1980-2010)

Year	EC (μS/cm)	SAR (meq/L)	SAR Class	Ec Class	Water Classification
1980	2279	4.45	S1	C4	Poor
1981	2055	3.80	S1	C3	Permissible
1982	1964	3.52	S1	C3	Permissible
1983	2530	5.12	S1	C4	Poor
1984	3059	6.38	S1	C4	Poor
1985	2630	3.16	S1	C4	Poor
1986	2973	3.86	S1	C4	Poor
1987	2982	3.58	S1	C4	Poor
1988	1957	3.50	S1	C3	Permissible
1989	2134	4.04	S1	C3	Permissible
1990	3563	7.43	S1	C4	Poor
1991	2341	4.62	S1	C4	Poor
1992	2102	3.94	S1	C3	Permissible
1993	2050	4.37	S1	C3	Permissible
1994	1998	7.30	S1	C3	Permissible
1995	2180	6.85	S1	C3	Permissible
1996	3092	6.72	S1	C4	Poor
1997	3180	6.45	S1	C4	Poor
1998	2200	5.54	S1	C3	Permissible
1999	2185	4.19	S1	C3	Permissible
2000	3839	7.96	S1	C4	Poor
2001	3052	6.36	S1	C4	Poor
2002	1749	3.17	S1	C3	Permissible
2003	1859	3.49	S1	C3	Permissible
2004	1747	5.68	S1	C3	Permissible
2005	2161	5.69	S1	C3	Permissible
2006	3703	2.32	S1	C4	Poor
2007	2907	1.51	S1	C4	Poor
2008	3055	1.80	S1	C4	Poor
2009	2983	1.83	S1	C4	Poor

Table 5.4: Annual rate of discharge and revenue of the Udhaim Dam during 1980-2010

Water Year	Annual discharge (m^3/s)	Annual Revenue (Inflow)	
		(10^9 m^3)	(m^3/s)
1980	11.3	0.356357	11.3
1981	26.9	0.848318	26.9
1982	41.5	1.308744	41.5
1983	8.2	0.258595	8.2
1984	14.3	0.450965	14.3
1985	11.8	0.372125	11.8
1986	11.1	0.35005	11.1
1987	16.0	0.504576	16.0
1988	55.4	1.747094	55.4
1989	21.7	0.684331	21.7
1990	15.1	0.476194	15.1
1991	19.2	0.920851	29.2
1992	53.6	1.69033	53.6
1993	47.6	1.501114	47.6
1994	45.9	1.447502	45.9
1995	42.4	1.337126	42.4
1996	31.6	0.99658	31.6
1997	17.4	0.548726	17.4
1998	63.0	1.986768	63.0
1999	41.3	1.302437	41.3
2000	8.3	0.261749	8.3
2001	11.0	0.346896	11.0
2002	33.1	1.043842	33.1
2003	33.3	1.050149	33.3
2004	31.4	0.99023	31.4
2005	30.4	0.958694	30.4
2006	33.0	0.98234	31.1
2007	28.0	0.92344	29.3
2008	12.0	0.35657	11.3
2009	6.0	0.23345	7.4
2010	13.0	0.36546	11.6

Source: Iraqi Ministry of Water Resources, General Authority for Dams and Reservoirs (SOD) management of the Udhaim Dam, (2013) (unpublished data).

CHAPTER SIX:

6. CONCLUSIONS AND RECOMMENDATIONS

This research was conducted on the impact of drought conditions on the environment of the Udhaim River basin in Iraq. The Standardized Precipitation-Evapotranspiration Index was applied to analyze drought development over the period 1980-2010. Trends in SPEI time series in the years 1980-2010 were analyzed. Following this, the impacts of drought on land degradation, water discharge and water quality were investigated.

The following conclusions were derived:

1. The results of the SPEI analysis show that the area witnessed drought conditions ranging from moderate to extreme in all parts of the basin. The most severe and extreme droughts of 3- to 24-month duration were recorded in two periods, namely in the years 1998-1999 and 2007-2010. It was observed that the occurrence of months in which drought is detected in all severity classes was within the range 82-109 and corresponds to about 22-29% of the entire time under analysis. Most often, the drought conditions occur over the basin simultaneously.
2. Droughts of different severity develop during the whole water year, both in the winter and the summer season. Extreme droughts, with a SPEI value below -2, have both short and long durations.
3. Drying trends were detected in the time series of SPEI. In the SPEI-3 monthly series, a drying trend occurred only in March, while it was marked over the whole year in time series representing longer time scales. Series of annual mean values of SPEI-9, SPEI-12, and SPEI-24 show also statistically significant drying trend. Drying signals were detected in case of the other time series. Thus, results showed that in the analyzed period, there were either drying trends or drying signals.
4. Inter-annual variability of meteorological conditions played a significant role in degradation of vegetated area. In the period from 2007 to 2015, the area covered by vegetation has dramatically decreased by over 300 square kilometers and was transformed into unused soil crust areas. This was caused by greatly reduced annual precipitation, increased air temperature and water atmospheric demand, and in turn reduced the recharge of water resources and causing water shortage for vegetation. The

main water body in the Udhaim basin is the Udhaim reservoir which has shrunk by approximately 24 km^2.

5. Human activities have a huge impact on the decrease of vegetation cover. Among these activities are military actions in the study area, causing the partial or complete abandonment of agricultural practices including irrigation. Moreover, the expansion of built-up urban areas from 241 km^2 in 2007 to 308 km^2 in 2015 is an additional stressor to the environment.
6. The flow regime of the Udhaim River has dramatically changed over time since the construction of a large dam in 2003 for agricultural purpose and hydropower generation. The inter-annual and seasonal flow variations have been reduced. The modified flow regime of the Udhaim River, with reduced discharge rates, has a direct impact on the reduced inflow to the Tigris River.
7. The results of the water quality analysis indicate that the water falls into poor or permissible categories. Results confirm that the poor quality of water is connected with the low water inflow, whereas permissible water occur in years with high water inflow to the reservoir. Water of poor quality occurred in the periods 1983-1987 and 2006-2010, which were affected by low revenue. Significant decrease of inflow to the reservoir in some years have had a direct impact on activities such as agriculture, herding, hydropower, and human activity.

This research addresses selected key issues related to the occurrence of droughts and their impacts on the environment in the mesoscale basin of the Udhaim River, the left tributary of the Tigris River. It highlights the importance of water resources, dependent on climate and human activity, and exposed to drought hazard. The study results may help develop sustainable water management strategies important to mitigate water shortage. They can be used as a baseline for further research on improving water management in the region. The main contribution of this research include: (1) multi-year analysis of drought development of variable duration in the mesoscale basin; (2) extended understanding of drying trends explained by using the statistical tests; (3) improved knowledge on the scale of land degradation, through remote sensing data sets and application of advanced GIS techniques; (4) improved understanding of the water quality changes and their linkages with the magnitude of water resources revenue.

The following recommendations are proposed:

1. The available information and data sets on discharge, water levels, and water quality is limited and of raw temporal resolution. It is necessary to install proper network of gauging stations to carry out systematic measurements, in order to trace the decrease in river flows from upstream to downstream.
2. Extensive and further studies on recharge by precipitation require a denser network of reference, ground weather stations. The use of climatic data and drought indices at a resolution of 0.5 latitudinal and longitudinal degrees provides a first insight into the temporal and spatial drought development, but limits analysis to a sub-basin scale. Low-density rain gauge networks do not provide adequate information and do not capture temporal and spatial heterogeneity of precipitation
3. Operational programs should be introduced to acquire information from satellite images to introduce the monitoring of land and water resources using geoinformatic techniques. Conventional hydro-meteorological measurements should be combined with satellite and air-born sensors to provide useful and cost-effective data for mapping and monitoring water resources and the status of vegetation. This is especially important in the case of extensive basins. The Udhaim River basin is one such example.
4. As water is an important element keeping the environment unharmed in this semi-dry basin, the monitoring of water resources, water management, and water protection are a prerequisites for water accessibility and its rational use. Both governmental efforts supported by local communities should be undertaken to enjoy a safe, prosperous and stable life in the basin.

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Annexes:

Annex 1: Monthly and annual precipitation (mm) averaged over the Udhaim River basin based on the the CRU TS3.24.01 dataset

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1980	19	22	72	49	73	72	30	11	0	0	0	0	348
1981	2	40	65	46	79	104	28	24	5	1	0	0	394
1982	15	50	26	51	90	59	61	34	0	0	0	2	387
1983	27	58	35	46	45	69	28	22	1	0	0	0	330
1984	0	35	55	20	25	49	25	16	0	0	0	0	227
1985	25	143	67	89	51	52	40	4	1	0	0	0	473
1986	1	60	61	14	72	28	55	18	1	1	0	0	311
1987	10	70	31	11	48	101	20	11	0	1	1	0	305
1988	38	24	126	71	70	90	54	7	1	1	1	0	482
1989	14	16	70	28	27	63	15	10	0	0	0	0	243
1990	9	54	44	50	51	61	50	6	0	0	0	0	325
1991	12	13	32	40	57	76	23	7	0	0	0	0	260
1992	13	23	83	58	89	63	19	29	1	0	0	0	378
1993	0	67	77	33	54	37	76	46	1	1	0	0	393
1994	14	24	48	69	45	47	37	11	0	0	0	1	297
1995	20	130	58	23	54	22	45	17	1	0	0	2	372
1996	0	18	11	72	48	112	59	8	0	1	0	0	329
1997	2	21	52	56	30	64	34	7	0	0	0	0	268
1998	10	48	45	83	47	76	33	15	1	0	0	0	359
1999	0	11	21	52	43	20	21	2	0	0	1	0	173
2000	7	18	17	84	36	35	28	4	0	0	0	1	231
2001	10	27	81	47	46	49	32	14	0	0	0	1	308
2002	4	14	74	85	39	56	69	11	0	0	0	0	352
2003	12	36	76	45	84	65	24	9	1	0	0	0	352
2004	10	59	74	98	61	28	34	22	0	1	0	0	387
2005	2	47	20	57	55	55	26	14	0	0	0	0	277
2006	3	26	49	66	130	26	66	6	0	0	0	0	373
2007	26	33	40	34	59	41	52	6	1	0	0	0	292
2008	2	7	27	42	31	12	11	6	0	0	0	1	139
2009	19	29	19	16	35	26	38	3	1	0	1	4	189
2010	20	59	31	49	54	28	39	28	0	0	0	0	310
Mean	**11**	**41**	**51**	**51**	**56**	**54**	**38**	**14**	**1**	**0**	**0**	**0**	**318**
2011	3	1	36	63	27	28	66	16	0	0	0	1	241
2012	12	17	49	32	45	29	24	4	1	1	0	0	215
2013	9	50	66	111	26	55	35	17	0	0	0	0	371
2014	1	58	58	54	24	58	15	9	1	0	0	0	277
2015	23	43	40	11	18	31	8	8	1	0	0	1	184

Annex 2: Daily mean air temperature (°C) averaged over the Udhaim River basin based on the CRU TS3.24.01 dataset

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1980	25.0	17.5	10.1	6.7	9.1	13.7	19.3	26.4	31.4	35.9	33.6	28.6	21.4
1981	21.4	16.2	10.8	9.3	12.0	15.0	18.1	24.1	30.3	34.5	33.9	30.0	21.3
1982	24.2	15.7	13.3	9.2	6.0	10.9	20.6	26.4	30.6	32.9	32.5	30.4	21.1
1983	22.7	12.7	5.0	5.8	7.6	11.4	18.5	25.5	30.6	34.0	33.2	29.3	19.7
1984	23.3	18.5	11.2	11.3	11.9	15.6	19.7	23.8	31.9	35.1	32.9	30.1	22.1
1985	23.0	16.0	7.0	10.7	10.3	10.7	20.3	26.2	31.5	33.9	34.4	29.9	21.2
1986	22.4	18.8	9.9	10.5	13.6	13.8	20.1	25.1	29.3	35.7	34.8	31.6	22.1
1987	24.6	15.5	9.0	12.4	14.3	12.3	19.6	27.1	31.9	33.4	33.1	28.5	21.8
1988	22.7	15.1	11.5	8.0	9.8	12.7	17.4	25.2	30.1	33.5	32.2	28.5	20.6
1989	23.9	14.4	10.2	2.8	3.8	13.2	20.8	25.6	30.3	34.5	32.9	28.2	20.1
1990	23.9	15.9	10.8	6.7	10.0	12.8	18.5	24.9	30.5	34.3	32.5	28.6	20.8
1991	22.8	17.4	10.0	9.3	10.1	14.2	21.1	24.5	31.9	33.8	34.5	29.9	21.6
1992	24.1	17.0	8.8	6.6	8.4	10.0	18.6	24.3	29.9	33.5	33.1	28.2	20.2
1993	23.5	15.4	9.3	9.2	10.0	13.3	19.4	24.1	30.7	34.5	33.9	30.0	21.1
1994	23.8	14.4	9.0	11.6	11.1	14.8	22.0	26.4	31.6	34.3	34.0	30.1	21.9
1995	25.0	16.7	8.1	11.3	13.0	14.7	19.2	26.6	31.5	34.2	34.5	29.5	22.0
1996	23.9	15.4	9.4	9.3	13.0	13.9	19.9	27.1	31.6	35.6	34.6	30.7	22.0
1997	23.8	15.8	14.0	10.8	9.6	11.4	19.0	26.1	31.8	34.0	33.9	28.7	21.6
1998	24.9	16.2	11.3	8.2	9.5	13.7	20.6	27.3	33.7	35.6	34.8	30.6	22.2
1999	24.4	19.7	13.8	11.2	13.3	14.6	20.4	28.0	32.8	35.0	35.8	29.9	23.2
2000	25.7	15.8	11.3	9.6	10.6	13.3	21.6	27.3	32.3	36.9	34.9	29.9	22.4
2001	23.2	15.5	11.3	10.0	11.6	16.5	20.5	25.4	31.7	35.2	34.0	29.6	22.0
2002	24.6	15.3	13.9	9.2	12.4	15.4	19.1	25.1	29.6	34.2	33.1	29.2	21.8
2003	25.4	16.1	8.8	10.2	11.4	12.9	20.0	26.4	30.9	34.0	34.4	29.4	21.7
2004	25.7	15.4	10.5	11.7	12.1	16.2	18.6	24.8	30.7	33.5	33.4	29.7	21.9
2005	25.1	15.4	8.1	8.3	9.1	14.3	20.6	25.4	30.5	34.8	34.5	29.3	21.3
2006	23.4	15.6	13.2	9.1	12.4	15.0	19.9	25.4	32.5	34.2	35.2	29.3	22.1
2007	24.7	14.1	5.9	6.9	12.3	12.9	18.2	27.5	31.9	34.3	34.2	30.4	21.1
2008	25.0	16.2	9.3	3.0	9.7	17.9	22.4	26.1	31.7	34.8	35.3	30.5	21.8
2009	24.5	15.7	10.5	9.1	13.9	14.5	18.3	25.8	31.6	33.9	32.8	28.2	21.6
2010	23.9	15.8	13.0	13.7	13.8	17.2	20.3	26.4	32.3	35.1	35.0	31.5	23.2
Mean	**24.0**	**16.0**	**10.3**	**9.1**	**10.8**	**13.8**	**19.8**	**25.8**	**31.3**	**34.5**	**33.9**	**29.6**	**21.6**
2011	25.6	16.7	12.4	8.7	11.9	14.1	19.7	25.7	31.7	34.9	33.9	29.9	22.1
2012	22.9	13.1	9.7	10.0	10.6	11.3	20.9	27.0	33.6	34.1	34.4	30.1	21.5
2013	24.7	17.5	12.2	9.4	13.7	14.6	19.2	25.8	31.5	35.3	34.3	29.2	22.3
2014	22.8	17.3	7.6	8.6	11.1	16.4	21.2	27.6	32.2	35.6	35.7	30.5	22.2
2015	23.0	14.1	11.6	10.8	13.3	15.1	21.0	27.3	33.5	36.0	35.9	31.0	22.7

Annex 3: Daily potential evapotranspiration (mm) averaged over the Udhaim River basin based on the CRU TS3.24.01 dataset

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1980	3.6	2.1	1.1	1.0	1.6	2.6	3.9	6.4	8.2	8.7	7.6	5.7	4.4
1981	3.5	1.8	1.2	1.1	2.0	2.8	4.0	5.8	7.7	8.5	7.5	5.8	4.3
1982	3.7	1.9	1.3	1.2	1.4	2.4	4.2	5.9	7.9	8.3	7.3	5.7	4.3
1983	3.3	1.6	0.8	1.0	1.6	2.5	4.2	5.7	7.9	8.6	7.4	5.7	4.2
1984	3.7	2.0	1.2	1.4	2.1	3.0	4.2	5.6	8.2	8.3	7.4	5.9	4.4
1985	3.5	1.7	0.8	1.4	1.8	2.5	4.4	6.5	8.3	8.6	7.5	5.9	4.4
1986	3.6	2.2	1.1	1.4	2.2	2.9	4.1	6.0	7.6	8.8	7.5	5.9	4.4
1987	3.6	1.7	1.1	1.6	2.2	2.5	4.5	6.5	8.3	8.4	7.4	5.6	4.5
1988	3.3	1.9	1.2	1.1	1.6	2.5	3.7	6.2	7.5	8.2	7.1	5.7	4.2
1989	3.6	1.8	1.0	0.7	1.1	2.6	4.7	6.4	8.1	8.7	7.5	5.6	4.3
1990	3.6	1.8	1.1	1.0	1.8	2.8	4.0	6.5	8.1	8.4	7.5	5.8	4.4
1991	3.5	2.0	1.0	1.2	1.8	2.8	4.4	5.9	8.0	8.3	7.5	5.8	4.4
1992	3.5	2.0	0.9	1.1	1.6	2.4	4.3	5.7	7.5	8.5	7.3	5.5	4.2
1993	3.8	1.8	1.1	1.3	1.9	2.9	4.2	5.6	7.9	8.4	7.4	5.9	4.4
1994	3.7	1.7	1.0	1.4	1.9	3.0	4.8	6.3	8.1	8.5	7.6	5.7	4.5
1995	3.6	1.9	1.0	1.4	2.2	3.1	4.2	6.4	8.0	8.6	7.8	5.6	4.5
1996	3.8	1.9	1.2	1.2	2.1	2.9	4.4	6.2	8.0	8.3	7.4	5.8	4.4
1997	3.5	1.9	1.4	1.4	1.8	2.4	4.1	6.2	8.0	8.2	7.6	5.6	4.3
1998	3.5	1.9	1.2	1.0	1.7	2.7	4.2	6.3	8.4	8.4	7.6	5.8	4.4
1999	3.8	2.4	1.5	1.3	2.2	2.9	4.3	6.6	8.2	8.8	7.7	5.8	4.6
2000	3.9	1.9	1.2	1.3	1.9	2.9	4.5	6.4	8.2	8.8	7.5	5.8	4.5
2001	3.6	1.9	1.2	1.4	2.1	3.3	4.3	5.9	8.2	8.6	7.5	5.7	4.5
2002	3.7	1.8	1.4	1.2	2.0	3.0	3.8	6.0	7.7	8.2	7.4	5.7	4.3
2003	3.7	1.7	1.0	1.3	1.9	2.6	4.2	6.1	7.9	8.6	7.7	5.8	4.4
2004	3.7	1.8	1.1	1.5	2.0	3.2	4.0	5.8	8.0	8.4	7.6	5.8	4.4
2005	3.8	1.7	1.0	1.2	1.6	2.8	4.5	6.0	7.8	8.6	7.4	5.7	4.3
2006	3.6	1.8	1.4	1.2	2.1	3.1	4.0	6.0	8.3	8.4	7.5	5.7	4.4
2007	3.4	1.7	0.8	1.1	2.0	2.7	3.5	5.9	8.2	8.4	7.4	5.9	4.3
2008	3.7	1.9	1.0	0.7	1.8	3.5	4.7	6.1	8.1	8.5	7.5	5.6	4.4
2009	3.6	1.7	1.2	1.3	2.1	2.8	3.8	6.0	7.6	8.4	7.3	5.3	4.3
2010	3.4	1.7	1.2	1.6	2.1	3.1	4.0	5.8	8.1	8.8	7.4	5.9	4.4
Mean	**3.6**	**1.9**	**1.1**	**1.2**	**1.9**	**2.8**	**4.2**	**6.1**	**8.0**	**8.5**	**7.5**	**5.7**	**4.4**
2011	3.7	2.0	1.3	1.1	2.0	2.9	3.8	5.8	8.0	8.4	7.4	5.6	4.3
2012	3.3	1.6	1.1	1.3	1.9	2.5	4.5	6.1	8.2	8.4	7.5	5.7	4.3
2013	3.5	1.8	1.2	1.2	2.2	3.0	4.3	5.9	8.1	8.8	7.6	5.6	4.4
2014	3.5	1.8	1.0	1.2	2.0	3.1	4.6	6.3	8.1	8.7	7.6	5.6	4.5
2015	3.2	1.6	1.1	1.4	2.1	3.0	4.6	6.3	8.2	8.6	7.6	5.6	4.4

Annex 4: SPEI-3 averaged over the Udhaim River basin, based on data from SPEIbase, version 2.5

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1980	0.341	-0.146	0.704	0.617	0.526	0.004	-0.875	-0.6	-1.481	-1.317	-1.093	-0.235	-0.296
1981	0.203	0.054	0.612	1.288	1.231	1.146	-0.135	1.322	1.33	-0.376	0.647	0.703	0.669
1982	-0.34	-0.539	0.078	0.76	1.197	1.081	1.332	1.624	-0.143	1.034	1.951	1.382	0.785
1983	0.639	-0.19	-1.028	-0.17	-0.286	0.229	-0.416	0.805	-0.078	-0.735	-1.539	-0.607	-0.281
1984	-0.331	-1.058	-1.749	-1.784	-1.388	-0.701	-0.839	0.205	-0.401	-0.234	1.697	2.564	-0.335
1985	2.523	2.314	0.945	0.565	-0.297	-0.516	-0.706	-1.277	-0.777	-1.357	-1.386	0.585	0.051
1986	0.614	-0.394	-0.493	-1.321	0.031	-0.344	0.636	0.532	0.122	-1.366	0.024	1.155	-0.067
1987	0.294	-1.014	-2.014	-0.21	0.352	0.556	-1.351	-0.431	0.071	0.972	2.382	0.549	0.013
1988	1.848	1.413	1.839	1.315	1.292	1.04	0.189	-0.753	1.04	1.207	0.727	-0.844	0.859
1989	-0.046	-0.927	-1.032	-1.187	-1.235	-0.802	-1.593	-0.641	-1.417	-0.793	-0.119	0.66	-0.761
1990	0.175	0	-0.528	-0.114	0.198	0.129	-0.206	-1.211	-0.885	-0.738	0.301	-1.112	-0.333
1991	-1.446	-1.765	-0.97	0.128	0.041	-0.21	-1.39	-1.008	-0.707	-0.704	0.492	-0.526	-0.672
1992	0.493	0.348	1.333	0.951	0.434	-0.02	-0.513	1.33	0.929	0.298	-1.505	0.803	0.407
1993	1.147	0.667	-0.063	-1.078	0.285	1.161	2.03	2.201	0.555	-0.373	0.596	-0.383	0.562
1994	-0.443	-0.18	-0.085	-0.189	-0.67	-0.603	-0.571	-0.472	-1.059	-0.206	1.282	2.372	-0.069
1995	2.163	1.243	-0.837	-1.68	-0.857	-0.935	0.123	0.266	-0.852	0.032	-1.231	-1.34	-0.325
1996	-2.323	-1.33	-0.933	1.329	1.349	1.554	0.268	-0.739	-0.081	0.209	-1.166	-1.119	-0.249
1997	0.209	-0.499	-0.706	-0.42	-0.637	-0.215	-0.828	-0.966	-0.362	0.028	0.264	0.494	-0.303
1998	0.121	0.684	0.276	0.87	0.026	0.309	-0.576	0.044	-1.121	-0.816	-1.565	-1.84	-0.299
1999	-2.239	-1.826	-1.352	-1.301	-1.725	-2.213	-1.705	-1.819	-1.427	-1.162	-0.536	-1.161	-1.539
2000	-1.945	-0.83	-0.774	-0.353	-1.398	-1.484	-1.274	-1.498	-1.475	-0.622	0.276	-0.399	-0.981
2001	0.583	0.239	0.301	-0.643	-0.709	-0.554	-0.56	-0.008	-1.189	-0.188	-0.718	-1.391	-0.403
2002	-0.343	0.517	0.679	0.272	0.24	0.68	0.872	-0.367	0.26	0.151	0.374	0.056	0.283
2003	0.686	0.233	0.864	0.559	0.404	-0.453	-1.2	-0.634	-0.772	-1.598	-0.075	0.837	-0.096
2004	1.128	1.577	1.39	0.429	-0.796	-0.925	-0.17	0.739	-0.561	-0.675	-1.344	0.104	0.075
2005	-1.026	-0.657	-0.884	-0.012	-0.657	-0.521	-0.878	0.019	-0.451	-0.664	-1.112	-0.844	-0.641
2006	-0.759	-0.177	1.579	1.167	1.414	-0.442	0.548	-1.084	-1.33	-0.603	1.754	0.484	0.213
2007	-0.054	-1.145	-0.859	-0.853	-0.069	-0.418	-0.026	-0.904	-0.214	-0.584	-1.306	-2.031	-0.705
2008	-2.139	-2.015	-1.73	-1.956	-2.393	-2.654	-1.918	-1.147	-0.944	0.083	1.308	0.128	-1.281
2009	-1.107	-2.372	-2.541	-2.152	-1.407	-1.452	-0.745	-1.333	1.012	2.166	1.677	1.293	-0.580
2010	0.353	-0.215	-0.83	-0.929	-0.845	-0.578	0.313	1.183	-1.226	-1.587	-1.147	-2.31	-0.652

Annex 5: SPEI-6 averaged over the Udhaim River basin, based on data from SPEIbase, version 2.5

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1980	0.596	0.195	0.408	0.089	0.34	-0.043	-0.919	-1.047	-0.306	0.163	-0.14	0.334	-0.028
1981	1.037	0.822	0.994	1.027	1.411	1.24	-0.143	1.236	0.841	-0.344	-0.417	0.34	0.670
1982	0.363	0.48	0.629	1.169	1.443	1.056	1.37	2.109	1.351	0.678	0.301	-0.002	0.912
1983	0.225	-0.358	-0.601	-0.381	-0.136	0.224	-0.443	-0.203	-0.605	-0.352	-1.321	-1.73	-0.473
1984	-1.535	-1.527	-1.487	-1.727	-1.259	-0.712	-0.853	1.159	2.558	2.524	2.391	2.249	0.148
1985	2.003	1.706	0.339	0.113	-0.562	-0.521	-0.753	-1.605	0.563	0.58	-0.629	-0.179	0.088
1986	-0.622	-0.275	-0.589	-0.825	0.089	-0.334	0.596	0.303	1.147	0.266	-1.01	-0.997	-0.188
1987	-0.01	-0.423	-1.03	-0.799	0.2	0.579	-1.278	1.526	0.563	1.867	1.743	1.732	0.389
1988	1.872	1.618	1.813	1.151	1.107	1.077	0.222	-0.134	1.077	-0.021	-0.788	-1.284	0.643
1989	-0.928	-1.369	-1.137	-1.582	-1.28	-0.834	-1.595	-0.588	0.604	0.156	-0.025	-0.163	-0.728
1990	-0.019	0.064	-0.353	-0.256	-0.09	0.094	-0.242	-0.703	-1.15	-1.467	-1.7	-1.324	-0.596
1991	-0.728	-1.05	-0.809	-0.551	-0.203	-0.244	-1.411	-0.459	-0.576	0.467	0.407	0.909	-0.354
1992	0.924	0.434	0.908	0.557	0.681	-0.007	-0.525	0.367	0.807	1.138	0.448	0.291	0.502
1993	-0.067	0.534	0.598	0.291	0.89	1.164	2.021	2.024	-0.348	-0.455	-0.078	-0.328	0.521
1994	-0.418	-0.597	-0.463	-0.459	-0.754	-0.631	-0.559	0.457	2.358	2.17	1.371	1.186	0.305
1995	0.545	0.348	-1.091	-1.321	-0.778	-0.95	0.165	-0.521	-1.357	-2.264	-1.529	-1.386	-0.845
1996	-0.165	0.191	0.429	1.197	1.156	1.536	0.272	-1.178	-1.108	-0.794	-0.702	-1.156	-0.027
1997	-0.794	-0.764	-0.643	-0.752	-0.813	-0.239	-0.844	-0.548	0.456	0.101	0.675	0.398	-0.314
1998	0.675	0.411	0.272	0.448	-0.027	0.278	-0.604	-0.837	-1.845	-2.243	-2.09	-1.883	-0.620
1999	-2.127	-2.107	-1.959	-1.703	-1.86	-2.206	-1.695	-1.521	-1.181	-1.936	-0.909	-1.19	-1.700
2000	-1.339	-1.413	-1.319	-0.884	-1.547	-1.505	-1.257	-0.892	-0.457	0.581	0.268	-0.011	-0.815
2001	-0.146	-0.359	-0.178	-0.814	-0.706	-0.583	-0.545	-0.463	-1.422	-0.338	0.399	-0.041	-0.433
2002	-0.021	0.422	0.765	0.552	0.09	0.659	0.849	-0.13	0.029	0.672	0.272	0.679	0.403
2003	0.733	0.337	0.309	-0.087	0.216	-0.469	-1.244	-0.559	0.804	1.096	1.537	1.449	0.344
2004	0.918	0.697	0.542	0.219	-0.609	-0.931	-0.19	-0.17	0.076	-1.036	-0.89	-0.747	-0.177
2005	-0.603	-0.729	-0.914	-0.451	-0.729	-0.534	-0.896	-0.627	-0.853	-0.776	-0.366	1.074	-0.534
2006	0.499	0.834	0.945	1.149	1.182	-0.482	0.507	0.552	0.422	-0.083	-0.681	-0.509	0.361
2007	-0.672	-0.773	-0.85	-0.749	-0.286	-0.407	-0.049	-1.344	-1.973	-2.136	-2.241	-2.22	-1.142
2008	-2.52	-2.59	-2.329	-2.206	-2.325	-2.654	-1.883	0.08	0.074	-1.096	-2.064	-2.031	-1.795
2009	-2.178	-2.177	-2.237	-1.976	-1.533	-1.402	-0.552	0.351	1.309	0.477	0.184	0.072	-0.805
2010	-0.503	-0.729	-0.905	-0.653	-0.53	-0.614	0.254	0.356	-2.314	-2.025	-1.556	-1.837	-0.921

Annex 6: SPEI-9 averaged over the Udhaim River basin, based on data from SPEIbase, version 2.5

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1980	0.202	0.076	0.38	0.065	0.156	-0.273	-0.373	-0.281	0.3	1.02	0.706	0.791	0.231
1981	0.853	0.96	1.058	1.025	1.447	1.26	-0.375	-0.042	0.43	0.36	0.527	0.751	0.688
1982	0.749	0.695	0.614	1.192	1.705	1.503	1.156	0.671	-0.021	0.25	-0.055	0.032	0.708
1983	0.008	-0.259	-0.601	-0.392	-0.364	-0.236	-0.527	-1.073	-1.723	-1.543	-1.653	-1.55	-0.826
1984	-1.551	-1.433	-1.49	-1.733	-0.929	1.757	2.007	2.345	2.245	2.003	1.831	1.724	0.565
1985	1.725	1.58	0.331	0.091	-0.758	-0.172	0.053	-0.893	-0.189	-0.644	-0.424	-0.378	0.027
1986	-0.359	-0.23	-0.584	-0.838	0.073	0.385	0.484	-0.872	-0.992	-0.026	-0.433	-0.503	-0.325
1987	-0.503	-0.496	-1.01	-0.768	0.787	0.658	1.086	1.639	1.74	1.887	1.863	1.777	0.722
1988	1.779	1.529	1.829	1.164	1.16	0.435	0.029	-0.932	0.435	-0.912	-1.294	-1.317	0.325
1989	-1.318	-1.388	-1.153	-1.588	-1.284	-0.356	-0.763	-0.18	-0.192	-0.03	0.039	-0.133	-0.696
1990	-0.145	-0.124	-0.372	-0.271	-0.06	-0.567	-1.23	-1.899	-1.345	-0.745	-1.021	-1.1	-0.740
1991	-1.1	-1.14	-0.825	-0.567	-0.135	-0.563	-0.381	0.188	0.889	0.911	0.466	0.621	-0.136
1992	0.634	0.59	0.91	0.55	0.459	0.359	0.649	0.706	0.297	-0.074	0.388	0.769	0.520
1993	0.775	0.91	0.606	0.285	0.938	0.717	0.985	0.618	-0.313	-0.425	-0.539	-0.599	0.330
1994	-0.593	-0.663	-0.481	-0.453	-0.508	1.519	1.687	1.255	1.169	0.547	0.487	0.479	0.370
1995	0.467	0.332	-1.1	-1.297	-0.939	-1.42	-1.624	-1.414	-1.399	-0.145	0.062	-0.064	-0.712
1996	-0.106	0.051	0.42	1.198	0.99	0.82	-0.479	-0.855	-1.159	-0.782	-0.883	-0.972	-0.146
1997	-0.782	-0.873	-0.655	-0.761	-0.792	0.012	-0.387	0.47	0.378	0.665	0.407	0.372	-0.162
1998	0.37	0.362	0.254	0.435	-0.261	-0.735	-1.923	-2.007	-1.893	-2.133	-2.211	-2.219	-0.997
1999	-2.225	-2.146	-1.958	-1.704	-1.893	-2.171	-2.224	-1.267	-1.2	-1.339	-1.448	-1.539	-1.760
2000	-1.539	-1.514	-1.333	-0.88	-1.501	-1.412	-0.24	-0.038	-0.04	-0.147	-0.342	-0.353	-0.778
2001	-0.375	-0.383	-0.197	-0.808	-0.807	-1.186	-0.605	0.348	-0.067	-0.019	0.338	0.249	-0.293
2002	0.235	0.321	0.754	0.543	0.122	0.446	0.899	0.155	0.667	0.726	0.352	0.233	0.454
2003	0.24	0.211	0.295	-0.112	0.185	0.04	0.289	1.405	1.438	0.898	0.673	0.728	0.524
2004	0.724	0.743	0.531	0.213	-0.799	-0.763	-0.894	-0.681	-0.757	-0.611	-0.868	-0.849	-0.334
2005	-0.844	-0.737	-0.92	-0.461	-0.737	-0.927	-1.065	-0.386	1.062	0.488	0.726	0.567	-0.270
2006	0.559	0.663	0.92	1.133	1.429	-0.2	0.18	-0.91	-0.541	-0.689	-0.518	-0.642	0.115
2007	-0.633	-0.877	-0.843	-0.755	-0.482	-1.324	-1.608	-2.347	-2.201	-2.516	-2.656	-2.556	-1.567
2008	-2.559	-2.506	-2.331	-2.202	-2.124	-1.958	-1.793	-2.236	-2.046	-2.167	-2.017	-2.032	-2.164
2009	-2.032	-2.165	-2.212	-1.91	-1.202	-0.251	-0.061	-0.1	0.092	-0.424	-0.484	-0.302	-0.921
2010	-0.367	-0.535	-0.923	-0.676	-0.695	-1.563	-1.35	-1.166	-1.856	-1.979	-1.465	-1.384	-1.163

Annex 7: SPEI-12 averaged over the Udhaim River basin, based on data from SPEIbase, version 2.5

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1980	0.185	-0.046	0.201	0.089	0.066	0.114	0.655	0.617	0.769	0.836	0.85	0.851	0.432
1981	0.852	1.009	1.131	0.621	0.727	0.9	0.227	0.71	0.814	0.747	0.736	0.738	0.768
1982	0.77	0.946	1.045	1.186	1.114	0.516	0.697	0.22	0.02	0.03	0.025	0.03	0.550
1983	-0.001	-0.413	-0.787	-0.519	-0.918	-1.251	-1.545	-1.545	-1.551	-1.555	-1.547	-1.552	-1.099
1984	-1.556	-1.241	0.369	0.528	1.416	1.789	1.784	1.828	1.716	1.721	1.715	1.715	0.982
1985	1.712	1.491	0.437	0.33	-0.823	-0.532	-0.888	-0.598	-0.382	-0.378	-0.372	-0.373	-0.031
1986	-0.371	-0.243	-0.101	-0.562	-0.605	-1.019	0.14	-0.377	-0.499	-0.516	-0.506	-0.486	-0.429
1987	-0.479	-0.075	-0.763	0.595	1.38	1.717	1.53	1.813	1.784	1.793	1.791	1.789	1.073
1988	1.784	1.576	1.496	0.872	0.282	-0.416	-0.827	-1.382	-0.416	-1.304	-1.318	-1.329	-0.082
1989	-1.323	-1.408	-0.863	-1.233	-0.967	-0.663	-0.659	-0.064	-0.153	-0.155	-0.147	-0.151	-0.649
1990	-0.157	-0.107	-0.728	-0.919	-1.093	-1.039	-0.813	-1.172	-1.116	-1.111	-1.112	-1.112	-0.873
1991	-1.112	-1.104	-0.954	-0.231	0.058	0.526	0.367	0.326	0.605	0.62	0.618	0.624	0.029
1992	0.629	0.453	1.043	0.978	0.655	0.099	-0.307	0.569	0.774	0.77	0.777	0.774	0.601
1993	0.77	0.956	0.374	-0.044	0.491	0.354	0.532	-0.049	-0.586	-0.598	-0.608	-0.613	0.082
1994	-0.589	-0.512	0.977	1.108	0.491	0.614	0.261	0.409	0.463	0.468	0.467	0.465	0.385
1995	0.482	0.215	-1.393	-1.939	-1.425	-1.52	-0.156	0.079	-0.076	-0.089	-0.074	-0.069	-0.497
1996	-0.102	-0.071	-0.022	0.573	0.37	0.079	-0.674	-0.987	-0.977	-0.971	-0.978	-0.98	-0.395
1997	-0.971	-0.871	-0.452	-0.586	-0.156	0.073	0.287	0.27	0.36	0.36	0.358	0.357	-0.081
1998	0.359	0.21	-0.373	-0.759	-1.245	-1.325	-2.061	-2.198	-2.229	-2.225	-2.227	-2.217	-1.358
1999	-2.226	-2.187	-2.06	-2.074	-1.833	-1.899	-1.766	-1.647	-1.547	-1.537	-1.54	-1.549	-1.822
2000	-1.536	-1.504	-1.364	-0.46	-0.993	-0.877	-0.65	-0.535	-0.372	-0.374	-0.367	-0.369	-0.783
2001	-0.371	-0.464	-0.645	-0.838	-0.287	-0.454	-0.294	0.308	0.231	0.236	0.237	0.239	-0.175
2002	0.229	0.343	0.642	0.709	0.15	0.789	0.916	0.278	0.225	0.232	0.226	0.222	0.413
2003	0.221	0.193	0.512	0.476	1.179	0.949	0.416	0.576	0.719	0.705	0.717	0.718	0.615
2004	0.719	0.622	0.448	-0.37	-0.995	-1.107	-0.676	-0.762	-0.856	-0.849	-0.863	-0.854	-0.462
2005	-0.851	-0.851	-1.125	-0.756	-0.851	0.531	0.092	0.695	0.558	0.549	0.551	0.544	-0.076
2006	0.546	0.876	0.94	0.846	0.396	-0.748	-0.494	-0.672	-0.664	-0.647	-0.64	-0.637	-0.075
2007	-0.638	-1.009	-1.348	-1.528	-1.48	-1.833	-2.227	-2.721	-2.554	-2.553	-2.556	-2.558	-1.917
2008	-2.556	-2.401	-2.099	-2.161	-2.629	-2.492	-2.451	-2.129	-2.046	-2.023	-2.022	-2.011	-2.252
2009	-1.979	-1.991	-1.578	-1.429	-1.036	-0.77	-0.719	-0.663	-0.285	-0.302	-0.307	-0.321	-0.948
2010	-0.386	-0.655	-1.473	-1.421	-1.285	-1.663	-1.684	-1.285	-1.401	-1.395	-1.391	-1.388	-1.286

Annex 8: SPEI-24 averaged over the Udhaim River basin, based on data from SPEIbase, version 2.5

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Annual
1980	0.649	0.616	0.89	0.455	0.489	0.648	0.536	0.805	1.003	1.003	1.007	1.009	0.759
1981	1.028	1.245	1.438	1.171	1.151	0.895	0.566	0.551	0.518	0.476	0.466	0.471	0.831
1982	0.472	0.333	0.169	0.486	0.159	-0.542	-0.628	-0.932	-1.08	-1.08	-1.077	-1.077	-0.400
1983	-1.098	-1.126	-0.35	-0.01	0.421	0.467	0.304	0.416	0.227	0.227	0.228	0.224	-0.006
1984	0.223	0.237	0.489	0.543	0.475	0.947	0.758	1.004	1.013	1.021	1.019	1.018	0.729
1985	1.018	0.892	0.17	-0.175	-0.949	-1.019	-0.53	-0.688	-0.634	-0.642	-0.631	-0.619	-0.317
1986	-0.615	-0.272	-0.632	0.014	0.582	0.551	1.118	1.097	1	1.001	1.006	1.014	0.489
1987	1.015	1.058	0.574	0.941	1.086	0.955	0.577	0.523	0.505	0.504	0.492	0.482	0.726
1988	0.486	0.209	0.51	-0.279	-0.493	-0.724	-0.983	-0.991	-0.724	-1.014	-1.019	-1.028	-0.504
1989	-1.029	-1.054	-1.086	-1.406	-1.332	-1.106	-0.973	-0.857	-0.888	-0.887	-0.883	-0.886	-1.032
1990	-0.89	-0.855	-1.142	-0.781	-0.717	-0.378	-0.332	-0.61	-0.392	-0.378	-0.381	-0.376	-0.603
1991	-0.372	-0.495	0.038	0.5	0.428	0.381	-0.01	0.515	0.857	0.865	0.869	0.871	0.371
1992	0.87	0.884	0.916	0.614	0.699	0.269	0.1	0.278	0.094	0.083	0.083	0.078	0.414
1993	0.09	0.28	0.861	0.701	0.587	0.598	0.462	0.166	-0.132	-0.137	-0.143	-0.148	0.265
1994	-0.12	-0.258	-0.339	-0.678	-0.65	-0.669	0.024	0.25	0.204	0.199	0.209	0.211	-0.135
1995	0.201	0.03	-1.019	-1.057	-0.749	-1.011	-0.582	-0.651	-0.75	-0.756	-0.752	-0.749	-0.654
1996	-0.772	-0.682	-0.386	-0.025	0.096	0.069	-0.297	-0.528	-0.47	-0.468	-0.474	-0.475	-0.368
1997	-0.468	-0.503	-0.618	-0.906	-0.962	-0.88	-1.272	-1.346	-1.371	-1.372	-1.375	-1.368	-1.037
1998	-1.369	-1.417	-1.653	-1.879	-1.923	-1.988	-2.301	-2.289	-2.288	-2.284	-2.288	-2.288	-1.997
1999	-2.283	-2.234	-2.121	-1.731	-1.8	-1.773	-1.569	-1.43	-1.3	-1.297	-1.295	-1.302	-1.678
2000	-1.295	-1.322	-1.356	-0.873	-0.868	-0.882	-0.654	-0.208	-0.151	-0.15	-0.144	-0.143	-0.671
2001	-0.153	-0.141	-0.059	-0.105	-0.133	0.206	0.394	0.31	0.242	0.251	0.248	0.246	0.109
2002	0.237	0.291	0.723	0.755	0.861	1.093	0.828	0.49	0.575	0.571	0.576	0.574	0.631
2003	0.572	0.482	0.591	0.057	0.167	-0.133	-0.212	-0.171	-0.133	-0.14	-0.14	-0.132	0.067
2004	-0.13	-0.205	-0.537	-0.764	-1.068	-0.432	-0.427	-0.084	-0.25	-0.253	-0.261	-0.259	-0.389
2005	-0.257	-0.015	-0.175	0.052	-0.015	-0.178	-0.311	-0.027	-0.122	-0.118	-0.111	-0.114	-0.116
2006	-0.115	-0.127	-0.339	-0.534	-0.765	-1.656	-1.775	-2.131	-2.078	-2.072	-2.073	-2.073	-1.312
2007	-2.068	-2.128	-2.138	-2.332	-2.526	-2.597	-2.753	-2.797	-2.704	-2.696	-2.7	-2.697	-2.511
2008	-2.674	-2.582	-2.253	-2.284	-2.316	-2.117	-2.041	-1.782	-1.575	-1.571	-1.574	-1.574	-2.029
2009	-1.584	-1.718	-1.914	-1.824	-1.489	-1.568	-1.551	-1.273	-1.149	-1.157	-1.157	-1.163	-1.462
2010	-1.196	-1.276	-1.608	-1.483	-1.642	-1.718	-1.71	-1.785	-1.914	-1.907	-1.897	-1.899	-1.670

Annex 9: Correlation coefficients between values of SPEI-3 at different grid cells in the years 1980-2010

Variable	Correlations (Grid-cells-SPEI-3) All correlations are significant at p < .05000 N=372												
	St-7	St-8	St-11	St-12	St-13	St-14	St-16	St-17	St-18	St-19	St-22	St-23	St-24
St-7		0.944	0.931	0.933	0.920	0.870	0.884	0.881	0.895	0.797	0.881	0.750	0.750
St-8	0.944		0.969	0.982	0.981	0.946	0.924	0.932	0.866	0.807	0.932	0.816	0.749
St-11	0.931	0.969		0.991	0.968	0.910	0.972	0.957	0.860	0.780	0.957	0.826	0.739
St-12	0.933	0.982	0.991		0.987	0.943	0.973	0.970	0.891	0.823	0.970	0.858	0.779
St-13	0.920	0.981	0.968	0.987		0.968	0.960	0.974	0.910	0.855	0.974	0.888	0.806
St-14	0.870	0.946	0.910	0.943	0.968		0.909	0.936	0.923	0.902	0.936	0.921	0.852
St-16	0.884	0.924	0.972	0.973	0.960	0.909		0.990	0.882	0.815	0.990	0.890	0.790
St-17	0.881	0.932	0.957	0.970	0.974	0.936	0.990		0.906	0.855	1.000	0.922	0.828
St-18	0.895	0.866	0.860	0.891	0.910	0.923	0.882	0.906		0.952	0.906	0.899	0.923
St-19	0.797	0.807	0.780	0.823	0.855	0.902	0.815	0.855	0.952		0.855	0.891	0.977
St-22	0.881	0.932	0.957	0.970	0.974	0.936	0.990	1.000	0.906	0.855		0.922	0.828
St-23	0.750	0.816	0.826	0.858	0.888	0.921	0.890	0.922	0.899	0.891	0.922		0.888
St-24	0.750	0.749	0.739	0.779	0.806	0.852	0.790	0.828	0.923	0.977	0.828	0.888	

Annex 10: Correlation coefficients between values of SPEI-6 at different grid cells in years 1980-2010

Variable	Correlations (Grid-cells-SPEI-6) All correlations are significant at p < ,05000 N=372												
	St-7	St-8	St-11	St-12	St-13	St-14	St-16	St-17	St-18	St-19	St-22	St-23	St-24
St-7		0.990	0.984	0.981	0.965	0.929	0.950	0.938	0.918	0.869	0.938	0.830	0.821
St-8	0.990		0.973	0.985	0.985	0.965	0.947	0.950	0.941	0.909	0.950	0.866	0.858
St-11	0.984	0.973		0.993	0.971	0.930	0.986	0.971	0.941	0.887	0.971	0.877	0.854
St-12	0.981	0.985	0.993		0.992	0.965	0.986	0.985	0.968	0.927	0.985	0.911	0.890
St-13	0.965	0.985	0.971	0.992		0.990	0.971	0.985	0.983	0.959	0.985	0.935	0.920
St-14	0.929	0.965	0.930	0.965	0.990		0.937	0.968	0.984	0.982	0.968	0.948	0.942
St-16	0.950	0.947	0.986	0.986	0.971	0.937		0.992	0.968	0.920	0.992	0.931	0.903
St-17	0.938	0.950	0.971	0.985	0.985	0.968	0.992		0.990	0.958	1.000	0.964	0.939
St-18	0.918	0.941	0.941	0.968	0.983	0.984	0.968	0.990		0.987	0.990	0.980	0.969
St-19	0.869	0.909	0.887	0.927	0.959	0.982	0.920	0.958	0.987		0.958	0.981	0.982
St-22	0.938	0.950	0.971	0.985	0.985	0.968	0.992	1.000	0.990	0.958		0.964	0.939
St-23	0.830	0.866	0.877	0.911	0.935	0.948	0.931	0.964	0.980	0.981	0.964		0.981
St-24	0.821	0.858	0.854	0.890	0.920	0.942	0.903	0.939	0.969	0.982	0.939	0.981	

Annex 11: Correlation coefficients between values of SPEI-9 at different grid cells in the years 1980-2010

Variable	Correlations (Grid-cells-SPEI-9) All correlations are significant at p < ,05000 N=372												
	St-7	St-8	St-11	St-12	St-13	St-14	St-16	St-17	St-18	St-19	St-22	St-23	St-24
St-7		0.991	0.987	0.982	0.964	0.929	0.955	0.939	0.915	0.869	0.939	0.830	0.822
St-8	0.991		0.978	0.987	0.984	0.964	0.954	0.952	0.940	0.909	0.952	0.865	0.859
St-11	0.987	0.978		0.994	0.974	0.938	0.987	0.971	0.944	0.896	0.971	0.879	0.862
St-12	0.982	0.987	0.994		0.993	0.970	0.988	0.985	0.969	0.933	0.985	0.912	0.896
St-13	0.964	0.984	0.974	0.993		0.991	0.976	0.987	0.983	0.961	0.987	0.937	0.923
St-14	0.929	0.964	0.938	0.970	0.991		0.949	0.974	0.986	0.982	0.974	0.952	0.945
St-16	0.955	0.954	0.987	0.988	0.976	0.949		0.993	0.973	0.933	0.993	0.935	0.915
St-17	0.939	0.952	0.971	0.985	0.987	0.974	0.993		0.993	0.966	1.000	0.965	0.945
St-18	0.915	0.940	0.944	0.969	0.983	0.986	0.973	0.993		0.989	0.993	0.983	0.972
St-19	0.869	0.909	0.896	0.933	0.961	0.982	0.933	0.966	0.989		0.966	0.985	0.984
St-22	0.939	0.952	0.971	0.985	0.987	0.974	0.993	1.000	0.993	0.966		0.965	0.945
St-23	0.830	0.865	0.879	0.912	0.937	0.952	0.935	0.965	0.983	0.985	0.965		0.985
St-24	0.822	0.859	0.862	0.896	0.923	0.945	0.915	0.945	0.972	0.984	0.945	0.985	

Annex 12: Correlation coefficients between values of SPEI-12 at different grid cells in the years 1980-2010

Variable	Correlations (Grid-cells-SPEI-12) Marked correlations are significant at p<.05000 N=372												
	St-7	St-8	St-11	St-12	St-13	St-14	St-16	St-17	St-18	St-19	St-22	St-23	St-24
St-7		0.991	0.988	0.982	0.963	0.929	0.958	0.941	0.917	0.871	0.941	0.838	0.831
St-8	0.991		0.980	0.988	0.984	0.964	0.958	0.956	0.943	0.913	0.956	0.876	0.870
St-11	0.988	0.980		0.994	0.975	0.941	0.988	0.973	0.947	0.900	0.973	0.887	0.870
St-12	0.982	0.988	0.994		0.993	0.971	0.989	0.987	0.971	0.936	0.987	0.920	0.903
St-13	0.963	0.984	0.975	0.993		0.992	0.978	0.988	0.985	0.964	0.988	0.944	0.930
St-14	0.929	0.964	0.941	0.971	0.992		0.953	0.976	0.988	0.984	0.976	0.959	0.953
St-16	0.958	0.958	0.988	0.989	0.978	0.953		0.993	0.974	0.935	0.993	0.938	0.918
St-17	0.941	0.956	0.973	0.987	0.988	0.976	0.993		0.993	0.967	1.000	0.968	0.948
St-18	0.917	0.943	0.947	0.971	0.985	0.988	0.974	0.993		0.990	0.993	0.985	0.974
St-19	0.871	0.913	0.900	0.936	0.964	0.984	0.935	0.967	0.990		0.967	0.987	0.986
St-22	0.941	0.956	0.973	0.987	0.988	0.976	0.993	1.000	0.993	0.967		0.968	0.948
St-23	0.838	0.876	0.887	0.920	0.944	0.959	0.938	0.968	0.985	0.987	0.968		0.985
St-24	0.831	0.870	0.870	0.903	0.930	0.953	0.918	0.948	0.974	0.986	0.948	0.985	

Annex 13: Correlation coefficients between values of SPEI-24 at different grid cells in the years 1980-2010

Variable	Correlations (Grid-cells-SPEI-24) Marked correlations are significant at p<.05000 N=372												
	St-7	St-8	St-11	St-12	St-13	St-14	St-16	St-17	St-18	St-19	St-22	St-23	St-24
St-7		0.991	0.984	0.977	0.955	0.918	0.942	0.925	0.900	0.856	0.925	0.815	0.811
St-8	0.991		0.978	0.986	0.980	0.958	0.948	0.946	0.934	0.904	0.946	0.861	0.858
St-11	0.984	0.978		0.993	0.970	0.932	0.984	0.965	0.936	0.889	0.965	0.872	0.857
St-12	0.977	0.986	0.993		0.992	0.968	0.986	0.983	0.966	0.931	0.983	0.912	0.896
St-13	0.955	0.980	0.970	0.992		0.991	0.973	0.987	0.984	0.963	0.987	0.941	0.926
St-14	0.918	0.958	0.932	0.968	0.991		0.946	0.975	0.988	0.985	0.975	0.959	0.951
St-16	0.942	0.948	0.984	0.986	0.973	0.946		0.991	0.969	0.930	0.991	0.934	0.914
St-17	0.925	0.946	0.965	0.983	0.987	0.975	0.991		0.992	0.967	1.000	0.968	0.947
St-18	0.900	0.934	0.936	0.966	0.984	0.988	0.969	0.992		0.991	0.992	0.985	0.974
St-19	0.856	0.904	0.889	0.931	0.963	0.985	0.930	0.967	0.991		0.967	0.987	0.986
St-22	0.925	0.946	0.965	0.983	0.987	0.975	0.991	1.000	0.992	0.967		0.968	0.947
St-23	0.815	0.861	0.872	0.912	0.941	0.959	0.934	0.968	0.985	0.987	0.968		0.984
St-24	0.811	0.858	0.857	0.896	0.926	0.951	0.914	0.947	0.974	0.986	0.947	0.984	

Annex 14: Correlation coefficients between SPEI-3, and monthly discharges

Variable	Marked correlations (in bold) are significant at p < 0.05. N=31											
	SPEI3-Oct	SPEI3-Nov	SPEI3-Dec	SPEI3-Jan	SPEI3-Feb	SPEI3-Mar	SPEI3-Apr	SPEI3-May	SPEI3-Jun	SPEI3-Jul	SPEI3-Aug	SPEI3-Sep
Q-Oct	0.005											
Q-Nov		0.063										
Q-Dec			0.242									
Q-Jan				**0.493**								
Q-Feb					0.274							
Q-Mar						**0.416**						
Q-Apr							**0.655**					
Q-May								**0.394**				
Q-Jun									-0.064			
Q-Jul										-0.198		
Q-Aug											-0.138	
Q-Sep												-0.362

Annex 15: Correlation coefficients between SPEI-6, and monthly discharges

Variable	Marked correlations (in bold) are significant at p<0.05. N=31											
	SPEI6-Oct	SPEI6-Nov	SPEI6-Dec	SPEI6-Jan	SPEI6-Feb	SPEI6-Mar	SPEI6-Apr	SPEI6-May	SPEI6-Jun	SPEI6-Jul	SPEI6-Aug	SPEI6-Sep
Q-Oct	0.014											
Q-Nov		-0.041										
Q-Dec			0.332									
Q-Jan				**0.598**								
Q-Feb					0.294							
Q-Mar						**0.421**						
Q-Apr							**0.655**					
Q-May								0.299				
Q-Jun									-0.197			
Q-Jul										-0.454		
Q-Aug											-0.239	
Q-Sep												-0.361

Annex 16: Correlation coefficients between SPEI-9, and monthly discharges

Variable	Marked correlations (in bold) are significant at p<0.05. N=31											
	SPEI9-Oct	SPEI9-Nov	SPEI9-Dec	SPEI9-Jan	SPEI9-Feb	SPEI9-Mar	SPEI9-Apr	SPEI9-May	SPEI9-Jun	SPEI9-Jul	SPEI9-Aug	SPEI9-Sep
Q-Oct	0.084											
Q-Nov		-0.022										
Q-Dec			0.334									
Q-Jan				**0.602**								
Q-Feb					0.196							
Q-Mar						0.207						
Q-Apr							0.185					
Q-May								0.033				
Q-Jun									-0.021			
Q-Jul										-0.403		
Q-Aug											-0.301	
Q-Sep												-0.350

Annex 17: Correlation coefficients between SPEI-12, and monthly discharges

	Marked correlations (in bold) are significant at p < 0.05. N=31											
Variable	SPEI12-Oct	SPEI12-Nov	SPEI12-Dec	SPEI12-Jan	SPEI12-Feb	SPEI12-Mar	SPEI12-Apr	SPEI12-May	SPEI12-Jun	SPEI12-Jul	SPEI12-Aug	SPEI12-Sep
Q-Oct	0.090											
Q-Nov		-0.004										
Q-Dec			0.281									
Q-Jan				0.348								
Q-Feb					-0.018							
Q-Mar						0.157						
Q-Apr							0.148					
Q-May								-0.061				
Q-Jun									-0.139			
Q-Jul										-0.410		
Q-Aug											-0.325	
Q-Sep												-0.352

Annex 18: Correlation coefficients between SPEI-24, and monthly discharges

	Marked correlations (in bold) are significant at p < 0.05. N=31											
Variable	SPEI24-Oct	SPEI24-Nov	SPEI 24Dec	SPEI24-Jan	SPEI24-Feb	SPEI24-Mar	SPEI24-Apr	SPEI24-May	SPEI24-Jun	SPEI24-Jul	SPEI24-Aug	SPEI24-Sep
Q-Oct	-0.147											
Q-Nov		-0.034										
Q-Dec			0.323									
Q-Jan				0.112								
Q-Feb					0.026							
Q-Mar						0.069						
Q-Apr							0.025					
Q-May								-0.190				
Q-Jun									-0.310			
Q-Jul										-0.550		
Q-Aug											-0.390	
Q-Sep												-0.608