SWIM-H2020 SM Expert Facility Activity
EFS-JO-1, Task 2

Drought Hazard in the Amman-Zarqa catchment in Jordan

February 2019

Version	Document Title	Author	Review and Clearance
1.0	Drought Hazard in the Amman-Zarqa catchment in Jordan	Demetris Zarris (SWIM-H2020 SM) non-key expert	Suzan TAHA (SWIM-H2020 SM) key water expert

THE SWIM AND H2020 SUPPORT MECHANISM PROJECT (2016-2019)

The SWIM-H2020 SM is a Regional Technical Support Program that includes the following Partner Countries (PCs): Algeria, Egypt, Israel, Jordan, Lebanon, Libya, Morocco, Palestine, [Syria] and Tunisia. However, in order to ensure the coherence and effectiveness of Union financing or to foster regional co-operation, eligibility of specific actions will be extended to the Western Balkan countries (Albania, Bosnia Herzegovina and Montenegro), Turkey and Mauritania. The Program is funded by the European Neighborhood Instrument (ENI) South/Environment. It ensures the continuation of EU's regional support to ENP South countries in the fields of water management, marine pollution prevention and adds value to other important EU-funded regional programs in related fields, in particular the SWITCH-Med program, and the Clima South program, as well as to projects under the EU bilateral programming, where environment and water are identified as priority sectors for the EU co-operation. It complements and provides operational partnerships and links with the projects labelled by the Union for the Mediterranean, project preparation facilities in particular MESHIP phase II and with the next phase of the ENPI-SEIS project on environmental information systems, whereas its work plan will be coherent with, and supportive of, the Barcelona Convention and its Mediterranean Action Plan.

The overall objective of the Program is to contribute to reduced marine pollution and a more sustainable use of scarce water resources. The Technical Assistance services are grouped in 6 work packages: WP1. Expert facility, WP2. Peer-to-peer experience sharing and dialogue, WP3. Training activities, WP4. Communication and visibility, WP5. Capitalizing the lessons learnt, good practices and success stories and WP6. Support activities.

Acknowledgements:

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ABBREVIATIONS

AZ	Amman-Zarqa
AZB	Amman Zarqa Basin
DMS	Drought Monitoring System
DMU	Drought Management Unit
DRM	Drought Risk Management
DRMP	Drought Risk Management Plan
JVA	Jordan Valley Authority
MWI	Ministry of Water and Irrigation
MCM	Million Cubic Meters
PET	Potential Evapotranspiration
RDI	Reconnaissance Drought Index
SPI	Standrardized Precipitation Index
SPEI	Standrardized Precipitation – Evapotranspiration Index

1 INTRODUCTION

1.1 BACKGROUND

Jordan has prepared a National Water Sector Strategy (NWSS) (2016-2025) which refers to the need to address drought management and adaptation to climate change through proper policies and regulations. The Water Reallocation Policy calls for launching awareness campaigns addressing the importance of issues such as water harvesting, conserving and protecting resources, while the Water Substitution and Reuse Policy proposes the reuse of treated wastewater in irrigation, in order to enable freeing fresh water to be utilized for municipal uses. It also provides for using the treated wastewater in other economic activities, avoiding negative impacts on water and soil quality. Under this context, activities related to drought risk management mainstreaming are highly relevant to the Country's Strategic Framework.

During 2013, under the framework of the EU-funded Sustainable Water Integrated Management - Support Mechanism (SWIM-SM) project, a regional assessment[1] of past drought and flood events in the SWIM partner countries was undertaken, in order to identify their prevailing characteristics (frequency of occurrence, severity/magnitude, and geographic extent) and potential environmental and socio-economic impacts. The assessment also involved a detailed analysis of the prevailing drought management practices and response actions implemented in three focus countries, Jordan being one of them. The main finding of the assessment for Jordan, in terms of drought risk management, indicated a currently weak institutional setting, scattered efforts, inadequate infrastructure, lack of dedicated budget to disaster response. Additionally, the lack of a proper legal framework, clear mandates and coordination mechanisms impedes the implementation of coherent and proactive drought risk management. In view of this findings, activities targeting the strengthening of the current drought management approach in Jordan, be it related to the identification of vulnerability and risk, the incorporation of prevention, mitigation and preparedness measures, or the integration of drought risk management into existing frameworks are of paramount importance.

During the kick-off meeting at the MWI on the 13th of July 2017, the KE and the NKEs were informed that an almost identical project funded by the United Nations Development Program (UNDP) was then under completion.

The Ministry of Environment commenced (March 2015) a three-year medium size GEF-funded UNDP supported project that aimed at Mainstreaming Rio Convention provisions into key national sectoral policies and/or legislation in Jordan. Under this objective, the UNDP project was to produce core outputs leading to mainstreaming Rio Convention into three priority strategies namely: the National Drought

1 Taha, S., Rabi, A., Touzi, S. 2014. Regional assessment of past drought & flood episodes and their management in selected SWIM-SM PCS (Tunisia, Jordan and Palestine). SWIM-SM Report, WP1, Water Governance and Mainstreaming, Activity 1.3.3.1, February 2014 (*accessed 28.03.2016*)

Strategy under the mandate of the Ministry of Water & Irrigation (MWI) and other two projects related to Rangeland and Energy Sector at the Ministry of Agriculture (MoA) and Ministry of Energy, respectively.

The purpose of the UNDP project was to support Jordan obtaining a higher level of preparedness for drought management and response through the development of national strategy and action plan as a part of the United Nations Convention to Combat Desertification (UNCCD). The first expected outcome was to strengthen the institutional capacities to formulate sectoral policies that are embedded with Rio Convention provisions. The second expected outcome complementing to the first, was to improve awareness and understanding of Rio Conventions contributions to sustainable development process by the end of the mainstreaming project.

The expected outputs of the UNDP project are summarised below:

1. Institutional and legal set ups related to drought management revamped.
2. Training programme designed and implemented.
3. Awareness raising program on drought hazards and the underlying causes of its impacts.
4. Drought mitigation measures are mainstreamed into Disaster Risk Reduction Fund.
5. A national drought resilience strategy and action plan developed in a participatory manner.
6. An early warning system established in the most vulnerable areas in the country.
7. Pilot priority interventions at the local level.

The progress of the UNDP project as of the state of starting this activity can be schematized as follows:

- Thorough institutional and legal analyses were carried out to define the gaps in the current institutional - regulatory framework related to drought management.
- A new institutional and governance structure related to drought management was proposed.
- A policy statement on drought management was developed.
- A National Drought Management Plan in the Water Sector was developed.
- An early warning system was designed based on effective drought monitoring indices.
- Training on drought monitoring in cooperation with the International Centre for Bio-saline Agriculture (ICBA) was carried out. Training specifically was on software developed by ICBA using the Composite Drought Index (CDI).
- Pilots on adaptation to drought was designed and funded to be implemented by two NGOs on the local level.

The ongoing activities for the total completion of the project are the following:

- Producing the Drought Vulnerability and Impact Assessment in Jordan.
- Establishing the drought management unit at MWI.
- Developing Drought Management Plan in Health and Agriculture Sectors.
- Setting up the drought early warning system.

Obviously, the scope of the UNDP project has common elements with the Expert Facility Activity No: EFS-JO-1 and the two projects were overlapping in major areas. **However, despite the initial approval of the previous version of the TOR, and considering that the SWIM-H2020 SM activity was not yet launched, it was considered essential that the EFS-JO-1 TOR was revised** in order to be adjusted to the new situation.

As discussed with the Jordanian FP during the kick-off meeting, it was proposed to implement the ToR tasks in a pilot Jordanian basin, streamlining them with UNDP methodology, namely in the Amman –

Zarqa basin (catchment area 3739 km^2). SWIM-H2020 SM has received from the UNDP Focal Point (FP) at the MWI, copies of the UNDP deliverables submitted to date:

These included the following volumes:

1. Analytical Framework for Drought Governance in Jordan and a National Drought Resilience Strategy and Action Plan. Stakeholders and Institutional Gap Analysis (published in June 2016).
2. The National Drought Early Warning System & its Set of Procedures (SOPs) (published in December 2016).
3. Policy Statement on Drought Management (published in December 2016).
4. Institutional Setup & Regulatory Framework to Drought Management (published in December 2016).
5. The National Drought Management Plan in the Water Sector (published in February 2017).

The Non-key Experts (NKEs) initially reviewed the submitted volumes. The first finding was as stated in the Deliverable #1 above, that the meteorological analysis to assess drought occurrence is still pending and the description of the available Drought Hazard Indicators (i.e. relevant to Task 2 of the current SWIM-H2020 SM activity) is in general terms without proposing specific indicators for monitoring and analyses. Drought vulnerability indicators on the other hand (also relevant to Task 2 of the current activity) were not presented in these volumes. More review work is needed to assess the status and the level of analyses carried out by the UNDP personnel.

1.2 OBJECTIVES

The main objectives of the SWIM-H2020 SM activity' are the following:

1 Support the development of a comprehensive detailed action plan, along with specific tools and procedures, for managing drought risk in the pilot area of Amman-Zarqa in Jordan;

2 Critical assessment of the reports produced by the UNDP and identification of gaps in the formulation of the composite drought hazard indices and drought vulnerability indicators/ methodology (it is a precondition that reading material on the indicators' methodology and results are provided to the Consultant);

3 Development of drought hazard indicators at the detailed local level (in the Amman-Zarqa pilot catchment) in harmonisation with the UNDP's methodology for the pilot catchment of Amman – Zarqa;

4 Development of a mechanism to ensure the monitoring of drought, and the dissemination of timely and accurate information on drought conditions to the different stakeholders on the Amman-Zarqa catchment, the media and the general public (Drought Bulleting based on a Drought Monitoring System);

5 Strengthening the institutional mechanisms and capacities, and provision of tools and methods to MWI and stakeholders in the Amman-Zarqa catchment to enhance their resilience against drought hazards and disasters;

6 Setting the cornerstones for mainstreaming Drought Risk Management: initiate a participatory approach with stakeholders in Amman-Zarqa catchment, in defining targets, measures, etc., draft an organizational structure that assures information flow between and within levels of government agencies and defines the duties and responsibilities of all agencies with respect to drought (in coherence with the national drought policies);

7 Training and capacity building of the MWI staff on aspects of Drought Risk Management, including the practical implementation and operation of a Drought Monitoring System (DMS) and Early Warning system (EWS).

The expected results of the activity are as follows:

1 Establishment of a Drought Monitoring System (DMS) on the basis of composite indicators and application in the pilot area of Amman-Zarqa;

2 Analysis of the drought vulnerability, on the basis of agreed indicators which can be subsequently used by MWI staff to determine priorities for action and application in the pilot area of Amman-Zarqa;

3 Preparing drought hazard maps and vulnerability maps in the pilot area of Amman-Zarqa;

4 Technical training of the MWI staff (and related actors such as the Drought Management Unit (DMU)) on: (a) drought monitoring and early warning system, and (b) on the application of the "Water Evaluation and Planning" (WEAP) system in drought risk management;

5 Initiation and first results for a participatory approach with stakeholders in the Amman-Zarqa pilot catchment to define and contribute to elements of the Drought RIsk Management Plan (DRMP) (i.e. definition of targets, preliminary list of proactive measures, definition of actions and roles, identification of entry points for mainstreaming the DRMP and synergies with other sectors and policies;

6 Action Plan for the development of the Amman-Zarqa pilot catchment DRMP and draft contents/structure of the DRMP.

1.3 SCOPE OF WORK

In order to be able to define proactive measures on Drought Risk Management (DRM), a drought risk profile of areas of interest needs to be developed first, analyzing and characterizing the hazard and related vulnerability of the affected communities and systems, and having a good knowledge of the specific impacts on the different sectors. On this basis, targets and measures for reducing vulnerability can be defined, also through a participatory approach so that their acceptability is strengthened. As such, a stepwise approach is followed, so that the identified measures are tailored to the Jordanian context, rather than being generic. This stepwise approach can lead to the development of a holistic Drought Risk Management Plan (DRMP) for Jordan.

The activity comprised several tasks. The one that is relevant to this report is related to task 2 described below:

Task 2: Drought Identification and characterisation in the Amman-Zarqa catchment

The Consultant will adjust and further develop drought indicators (and/or composite indices) as proposed by UNDP which can be used for drought identification and characterization, incorporating different hydrological elements, such as surface water flows, spring discharge, groundwater level and level of water reservoir, tailored for the Amman-Zarqa catchment. Indicators which can potentially be used for early warning will also be investigated. On the basis of these indicators a Drought Monitoring System (DMS) will be further elaborated as stated in the UNDP project with a focus on the Amman – Zarqa catchment, including guidelines on how to use the indicators (individually and synergistically) (incl. monitoring frequency, responsibilities' allocation among the involved actors, etc.), how to operate the system and conduct periodic assessments of drought conditions (e.g. drafting a drought bulletin targeting decision-makers and the general public so that they are aware of drought as soon as it begins).On the basis of the above indicators, an assessment of drought duration, severity, intensity and drought spells will be conducted in the pilot catchment of Amman-Zarqa in Jordan. The indicators will also be streamlined with the UNDP indicators, but some additional may be proposed in case it is necessary (depending on the specificities of the catchment) since the focus is at the local level.

The collection of the data (time series) necessary for analyzing and developing the drought indicators (of Task 2) and transfer of these data to the SWIM experts will be undertaken by the country.

Note: It is assumed that the data (time series) necessary for analyzing and developing these indicators are adequate and provided to the Consultant in an adequate format and in due time to realize this task.

Expected Deliverable: *A Report describing in detail the Drought Monitoring System (DMS) and its indicators/ indices, including guidelines for calculating the indicators, for operating the system and conducting periodic assessments of drought conditions (e.g. drafting a drought bulletin) in the Amman-Zaqa catchment. The Report will contain the results of the application of the DMS indicators in the Amman-Zarqa, including the identification/ mapping of drought characteristics of the pilot area (using the aforementioned drought indicators of the DMS).*

2 PILOT CATCHMENT OVERVIEW

Amman Zarqa Basin (AZB) lies in the northern part of Jordan, the area of which is about 4,586 km^2 with about 4,074 km^2 in Jordan and 512 km^2 in Syria (ARD, 2001). The average annual precipitation in the western part of the basin is about 400 mm, while the average annual precipitation in the eastern part is about 150 mm with most of the precipitation occurring between October and May (Abderahman and Abu Rukah 2006). AZB, shown in Figure 2-1 includes the two largest cities in Jordan which are the capital Amman, and Zarqa city in addition to large parts of Mafraq, Jerash and Balqa governorates. About 52% of the industries in Jordan are located in Zarqa city which is part of AZB (Mrayyan and Hussein 2004).

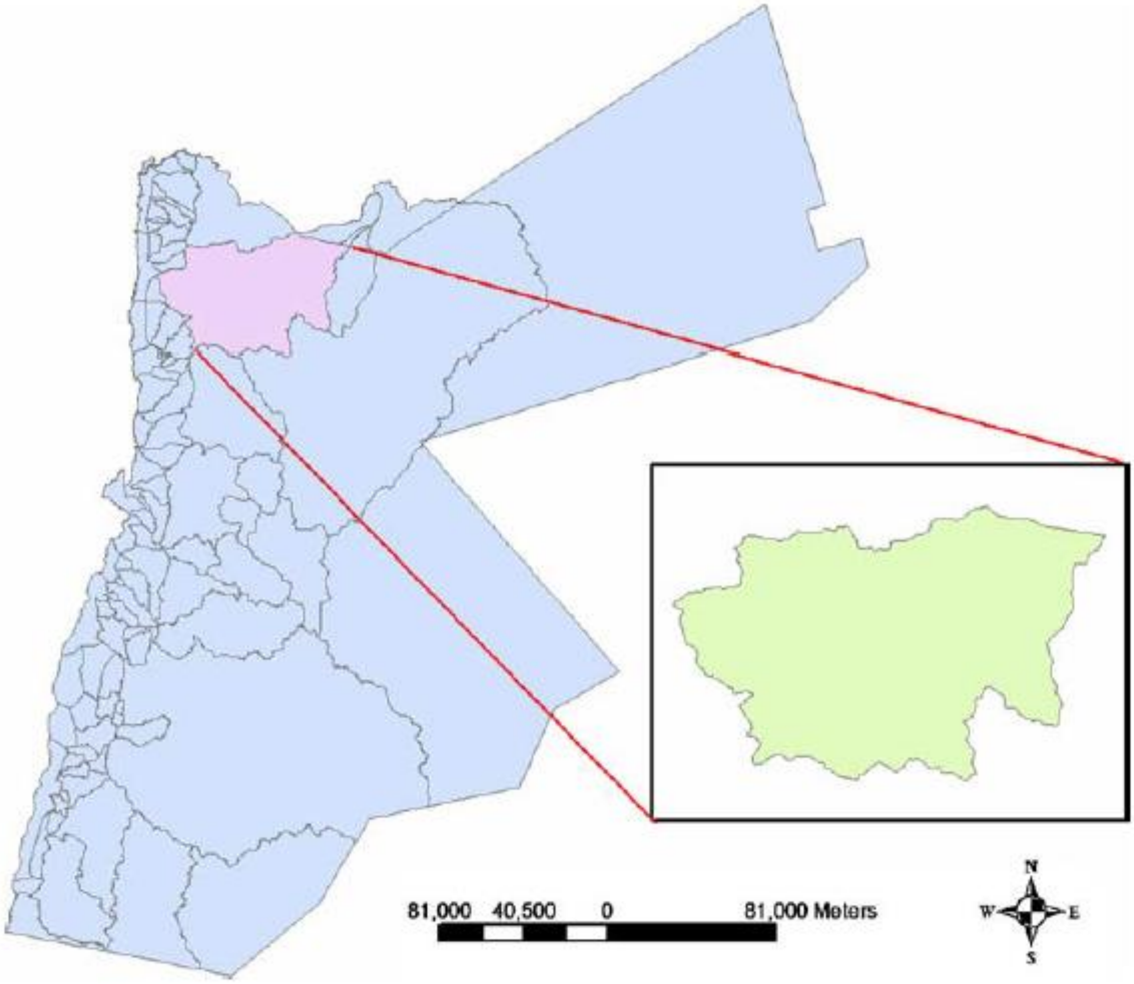


Figure 2-1: Amman Zarqa basin in Jordan

The western hilly areas of Amman–Zarqa basin is densely populated, while the southeast of the basin is a desert and almost without population. More than half of Jordan's population is found inside the Amman–Zarqa Basin area. The cities and towns in the basin can be classified by the governorate; where the basin consists of five major governorates, and they are the Zarqa governorate, Al-Mafraq governorate, Jerash governorate, Al-Balqaa governorate and Amman governorate. Figure 2-2 shows the villages and towns inside the basin. The total area of the towns inside the basin was calculated using GIS to be 145.4 km^2.

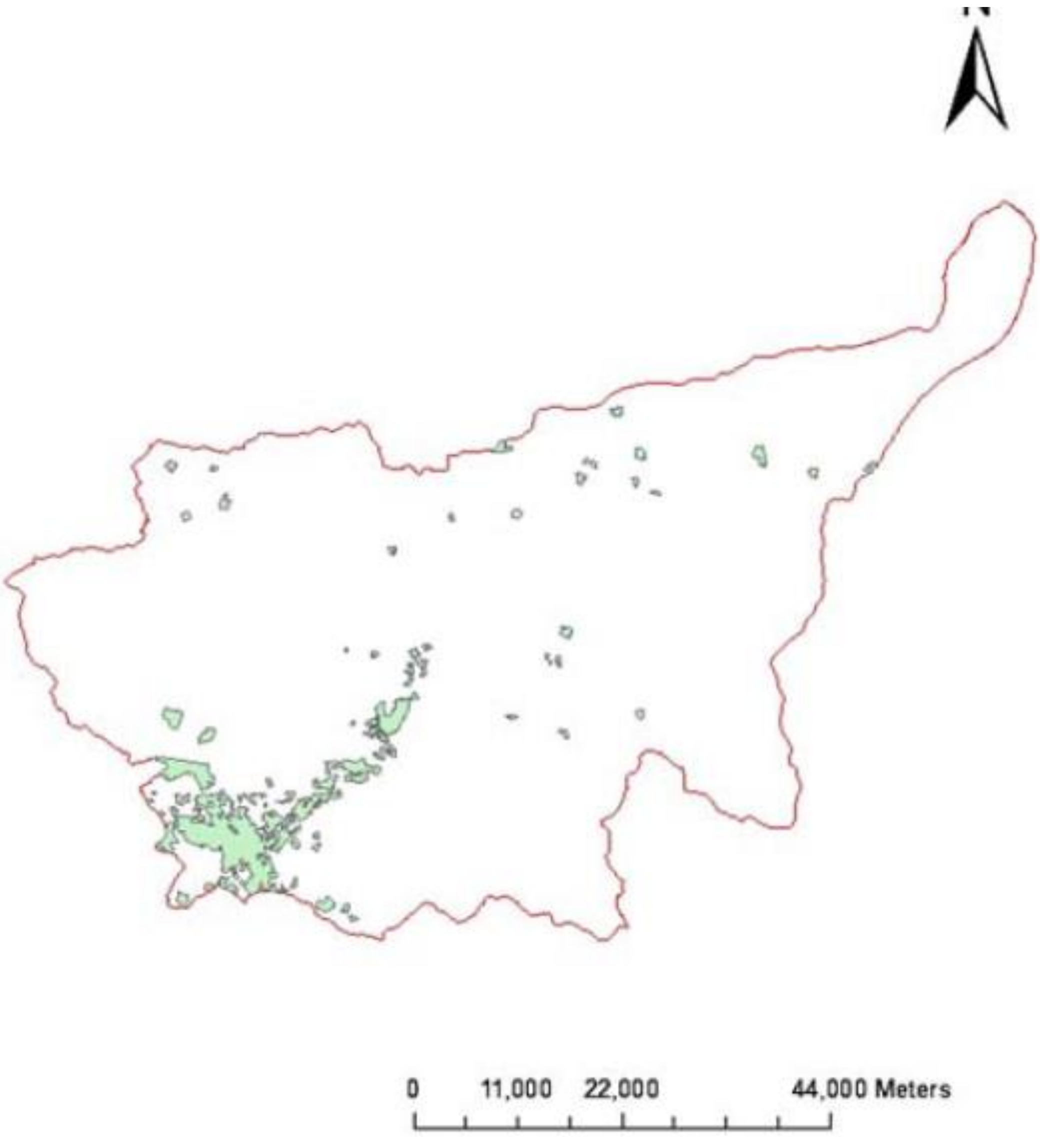


Figure 2-2: Zarqa River Basin towns and urban areas

The Zarqa River is controlled by King Talal Dam which was built in 1976 and raised in 1987 to provide a storage capacity of 86 MCM. The river flow is affected by two main factors, the first is the excessive withdrawals from aquifers in the upper Amman–Zarqa groundwater basin. This resulted in a decrease of the river natural base flow. The second factor is the discharge of the treated domestic and industrial wastewater in the river. The treatment plants' effluent in the summer months accounts to most of the river discharge. The treated wastewater comes mostly from As-Samra treatment Plant, and less proportion comes from Jerash, Abu Nseir and Baq'a treatment plants. In general, the Zarqa River is a perennial river with typical **monthly flows** of 2 to 3MCM during the summer and 5 to 8 MCM during the winter months. The **average annual surface runoff** in the Zarqa River as measured at new Jarash bridge is around 68MCM (43 and 25 MCM for base flow and flood flow, respectively) for the period (1969–1999; Al-Haddadin 2002). Groundwater flow from the Basalt aquifer outside the basin into the B2/A7 aquifer within the neighbouring basins is estimated at 23 MCM.

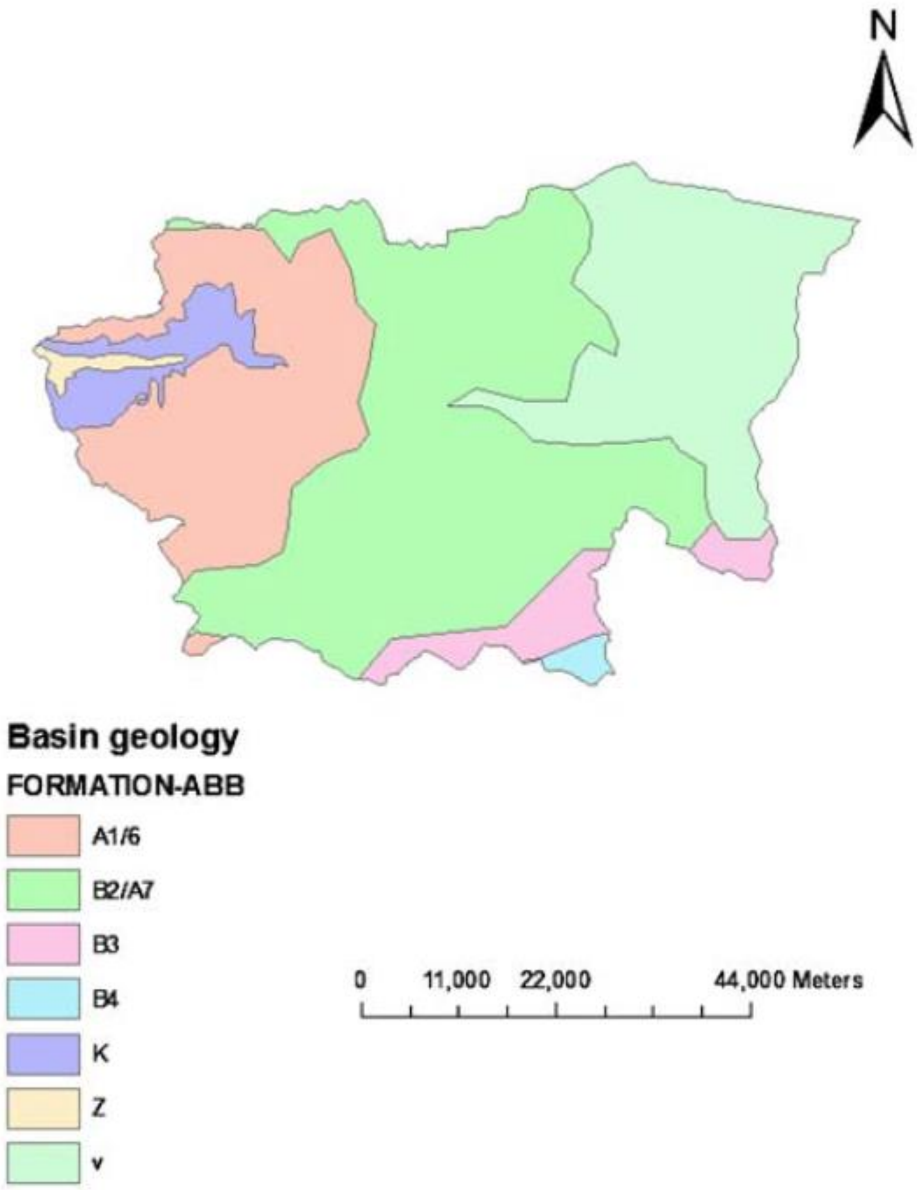


Figure 2-3: Zarqa River basin geology

The soil texture in the Zarqa basin is dominated by silty clay loam (SICL) which covers about 50% of the basin area and silt loam (SIL) which covers about 30% of the basin. Clay loam (CL) and silt clay (SIC) cover about 8% each of the basin area. Clay (C) covers less than 1% of the basin area as shown in Figure 2-3.

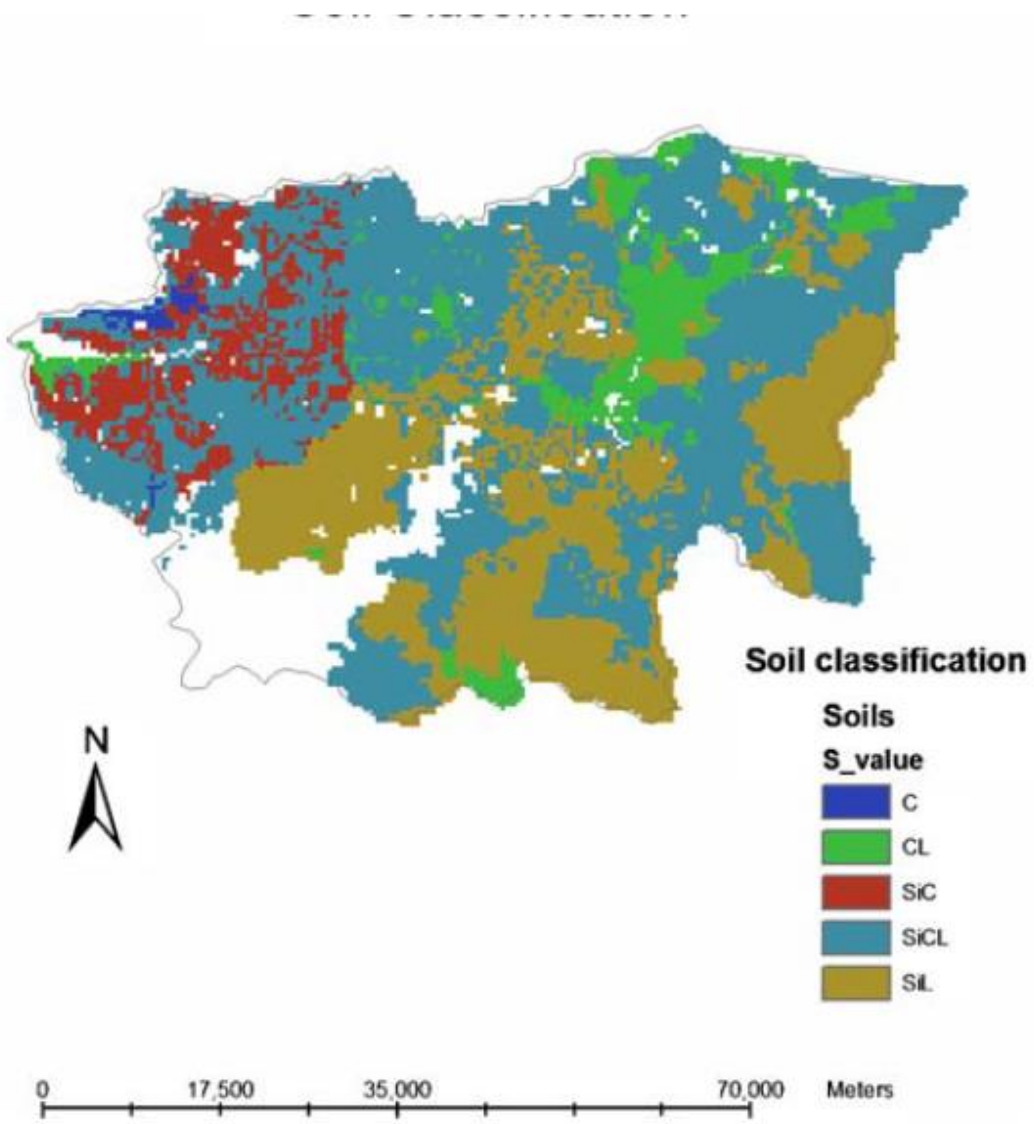


Figure 2-4: Soil classification map of the Zarqa River Basin

The main water resources in AZB are ground water, surface water and treated wastewater. The safe yield of AZB aquifer is estimated at 88 MCM/year (ARD 2001). Water is abstracted from more than 800 abstraction wells in AZB for different purposes, domestic, agricultural, and industrial, the majority of which are privately owned. Figure 2-5 shows the spatial distribution of abstraction wells and springs in AZB for the different uses.

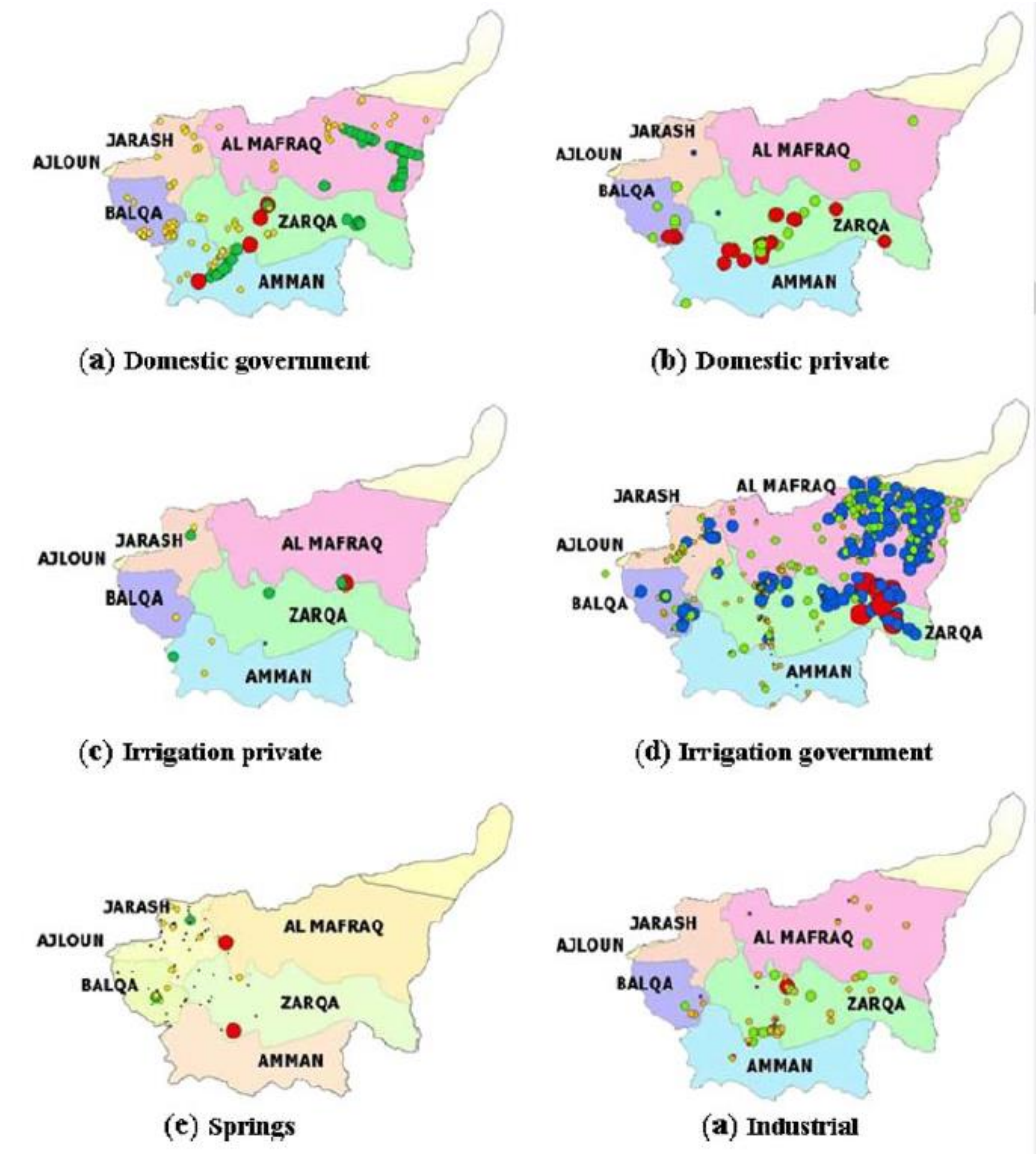


Figure 2-5: Spatial distribution of abstraction wells and springs in AZB

Based on historical abstractions from these wells, AZB aquifer was divided into 14 abstraction zones as shown in Figure 2-6.

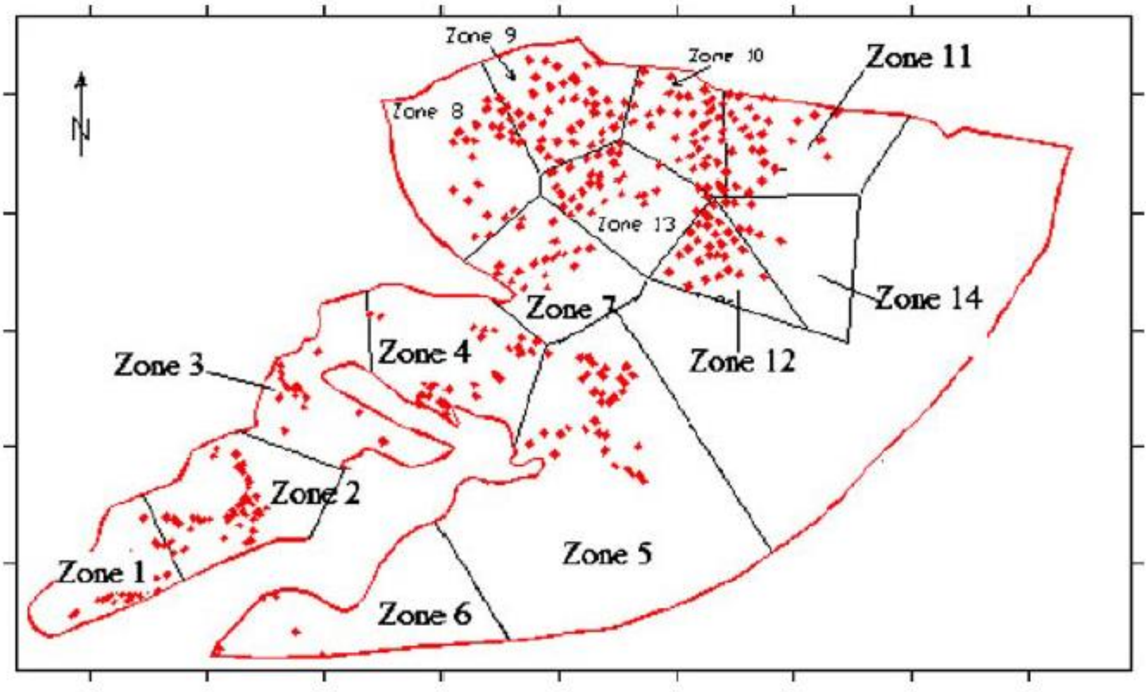


Figure 2-6: Ground water abstraction zones in AZB

Zarqa River is the main water course in the basin. The catchment area of the Zarqa River watershed is about 3,900 km^2. The Zarqa River watershed has two main branches which are the Amman-Zarqa draining the high rainfall areas of the Eastern Escarpment of the Jordan Rift Valley and parts of the Jordan Highlands, and the Wadi Dhuliel draining the more arid areas of the Jordan Highlands and Plateau. The average **annual stream flow of Zarqa River is estimated at 68MCM** (Al-Salihi 2006).

Treated wastewater is an important water resource in the basin. Currently there are five Wastewater Treatment Plants (WWTPs) in AZB which are As Samra, Al-Baqa'a, Jerash, Abu Nsair, and Al-Mafraq. The first four of these WWTPs discharge their effluent to Zarqa River. Among these WWTPs, As Samra is the largest which treats about 90% of the wastewater generated in the basin. The influent to these WWTPs was estimated at about 95 MCM for the year 2005 (MWI 2004). Springs are another fresh water resource in the basin. There are about 150 springs in AZB the annual discharge of which is estimated at 8 MCM. Some of these springs with relatively considerable discharge are utilized for domestic water supply such as Al-Qayrawan spring which supplies Jerash city with water for domestic use.

Topography: A sloping terrain from 950m near the Arab Mountain to 620m near the Sukhna area and 735m southwest of Amman characterizes the study area. The topography reflects the geology consisting mainly of a basaltic mountain that slopes down to a central, gently rolling plateau bounded from north and south by rugged and dissected limestone hills. The stream flow of the Zarqa River is impounded by King Talal Dam at an elevation of 120 m and a capacity of 82MCM. The area behind the river is about 3100 km^2 producing an (average) annual runoff of about 60 MCM.

3 AVAILABLE DATA FOR DROUGHT ANALYSES

For drought analyses purposes, it is essential to gather all the relevant information. Rainfall is, obviously, the main drought factor, mainly due to SPI, but also potential (or actual) evapotranspiration plays also a very important role. Potential Evapotranspiration (PET) is computed after meteorological information is also archived and processed. Meteorological variables necessary for PET calculations are: (a) Temperature (mean monthly or mean monthly maximum and minimum) (ºC), (b) Relative humidity (%), (c) Wind Speed (m/s at 2 m height of the sensor), and (d) sunshine duration (h).

3.1 RAINFALL

Rainfall data are the main and primary information for studying drought hazard. Monthly rainfall data for 27 rainfall stations in and around Amman Zarqa (AZ) catchment have been submitted to the Consultant. Table 3-1 presents the general characteristics of the rainfall stations. The geographical location of the rainfall stations is presented in Figure 3-1.

All stations, but *Amman Airport* station, start recording rainfall depths from the hydrologic year 1964-65 to 2016-17. Few stations start recording a few years later, but, as it will be described in the following paragraphs, it was a relatively easy task to extend the data, in such a way that it is possible to have data from hydrologic year 1964-65 to 2016-17. *Amman Airport* rainfall station is a particular case, because rainfall data are recorded since the hydrologic year 1937-38. On top of that, it seems to be a very reliable station, so it will be used as the central station for managing drought in the AZB.

Table 3-1: Main characteristics of the 27 rainfall stations

a/a	Station Name	Elevation (m)	Mean Annual Rainfall (mm)	Data Availability	
				From (Year)	To (Year)
1	AMMAN AIRPORT (METEO DEPT)	790	252,5	1937	2017
2	AMMAN HUSSEIN COLLEGE	834	393,2	1964	2017
3	BAL'AMA	695	215,3	1964	2017
4	DEIR ALLA AGR. STATION	930	272,4	1964	2017
5	HASHIMIYA	550	128,1	1968	2017
6	JARASH	585	358,6	1964	2017
7	JUBEIHA	980	480,7	1964	2017
8	K.H. NURSERY EVAP.ST(BAQ'A)	700	336,0	1964	2017
9	KHALDIYA	630	127,7	1967	2017
10	KING TALAL DAM	218	272,1	1971	2017
11	KITTA	665	517,3	1964	2017
12	MIDWAR	760	231,7	1950	2017
13	NAWASIF	590	132,4	1964	2016
14	QAFQAFA	1000	315,4	1967	2017

a/a	Station Name	Elevation (m)	Mean Annual Rainfall (mm)	Data Availability	
				From (Year)	To (Year)
15	QASR EL-HALLABAT	610	91,9	1967	2017
16	PRINCE FEISAL NURSERY	300	327,9	1964	2017
17	RUMEIMIN	675	357,9	1964	2017
18	RUSEIFA	655	149,9	1964	2017
19	SABHA AND SUBHIYEH	850	123,1	1967	2017
20	SIHAN	495	381,7	1967	2017
21	SUBEIHI	500	406,8	1964	2017
22	SUKHNA	500	148,0	1964	2017
23	UM EL-JUMAL EVAP .ST	650	118,8	1967	2017
24	UM JAUZA	860	496,6	1967	2017
25	WADI DHULEIL NURSERY (METEO DEPT)	575	127,4	1972	2017
26	UM EL-QUTTEIN	986	142,0	1964	2017
27	WADI ES-SIR (NRA)YARD	900	513,5	1978	2017

From Figure 3-1 we can realize that the stations' density in the western part of the AZB is satisfactory and the opposite is valid for the eastern part of the catchment. Anyway, the eastern part of the catchment is less inhabited, so the use of local water resources is limited. After all rain data were archived, all typical statistical processes were carried out. These processes are:

1. ***Correlation matrix: Correlation matrix between all annual rainfall and monthly values between all stations. Define rainfall stations with constant high correlation values especially with the adjacent stations. Select those as base stations. <u>These stations are illustrated in Table 3-2</u> with blue color on the regression coefficients values.***
2. **Double Mass Curves:** Perform double mass curves analysis to further **evaluate data consistency** in rainfall stations. **Figure 3-2** presents an example of the double mass curves that **generally illustrate coherent rainfall data between adjacent stations**
3. **Data gap filling:** The base **stations should have all datasets filled for all months of the finally selected time analysis.** Certain, sparse, gaps can be filled according to the correlation equation. **For processing reasons we make a complete sample for all stations from the hydrologic tear 1964-65 to 2016-17, that means 53 years of data.**
4. **Data extension:** Reliable rainfall station with time of operation less than the defined one can be extended to the required one according to the correlation analyses.
5. **Spatial Integration of Point Rainfall:** The transition from point to surface rainfall can be done by means of the Thiessen polygons (Figure 3-4).
6. **Define the altitude-rainfall lapse rate:** For the computation of the surface rainfall, the rate of change between rainfall and elevation must be defined with satisfactory correlation coefficients. However, it seems that there is no **statistically significant correlation between altitude and annual rainfall depth** (see Figure 3-3). Therefore, surface rainfall for the King Talal Dam Catchment will be computed only according to Thiessen polygons and without altitude correction. **We are using King Talal catchment for our calculations since it occupies the vast majority**

of the whole AZB but also because it is an extremely important dam for the water security of the whole region.

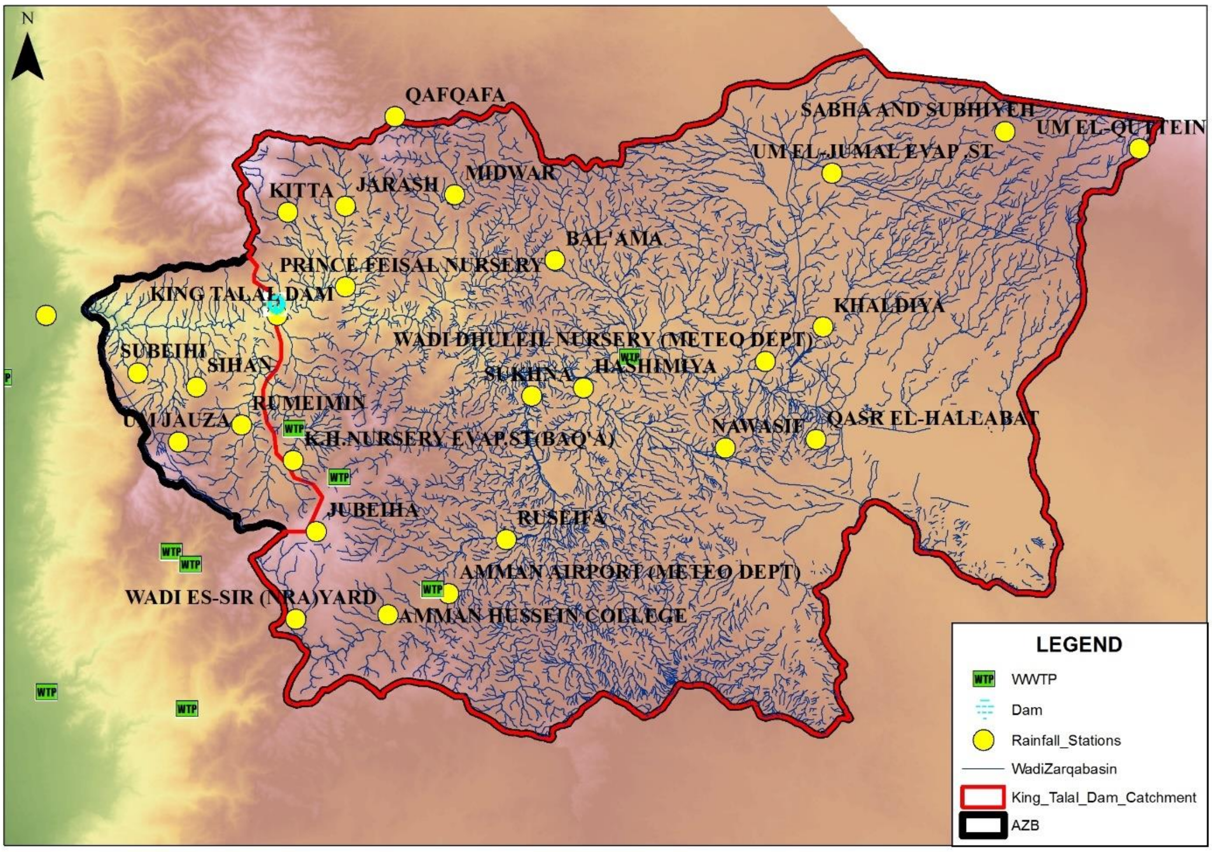
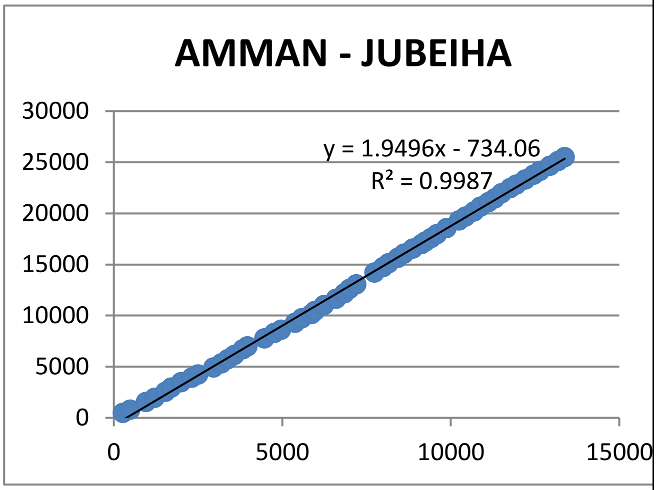
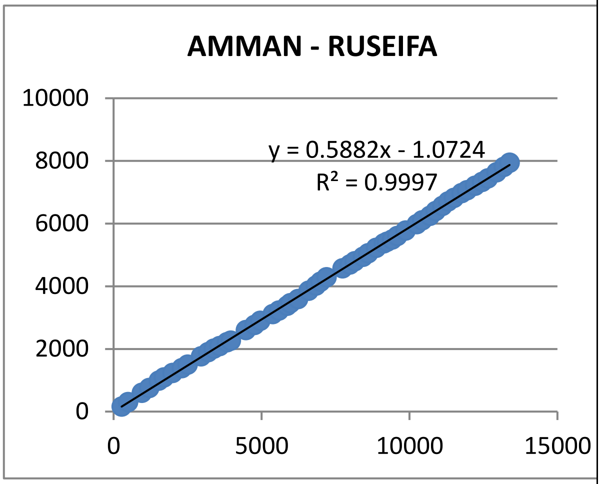
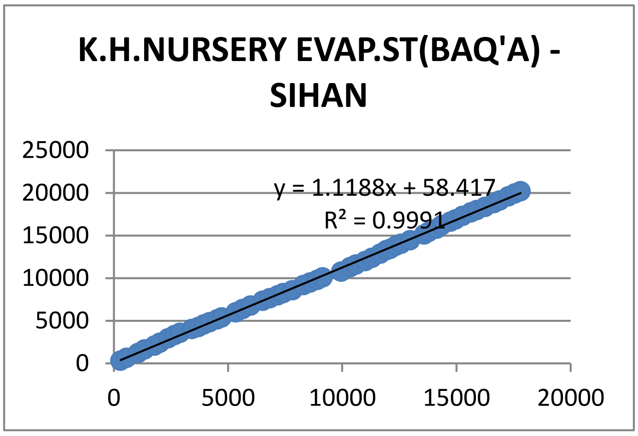
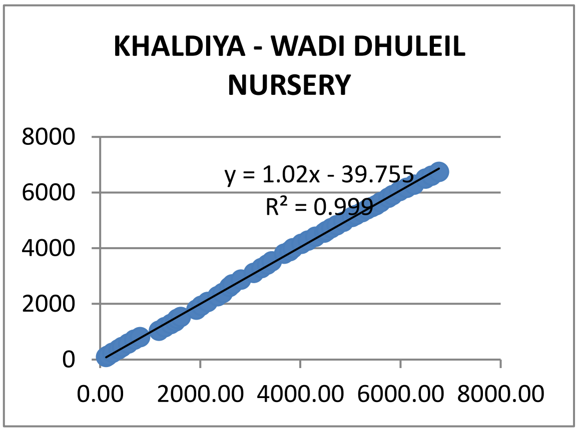


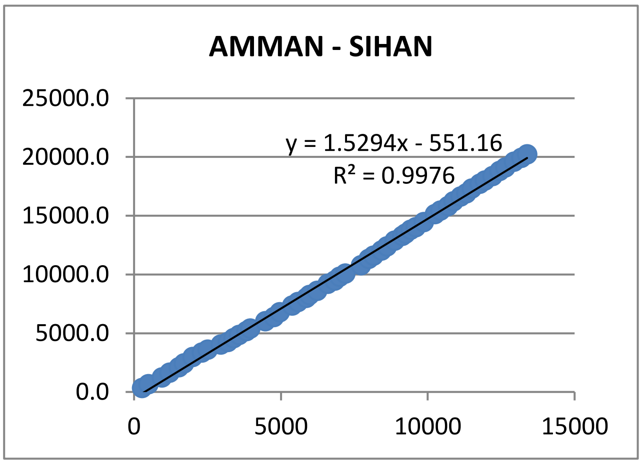
Figure 3-1: MAP OF AVAILABLE RAINFALL STATIONS IN THE AZB

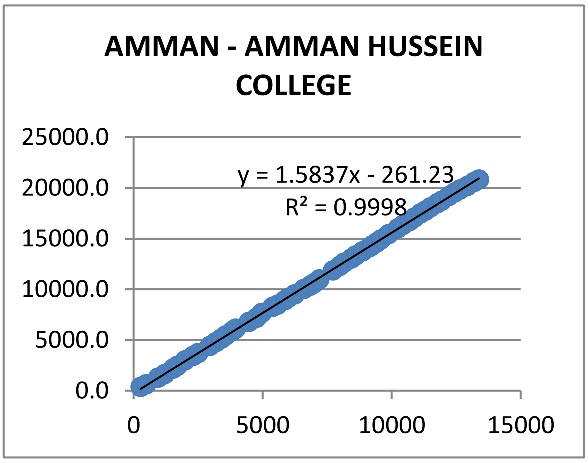

AMMAN - JUBEIHA
y = 1.9496x - 734.06
R² = 0.9987
30000
25000
20000
15000
10000
5000
0
0
5000
10000
15000


AMMAN - RUSEIFA
y = 0.5882x - 1.0724
R² = 0.9997
10000
8000
6000
4000
2000
0
0
5000
10000
15000


K.H.NURSERY EVAP.ST(BAQ'A) - SIHAN
y = 1.1188x + 58.417
R² = 0.9991
25000
20000
15000
10000
5000
0
0
5000
10000
15000
20000


KHALDIYA - WADI DHULEIL NURSERY
y = 1.02x - 39.755
R² = 0.999
8000
6000
4000
2000
0
0.00
2000.00
4000.00
6000.00
8000.00


AMMAN - SIHAN
y = 1.5294x - 551.16
R² = 0.9976
25000.0
20000.0
15000.0
10000.0
5000.0
0.0
0
5000
10000
15000


AMMAN - AMMAN HUSSEIN COLLEGE
y = 1.5837x - 261.23
R² = 0.9998
25000.0
20000.0
15000.0
10000.0
5000.0
0.0
0
5000
10000
15000

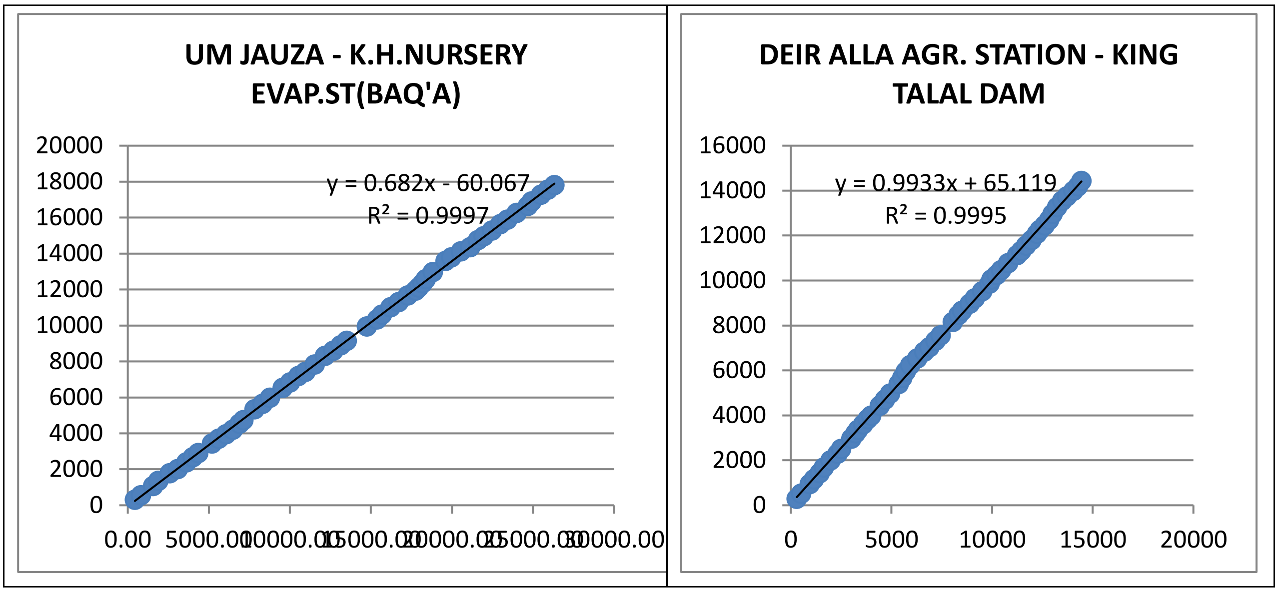


Figure 3-2: Double mass curves for some rainfall stations.

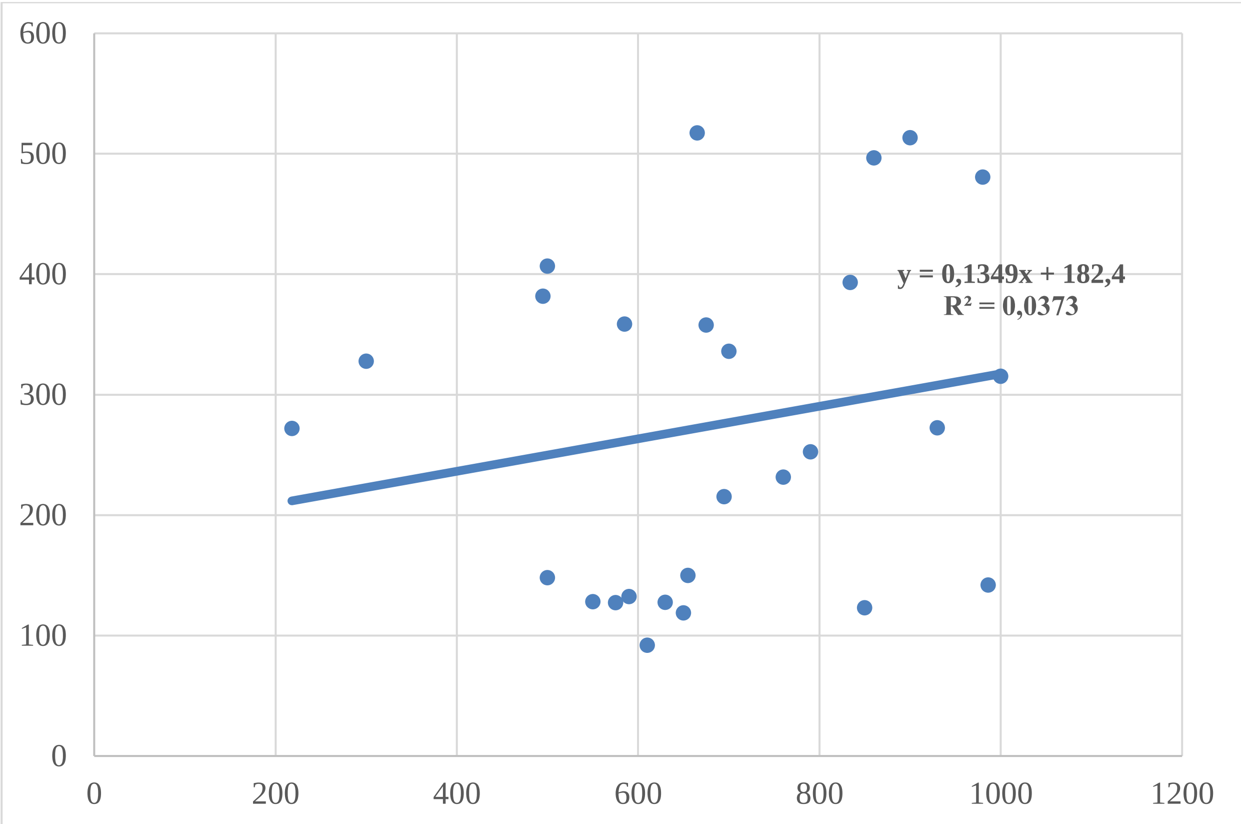


Figure 3-3: regression analysis between rainfall depth and altitude

Table 3-2: Correlation matrix for mean annual rainfall depths for 24 rainfall stations of the azb (blue cells meaning statistical significant correlation).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
AMMAN AIRPORT (1)	1																							
AMMAN HUSSEIN COLLEGE (2)	0,933	1																						
BAL'AMA (3)	0,639	0,536	1																					
DEIR ALLA AGR. STATION (4)	0,839	0,832	0,523	1																				
HASHIMIYA (5)	0,751	0,673	0,578	0,734	1																			
JARASH (6)	0,843	0,823	0,648	0,805	0,759	1																		
JUBEIHA (7)	0,906	0,905	0,481	0,857	0,696	0,845	1																	
K.H.NURSERY EVAP. ST.) (8)	0,904	0,919	0,553	0,853	0,761	0,857	0,935	1																
KHALDIYA (9)	0,791	0,693	0,648	0,758	0,789	0,655	0,660	0,728	1															
KING TALAL DAM (10)	0,823	0,827	0,475	0,883	0,701	0,744	0,838	0,871	0,693	1														
KITTA (11)	0,763	0,770	0,475	0,754	0,646	0,802	0,817	0,808	0,606	0,740	1													
MIDWAR (12)	0,521	0,491	0,455	0,482	0,506	0,640	0,541	0,531	0,464	0,406	0,597	1												
NAWASIF (13)	0,795	0,742	0,729	0,706	0,725	0,636	0,666	0,733	0,793	0,676	0,555	0,356	1											
PRINCE FEISAL NURSERY (14)	0,860	0,830	0,511	0,875	0,718	0,807	0,859	0,862	0,682	0,829	0,807	0,406	0,698	1										
QAFQAFA (15)	0,694	0,698	0,495	0,690	0,622	0,765	0,766	0,759	0,564	0,648	0,787	0,706	0,434	0,671	1									
RUMEIMIN (16)	0,761	0,782	0,473	0,751	0,663	0,761	0,795	0,787	0,640	0,730	0,741	0,480	0,582	0,839	0,674	1								
RUSEIFA (17)	0,926	0,850	0,628	0,761	0,754	0,787	0,823	0,819	0,822	0,733	0,715	0,530	0,776	0,801	0,655	0,762	1							
SABHA AND SUBHIYEH (18)	0,530	0,482	0,418	0,412	0,427	0,429	0,481	0,422	0,505	0,299	0,340	0,276	0,554	0,460	0,413	0,454	0,623	1						
SIHAN (19)	0,825	0,828	0,591	0,803	0,748	0,909	0,821	0,896	0,642	0,764	0,814	0,490	0,621	0,815	0,742	0,734	0,776	0,392	1					
SUBEIHI (20)	0,739	0,768	0,508	0,756	0,752	0,816	0,758	0,769	0,662	0,673	0,691	0,588	0,565	0,694	0,636	0,788	0,735	0,344	0,800	1				
SUKHNA (21)	0,841	0,734	0,616	0,669	0,646	0,755	0,719	0,737	0,775	0,625	0,619	0,559	0,717	0,689	0,587	0,688	0,857	0,555	0,717	0,681	1			
UM EL-JUMAL EVAP. ST. (22)	0,777	0,706	0,616	0,635	0,650	0,634	0,636	0,661	0,662	0,625	0,463	0,302	0,763	0,608	0,508	0,571	0,780	0,690	0,610	0,535	0,535	1		
UM JAUZA (23)	0,687	0,677	0,306	0,651	0,566	0,621	0,780	0,855	0,604	0,764	0,769	0,516	0,523	0,686	0,660	0,645	0,669	0,266	0,686	0,643	0,578	0,370	1	
WADI DHULEIL NURSERY (24)	0,655	0,628	0,539	0,598	0,774	0,505	0,639	0,704	0,867	0,668	0,561	0,237	0,705	0,612	0,562	0,494	0,629	0,542	0,717	0,417	0,523	0,817	0,736	1

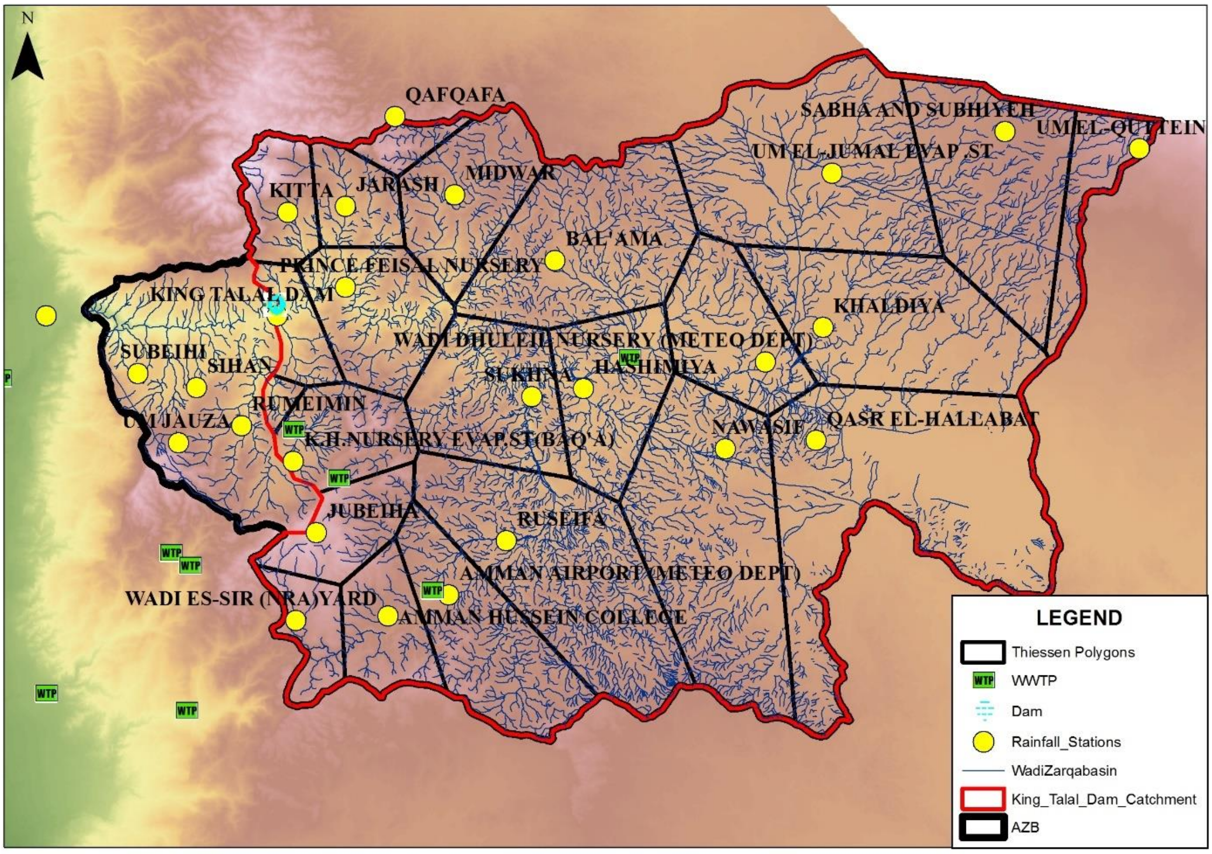


Figure 3-4: thiessen polygons for the king talal dam catchment

Monthly and annual rainfall values for the King Talal Dam catchment is presented in Table 3-3. Mean annual rainfall is equal to 189.1 mm ranging from maximum 352,6mm (in 1991-92) to only 80,7 mm (in 1998-99). Rainfall values are completely zero for June up to September with little rainfall for October (the first month of the hydrologic year) as well.

Table 3-3: monthly rainfall values for the king talal catchment surface rainfall

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL
1964-65	0,0	22,5	32,4	77,5	20,9	14,1	19,6	0,0	0,0	0,0	0,0	0,0	187,0
1965-66	9,1	5,8	23,9	19,4	21,2	57,3	0,1	0,4	0,0	0,0	0,0	0,0	137,2
1966-67	14,2	11,2	69,6	54,6	19,1	76,6	0,5	4,1	0,0	0,0	0,0	0,0	250,0
1967-68	20,0	32,9	26,2	72,1	19,7	13,8	6,7	3,5	0,0	0,0	0,0	0,0	194,8
1968-69	2,7	15,5	43,3	63,9	13,6	86,2	8,4	1,6	0,0	0,0	0,0	0,0	235,2
1969-70	12,6	13,8	8,9	39,5	16,7	51,2	7,2	0,2	0,0	0,0	0,0	0,0	150,1
1970-71	0,6	4,9	31,3	33,1	29,4	32,3	96,3	0,5	0,0	0,0	0,0	0,0	228,6
1971-72	0,2	17,0	72,5	24,0	44,1	36,4	27,2	1,7	0,0	0,0	0,0	0,0	223,1
1972-73	1,4	28,0	1,8	54,8	16,9	34,3	3,1	0,5	0,0	0,0	0,0	0,0	140,8
1973-74	0,8	34,9	19,8	154,9	70,0	13,2	14,5	0,0	0,0	0,0	0,0	0,0	308,1
1974-75	0,0	17,1	18,9	16,6	85,1	29,5	7,1	0,1	0,0	0,0	0,0	0,0	174,3
1975-76	0,3	13,9	26,9	22,1	40,1	51,0	9,4	1,9	0,0	0,0	0,0	0,0	165,6
1976-77	3,2	14,2	3,4	36,3	20,5	34,6	30,2	0,1	0,0	0,0	0,0	0,0	142,5

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL
1977-78	18,3	3,7	46,6	24,4	19,8	38,5	4,8	0,0	0,0	0,0	0,0	0,0	156,0
1978-79	4,3	3,8	35,7	28,6	15,2	21,8	2,8	0,2	0,0	0,0	0,0	0,0	112,4
1979-80	14,5	74,0	74,2	49,7	54,3	71,9	10,2	0,0	0,0	0,0	0,0	0,0	348,8
1980-81	2,2	5,9	114,2	28,3	33,8	24,1	5,6	1,8	0,0	0,0	0,0	0,0	216,1
1981-82	0,2	18,2	2,4	43,7	51,2	27,7	12,1	11,4	0,0	0,0	0,0	0,0	166,9
1982-83	12,1	27,3	18,2	69,3	71,9	56,7	5,8	4,9	0,0	0,0	0,0	0,0	266,3
1983-84	0,4	8,0	2,9	45,0	17,4	66,2	6,1	0,0	0,0	0,0	0,0	0,0	146,0
1984-85	13,2	15,6	25,8	18,1	98,9	28,6	6,2	1,0	0,0	0,0	0,0	0,0	207,5
1985-86	3,1	5,2	24,6	17,3	44,8	4,8	8,7	7,1	0,0	0,0	0,0	0,0	115,6
1986-87	15,2	85,4	21,2	37,7	16,8	38,8	0,0	0,0	0,0	0,0	0,0	0,0	215,1
1987-88	24,3	6,7	57,5	56,7	89,9	49,2	10,8	0,0	0,0	0,0	0,0	0,0	295,2
1988-89	4,2	10,9	103,9	38,1	21,5	27,0	0,4	0,0	0,0	0,0	0,0	0,0	206,1
1989-90	1,4	19,1	21,2	44,2	33,2	35,8	16,3	0,0	0,0	0,0	0,0	0,0	171,0
1990-91	3,2	9,8	1,9	68,0	33,8	37,4	5,5	0,5	0,0	0,0	0,0	0,0	160,2
1991-92	5,4	20,0	119,5	68,2	122,4	15,7	0,2	1,1	0,0	0,0	0,0	0,0	352,6
1992-93	0,2	26,1	58,5	42,5	28,6	13,8	0,3	6,5	0,0	0,0	0,0	0,0	176,5
1993-94	3,1	10,7	10,8	60,1	20,7	28,1	1,3	0,0	0,0	0,0	0,0	0,0	134,8
1994-95	7,1	78,4	65,4	3,1	32,6	15,4	2,8	0,0	0,0	0,0	0,0	0,0	204,9
1995-96	0,4	11,5	12,9	59,4	8,3	56,1	3,2	0,1	0,0	0,0	0,0	0,0	151,9
1996-97	5,3	19,2	24,9	56,7	58,9	36,9	2,0	1,4	0,0	0,0	0,0	0,0	205,4
1997-98	11,9	15,2	42,6	55,2	18,4	61,1	1,6	0,0	0,0	0,0	0,0	0,0	206,1
1998-99	0,8	0,3	5,7	24,7	38,2	7,6	3,4	0,1	0,0	0,0	0,0	0,0	80,7
1999-00	0,3	0,7	6,1	89,4	16,8	25,5	0,3	0,9	0,0	0,0	0,0	0,0	140,0
2000-01	13,3	4,9	57,2	30,5	26,7	6,5	7,6	5,1	0,0	0,0	0,0	0,0	151,8
2001-02	2,6	17,5	47,3	77,8	24,6	32,7	15,9	1,0	0,0	0,0	0,0	0,0	219,4
2002-03	2,4	17,7	77,2	28,7	97,0	51,0	3,6	0,0	0,0	0,0	0,0	0,0	277,5
2003-04	0,3	10,5	52,9	41,8	35,3	6,8	2,6	2,3	0,0	0,0	0,0	0,0	152,6
2004-05	0,8	45,9	14,9	43,5	51,5	15,4	6,6	3,6	0,0	0,0	0,0	0,0	182,3
2005-06	0,8	10,4	37,5	28,5	43,8	3,6	32,1	0,0	0,0	0,0	0,0	0,0	156,8
2006-07	8,4	1,7	29,3	40,5	41,3	35,2	5,8	4,8	0,0	0,0	0,0	0,0	167,0
2007-08	2,1	20,0	14,6	53,5	44,1	4,5	0,0	0,0	0,0	0,0	0,0	0,0	138,8
2008-09	10,3	4,7	17,9	6,6	80,3	33,0	1,6	0,0	0,0	0,0	0,0	0,0	154,3
2009-10	6,8	27,3	41,2	40,5	64,7	11,5	0,1	0,4	0,0	0,0	0,0	0,0	192,6
2010-11	1,1	0,3	22,5	36,5	51,1	12,7	6,8	6,3	0,0	0,0	0,0	0,0	137,3
2011-12	0,2	22,6	15,0	53,8	58,9	50,6	0,2	0,0	0,0	0,0	0,0	0,0	201,4
2012-13	0,1	15,4	24,8	107,3	17,0	1,0	8,6	3,4	0,0	0,0	0,0	0,0	177,6
2013-14	2,0	9,6	54,4	4,6	3,1	52,9	0,0	15,6	0,0	0,0	0,0	0,0	142,2
2014-15	8,1	54,6	24,3	61,4	57,4	8,2	12,0	0,1	0,0	0,0	0,0	0,0	226,1
2015-16	14,0	18,3	13,2	74,1	27,4	16,5	11,0	0,1	0,0	0,0	0,0	0,0	174,6
2016-17	1,7	1,6	107,1	36,5	29,7	16,4	2,0	0,0	0,0	0,0	0,0	0,0	194,8

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL
AVER.	**5,5**	**18,7**	**36,4**	**46,5**	**40,0**	**31,6**	**8,6**	**1,8**	**0**	**0**	**0**	**0**	**189,1**
S. D.	**6,1**	**18,6**	**29,6**	**26,5**	**26,1**	**20,6**	**14,3**	**3,1**	**0**	**0**	**0**	**0**	**55,9**
C.V	**1,1**	**1,0**	**0,8**	**0,6**	**0,7**	**0,7**	**1,7**	**1,7**	**-**	**-**	**-**	**-**	**0,30**

Aver: Average, S.D. Standard Deviation, C.V.: Coefficient of Variation

Figure 3-5 presents the annual rainfall data and the 5-year moving average for the **Amman Airport** rainfall station from 1937-38 up to date. From the 5-year moving average, we can define two distinct circles of diminishing rainfall depths that culminate around 1962 and 1999 respectively. These downward trends will obviously influence the drought periods in the area.

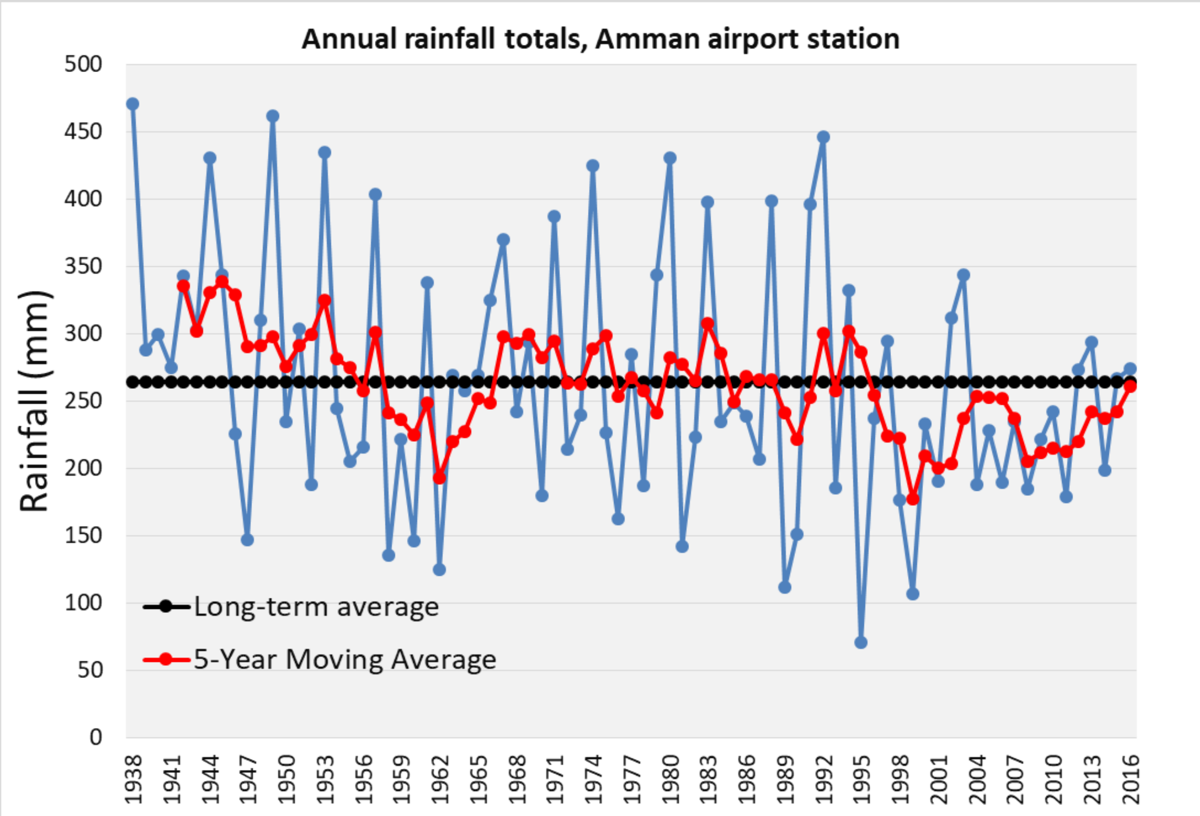


Figure 3-5: annual rainfall data and 5-year moving average for the amman airport station

We can also identify a mild but consistent drop during the last 15 years. A few periods with very low rainfall (worse in 1995) are followed on average by wet years. This behavior is expected to be revealed by the indices taking into account rainfall at the annual and across annual scales (SPI-12, SPI-24 etc).

The historical record of monthly rainfall at Amman Airport Station covers an extensive period between 1938-2016. Rainfall shows a very seasonal behavior while January and February are the wettest months and June to September are always dry. This behavior is expected to be revealed by the indices taking into account rainfall at the monthly scales (SPI-3, SPI-6 etc).

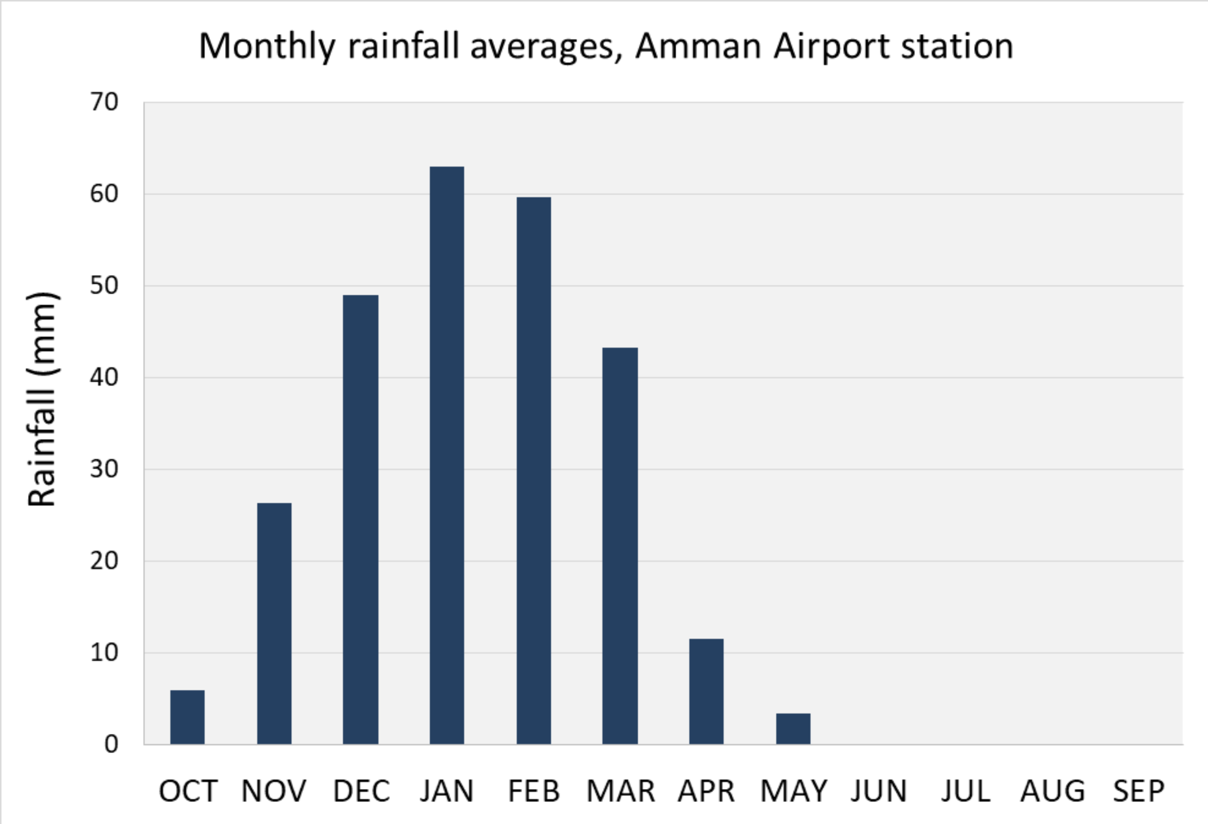


Figure 3-6: monthly rainfall average for the amman airport station

3.2 POTENTIAL EVAPOTRANSPIRATION

Potential Evapotranspiration (ET) is computed throughout the methodological context using the Penman -Monteith (P-M) method. It was developed by Howard Penman in 1948 (later modified by John Monteith et al. to yield the Penman–Monteith model). It is well established and a basis for further theoretical development in the field of evaporation research. Basically, it is a combination of turbulent transfer and energy-balance approaches (3 equations)

$$\lambda ET_o = \frac{\Delta (R_n - G) + \frac{86{,}400\, \rho_a C_P (e_s^{\,o} - e_a)}{r_{av}}}{\Delta + \gamma \left(1 + \frac{r_s}{r_{av}}\right)}$$

ET_o	=	Reference Evapotranspiration
R_n	=	Net radiation flux in MJ m^{-2} d^{-1},
G	=	Sensible heat flux into the soil in MJ m^{-2} d^{-1}
p_a	=	Air density in kg m^{-3}
C_p	=	Specific heat of dry air [~1.013 x 10^{-3}MJ kg^{-1} °C^{-1}]

e_a	=	Saturation vapor pressure at mean air temperature in kPa
e_s	=	Saturation vapor pressure at dew point in kPa
r_s	=	Canopy surface resistance in s m^{-1}.
r_a	=	Bulk surface aerodynamic resistance for water vapor in s m^{-1}
λ	=	Latent heat of vaporization in MJ kg-1
γ	=	Psychrometric constant in kPa $^oC^{-1}$
Δ	=	Slope of the saturated vapor pressure curve.

As already stated, Penman-Moneith method needs the following data, (a) Temperature (mean monthly or mean monthly maximum and minimum) (ºC), (b) Relative humidity (%), (c) Wind Speed (m/s at 2 m height of the sensor), and (d) sunshine duration (h). These types of data are not available even in technologically developed countries, so a fair approximation of P-M method, is the Hargreaves method.

Hargreaves method was originally developed in 1975 and uses solar radiation and temperature data inputs.

It was updated in 1982 and 1985 to accommodate grass reference ET (ETo) estimates. The Hargreaves equation is the following:

$$ET_o = 0.0023(T_{max} - T_{min})^{0.5} (T_{mean} + 17.8) R_a$$

where,

Ra = Extraterrestrial solar radiation (MJ/m2/day),

Hargreaves method can be used to compute daily PET. It is a simple and easy to use method with Minimal data requirements—maximum and minimum air temperature, has better predictive accuracy in arid climates than other empirical methods (such as modified Blaney-Criddle), it needs only the max-min temperature difference and the extra-terrestrial radiation.

3.2.1 TEMPERATURE DATA

Temperature data are provided only for 6 stations. Average temperatures are calculated as the average values of the minimum and maximum monthly temperatures.

Table 3-4: temperature data for the azb

Station	Data Period (with gaps)	Type of Data	Average Temperature (ºC)
AMMAN AIRPORT (METEO DEPT)	1966 – 2017 (10 years gap)	Maximum and Minimum temperatures	17,88
K.H. NURSERY EVAP.ST(BAQ'A)	1968 – 2016 (3 years gap)	Maximum and Minimum temperatures	17,45
KHIREBIT ES SAMRA EVAP .ST	1986 – 2016 (1 year gap)	Maximum and Minimum temperatures	18,59
KING TALAL DAM	1973 – 2017 (12 years	Maximum and Minimum	21,55

Station	Data Period (with gaps)	Type of Data	Average Temperature (ºC)
	gap)	temperatures	
UM EL-JUMAL EVAP .ST	1968 – 2017 (1 year gap)	Maximum and Minimum temperatures	18,83
WADI ES-SIR (NRA)YARD	2003 – 2006	Maximum and Minimum temperatures	---

3.2.2 RELATIVE HUMIDITY DATA

Relative humidity data are provided only for 6 stations. Average relative humidity values are calculated from the dry and wet bulb temperatures that were the original data.

Table 3-5: relative humidity data for the azb

Station	Data Period (with gaps)	Type of Data	Average Relative Humidity (%)
AMMAN AIRPORT (METEO DEPT)	1966 – 2017 (10 years gap)	Dry & Wet Bulb Temperatures	74,2
K.H. NURSERY EVAP.ST(BAQ'A)	1968 – 2016 (3 years gap)	Dry & Wet Bulb Temperatures	75,6
KHIREBIT ES SAMRA EVAP .ST	1986 – 2016 (1 year gap)	Dry & Wet Bulb Temperatures	84,0
KING TALAL DAM	1973 – 2017 (12 years gap)	Dry & Wet Bulb Temperatures	79,3
UM EL-JUMAL EVAP .ST	1968 – 2017 (1 year gap)	Dry & Wet Bulb Temperatures	77,6
WADI ES-SIR (NRA)YARD	2003 – 2006	Dry & Wet Bulb Temperatures	---

3.2.3 SUNSHINE DURATION DATA

Sunshine duration data are provided only for 3 stations. Average temperatures are calculated as the average values of the minimum and maximum monthly temperatures.

Table 3-6: sunshine duration data for the azb

Station	Data Period (with gaps)	Type of Data	Average Daily Sunshine Duration (h)
AMMAN AIRPORT (METEO DEPT)	1966 – 2017 (10 years gap)	Average Sunshine Duration	9,69
KHIREBIT ES SAMRA EVAP	1988 – 2012 (5 years	Average Sunshine Duration	8,16

.ST	gap)		
UM EL-JUMAL EVAP .ST	1983 – 2016 (1 year gap)	Average Sunshine Duration	9,39

3.2.4 WIND SPEED DATA

Wind Speed data are provided for 5 meteorological stations and are measured in km/h.

Table 3-7: wind speed data for the azb

Station	Data Period (with gaps)	Type of Data	Average Wind Speed (km/h)
AMMAN AIRPORT (METEO DEPT)	1988 – 2016 (no gaps)	Average Wind Speed	9,69
K.H. NURSERY EVAP.ST(BAQ'A)	1968 – 2015 (6 years gap)	Average Wind Speed	6.33
KING TALAL DAM	1973 – 2017 (12 years gap)	Average Wind Speed	7,24
KHIREBIT ES SAMRA EVAP .ST	1988 – 2012 (5 years gap)	Average Wind Speed	8,16
UM EL-JUMAL EVAP .ST	1969 – 2014 (2 years gap)	Average Wind Speed	10,55

3.2.5 PET COMPUTATIONS

Values of PET are computed both with PM and HG methods and the results are summarized in the following Table. Generally, it is not possible to directly compare PM to HG because common periods with PET estimates are not generally available, but we can see that HG method provide higher values of PET.

Table 3-8: PET esimates with PM and HG methods

Station	Data Period (with gaps)	PET Penman Monteith (mm/y)	PET Hargreaves (mm/y)
AMMAN AIRPORT (METEO DEPT)	1966 – 2016 (significant gaps)	1133,5	1356,7
K.H. NURSERY EVAP.ST(BAQ'A)	1966 – 2014 (2 years gap)	NO DATA	1398,7
KING TALAL DAM	1973 – 2017 (12 years gap)	NO DATA	1588,6
KHIREBIT ES SAMRA EVAP .ST	1985 – 2015 (2 years gap)	1066,2	1683,6

UM EL-JUMAL EVAP .ST	1982 – 2014 (2 years gap)	1179,8	1543,0

The **direct comparison between PM and HG methods are only possible for the Amman Airport station** (Figure 3-7). It can be seen that **HG estimates are higher than PM because HG overestimates PET during winter months**.

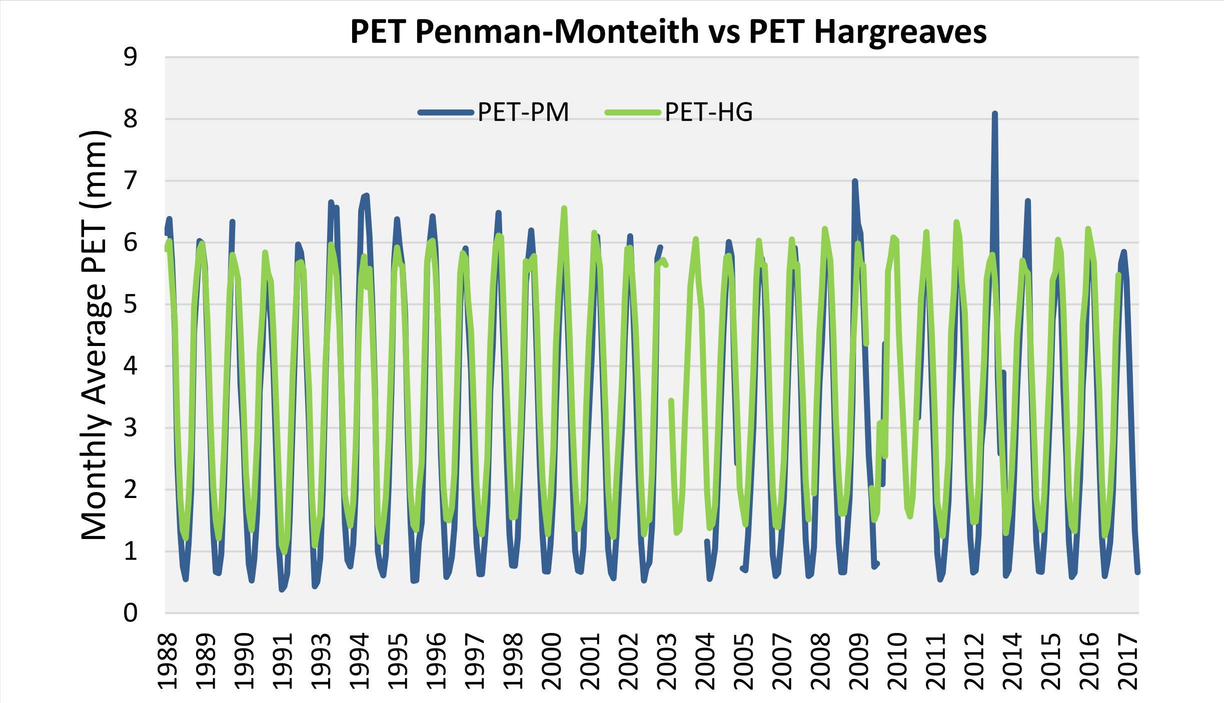


Figure 3-7: Direct comparison between PM and HG methods for the pet estimation

4 DROUGHT HAZARD

4.1 INTRODUCTION

Yevjevich (1967) proposed the theory for identifying drought parameters and investigating their statistical properties: (a) duration, (b) severity, and (c) intensity. The most basic element for deriving these parameters is the truncation or threshold level, which may be a constant or a function of time. A run is defined as a portion of time series of drought variable Xt, in which all values are either below or above the selected truncation level of X_o; accordingly, it is called either a negative run or a positive run. Fig. 1 represents a plot of a drought variable denoted by Xt, which is intersected at many places by the truncation level X_o, which can be a deterministic variable, a stochastic variable, or a combination thereof. Various statistical parameters concerning drought duration, severity and intensity at different truncation levels are much useful for drought characterization.

A drought event has the following major components (Dracup et al., 1980) as derived from Fig. 1 which include: (a) Drought initiation time (ti): it is the starting of the water shortage period, which indicates the beginning of a drought. (b) Drought termination time (te): it is the time when the water shortage becomes sufficiently small so that drought conditions no longer persist. (c) Drought duration (Dd): it is expressed in years/months/weeks, etc., during which a drought parameter is continuously below the critical level. In other words, it is the time period between the initiation and termination of a drought. (d) Drought severity (Sd): it indicates a cumulative deficiency of a drought parameter below the critical level. (e) Drought intensity (Id): it is the average value of a drought parameter below the critical level. It is measured as the drought severity divided by the duration.

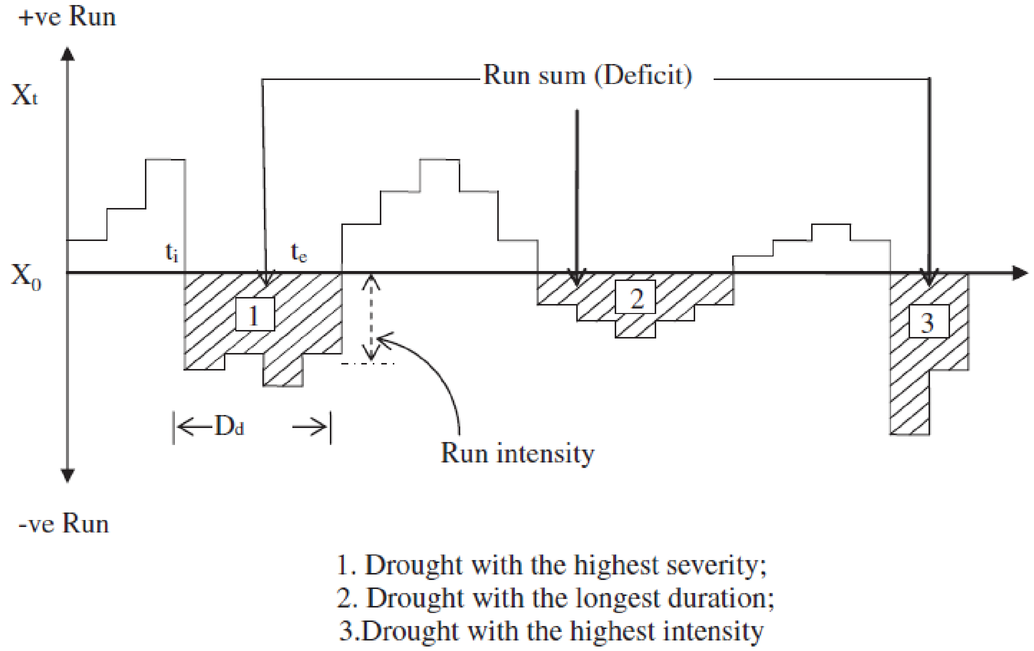


Figure 4-1: definition of drought SEVERITY/magnitude, INTENSITY AND DURATION

4.2 THE DECILE INDEX

In this approach suggested by Gibbs and Maher (1967) and widely used in Australia (Coughlan, 1987), monthly precipitation totals from a long-term record are first ranked from highest to lowest to construct a cumulative frequency distribution. The distribution is then split into 10 parts (tenths of distribution or deciles). The first decile is the precipitation value not exceeded by the lowest 10% of all precipitation values in a record. The second decile is between the lowest 10 and 20% etc. Comparing the amount of precipitation in a month (or during a period of several months) with the long-term cumulative distribution of precipitation amounts in that period, the severity of drought can be assessed. The deciles are grouped into five classes, two deciles per class. If precipitation falls into the lowest 20% (deciles 1 and 2), it is classified as much below normal. Deciles 3 to 4 (20 to 40%) indicate below normal precipitation, deciles 5 to 6 (40 to 60%) indicate near normal precipitation, 7 and 8 (60 to 80%) indicate above normal precipitation and 9 and 10 (80 to 100%) indicate much above normal precipitation.

4.3 THE STANDARDIZED PRECIPITATION INDEX (SPI)

4.3.1 INTRODUCTION- THEORETICAL BACKGROUND

The SPI was designed to quantify the precipitation deficit for multiple timescales. These timescales reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee and others (1993) originally calculated the SPI for 3-, 6-,12-, 24- and 48-month timescales.

The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). **Positive SPI values indicate greater than median precipitation and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way; thus, wet periods can also be monitored using the SPI.**

McKee et al. (1993, 1995) fitted a gamma distribution to the precipitation histogram for calculating SPI. Using an equiprobable transformation, the cumulative density function (CDF) of the gamma distribution was then transformed to the CDF of the standard normal distribution. The transformed standard deviate is the SPI for the given precipitation total (Kim et al. 2006). The SPI is computed by dividing the difference between the normalised seasonal precipitation and its long-term seasonal mean by the standard deviation (Bhuiyan et al. 2006):

$$SPI = (Xij - Xim)/\sigma$$

where, X_{ij} is the seasonal precipitation at the i_{th} raingauge station and jth observation, Xim the long-term seasonal mean and σ is its standard deviation. Since the SPI is equal to the z-value of the normal distribution, McKee et al. (1993, 1995) proposed a seven-category classification for the SPI: extremely wet (z>2.0), very wet (1.5 to 1.99), moderately wet (1.0 to 1.49), near normal (−0.99 to 0.99), moderately dry (−1.49 to 1.0), severely dry (−1.99 to 1.5), and extremely dry (<−2.0) (Table 4-1). The expected time in each drought category was based on an analysis of a large number of rainfall stations across Colorado, USA.

McKee and others (1993) used the classification system shown in the SPI value table below (Table 4-1) to define drought intensities resulting from the SPI. They also defined the criteria for a drought event for any of the timescales. A drought event occurs any time the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive.

Table 4-1: DROUGHT CHARACTERIZATION ACCORDING TO SPI

SPI>2.0	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-.99 to .99	Near Normal

-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

Based on an analysis of stations across Colorado in the United States, McKee determined that the SPI indicates mild drought 24% of the time, moderate drought 9.2% of the time, severe drought 4.4% of the time and extreme drought 2.3% of the time (McKee et al.,1993). Because the SPI is standardized, these percentages are expected from a normal distribution of the SPI. The 2.3% of SPI values within the “extreme drought” category is a percentage that is typically expected for an “extreme” event. In contrast, the Palmer Drought Severity Index reaches its “extreme” category more than 10% of the time across portions of the central Great Plains in the United States. This standardization allows the SPI to determine the rarity of a current drought, as well as the probability of the precipitation necessary to end it (McKee et al., 1993). It also allows the user to confidently compare historical and current droughts between different climatic and geographic locations when assessing how rare, or frequent, a given drought event is.

The SPI calculated in this way has the following desirable traits:

- The SPI is uniquely related to probability.
- The precipitation used in SPI can be used to calculate the precipitation deficit for the current period.
- The precipitation used in SPI can be used to calculate the current percent of average precipitation for time period of i months.
- Simplicity of use since it needs only rainfall data.
- Its variable time scale, which allows it to describe drought conditions important for a range of meteorological, agricultural, and hydrological applications. This temporal versatility is also helpful for the analysis of drought dynamics, especially the determination of onset and cessation, which have always been difficult to track with other indices.
- Its standardization, which ensures that the frequency of extreme events at any location and on any time scale are consistent.

The standardized precipitation index (SPI) for any location is calculated, based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed to a normal distribution so that the mean SPI for the location and desired period is zero (McKee et al., 1993; Edwards and McKee, 1997). The fundamental strength of SPI is that it can be calculated for a variety of time scales. This versatility allows SPI to monitor short-term water supplies, such as soil moisture which is important for agricultural production, and long-term water resources, such as groundwater supplies, streamflow, and lake and reservoir levels. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the longterm precipitation anomalies.

The length of precipitation record and nature of probability distribution play an important role for calculating SPI and the following section discusses limitations of SPI. The length of a precipitation record has a significant impact on the SPI values. Similar and consistent results are observed when the SPI values, computed from different lengths of record, have similar gamma distributions over different time periods. However, the SPI values are significantly discrepant when the distributions are different. It is recommended that the SPI user should be aware of the numerical differences in the SPI values if different lengths of record are used in interpreting and making decisions based on the SPI values. For example, Wu et al. (2005) investigated the effect of the length of record on the SPI calculation by examining correlation coefficients, the index of agreement, and the consistency of dry/wet event categories between the SPI values derived from different precipitation record lengths. The reason for discrepancy in the SPI value is due to changes in the shape and scale parameters of the gamma distribution when different lengths of record are involved.

The use of different probability distributions affect the SPI values as the SPI is based on the fitting of a distribution to precipitation series. Some of the commonly applied distributions include: gamma distribution (McKee et al., 1993; Edwards and McKee, 1997; Mishra and Singh, 2009); and Pearson Type III distribution (Guttman, 1999); and lognormal, extreme value, and exponential distributions have been widely applied to simulations of precipitation distributions (Lloyd-Hughes and Saunders, 2002; Madsen et al., 1998; Todorovic and Woolhiser, 1976; Wu et al., 2007).

Two types of problems arise: (i) When SPIs are calculated for long time scales (longer than 24 months) fitting a distribution might be biased due to the limitation in data length and it is true that when finer resolutions of spatial analysis need to be investigated, long data sets are not available in many catchments around the world. Lloyd-Hughes and Saunders (2002) and Sonmez et al. (2005) reported biased SPI values. (ii) For dry climates where precipitation is seasonal in nature and zero values are common, there will be too many zero precipitation values in a particular season. In these climatic zones, the calculated SPI values at short time scales may not be normally distributed because of the highly skewed underlying precipitation distribution and because of the limitation of the fitted gamma distribution. This may be prone to large errors while simulating precipitation distributions in dry climates from small data samples.

The SPI calculated in this way has the following disadvantages:

- The assumption that a suitable theoretical probability distribution can be found to model the raw precipitation data prior to standardization. An associated problem is the quantity and reliability of the data used to fit the distribution. McKee et al. (1993) recommend using at least 30 years of high-quality data.
- A second limitation of the SPI arises from the standardized nature of the index itself; namely that extreme droughts (or any other drought threshold) measured by the SPI, when considered over a long time period, will occur with the same frequency at all locations. Thus, the SPI is not capable of identifying regions that may be more ‘drought prone’ than others.
- A third problem may arise when applying the SPI at short time scales (1, 2, or 3 months) to regions of low seasonal precipitation. In these cases, misleadingly large positive or negative SPI values may result.

The SPI calculated in this way has the following desirable traits:

- Soil moisture conditions respond to precipitation anomalies on a relatively short timescale. Groundwater, streamflow and reservoir storage reflect the longer-term precipitation anomalies. So, for example, one may want to look at a 1- or 2-month SPI for meteorological drought, anywhere from 1-month to 6-month SPI for agricultural drought, and something like 6-month up to 24-month SPI or more for hydrological drought analyses and applications.

1-month SPI: A 1-month SPI map is very similar to a map displaying the percentage of normal precipitation for a 30-day period. In fact, the derived SPI is a more accurate representation of monthly precipitation because the distribution has been normalized. For example, a 1-month SPI at the end of November compares the 1-month precipitation total for November in that particular year with the November precipitation totals of all the years in record. **Because the 1-month SPI reflects short-term conditions, its application can be related closely to meteorological types of drought along with short-term soil moisture and crop stress, especially during the growing season**.

3-month SPI: The 3-month SPI provides a comparison of the precipitation over a specific 3-month period with the precipitation totals from the same 3-month period for all the years included in the historical record. In other words, a 3-month SPI at the end of February compares the December–January–February precipitation total in that particular year with the December–February precipitation totals of all the years in record for that location. Each year data is added, another year is added to the period of record, thus the values from all years are used again. The values can and will change as the current year is compared historically and statistically to all prior years in the record of observation. **A 3-month SPI reflects short- and medium-term moisture conditions and provides a seasonal estimation of precipitation. In primary agricultural regions, a 3-month SPI might be more effective in highlighting available moisture conditions**

6-month SPI: The 6-month SPI compares the precipitation for that period with the same 6-month period over the historical record. For example, a 6-month SPI at the end of September compares the precipitation total for the April–September period with all the past totals for that same period. The 6-month SPI indicates seasonal to medium-term trends in precipitation and is still considered to be more sensitive to conditions at this scale than the Palmer Index. **A 6-month SPI can be very effective in showing the precipitation over distinct seasons. For example, a 6-month SPI at the end of March would give a very good indication of the amount of precipitation that has fallen during the very important wet season period from October through March for certain Mediterranean locales**. **Information from a 6-month SPI may also begin to be associated with anomalous streamflows and reservoir levels, depending on the region and time of year.**

4.3.2 DROUGHT ANALYSIS IN THE AZ CATCHMENT

In Jordan, due to the absence of rainfall from June to September, SPI-3 is only informative for the first half of the year (from October to December SPI-3 computed in January each year). For generally dry periods, even small deviations from the long term mean, will give large SPI values, therefore **SPI-3 is not an appropriate measure of drought and it is important to compare the SPI3 with longer timescales such as SPI-6 and SPI-12 (**see Figure 4-2) where SPI3 is frequently higher than SPI12)**..**

Very negative SPI-3 values can occur in the middle of generally wetter periods, and likewise, very positive SPI-3 values may occur in the middle of long-term drought periods. Amman Airport –SPI 3 & SPI-12 (1938-2017)

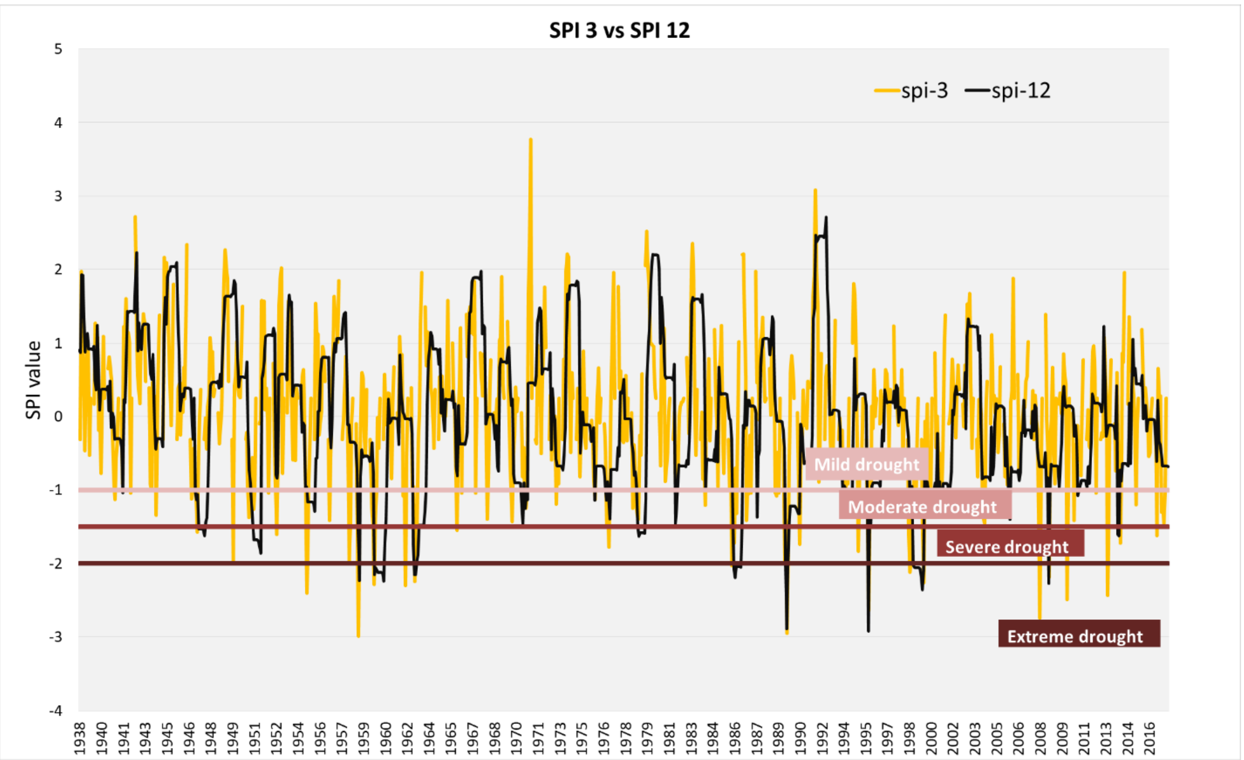


Figure 4-2: SPI-3 and spi-12 comparison for amman airport rainfall station

It is also important to compare the SPI-12 with longer timescales, while very negative SPI-12 values can occur in the middle of generally wetter periods, and likewise, very positive SPI-12 values may occur in the middle of long-term drought periods.

Figure 4-4 presents the SPI-12 for the AZB where the identification of three major drought events is possible: (a) 1995-96, (b) 1998-2001, and (c) 2007-2009. Table 4-2 presents the most significant drought periods in the AZB.

Table 4-2: identification of most significant drought periods in the azb

MOST SIGNIFICANT DROUGHT PERIODS
[1995 1996 1997 1998 1999 2000 2001 2002]
[1975 1976 1977 1978 1979]
[2004 2005 2006 2007 2008 2009]
[1989 1990 1991]
[1965 1966 1967 1968 1969]
[2013 2014 2015 2016 2017]
[1983 1984 1985 1986 1987 1988]

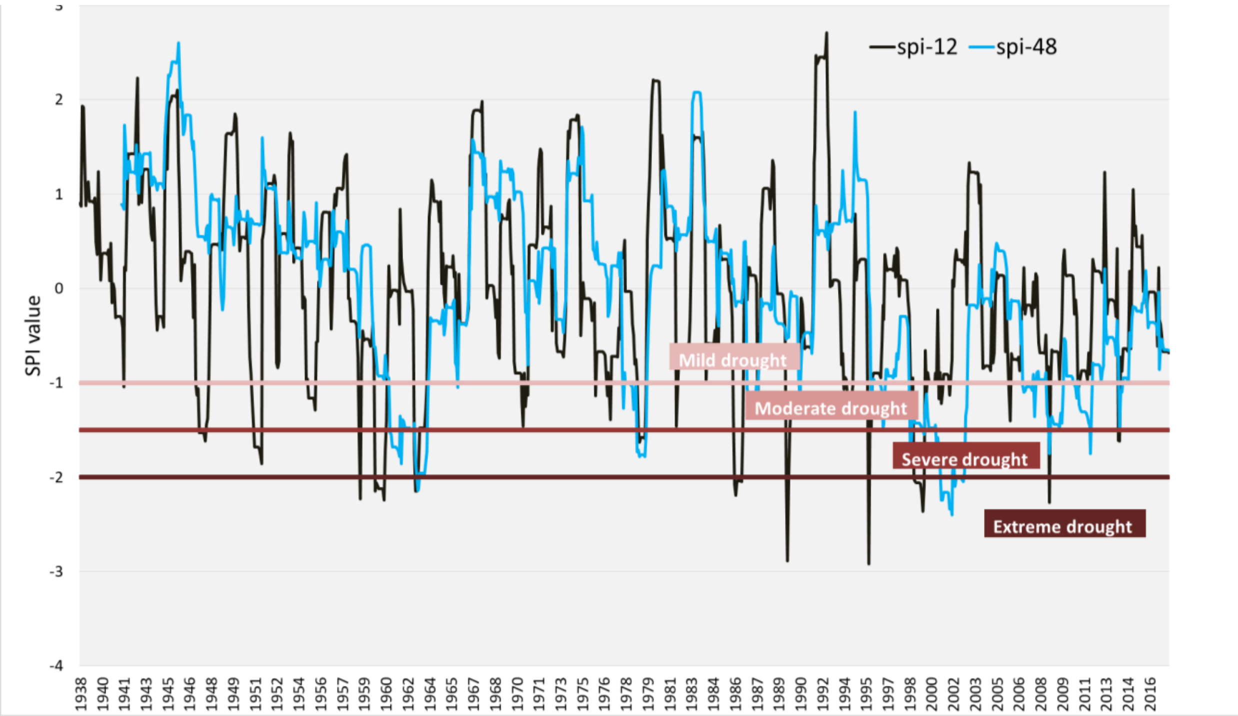


Figure 4-3: SPI-12 and spi-48 comparison for amman airport rainfall station

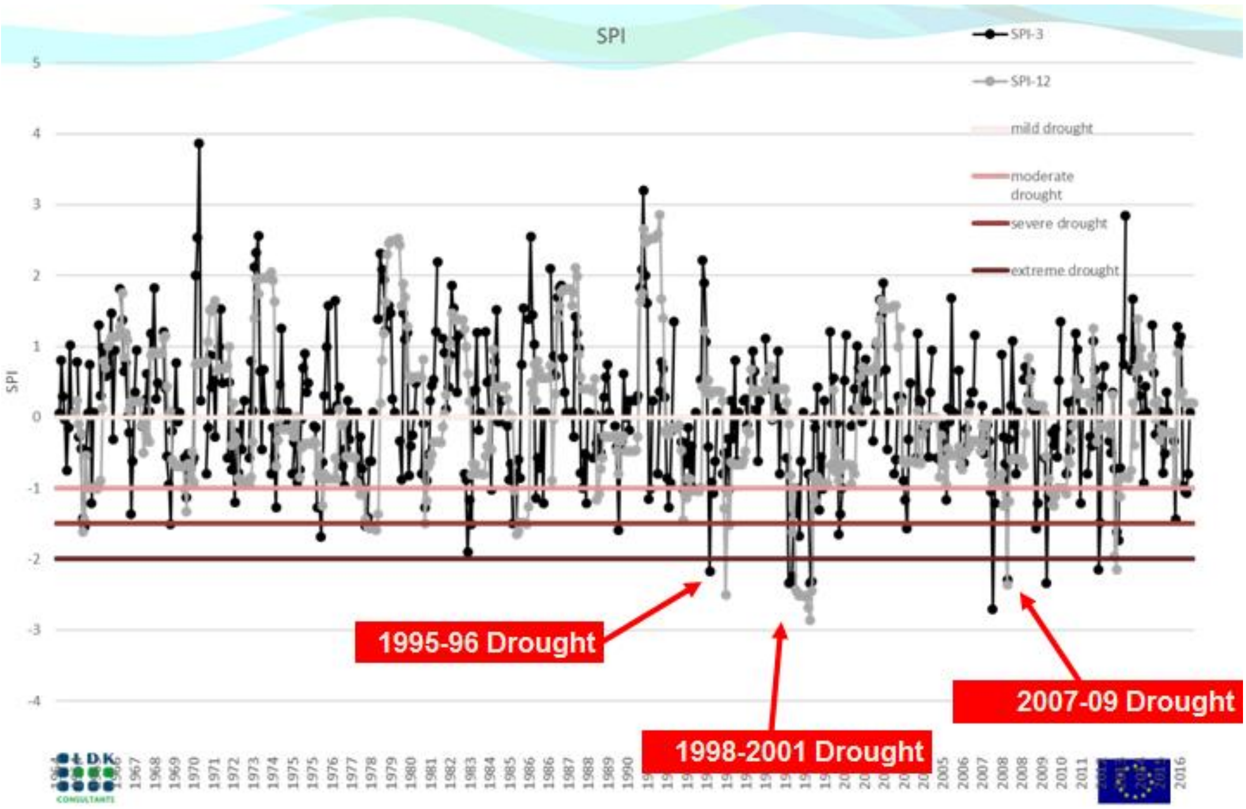


Figure 4-4: spi-12 and identification of major droughts for surface rainfall for AZB

Table 4-3 presents drought magnitude (D) values for all the significant drought events for the whole of the AZB. The event with the highest magnitude is for the years 1998-2001 where D=45,11.

Table 4-3: drought magnitude for most significant drought events in the azb

Year	Duration (months)	Drought Magnitude	Month
[1970 1971]	[13.]	12,4	[3 4 5 ..., 12 1 2]
[1975 1976 1977]	[32.]	16,46	[4 5 6 ..., 1 2 3]
[1978 1979]	[13.]	14,83	[10 11 12 ..., 7 8 9]
[1981 1982]	[13.]	8,98	[12 1 2 ..., 9 10 11]
[1986]	[12.]	17,31	[1 2 3 ..., 10 11 12]
[1987 1988]	[3.]	2,18	[11 12 1]
[1989 1990 1991]	[26.]	24,03	[10 11 12 ..., 7 8 9]
[1993 1994]	[12.]	10,68	[11 12 1 ..., 8 9 10]
[1995 1996 1997]	[15.]	14,34	[11 12 1 ..., 8 9 10]
[1998 1999 2000 2001]	[39.]	45,11	[10 11 12 ..., 7 8 9]
[2005 2006 2007]	[16.]	10,33	[11 12 1 ..., 8 9 10]
[2008 2009]	[22.]	15,14	[3 4 5 ..., 12 1 2]
[2010 2011 2012]	[16.]	10,64	[11 12 1 ..., 8 9 10]
[2014]	[10.]	8,08	[1 2 3 4 5 6 7 8 9 10]

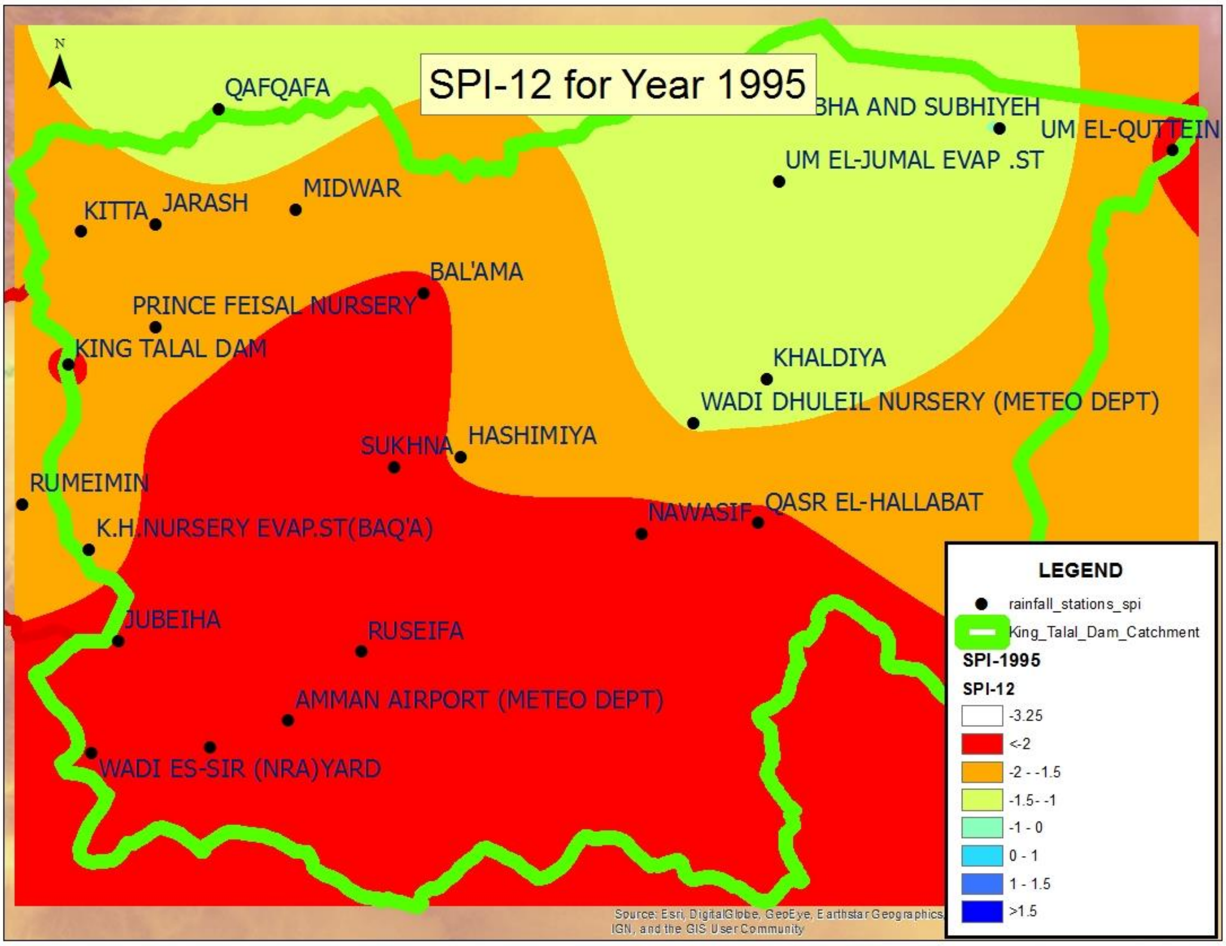


Figure 4-5: drought hazard mapping (spi-12) for 1995 for AZB.

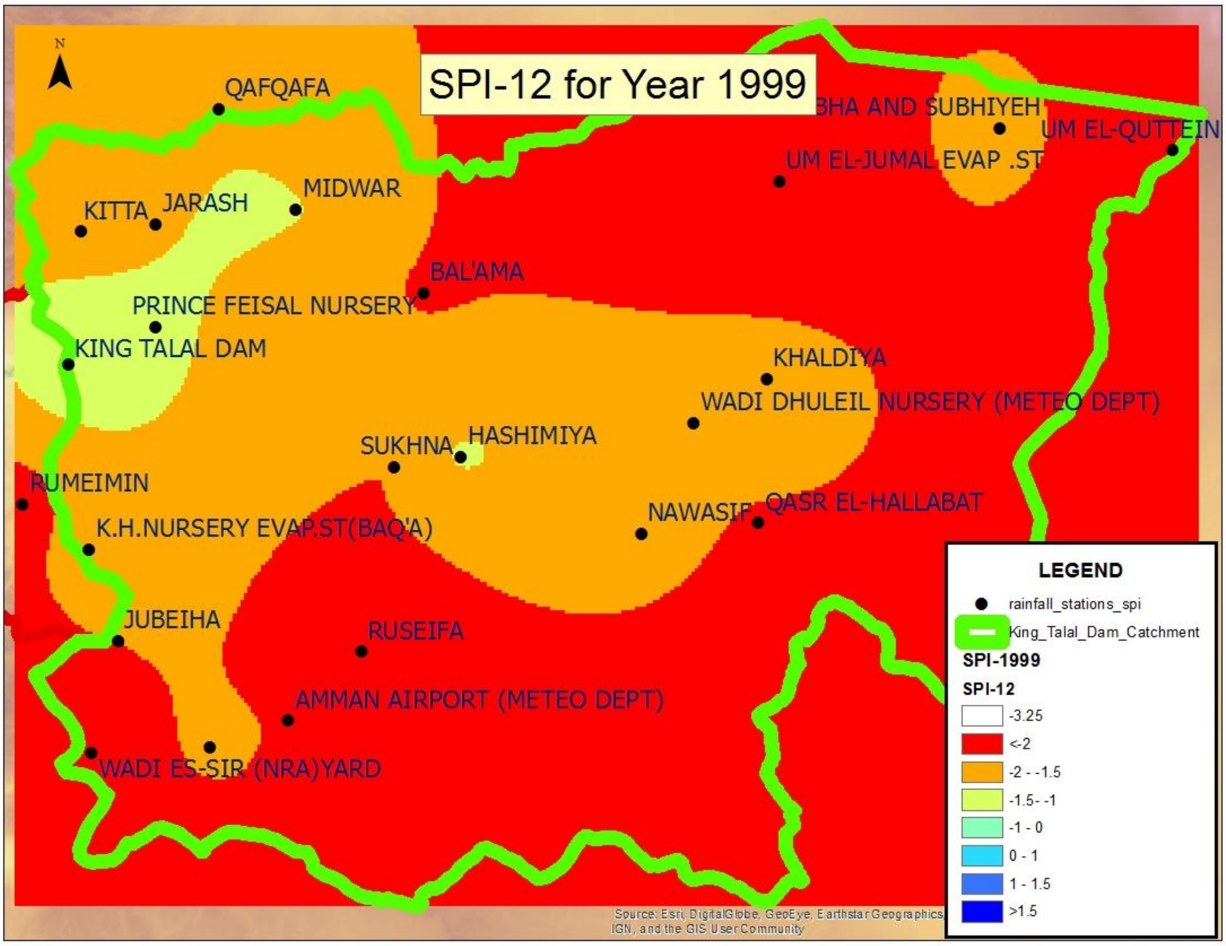


Figure 4-6: : drought hazard mapping (spi-12) for 1999 for AZB.

4.4 THE STANDARDIZED PRECIPITATION – EVAPOTRANSIRATION INDEX (SPEI)

The Standardized Precipitation Evapotranspiration Index (SPEI) is an extension of the widely used Standardized Precipitation Index (SPI). The SPEI is designed to take into account both precipitation and potential evapotranspiration (PET) in determining drought. Thus, unlike the SPI, the SPEI captures the main impact of increased temperatures on water demand. Like the SPI, the SPEI can be calculated on a range of timescales from 1-48 months. If only limited data are available, say temperature and precipitation, PET can be estimated with the simple Thornthwaite method. In this simplified approach, variables that can affect PET such as wind speed, surface humidity and solar radiation are not accounted for. In cases where more data are available, a more sophisticated method to calculate PET is often preferred in order to make a more complete accounting of drought variability. However, these additional variables can have large uncertainties.

Vicente-Serrano et al. (2010) formulated a new drought index [the standardized precipitation evapotranspiration index (SPEI)] based on precipitation and potential evapotranspiration (PET). The

SPEI combines the sensitivity of the Palmer Drought Severity Index (PDSI) to changes in evaporation demand (caused by temperature fluctuations and trends) with the multitemporal nature of the SPI.

The SPEI has great promise as a drought index because it captures a broader measure of the available water (climatic water balance) and avoids issues inherent in the SPI, such as fitting periods with zero precipitation. However, as a newer index, it requires more rigorous testing with respect to its methodology and assumptions before it can gain widespread acceptance within the drought community. Index sensitivity to PET calculation method has already been addressed but to date there has been little testing of the univariate distributions used to normalize the SPEI.

The procedure for calculating the SPEI is similar to that for the SPI. However, the SPEI uses “climatic water balance”, the difference between precipitation and reference evapotranspiration ($P–ET_o$), rather than precipitation(P) as the input. The climatic water balance compares the available water (P) with the atmospheric evaporative demand (ET_o), and therefore provides a more reliable measure of drought severity than only considering precipitation. The climatic water balance is calculated at various time scales (i.e. over one month, two months, three months, etc.), and the resulting values are fit to a loglogistic probability distribution to transform the original values to standardized units that are comparable in space and time and at different SPEI time scales.

The presence of negative values in the P-ET terms can impose errors in the statistical manipulations. Therefore, we use the Reconnaissance Drought Index (RDI) instead which uses the P and ETo ratio instead of the difference between P and ETo.

4.5 THE RECONNAISSANCE DROUGHT INDEX (RDI)

4.5.1 INTRODUCTION - THEORETICAL BACKGROUND

The Reconnaissance Drought Index (RDI) was developed to approach the water deficit in a more accurate way, as a sort of balance between input and output in a water system (Tsakiris and Vangelis 2005; Tsakiris et al. 2007). It is based both on cumulative precipitation (P) and potential evapotranspiration (PET), of which one is measured (P) and one is calculated (PET) determinant.

It should be emphasized that the RDI is based both on precipitation and on potential evapotranspiration. The mean initial index (α_κ) represents the normal climatic conditions of the area and is equal to the Aridity Index as was proposed by the FAO. Among others, some of the advantages of the RDI are as follows:

1. It is physically sound, since it calculates the aggregated deficit between precipitationand the evaporative demand of the atmosphere.
2. It can be calculated for any period of time (e.g., 1 month, 2 months etc).
3. The calculation always leads to a meaningful figure.
4. It can be effectively associated with agricultural drought.
5. It is directly linked to the climatic conditions of the region, since for the yearly value it can be compared with the FAO Aridity Index.
6. It can be used under “climate instability” conditions, for examining the significance of various changes of climatic factors related to water scarcity. From the above advantages, it can be

concluded that the RDI is an ideal index for the reconnaissance assessment of drought severity for general use giving comparable results within a large geographical area, such as the Mediterranean.

The initial value (α_k) of RDI is calculated for the i-th year in a time basis of k (months) as follows:

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}}, \ i = 1(1)N \ \text{ and } \ j = 1(1)k$$

in which Pij and PETij are the precipitation and potential evapotranspiration of the j-th month of the i-th year and N is the total number of years of the available data.

The values of α_k follow satisfactorily both the lognormal and the gamma distributions in a wide range of locations and different time scales, in which they were tested (Tigkas 2008; Tsakiris et al. 2008). By assuming that the lognormal distribution is applied, the following equation can be used for the calculation of the standardized RDIst:

$$RDI_{st}^{(i)} = \frac{y^{(i)} - \bar{y}}{\hat{\sigma}_y}$$

in which y(i) is the ln(αk(i)), y is its arithmetic mean and σy is its standard deviation.

In case the gamma distribution is applied, the RDIst can be calculated by fitting the gamma probability density function (pdf) to the given frequency distribution of αk (Tsakiris et al. 2008; Tigkas 2008). For short reference periods (e.g. monthly or 3-months) which may include zero values for the cumulative precipitation of the period, the RDIst can be calculated based on a composite cumulative distribution function including the probability of zero precipitation and the gamma cumulative probability.

Positive values of RDIst indicate wet periods, while negative values indicate dry periods compared with the normal conditions of the area. Drought severity can be categorised in mild, moderate, severe and extreme classes, with corresponding boundary values of RDIst (-0.5 to -1.0), (-1.0 to -1.5), (-1.5 to -2.0) and (< -2.0), respectively.

SPI values	Classification
2.0 or more	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-.99 to .99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 or less	Extremely Dry

It should be mentioned that usually droughts in the Mediterranean are accompanied by high temperatures, which lead to higher evapotranspiration rates. Evidence for this has been produced from simultaneous monthly data of precipitation and evapotranspiration in many Greek watersheds. From the cases analyzed it seems that about 90% of them comply with the previous statement (Tsakiris and Vangelis2005). Therefore, the RDI is expected to be more sensitive index than those related only to precipitation, such as the SPI. The RDI can be calculated for any period of time from 1 month to the entire year, even starting from a month different than October, which is customary for the Mediterranean. Very significant results can be derived if the period of analysis coincides with the growing season of the maincrops of the area under study or other periods related to sensitive stages of crop growth. Then, **the RDI can be associated successfully with the expected loss in rainfed crop production, which in turn is linked to the anticipated hazard in the agricultural sector due to drought occurrence**. As it was shown from previous studies, precipitation (and therefore the SPI) was not successfully correlated to agricultural production (Tsakiris and Vangelis, 2005). However, the inclusion of potential evapotranspiration (PET) in the calculation of the RDI enhances its validity in studies aiming at risk assessment in agriculture caused by drought occurrence. Likewise, PET may be a representative quantity of the consumption in various sectors apart from agriculture. Water demand is increasing in general in case of higher temperatures. Therefore, the RDI could be modified to be used in the future as an indicator for the drought risk assessment related to the various sectors of water use.

4.5.2 DROUGHT ANALYSIS IN THE AZ CATCHMENT

The RDI was calculated only for the Amman Airport Station provided the problems with PET computation for PM and HG. For the Amman Airport Station we made the comparison between RDI 12 and SPI 12 for the PM estimations of PET. Figure 4-7 presents the comparison between RDI-12 and SPI-12 where common values are very similar to each other. **That means that the addition of PET in the drought hazard computation mechanism provides no more advancement compared to SPI only**.

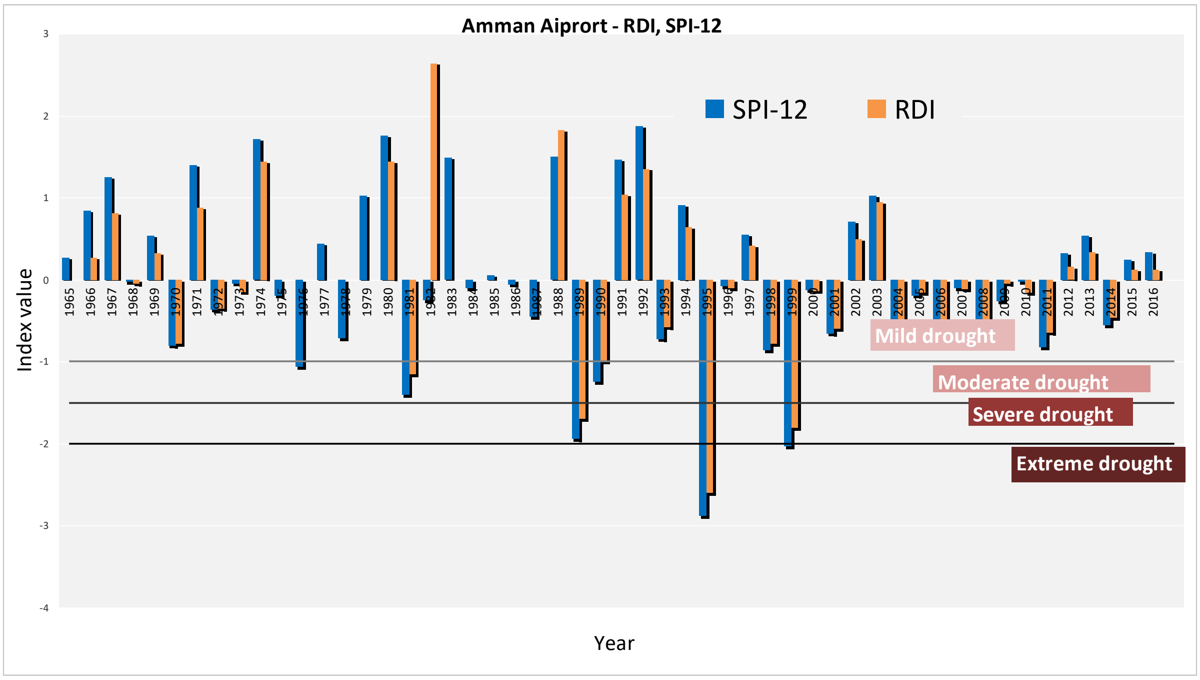


Figure 4-7: Comparison between rdi-12 and SPI-12 for the Amman AIRPORT RAINFALL Station

4.6 THE STREAMFLOW DROUGHT INDEX (SDI)

Streamflow commonly shows a greater spatial variability than climatic variables that are used to derive drought indicators. This is because of the influence of a number of factors, including topography, lithology, vegetation, and human management; it is also a consequence of the spatial aggregation of the flows, which changes the statistical properties of the series downstream. Based on the SPI developing concepts, the SDI was developed by Nalbantis and Tsakiris (2009) for characterizing hydrological drought. To compute SDI, it is assumed that a time series of monthly streamflow volumes $Q_{i,j}$ is available where *i* denotes the hydrological year and *j* the month within that hydrological year (j01 for October andj012 for September). Based on this series, cumulative streamflow volume is computed as follows according to Nalbantis (2008),

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \quad i = 1, 2, \ldots \quad j = 1, 2, \ldots, 12 \quad k = 1, 2, 3, 4$$

in which $V_{i,k}$ is the cumulative streamflow volume for the i-th hydrological year and the k-th reference period, k = 1 for October-December, k = 2 for October-March, k = 3 for October-June, and k = 4 for October-September.

Based on the cumulative streamflow volumes Vi,k, the Streamflow Drought Index (SDI) is defined for each reference period k of the i-th hydrological year as follows:

$$\mathrm{SDI}_{i,k} = \frac{V_{i,k} - \overline{V}_k}{s_k} \quad \mathrm{i} = 1, 2, \ldots, \quad \mathrm{k} = 1, 2, 3, 4$$

in which Vk and sk are respectively the mean and the standard deviation of cumulative streamflow volumes of the reference period k as these are estimated over a long period of time.

According to Nalbantis and Tsakiris (2009), states (classes) of hydrological drought are defined for SDI in an identical way to those used in the meteorological drought indices SPI and RDI. Five states are considered, which are denoted by an integer number ranging from 0 (non-drought) to 4 (extreme drought) and are defined through the criteria

State	Description	Criterion
0	Non-drought	$SDI \geq 0.0$
1	Mild drought	$-1.0 \leq SDI < 0.0$
2	Moderate drought	$-1.5 \leq SDI < -1.0$
3	Severe drought	$-2.0 \leq SDI < -1.5$
4	Extreme drought	$SDI < -2.0$

This index cannot be applied to AZB because there are no natural runoff series without distortion from unknown abstractions.

4.7 PALMER’S DROUGHT SEVERITY INDEX (PDSI)

In 1965, W. Palmer published his model for a drought index that incorporated antecedent precipitation, moisture supply, and moisture demand (based on the pioneering evapotranspiration work by Thornthwaite) into a hydrologic accounting system (Palmer 1965). He used a two-layered model for soil moisture computations and made certain assumptions concerning field capacity and transfer of moisture to and from the layers. These assumptions include the following: the top soil layer ("plough layer") has a field capacity of 1 inch (2.54 cm), moisture is not transferred to the bottom layer ("root zone") until the top layer is saturated, runoff does not occur until both soil layers are saturated, and all of the precipitation occurring in a month is utilized during that month to meet evapotranspiration and soil moisture demand or be lost as runoff. Palmer applied what he called Climatologically Appropriate for Existing Conditions (CAFEC) quantities to normalize his computations so he could compare the dimensionless index across space and time. This procedure enables the index to measure abnormal wetness (positive values) as well as dryness (negative values), with persistently normal precipitation and temperature theoretically resulting in an index of zero in all seasons in all climates. The term "Palmer Index" refers collectively to three indices that have come to be known as the PDSI, PHDI, and the Z Index.

The computation of Palmer's indices consists of the following steps:

1) Carry out a monthly hydrologic accounting for a long series of years using five parameters: precipitation, evapotranspiration, soil moisture loss and recharge, and runoff. Potential and actual values are computed for the last four. Palmer used monthly averages, but other timescales (such as weeks or days) can be used as well. Means of the potential and actual values for these parameters are computed over a calibration period that is usually, but not necessarily, the data period of the records.

2) Summarize the results to obtain coefficients (of evapotranspiration, recharge, runoff, and loss) that are dependent on the climate of the location being analyzed. These coefficients are computed by dividing the mean actual quantity by the mean potential quantity.

3) Reanalyze the series using the derived coefficients to determine the amount of moisture required for "normal" weather during each month. These normal, or CAFEC, quantities are computed for each of the parameters listed in step 1).

4) Compute the precipitation departure (precipitation minus CAFEC precipitation) for each month, then convert the departures to indices of moisture anomaly. This moisture anomaly index has come to be known as the Palmer Z Index and reflects the departure of the weather of a particular month from the average moisture climate for that month, regardless of what has occurred in prior or sub-sequent months.
5) Analyze the index series to determine the beginning, ending, and severity of the drought periods. In Palmer's computations, the drought severity for a month depends on the moisture anomaly for that month and on the drought severity for the previous and subsequent months (see Table 4-4).

The Palmer Index was a landmark in the development of drought indices. However, it is not without limitations. The index was specifically designed to treat the drought problem in semiarid and dry subhumid climates where local precipitation is the sole or primary source of moisture (Doesken et al. 1991). Palmer himself cautioned that extrapolation beyond these conditions may lead to unrealistic results (Palmer 1965; Guttman 1991). During the last 30 years, several scientists have evaluated the model as applied under different climate regimes and have expressed concerns with some of the model's assumptions.

These concerns fall into two broad categories: the use of water balance models in general, and Palmer's model in particular. Alley (1984) expressed concerns regarding how water balance models treat potential evapotranspiration, soil moisture, runoff, distribution of precipitation, and evapotranspiration within a month or week, and how they fail to consider seasonal or annual changes in vegetation cover and root development. **This index cannot be applied to AZB because it needs an extensive hydrological modeling to estimate soil wetness.**

Table 4-4: DROUGHT CHARACTERIZATION ACCORDING TO PALMER'S INDEX

Moisture category	PDSI
Extremely wet	≥ 4.00
Very wet	3.00 to 3.99
Moderately wet	2.00 to 2.99
Slightly wet	1.00 to 1.99
Incipient wet spell	0.50 to 0.99
Near normal	0.49 to −0.49
Incipient drought	−0.50 to −0.99
Mild drought	−1.00 to −1.99
Moderate drought	−2.00 to −2.99
Severe drought	−3.00 to −3.99
Extreme drought	≤−4.00

4.8 SOIL MOISTURE DEFICIT INDEX (SMDI)

The Soil Moisture Deficit Index (SMDI) was originally developed from research at the Texas Agricultural Experiment Station, United States. To evaluate soil moisture variations in the dry and wet periods, a Soil Water Deficit Index (SWDI), was developed based on SMI values with 8-day time steps as:

$$\mathrm{SD}_{i,j} = \frac{\mathrm{SW}_{i,j} - \mathrm{MSW}_j}{\mathrm{MSW}_j - \min SW_j} \times 100, \quad \text{if } \mathrm{SW}_{i,j} = \mathrm{MSW}_j$$

$$\mathrm{SD}_{i,j} = \frac{\mathrm{SW}_{i,j} - \mathrm{MSW}_j}{\max SW_j - \mathrm{MSW}_j} \times 100, \quad \text{if } \mathrm{SW}_{i,j} > \mathrm{MSW}_j$$

whereby:

SDij = the soil water deficit (%)

SWij = the mean weekly soil water available in the soil profile (mm),

MSWj = the long-term median available soil water in the soil profile (mm)

maxSWj = he long-term maximum available soil water in the soil profile (mm)

minSWj = he long-term minimum available soil water in the soil profile (mm) After daily soil water content has been computed, monthly (or weekly) values are derived. For every month a Soil Moisture Deficit value is computed based on the median value (MSW), the long-term maximum (maxSW) and the long term minimum (minSW) value of the calculations.

The SD values during a month will range between -100 and +100 stating very dry and very wet soil respectively. Drought occurs only when dryness continues for a prolonged period of time that can affect crop yield in rainfed agriculture.

A transformation is being made in order to be compatible with the PDSI scale (-4 to +4) in the following way, where the SMDI is the Soil Moisture Deficit Index (where t is the number of months in our calculations)

$$\mathrm{SMDI}_j = \frac{\sum_{t=1}^{j} \mathrm{SD}_t}{25t + 25}$$

For the first month of our sample SMDI(1) will be equal to SD1/50.

The SMDI(j) is then calculated by the following equation:

$$\mathrm{SMDI}_j = 0.5\mathrm{SMDI}_{j-1} + \frac{\mathrm{SD}_j}{50}$$

This index cannot be applied to AZB because it needs an extensive hydrological modeling to estimate soil wetness.

4.9 SOIL MOISTURE INDEX (SMI)

Soil water, an integral part of the hydrologic cycle and water balance, for a given time period (t):

$\partial S/\partial t = P - ET - Ro - Dr$

where $\partial S/\partial t$, P, ET, Ro, and Dr are the change in soil water, precipitation, evapotranspiration (ET), runoff and drainage for the same time period t. The soil water (S) is the equivalent depth of water:

$S = \theta \, \Delta d$

where θ is the average volumetric water content of the soil over a layer of soil and Δd is the thickness of the soil layer

The SMI is a continuous function and is scaled from 5.0 to −5.0, with 5.0 representing actual water content (θ) at field capacity and −5.0 representing θ at wilting point.

The available water content (FAW) in the soil is computed by the equation:

$FAW = (\theta - \theta W_P)/(\theta F_C - \theta W_P)$

where θ is the measured volumetric soil water content; θW_P is the volumetric soil water content at the wilting point; and θF_C is the volumetric soil water content at field capacity. Note that FAW varies from 0 to 1 as θ varies from wilting point to field capacity. An SMI was desired which would attribute negative values of SMI to drought and positive values to lack of drought. It was decided to scale the SMI values from −5 to 5 as FAW changed from 0 to 1.

This allows SMI to be written as follows:

$SMI = -5 + 10\, FAW$

$SMI = -5 + 10(\theta - \theta W_P)/(\theta F_C - \theta W_P)$

When FAW is 0.5 the value of SMI is zero. Thus, an SMI value of 0.0 separates the stress (negative values) versus non-stress situations (positive values).

This index cannot be applied to AZB because it needs an extensive hydrological modeling to estimate soil wetness.

5 DROUGHT HAZARD INDEX (DHI)

The 12-month Standard Precipitation Index (SPI-12) is proposed as the basis for the analysis of the meteorological drought episodes since it can capture long-term precipitation patterns usually associated with streamflows, reservoir levels and groundwater levels.

The 12-month SPI allows for the comparison of the cumulative precipitation of 12 consecutive months every year within the selected study period. It presents the advantage of eliminating seasonality (applicable in smaller temporal scales) and capturing signals of distinctive wet or dry trends. Based on the values of the SPI-12 the drought episodes within the reference period can be been identified in each rain gauge. A drought episode is identified when the SPI-12 first falls below zero (onset of the episode) and continues to increase (higher negative values) reaching a value equal or less than -1. When SPI-12 reaches again its first positive value this event has ended. If an SPI-12 value equal or less than -1 has not been reached, then this event is not characterized as drought (i.e. it is just low precipitation event but cannot be characterized as a drought episode).

The second step involved the **post-processing of the SPI-12 results** to derive four new sub-indicators that can reflect the severity, duration, and recurrence of the drought hazard in each rain gauge. The focus of this meta-analysis is to derive operational indicators each one reflecting common drought hazard characteristics, easy to reproduce, and blend into a Drought Hazard Index. **The following sub-indicators have been defined, to be computed at each rain gauge**.

FRQ: Number of drought episodes (events) observed within the reference period (expressed as absolute number or as % over the total duration of the period of analysis). This sub-indicator is used as metrics of “recurrence”.

FRQ24: Number of drought episodes with duration greater than 24 months, within the reference period. This sub-indicator is used as a sensible descriptor of prolonged drought and thus metrics of “severity”.

DMmax: Maximum drought magnitude observed within the reference period. This subindicator is used as metrics of “severity”.

dmax: Maximum duration (in months) among the drought episodes observed within the reference period. This sub-indicator is used as metrics of “duration”.

Following the calculation of the four sub-indicators for each rain gauge, a classification must be elaborated, assigning four classes and relevant 1-4 scores (less to more significant) across all gauges and for the same time periods.

We attempted to make a comparison between DM and actual stress in the water system. The only way to do that is to compare the reduction of flow series in spring runoff (provided that springs are remote and free from upstream abstractions). However, we cannot deduct a coherent trend of drought magnitude and level of reduction in runoff values. Therefore, we are using thresholds from international literature.

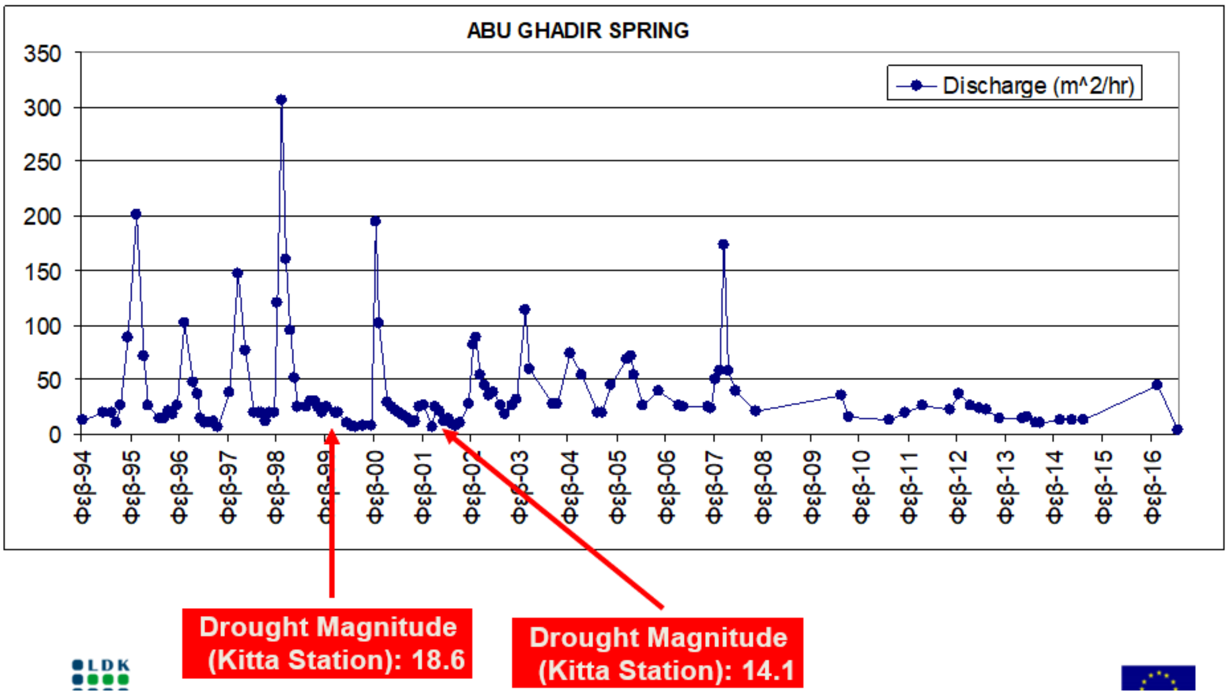


Figure 5-1: Flow rates and drought effects for abu ghadir spring

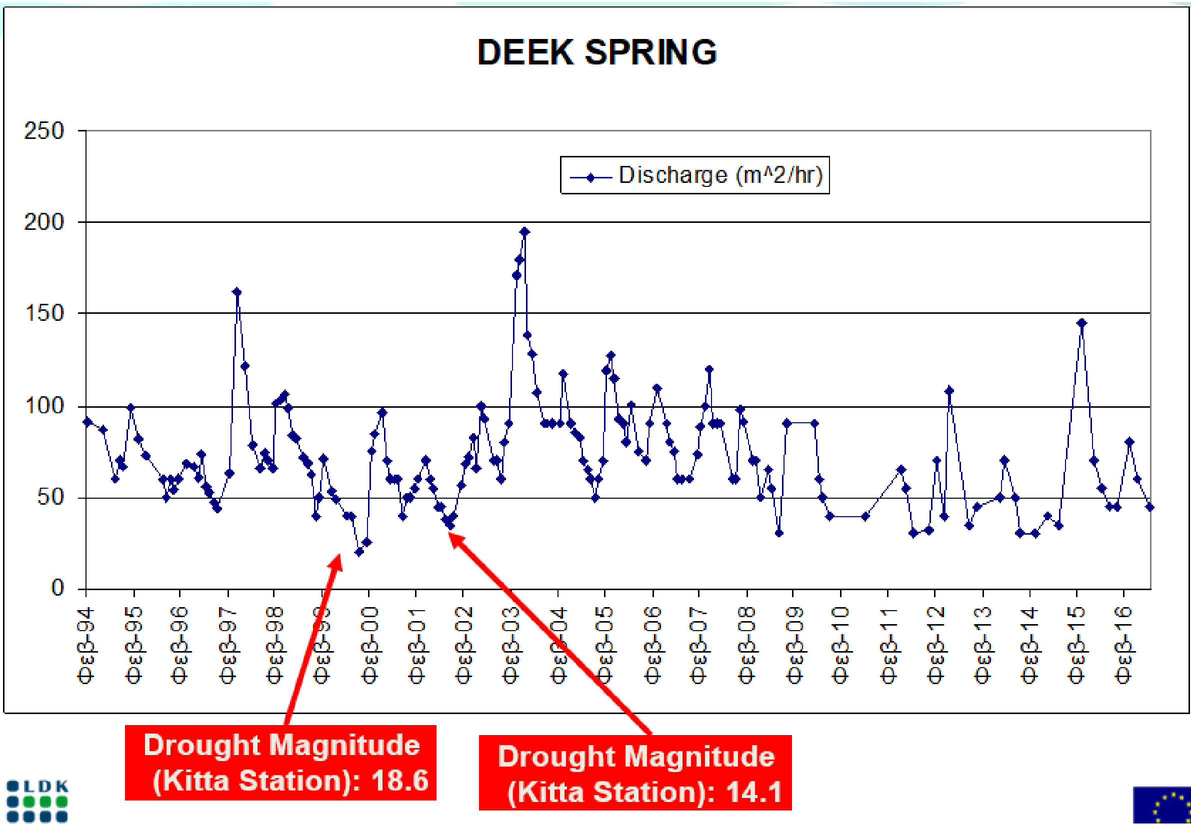


Figure 5-2: Flow rates and drought effects for DEEK spring

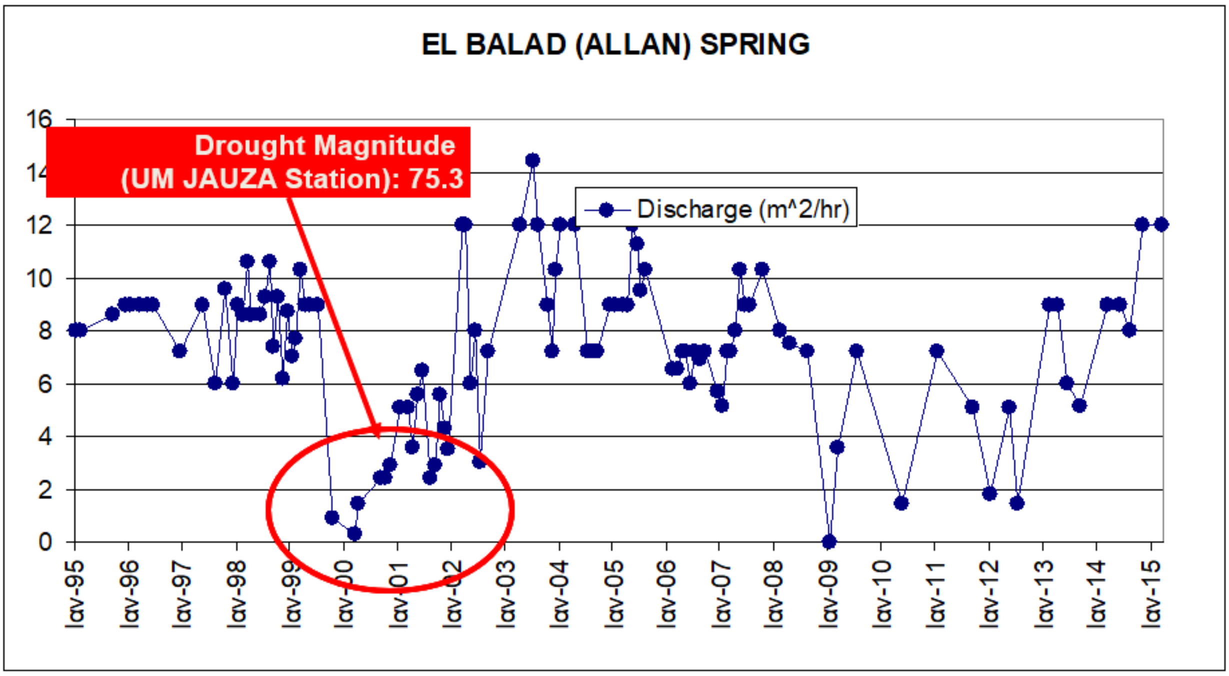


Figure 5-3: Flow rates and drought effects for EL BALAD (ALLAN) spring

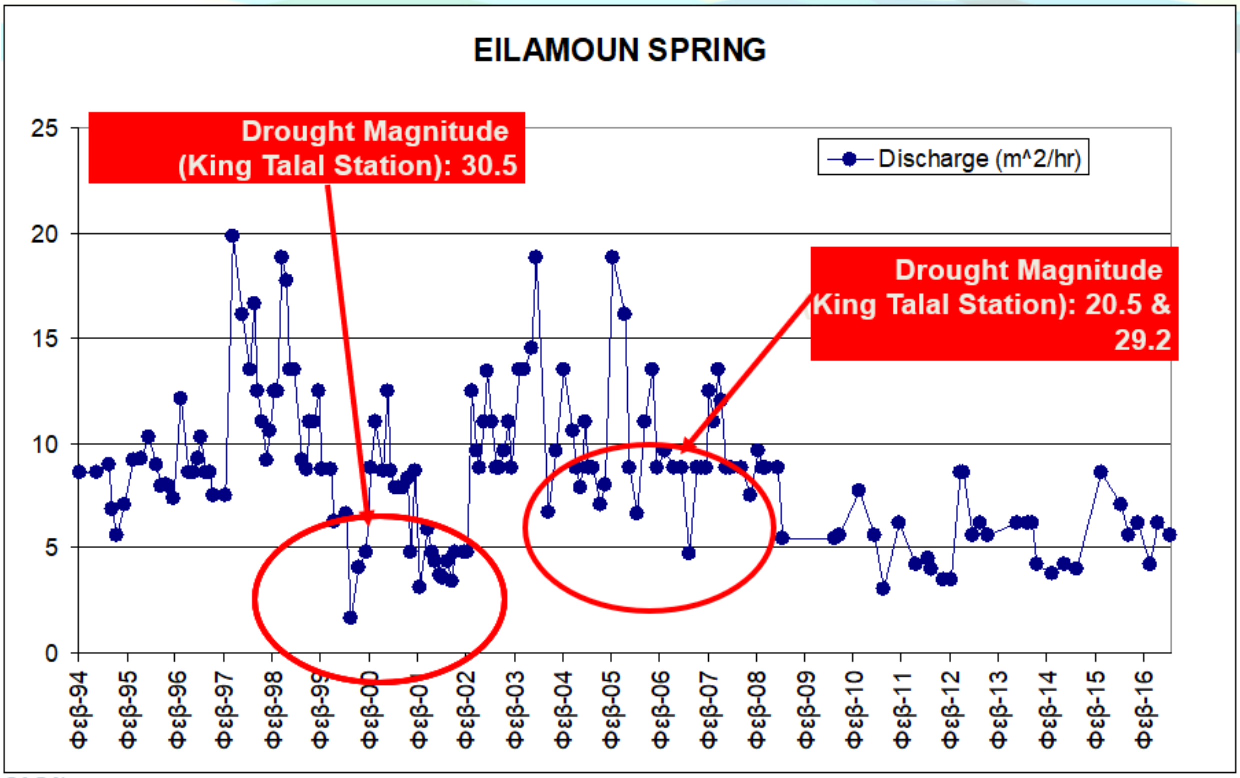


Figure 5-4: Flow rates and drought effects for EILAMOUN spring

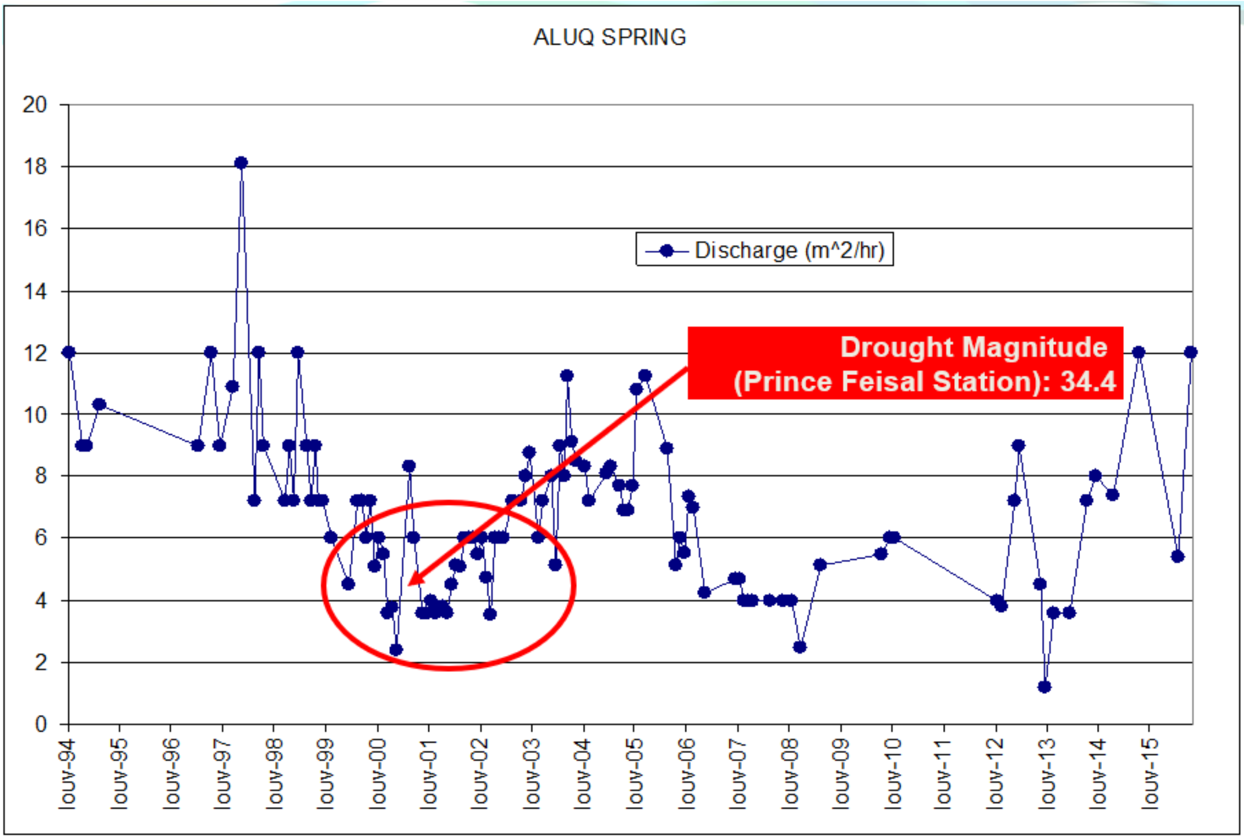


Figure 5-5: Flow rates and drought effects for aLUq spring

Table 5-1 presents the classification thresholds for each sub-indicator as it was deducted from international literature (Kossida, 2015) in areas with similar climatic characteristics

Table 5-1: Classification thresholds for each sub-indicator

Classification thresholds for each sub-indicator				
FRQ *Number of episodes (% over the years of the period)*	**FRQ24** *Number of episodes with d>24 months*	**DMmax** *Maximum Magnitude*	**dmax** *Maximum duration*	**Assigned Score / Class**
1 – 2 (≤5%)	1	1 ≤ 35.0	24 – 36	1
3 – 5 (5.1% - 10%)	2	35.1 – 50.0	37 – 48	2
6 – 10 (10.1% - 20%)	3	50.1 – 70.0	49 – 60	3
11 - 20 (> 20%)	≥ 4	≥ 70.1	≥ 61	4

Table 5-2: classification of the drought hazard index

DHI value	Score / Class
1.00 – 1.49	1 – low
1.50 – 1.99	2 – moderate
2.00 – 2.49	3 – severe
≥ 2.50	4 – extreme

Table 5-3: drought hazard index parameters for all the rainfall stations (listed according to orientation)

Station_Na	FRQ	FRQ24	Drmax	dmax	Orienation
HASHIMIYA	7	2	84,71	67	C
SUKHNA	11	3	99,43	95	C
KHALDIYA	9	4	35	50	E
WADI DHULEIL NURSERY	9	4	79,07	70	E
BAL'AMA	11	4	41,12	62	N
MIDWAR	13	5	33,57	34	N
QAFQAFA	12	4	62,36	37	N
SABHA AND SUBHIYEH	7	5	38,37	40	NE
SUBEIHI	10	4	61,89	62	NE
UM EL-JUMAL EVAP .ST	11	4	55,63	29	NE
UM EL-QUTTEIN	8	5	59,65	57	NE
UM JAUZA	10	4	75,27	50	NE
BEIR EL-AD'AM	15	4	28,14	37	NW
JARASH	15	4	56,31	62	NW
KING TALAL DAM	12	4	47,75	41	NW
KITTA	14	2	42,46	36	NW
PRINCE FEISAL NURSERY	10	4	65,53	56	NW
RUMEIMIN	8	5	48,32	58	NW
NAWASIF	11	3	79,75	69	SE
QASR EL-HALLABAT	10	5	41,17	36	SE
AMMAN AIRPORT (METEO DEPT)	13	3	45,11	39	SW
AMMAN HUSSEIN COLLEGE	14	4	30,68	33	SW
JUBEIHA	14	3	39,6	36	SW
K.H.NURSERY EVAP.ST(BAQ'A)	15	3	47,84	50	SW
RUSEIFA	11	2	55,99	59	SW
WADI ES-SIR (NRA)YARD	15	4	46,24	39	SW

It has been determined that unequal weights for one of the four subindicators (i.e. frequency of drought events is not that critical since most of them have low magnitudes). As follows, the sub-indicators are blended to derive a DHI value for each rain gauge for the entire study period (as well as for sub-periods if desired) based on the following equation:

$$DHI = (\theta_1 \times score_{FRQ}) + (\theta_2 \times score_{FRQ24}) + (\theta_3 \times score_{DM\max}) + (\theta_4 \times score_{d\max})$$

where θi are the weights of the sub-indicators (θ1=0.1, θ2-θ4=0.3)

Table 5-4 presents the drought hazard index score and classification for all rainfall stations in the AZB. It is evident that except for 5 stations, drought hazard index classification is defined as "Extreme", three stations as "Severe" and for 2 stations as "Moderate". However, there is no geographical linkage between the stations with classification other than "Extreme".

Table 5-4: drought hazard index classification

Station_Na	FRQ	FRQ24	Drmax	dmax	SCORE	CLASS
HASHIMIYA	3	2	4	4	3,3	4
SUKHNA	4	3	4	4	3,7	4
KHALDIYA	3	4	3	3	3,3	4
WADI DHULEIL NURSERY	3	4	4	4	3,9	4
BAL'AMA	4	4	4	4	4	4
MIDWAR	4	4	1	1	2,2	3
QAFQAFA	4	4	2	2	2,8	4
SABHA AND SUBHIYEH	3	4	2	2	2,7	4
SUBEIHI	3	4	3	4	3,6	4
UM EL-JUMAL EVAP .ST	4	4	3	1	2,8	4
UM EL-QUTTEIN	3	4	3	3	3,3	4
UM JAUZA	3	4	4	3	3,6	4
BEIR EL-AD'AM	4	4	1	2	2,5	4
JARASH	4	4	3	4	3,7	4
KING TALAL DAM	4	4	2	2	2,8	4
KITTA	4	2	2	1	1,9	2
PRINCE FEISAL NURSERY	3	4	3	3	3,3	4
RUMEIMIN	3	4	2	3	3	4
NAWASIF	4	3	1	4	2,8	4
QASR EL-HALLABAT	3	4	2	1	2,4	3
AMMAN AIRPORT (METEO DEPT)	4	3	2	2	2,5	4
AMMAN HUSSEIN COLLEGE	4	4	1	1	2,2	3
JUBEIHA	4	3	1	1	1,9	2
K.H.NURSERY EVAP.ST(BAQ'A)	4	3	2	3	2,8	4
RUSEIFA	4	2	3	3	2,8	4
WADI ES-SIR (NRA)YARD	4	4	2	2	2,8	4

6 DROUGHT EARLY WARNING SYSTEMS

6.1 Short – Term Drought Early Warning System for AZB

We are using rainfall data for the Amman Airport Station from 1937 and we are based on the transitional probabilities.

We analysed rainfall data between the first two months of the hydrologic year (October-November) and the 7 months with rainfall of a given year (October-April). Then, we calculated the deciles of the rainfall data for cumulative rainfall for October – November and October – April. Then, we calculated the probability that when the cumulative rainfall for October – November period is below the lower 20% percentile (very dry conditions), the cumulative rainfall for October – April also is below the corresponding 20% lower percentile. This probability is calculated equal to 0.56.

Furthermore, we calculated the probability that when the cumulative rainfall for October – November period is below the lower 30% percentile (also very dry), the cumulative rainfall for October – April also is below the corresponding 30% lower percentile. This probability is increased and calculated equal to 0.63.

For instance, for year 1946, we can see that cumulative rainfall for October to November (3.7mm) is less than the cumulative for 20% percentile (4.4mm). Finally, annual rainfall for 1946 is less (137.1mm) than the 20% percentile of annual rainfall depths (194.94mm).

Table 6-1: example of drought early warning system

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL
1937	4.6	14	1.1	97	132.8	66.4	1.3	24.1	0	0	0	0	341.3
1938	0.2	121.5	28.2	24.8	79.4	84.8	4.3	0	0	0	0	0	343.2
1939	3.3	71.8	20.4	124.1	5.2	30	31.4	0	0	0	0	0	286.2
1940	8.4	42.7	59	61.6	22.4	24	6.2	0	0	0	0	0	224.3
1941	2.2	3.5	155.1	56.9	86.6	96.9	0.3	0	0	0	0	0	401.5
1942	54.6	27.8	18.6	105.4	50.5	86.7	34.3	2.3	0	0	0	0	380.2
1943	4.5	0.6	18.2	141.7	12.6	20.2	11.7	13	0	0	0	0	222.5
1944	0	136.8	94	100.2	105.5	19.3	4.6	19.6	0	0	0	0	480
1945	0	33.7	60.4	15.3	120.3	26.1	0.9	30.6	0	0	0	0	287.3
1946	0.2	3.5	29.2	65	8.2	21	8.6	1.4	0	0	0	0	137.1
1947	0	22.2	21	92.8	69.1	76.1	12.8	1.3	0	0	0	0	295.3
1948	2.1	12.4	44.3	74.9	123.9	116	52.5	2	0	0	0	0	428.1
1949	0	0	92.3	74.1	77.3	31.5	11.5	15.4	0	0	0	0	302.1
1950	0	16.7	8.2	28.1	60.3	15.4	0.3	0	0	0	0	0	129
1951	0.9	19.9	179.8	35.6	79.7	46.9	0.4	0	0	0	0	0	363.2
1952	8.5	3.9	12.3	29.3	81.3	168.5	1.8	0	0	0	0	0	305.6
1953	1.5	91.2	60.5	17.7	90.3	12.8	16.2	0	0	0	0	0	290.2
1954	3.2	37.1	67.5	13.7	15.8	17.4	4.5	0	0	0	0	0	159.2
1955	0.4	91	62	67.1	16.2	68.2	24.4	2.4	0	0	0	0	331.7

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANNUAL
20% PERCENTILE	0.0	4.4	15.1	26.4	18.8	18.2	0.8	0.0	0	0	0	0	194.94

According to that, we can propose a general system for drought monitoring and alert level issuing according to the following Table 6-2.

Table 6-2: drought monitoring and planning system

ALERT LEVEL	MAIN INDEX
	SPI-12
ALERT OFF	> 0
LOW ALERT	-1 < SPI < 0
MODERATE ALERT	-1.5 < SPI < -1
HIGH ALERT	-2 < SPI < -1.5
EXTREMELY HIGH	< -2

Table 6-3 presents a complete system for drought monitoring taking into account all the above procedures.

Table 6-3: Proposed system for drought monitoring

Month	SPI-3 & SPI-12	Early Warning System	Estimate Severe Irrigation Cuts to Farmers	Groundwater Bodies
OCT	SPI-12 Calculation - Implementation of Alert System SPI-3 for rainfed agriculture After the end of the drought event, Drought Magnitude is estimated and DHI is attributed.			Evaluation of annual variation (drawdown) of aquifer levels and spring discharge taking into account SPI-12 in selected wells and springs in each aquifer.
NOV		Calculate Rainfall Depth for Oct - Nov and calculate decile. If less than 20% then..	First Warning Issue to Farmers	
DEC		Calculate Rainfall Depth for Oct - Dec and calculate decile. If less than 20% then..	Update Warning Issue to Farmers	
JAN		Monitoring Storage in King Talal Dam and GW levels		
FEB			Update Warning Issue to Farmers	
MAR				
APR		Calculate Rainfall Depth for Oct - April and calculate decile. Storage in King Talal Reservoir	Final Issue to Irrigation Cut to Farmers.	
MAY				
JUN				
JUL				
AUG				
SEP				

7 CONCLUSIONS

Drought Hazard for the AZB was investigated using actually two indices that are appropriate for the particular case, i.e. the SPI and the RDI, where the latter incorporates PET in addition with rainfall. However, it is evident that SPI-12 is the only appropriate index in areas with zero rainfall during summer period and with runoff series that are distorted from abstractions or when the natural system is not identifiable.

Drought hazard index and its classification was also proposed where nearly all the AZB is classified as "Extreme Drought Hazard".

Finally, a simple drought early warning system is proposed for the Amman Airport rainfall station based on transitional probabilities for cumulative rainfall between October and November to annual rainfall. The conclusions are valid for the whole of the AZB, since the Amman Airport Rainfall Station is strongly correlated with the whole rainfall set of the AZB.

8 REFERENCES

Abderahman, N., & Abu-Rukah, Y. H. 2006. An assessment study of heavy metal distribution within soil in upper course of Zarqa River basin/Jordan. Environmental Geology, 49(8), 1116-1124.

Alley, W. M., 1984: The Palmer Drought Severity Index: Limitations and assumptions. /. Climate Appl. Meteor., 23, 1100-1109.

Bhuiyan, C., Singh, R. P., & Kogan, F. N. 2006. Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data. International Journal of Applied Earth Observation and Geoinformation, 8(4), 289-302.

Doesken, N. J., T. B. McKee, and J. Kleist, 1991: Development of a Surface Water Supply Index for the western United States. Climatology Rep. 91-3, Colorado Climate Center, Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO, 76 pp.

Dracup, J. A., Lee, K. S., & Paulson Jr, E. G. 1980. On the definition of droughts. Water resources research, 16(2), 297-302

Edwards, D. C., & McKee, T. B. 1997. Characteristics of 20th century drought in the United States at multiple time scales (Climatology Report No. 97–2). Fort Collins, CO: Colorado State University.

Gibbs, W. J., & Maher, J. V. 1967. Rainfall deciles as drought indicators, bureau of meteorology bulletin no. 48. Commonwealth of Australia, Melbourne, 29.

Guttman, N. B., 1991: A sensitivity analysis of the Palmer Hydrologic Drought Index. Water Resour. Bull., 27, 797-807.

Kossida, M. (2015). Methods and tools supporting operational drought risk management in water stressed areas (Doctoral dissertation). National technical University of Athens.

Lloyd - Hughes, B., & Saunders, M. A. 2002. A drought climatology for Europe. International journal of climatology, 22(13), 1571-1592.

McKee, T. B., N. J. Doesken, and J. Kleist, 1993: The relationship of drought frequency and duration to time scales. Preprints, Eighth Conf. on Applied Climatology, Anaheim, CA, Amer. Meteor. Soc., 179-184.

Mrayyan, B., & Hussein, I. 2004. Integrated assessment of the control of wastewater pollution in Zarqa Governate, Jordan. International journal of environment and pollution, 22(5), 580-596.

Nalbantis, I., & Tsakiris, G. 2009. Assessment of hydrological drought revisited. Water Resources Management, 23(5), 881-897.

Palmer, W. C., 1965: Meteorological drought. U.S. Weather Bureau Research Paper 45, 58 pp. [Available from NOAA Library and Information Services Division, Washington, DC 20852.]

Todorovic, P., & Woolhiser, D. 1976. Stochastic structures of the local pattern of precipitation. Stochastic Approaches to Water Resources,, 2.

Tsakiris, G., & Vangelis, H. 2005. Establishing a drought index incorporating evapotranspiration. European Water, 9(10), 3-11.

Tsakiris, G., Pangalou, D., & Vangelis, H. 2007. Regional drought assessment based on the Reconnaissance Drought Index (RDI). Water Resources Management, 21(5), 821-833.

Vicente-Serrano SM, Beguer´ıa S, L´opez-Moreno JI. 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index – SPEI. J. Clim. 23: 1696–1718.

Wu, H., Hayes, M.J., Wilhite, D.A., Svoboda, M.D., 2005. The effect of the length ofrecord on the standardized precipitation index calculation. InternationalJournal of Climatology 25, 505–520.

Yevjevich, V. 1967. Objective approach to definitions and investigations of continental hydrologic droughts. Hydrology Paper 23, Colorado State U, Fort Collins, Aug 1967. 19 p, 9 fig, 1 tab, 12 ref.

9 ANNEXES

Annexes of the report are provided separately.