DOCTOR OF PHILOSOPHY

Evaluation of surface water resources of Marab Hassan in the Northeast Badia of Jordan

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Award date:
2002

Awarding institution:
Bangor University

EVALUATION OF SURFACE WATER RESOURCES OF MARAB HASSAN IN THE NORTHEAST BADIA OF JORDAN

by

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A thesis submitted for the degree of Doctor of Philosophy

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May, 2002

Dedicated to my beloved parents,
Brother and Sisters,
With all my love

ABSTRACT

The focus of this study was to devise a way in order to optimise the use of surface water resources of Marab Hassan catchment area in the northeast Badia of Jordan.

In order to achieve this aim different approaches have been used in the evaluation of the Marab's available surface water resources. The first approach was based on developing the synthetic unit hydrograph of the catchment area using the catchment characteristics, which were extracted from the catchment's Digital Elevation Model (DEM). However due to the lack of runoff data, the unit hydrograph could not be calibrated to establish the amount of water that the Marab area was receiving. As rainfall is the major source of runoff and due to its importance in the study area, a review of the rainfall records of the catchment area (both monthly and annually) was made.

The second approach was to develop a correlation between the global climatic indices (ENSO, NAO and Indian Ocean) and the Jordanian rainfall. The correlation between the Annual Regional Rainfall Index (ARRI) and the seasonal climatic indices showed that there was a significant correlation, which was used for developing the rainfall probability model for the region. The developed models were verified and gave quite high reliability. This approach is useful decision making in the Marab area, especially when a dry year is predicted to occur, as this gives the farmers a lead-time to prepare themselves in advance.

Review and analysis of Marab Hassan was a useful guide that lead to the identification of other Marabs that could possibly be developed. It also gave an indication about the sustainability and the planning of water harvesting technique that could be used to maximise the effective utilisation of the Marab and its present water resources.

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GLOSSARY OF TERMS AND ACRONYMS

Afeer: Arabic word for broadcasting the seeds (includes both dry and wet farming methods of cultivation).

ARI: Average Rainfall Index.

ARRI: Average Regional Rainfall Index.

Daim: Arabic word for frontal type of rainfall that lasts for more than 3-4 days.

Darou: Arabic word for a flood that is coming from a long distance.

DEM: Digital Elevation Model.

DJF: December, January and February.

ENSO: El-Niño Southern Oscillation.

GIS: Geographic Information System.

GIUH: Geomorphologic Instantaneous Unit Hydrograph.

Hafera: Arabic word for water harvesting pond.

Hareef: Arabic word for the rainfall that occurs at the beginning of the rainy season (October and November).

IO SST: Indian Ocean Sea Surface Temperature.

Khareef: Arabic word for the rainfall that occurs at the end of the rainy season (March-May).

JJA: June, July and August.

MAM: March, April and May.

Naou: Arabic word for frontal type of rainfall that lasts up to 3 days.

Marab: an area of sediment accumulation (e.g. a mudflat) within a wadi system with a definite outlet.

NAO: North Atlantic Oscillation.

NAOI: North Atlantic Oscillation Index.

PRA: Participatory Rural Appraisal.

Qa: is a low relief area of accumulated sediments, identified as mudflat that exhibits more than one inlet with no definite outlet, thus the water ponds and evaporates leaving saline unproductive land.

SCS: Soil Conservation Services.

Sail: Arabic word for flood.

SOI: Southern Oscillation Index

SON: September, October and November.

SPI: Standard Precipitation Index.

Tall: Arabic word for hill.

SST: Sea Surface Temperature.

Wadi: Arabic word for alluvial, normally dry valley bed, which floods after a storm.

ACKNOWLEDGEMENTS

First and Foremost I would like to thank Allah (God) the most Gracious and most Merciful for giving me the well and the strength to complete this work.

Then, I wish to express my sincerest thanks to my supervisor, Mr. Roger Cratchley, for providing perceptive comments and constructive criticisms. I would like to express my deepest gratitude to Mr. John Kay for always being ready to offer guidance, support and co-operation. I would like to extend my gratitude to Mr. Paul Smith for his help and guidance during the fieldwork. Special thanks go to. David Norris from CEH-Bangor for his help in analysing the GIS data. Many thanks also go to Martin Hollingham, Dr. Hussein Omed, Andrew Packwood, Mrs. Sandra Hughes, and last but not least the staff of the CAZS for their continuous assistance.

This thesis would not been possible without the financial aid from my sponsors, the Department for International Development, Karim Rida Said Foundation, Arab-British Chamber Charitable Foundation and finally to the Professional Classes Aid Council and the British Foundation for Women Graduates. I am grateful to all of them for the financial assistance.

In Jordan I would like to thank Her Highness Sharifa Zain bent Nasser, Mr. Mohammed Shabaz and the staff of the Badia Research and Development Programme. Also, special thanks addressed to Dr. Mohammed Shatnawi and Dr. Rakad Ta'any for their help in getting the rainfall data.

Finally I would like to thank all my friends here in United Kingdom and in Jordan for all their support and encouragement. Particularly, I would like to thank Inas, Lubna, Muna, Walid, Iman, Pei Yu, Amina, Leen, Ayman, Shatha, Adnan, Ghina, Serene, Shady, Zaid and Ashley for all the help and support they've given me and for making my stay in UK enjoyable. I wish them all a happy and successful future.

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Jordan is an arid to semi arid country with an area of 89,400km^{2}, of which 3% can be considered as Mediterranean. Located in the eastern Mediterranean basin, the country's climate is affected by the Mediterranean in the west and the desert in the east. According to Allison et al., 1998 Jordan can be divided into four climatic zones as shown in Figure 1.1, which are:

1. Jordan Valley and Southern Ghour: A narrow 660km strip of land, below sea level, extending from the lake Tiberius in the north to the Gulf of Aqaba in the South. The Jordan valley is used for intensive cultivation under irrigated farming systems. This area is used mainly for the production of vegetables and citrus fruits.

2. Highlands: A mountainous area adjacent to the Jordan Valley, which varies from 600m to 1500m above sea level. The Highlands are mostly used for rain-fed farming

3. Eastern Hills (or the steppe zone) are located around and to the east of the Highlands and are relatively plain lands with a gradual slope down towards the east. The steppe zone is dominated by an ecologically fragile system and vulnerable soils caused by climatic variation and overgrazing.

4. The Badia (Badia is a local name for the dry region) is dominated by a dry climate. The Badia covers more than 80% of the country's total area. Most of the Badia area is considered as "rangeland" that is defined as the regions unsuitable for rain-fed cropping, with annual rainfall below 200 mm, (Blench, 1995).

dependent on these countries for its water needs. A third problem is that Jordan's population has expanded enormously due to successive waves of refugees from Palestine and returning Jordanian nationals from Kuwait after the Gulf War. The increased population puts fresh demands on agricultural, industrial and domestic use of water. Finally modernisation and increasing expectations about the quality of life have also increased domestic water demands.

1.3 The North-eastern Badia

The Badia region extends from north to south in the eastern part of Jordan. It covers an area of 72,000 km^2 that contains more than 80% of the total area of the kingdom (89,411 km^2). The region is divided into three geographical areas; the northeastern Badia that comprises 35.5 % (25,600 km^2), the middle Badia with an area of 9,700 km^2 (13.5%) and the southern Badia, which comprises 51% (36,700 km^2) of the total area. The word Badia means the place where Bedouin people live. Most of the Bedouin belong to the tribe where the concept of *dirah* is highlighted, (Dutton, 1998). The Bedouin concept of territory was expressed by the term *dirah*, the area where a group of people have migrated, generally including pastures and some cultivated zones. The degree of control over the *dirah* depends to some extent on the number of people and their alliance, the personality of their leader, the number and type of livestock owned, the vagaries of the weather and the corresponding strength or weakness of neighbouring groups.

In the past the Bedouin used to be more nomadic than today, as they were travelling within and outside the country before the borders with the neighbouring countries were closed. Lately the lifestyle of the Bedouin has changed towards a settled style. This change in the way of living has increased the demand on infrastructure, facilities and services in the Badia area. Also, the number of villages and settlements in the Badia area has increased, which helped in the expansion of cultivated areas and coincides with a shift from nomadic pastoralism to farming based systems, (Millington et. al., 1999). Only five percent of the Badia population is still nomadic. The rest are now settled and involved in agriculture, livestock production, the civil service,

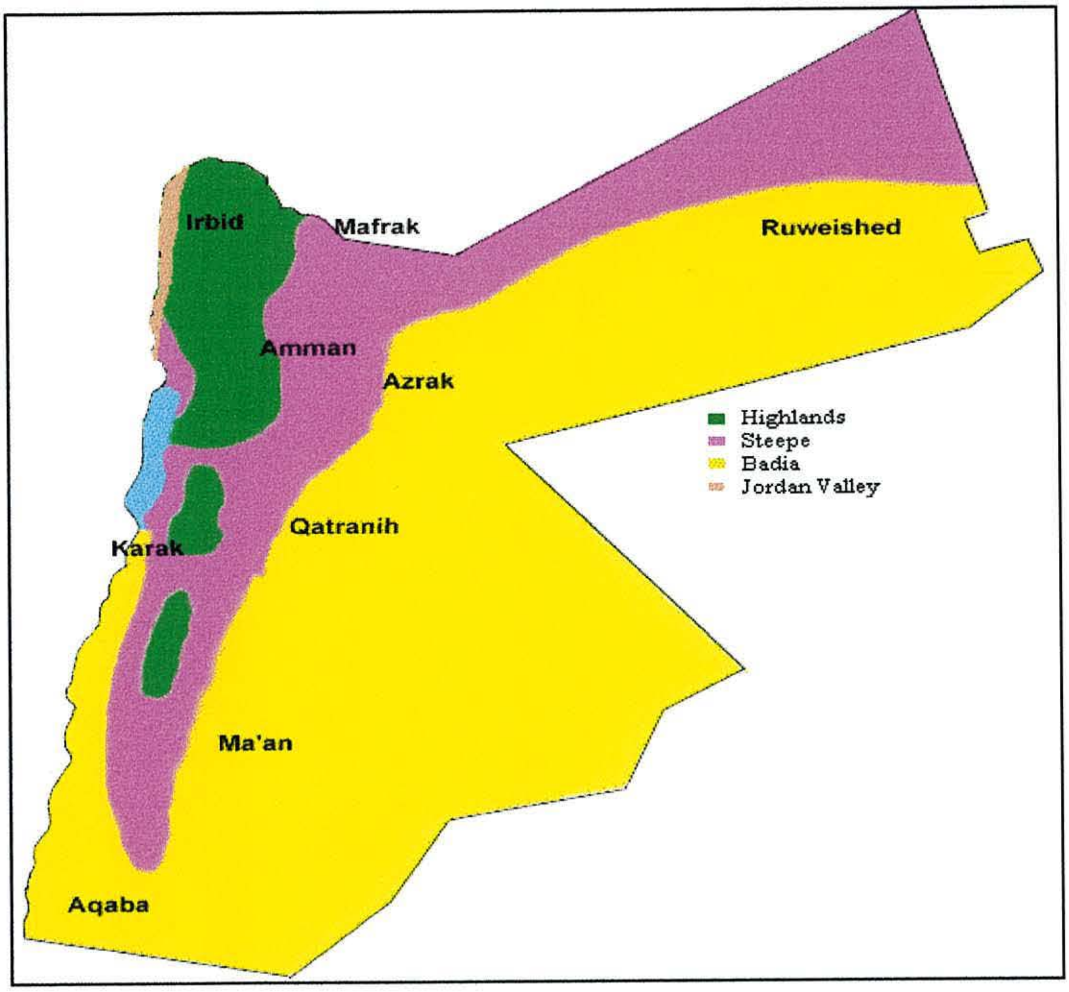

Figure 1.1: Climatic zones of Jordan (Source: Ministry of Agriculture web site[1])

1.2 THE PROBLEM OF WATER SCARCITY

Water is scarce across all the climatic regions of Jordan. Similar to tropical countries, Jordan experiences only two seasons, a rainy season and a dry season. The rainy season lasts from October through April, during which time the country receives 85% of its total annual rainfall. Precipitation is the predominant source of fresh water, feeding the Jordan and Zarqa Rivers and replenishing natural springs and groundwater. However, three problems curtail the availability of these fresh water resources. First, 92% of the rainfall is lost to evaporation. Second, over the years, Jordan's neighbours, Syria and Israel, have built hydroelectric dams further upstream on the Jordan River, diminishing water flow, (Haddadin, 2001). Subsequently, Jordan has become highly commerce, the armed forces, and mining and prospecting industries, (Allison et. al., 1998).

1.4 JORDAN BADIA RESEARCH AND DEVELOPMENT PROGRAMME

In 1992 the Jordan Badia Research and Development Programme was established, (of which *Marab* Hassan catchment area forms a part), under an agreement between the Jordanian Higher Council of Science and Technology (HCST) and the United Kingdom's Royal Geographic Society (RGS) and Centre of Overseas Research and Development (CORD) at Durham University that acts on behalf of RGS. The project has started with the northern Badia as a first phase, and has taken the town of Safawi 150 km east of Amman as a field centre. The programme covers an area of 11,210 km^2 that forms almost 44% of the northern Badia area (25,600 km^2) including 35 villages. The scientific framework of the programme concerns several aspects, which are human resources, water resources, land resources, livestock, geology, mineral resources, renewable resources, information management and documentation. The major aim of the Badia programme is the sustainable development of the Badia area and the development of the standard of living of the inhabitants, by using management systems that preserve the natural resources to keep the production levels sustainable in the long term.

The study area (*Marab* Hassan catchment area), which is located within the boundaries of the Badia programme area was selected by the programme personnel, as an area that has a priority to be analysed in terms of its surface water resources. The water resources aspect is one of the most important aspects that attract the attention of the Badia programme, especially in a country like Jordan where most of it is characterised as arid zone.

1.5 Aims and Objectives

The use of surface water resources in the Badia area has become a major issue, especially in a country like Jordan where the major rivers are shared with the neighbouring countries and the country relies heavily on groundwater resources.

The present study aims to evaluate the surface water resources of *Marab* Hassan catchment area in the Northeast Badia of Jordan, with the main objective of optimising water management particularly for agriculture. The evaluation will utilise three approaches which are; a) develop a rainfall-runoff model the for the catchment area, b) develop a rainfall probability model for the catchment area utilising correlations with global climatic indices and c) propose a water management plan for *Marab* Hassan that will help in making decision about the use of water for cultivation on the *Marab*.

a) Rainfall-runoff modelling for the catchment is approached using a number of synthetic unit hydrograph methods. In addition a GIS-based Digital Elevation Model has been used to evaluate a geomorphological unit hydrograph as a runoff model.

b) The objective of the rainfall probability model is to predict the rainfall for the whole of Jordan as well as the catchment area, by establishing the correlation between the global climatic indices, (El-Niño Southern Oscillation Sea Surface Temperature (ENSO SST), El- Niño Southern Oscillation Index (SOI), North Atlantic Oscillation Index (NAOI) and Indian Ocean Sea Surface Temperature Anomalies) and the Jordanian rainfall.

c) The water resources management plan objective is to attempt to use correlations between the global climatic indices and the catchment's rainfall, in order to improve the traditional management approaches that are used in the cultivation of the *Marab*.

1.6 Field and Laboratory Work

The fieldwork to produce this thesis was carried out in Jordan for the period between September -1998 to August -1999. Also, November 2000 to end of February 2001. Table 1.1 summaries that field work activities and the duration of each activity.

Table 1.1: The fieldwork activities and their duration

Activity	Duration
Checking the existing rain gauges	23-30/9/1998
Field visits and desk survey of the catchment area	1-14/10/1998
Supervisory visit by Paul Smith to the field site	18-30/10/1998
Installation of runoff plot experiments	1-30/11/1998
Measuring of soil moisture content at the *Marab* and	1-7/12/1998 , 7-14/1/1999
Soil texture	8-21/12/1998
Soil bulk density	23-12/1998 , 3-7/1/1999
Soil moisture release characteristics curve	24/1-11/2/1999
Infiltration rate test	14/2-19/3/1999
Investigation about the *Marab* and flow gauging sites, processing the paper work	21/3-30/4/1999
Surveying of the selected flow gauging sections	2-14/5/1999
Visiting water harvesting schemes in the NW part of the programme area	16-28/5/1999
Data collection and literature review about the catchment area	1/6-31/7/1999
Final checks of data collected	1-14/8/1999
Installation of new rain gauge (4 recording and 6 daily), and 3 crest gauges at the inlet and outlet of *Marab* Hassan	19-30/11/2000
Investigation of *Marab* Hassan features (ground truth)	2-25/12/2000
Indigenous knowledge questionnaire (PRA)	1-31/1/2001
Further data collection and literature review about the catchment area	1-28/2/2001

Measurements of wadi flow were severely curtailed by a continuing lack of flow gauges, due to vandalism of newly installed gauges and by the absence of significant rainfall and flows during one field season. For this reason the thesis relies on synthetic unit hydrograph approaches that tend to estimate rainfall-runoff model.

1.7 THESIS OUTLINE

This study investigates the evaluation of the surface water resources of *Marab* Hassan catchment area in the Northeastern Badia of Jordan. Chapter Two gives a description about the *Marab*s of the Badia area and their importance. Then it moves to describe *Marab* Hassan catchment area in detail including its location, size, climatic factors, geology, geomorphology, soil, groundwater and surface water resources.

The field and laboratory work that has been carried out in Jordan is described in Chapter Three. The work includes the measurements of soil physical properties at different locations of the catchment area in addition to the *Marab* and the lay out of runoff plot experiments. Also it describes the participatory rural appraisal and the role of the local community in giving useful information and evidence that help in decision making.

Chapter Four discusses the rainfall variability of Jordan with focus on the catchment area. Quantitative approaches that have been used to check the rain gauges consistency are discussed, as well as the rainfall pattern and synoptic situation through out different seasons.

Factors that affect the rainfall and types of runoff in general and the runoff generation in arid zones are described in Chapter Five. This chapter introduces the general aspects of rainfall-runoff modelling and synthetic approaches to develop the unit hydrograph. The applications of some of the synthetic approaches (Snyder, 1938) and SCS, (McCuen, 1982; Haan et. al., 1982)) to *Marab* Hassan catchment area are discussed.

Chapter Six discusses the use of Geographic Information System (GIS) in hydrologic modelling and describes the implementation of the GIS in developing the Geomorphologic Instantaneous Unit Hydrograph (GIUH) for the catchment area of *Marab* Hassan.

The correlation between the global climatic indices (ENSO SST, SOI, NAOI and Indian Ocean SST) and the Jordanian rainfall and the use of these correlations to develop the rainfall probability models is described in detail in Chapter Seven.

Chapter Eight focuses on use of the rainfall probability models in association with the traditional approaches that have been used in the *Marab* cultivation to propose management plans for the "best" water resources management of *Marab* Hassan. This chapter also cites a general literature about the water harvesting and the Jordanian experience in water harvesting.

Finally, Chapter Nine gives conclusions and recommendations for future work on the *Marabs* of Northeastern Badia area.

CHAPTER TWO

THE CATCHMENT AREA OF *MARAB* HASSAN

2.1 INTRODUCTION

The catchment area of *Marab* Hassan is one of the important catchments in the Badia area that have to be studied in detail. This Chapter focuses on studying the catchment area by covering different perspectives. A brief description about the catchment includes the catchment's general description in terms of location and number of sub-catchments. The climatological factors that affect the catchment area like rainfall, temperature, wind, evaporation and relative humidity will also be considered. The geology and the geomorphology of the catchment area will be discussed, mainly, the formation of the *Marab* and the importance of it. The general description of the catchment's soil types will be given. Ground and surface water resources in the area will be discussed in order to check the development possibilities. Finally the soil physical properties of the catchment area as well as the runoff plot experiments that were carried out at different sitesin the catchment will be described in detail.

2.2 *MARABS* IN THE BADIA AREA

In the Jordanian Eastern Badia there are many depressions or pans, composed of fine-grained sediments. These depressions are called *Qa* areas or mudflats. Mudflats have probably formed as a result of regional and local faults, that caused the formation of small depressions, where mud has accumulated from standing water fed by ephemeral wadis discharging into mudflats, (Ibrahim, 1997). Also, basalt eruptions and alteration of the area by localised Quaternary or Recent tectonic activities at some sites could form mudflats by causing local changes in topographic features. There are old and new mudflats depending on the age of the eruption of the basalt, (Sunna'a, 2000). Sequences of basalt eruption mean that the surface of Eastern Badia has been profoundly modified in the Recent geological past by interaction of tectonics and volcanism.

Three main mudflat types can be identified, based on their size, shape and drainage characteristics:

- Large or major mudflats, which have extensive catchments and fed by wadis. The surface area of a *Qa* can be many square kilometres. *Qas* are low relief areas, identified as mud flats that exhibit more than one inlet with no definite outlet, thus the water ponds and evaporates leaving saline unproductive land. An example of this kind of mud flat is Azraq *Qa*, into which Wadi Hassan discharges, (Sunna'a, 1999).

- The second type is the small or minor mudflat. They are similar to the large mudflats, but much smaller in scale, with cross sectional width of tens of metres rather than kilometres. The size and development of the mudflats is related to the age of the lava flows.

- The third type of pan is known as *Marab*. *Marabs* reflect areas where Wadi channels increase their width and water spreads across a wide area. Through the water movement sediments accumulate causing the flow velocity drops, (Allison et al., in press; Barrow et. al., 1998). A *Marab* is fed and drained by wadis, i.e. it receives and delivers water, which is the major difference between it and the *Qa*. Normally water leaves the *Marab* in the shape of a well-defined channel, as illustrated by *Marab* Hassan and as has been earlier discussed.

2.3 IMPORTANCE OF *MARABS* IN THE BADIA AREA

The ownership of *Marabs* and land in the Badia area is based on the concept of the "land tenure". As mentioned in Section 1.3 the concept of the *dirah* is highlighted and the degree of control over the land depends on the number of people who belong to the *dirah* and the tribe, as well as the personality of their leader. The concept of the land tenure has appeared in the Badia area at the end of the British mandate in the late 1940s when the Jordanian government declared that all the uncultivated land belonged to the state, (Dutton, 1998). But, in the Badia area the declaration did not take place, as it was impossible to interrupt the hold the tribes had over their traditional *dirah*, and their sense of responsibility for its resources. From early in the mandate period greater stability in the Mafarq area led to pastoralists acquiring land and settling to become farmers, (Jaradt et. al., 1993). The land was formally registered but the lands further east have never been registered, therefore individuals have laid claim to portions of the land by ploughing, as ownership is not recognised by law. In practice there is a state of confusion between traditional tenure (the *dirah*), and state and private ownership. For most of the lands in the Badia programme area no one has the right to keep other people's livestock off the land, and so nobody has the authority or responsibility for managing the range and protecting it from degradation.

The *Marabs* are nearly flat with relatively deep soil and receive floods from the surrounding catchments. The water rarely accumulates on the soil surface because of the gentle slope of the *Marabs*. This means that due to the relatively good drainage, the soil remains saturated for several days after each flood during the winter seasons. The estimated area of the *Marabs* in the Badia area is about 0.2 million ha, (Abu-Zanat, 1997). In the last 20 to 30 years, the best areas of these *Marabs* have been cultivated with wheat and barley, depending on the magnitude of the flood. But, continuous cultivation of these *Marabs* has led to the depletion of the native vegetation cover and has caused serious erosion problems. Moreover, the government's removal of the subsidies on the imported feed in 1996 and the high prices of imported feeds triggered factors for more intensive cultivation of the *Marabs*, which threaten their biodiversity and sustainability.

The majority of the Bedouin farmers' income comes from the sale of their animals and animal products like milk and yoghurt. So, the main concern for them is to haveenough food supply for their livestock (sheep and goats), for as long time as possible during the year, especially during summer months. This is the main reason why the farmers are using *Marabs* for cultivating barley. The cultivation of barley in the *Marabs* is still primitive, as most of the farmers who cultivate the *Marabs* are relying on using the traditional approaches of cultivation.

As will be discussed later in this chapter and in Chapter Four, most rainfall in Jordan falls between October and May, and mainly concentrated between December and March. Usually, farmers in the Badia area prepare their land for cultivation in late summer, waiting for the rain to come, using the "*Afeer*" (which is an Arabic word for broadcasting the seeds) concept for cultivation. If they have "local seeds" they sow them before the *Marab* receives any rainfall (i.e. dry farming). But, if the "local seeds" are not available they wait until the *Marab* receives a flood or enough rain to re-establish its moisture content (i.e. wet farming). This flood or early rain has to occur in October or the 20th of November at the latest. If it does not start raining in October or at the latest by the 20th of November they just leave the land bare without cultivation, providing that the local seeds are not available. This aspect will be discussed in detail in Chapter Eight (section 8.10).

This method of farming is called rain-fed farming as it mainly depends on the rainfall without using any artificial irrigation. Rain-fed farming has increased in parts of the Badia, like the Um Al-Quttein area in the northwestern part of the Badia programme area. The local people clear the basalt boulders from the soil surface to create small fields, practice this kind of farming for rain-fed barley cultivation. These crops are commonly used for forage production, as the lack of rainfall often prevents the heads of grain from developing, (Al-Bakri et. al., 2001).

Population growth is one reason for the increasing demand on the cultivated areas and on rain-fed agriculture. In addition the livestock owners started to move from subsistence to commercial production, which also increased the demand on animal feed, especially after 1996 when the government removed the subsidies. In the past the *Bedouin* had a cycle of movements inside and outside the Badia while looking for the availability of pasture and water for their livestock. Figure 2.1 shows the historical pattern of seasonal movements of the Bedouin in the northern part of the Badia area. From the Figure it is seen that they move eastwards in late winter and spring seasons as this saves them money, time and effort. For early summer until autumn they move north-westwards towards the Irbid area, looking for feed for their livestock. This is because the northwestern area receives more rainfall, so the grassland is more available in this area at this time of the year compared with the Badia area and the grazing is more reliable. By the end of autumn and beginning of winter people start to return back to their homes.

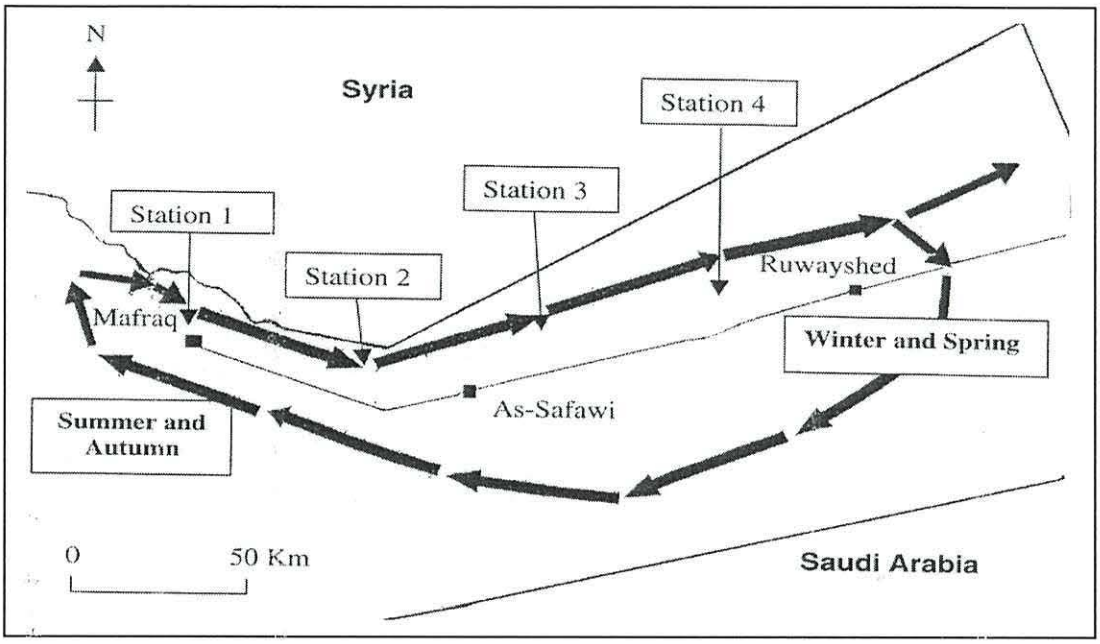

Figure 2.1: The pattern of seasonal movements of the Bedouin in the northern part of the Badia area, source (Al-Bakri et. al., 2001).

In recent years the lifestyle of the Bedouin has changed as they started to give up the nomadic lifestyle and became more settled than in the past, which means that they will use the land more intensively than before, (Dutton, 1998). The more settled lifestyle enables them to receive more and better services like schools, hospitals, communication systems, etc. On the other hand, this change has created an emphasis in agriculture with more interest in arable agriculture, either rain-fed or irrigated type.

The productivity of barley cultivation varies between wet and dry years. In wet years (that is when rainfall is above average and evenly distributed throughout the season) a grain crop is produced and the straw is stored and kept for use later in winter. However, in dry years when the crop does not reach the maturity, the crop is left for grazing by sheep in situ.

2.4 *Marab* Hassan Catchment Location

The *Marab* Hassan catchment area is an elongated catchment with an area of about 360 km^2(Figure 2.2). It is located in the northwestern part of Badia Programme area. The catchment consists of three wadis; the largest one starts from the Syrian Jebal Al-Arab in the north, then it is joined by the other near the bottom of the catchment. From the eastern side appears Wadi Hassan that starts from Jebal Al-Asfar. Then all the wadis reach a mud flat (an area of accumulated sediments), locally known as "*Marab* Hassan", as shown in Figures 2.2 and 2.4. Downstream of the *Marab* one wadi continues to the Azraq mud pan "*Qa* Al-Azraq", illustrated in Figure 2.3. *Qa* is a mudflat characterised by a wide area of low relief with no clearly identified outlet, in which ponded surface flows evaporate leaving saline deposits. While, mud flats that have identifiable outlets are termed *Marabs*, (Jolley, 1996).

From the aerial photograph as shown in Figure 8.2, it is clearly seen that the wadis that contribute to *Marab* Hassan catchment area are well defined, deep incised wadis with Wadi Hassan coming from the northeastern side of the *Marab* and the main wadi from the northwest. For simplicity the catchment has been divided into three main sub-catchments as shown in Figure 2.5. Downstream of the wadis *Marab* Hassan appears with an area of 3.5 km^2. The volcanic eruption of Tall Hassan to the eastern side of the *Marab*, as well as the existence of some faults and structural system have resulted in its formation. As shown in Figure 2.4 the *Marab* has two inlets and two outlets, one major outlet and one minor to the right that discharges water in high flood seasons only.

The flow pattern in the *Marab* takes two forms, sheet (overland flow) from the main Wadi in the west and a channel flow from the eastern Wadi. The *Marab* will be analysed in more details in Chapter Eight as it has agricultural potential. It has been used for barley cultivation for a long time.

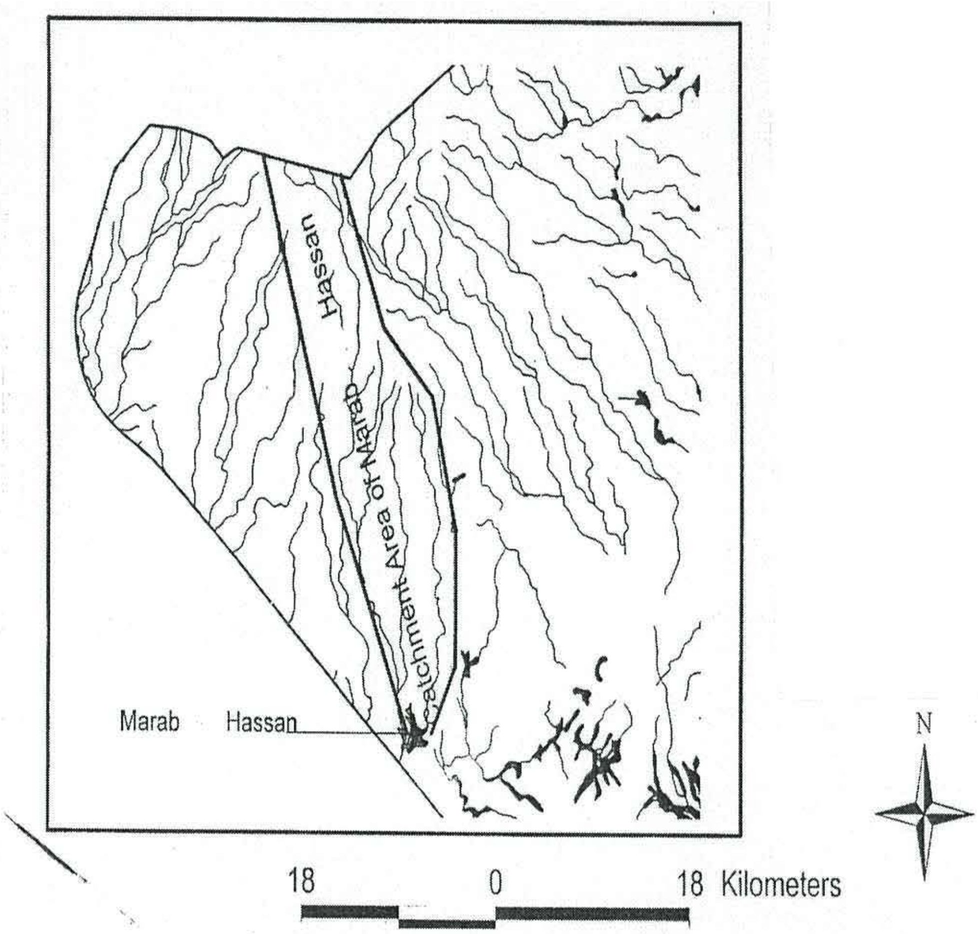

Figure 2.2: *Marab* Hassan Catchment area in Jordan NE Badia.

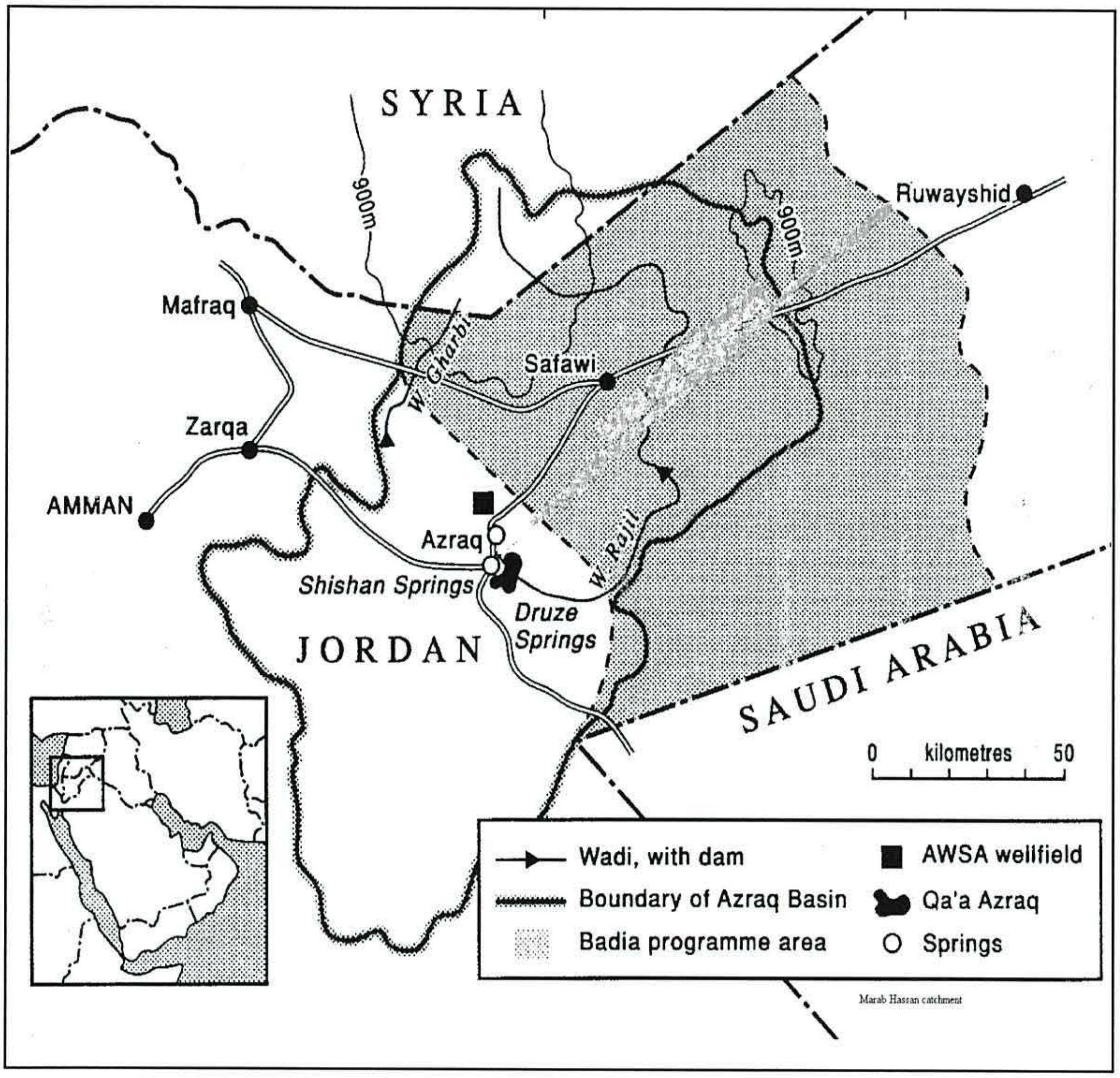

Figure 2.3: *Qa* Azraq in the northeastern Badia of Jordan, source (Dottridge 1998)

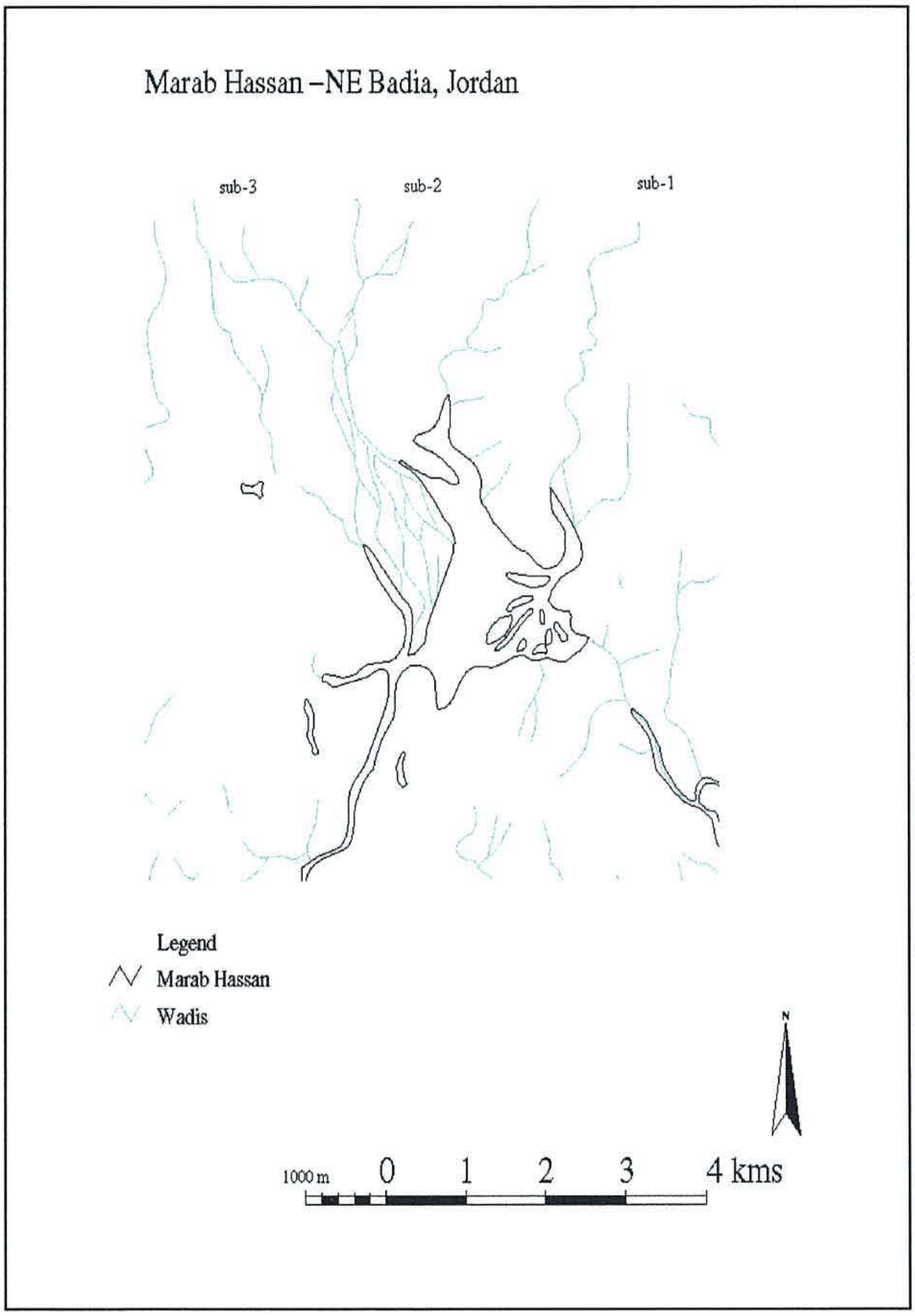

Figure 2.4: *Marab* Hassan, North Eastern Badia of Jordan.

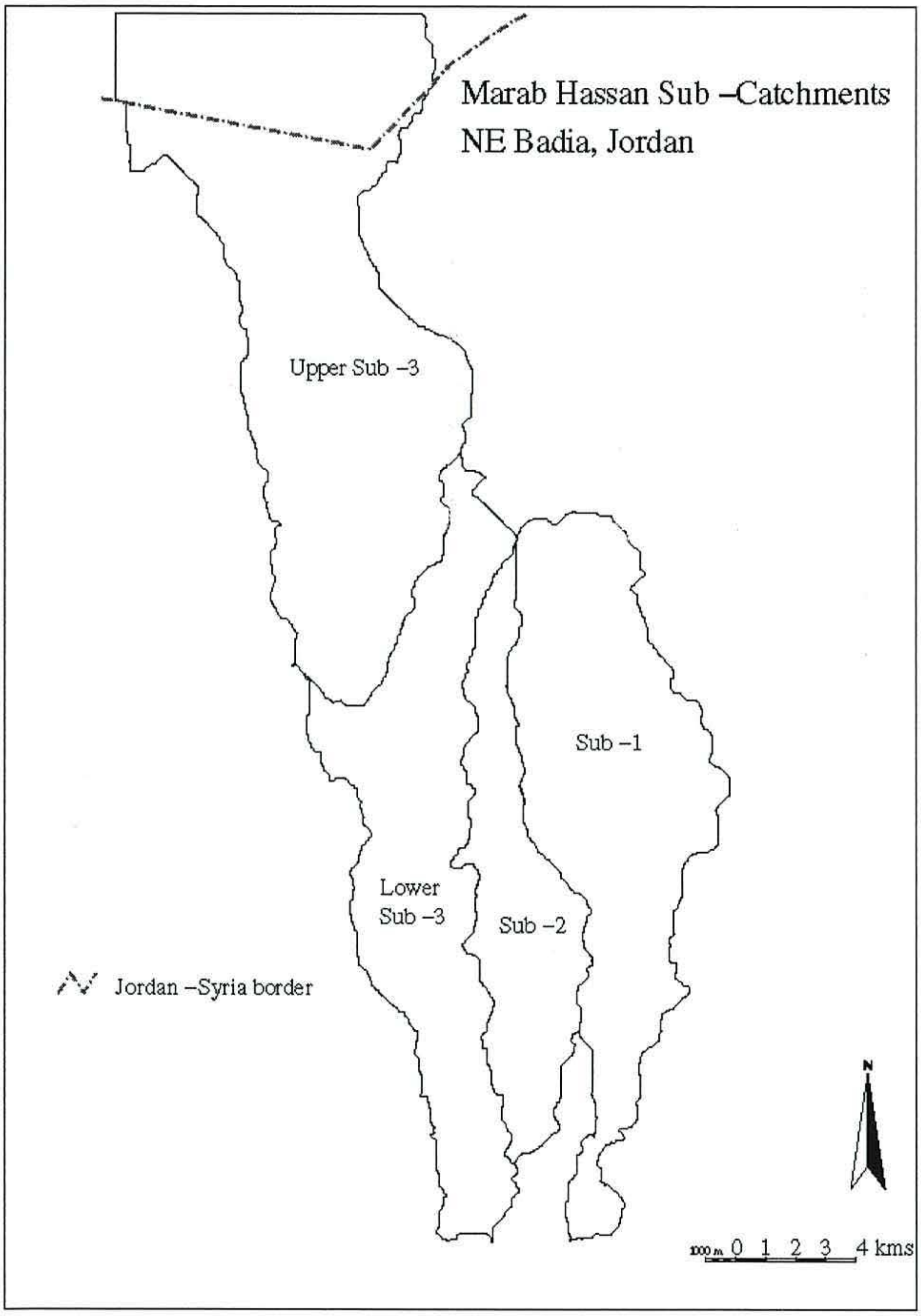

Figure 2.5: *Marab* Hassan sub-catchments.

2.5 CLIMATOLOGICAL ELEMENTS

Jordan's location near the Eastern Shore of the Mediterranean and on the northwestern edge of the Arabian Peninsula explains the nature of the country's climate. It is controlled by the general circulation of the atmosphere over the Mediterranean, that is mainly an interrupted westerly circulation in winter, and a subtropical desert climate that is associated with the subtropical high pressure cells in summer, (Shehadeh, 1985). Aspects of weather systems in Jordan will be discussed in more detail in the next chapter.

The classification of the Badia area varies between arid and transitional zone. According to the Ministry of Agriculture classification this area is classified as arid, (Al-Ayyash, 1993). While, Allison et al., (in press) consider the Jordanian Badia as a transition zone between mid altitude dry summer and interior warm semi-arid desert climates. Mean annual rainfall increases from 50 mm per year in the south to over 250 mm per year in the north near the Syrian border. The catchment area, as in the rest of the Badia programme area, is characterised by two seasons, hot, dry summer, and cold and relatively wet winter. The Badia programme area is considered part of the Azraq Basin, which is located in a climatically transitional zone with small changes in climate capable of having large impacts upon the physical environment.

2.5.1 Rainfall

The present day climate of the northeastern Badia is arid with 50 mm to 250mm of rainfall per annum. A feature of such arid regions is great rainfall variability in which there may be months without rainfall, yet when it rains it may be intense with a single storm producing as much as the mean annual precipitation. The only reliable surface water is the Azraq oasis, but rainpools and limited groundwater outflow provide a number of other temporary potential water sources, (Macumber, in press). Rainfall records are important input to any hydrologic design. In the Badia as well as other areas different causes or mechanisms of rainfall have been reported. Rainfall is divided into four major types; they are convective storms, orographic storms, cyclonic storms and tropical cyclones. They will be discussed in detail in Chapter Three.

The maximum amount of rainfall occurs between December and February. The average number of rainy days is 23 days and the average annual rainfall on the catchment is 194 mm, (UNDP, 1994). Figure 2.6 shows the rainfall distribution over the whole of Jordan, including the Badia programme area.

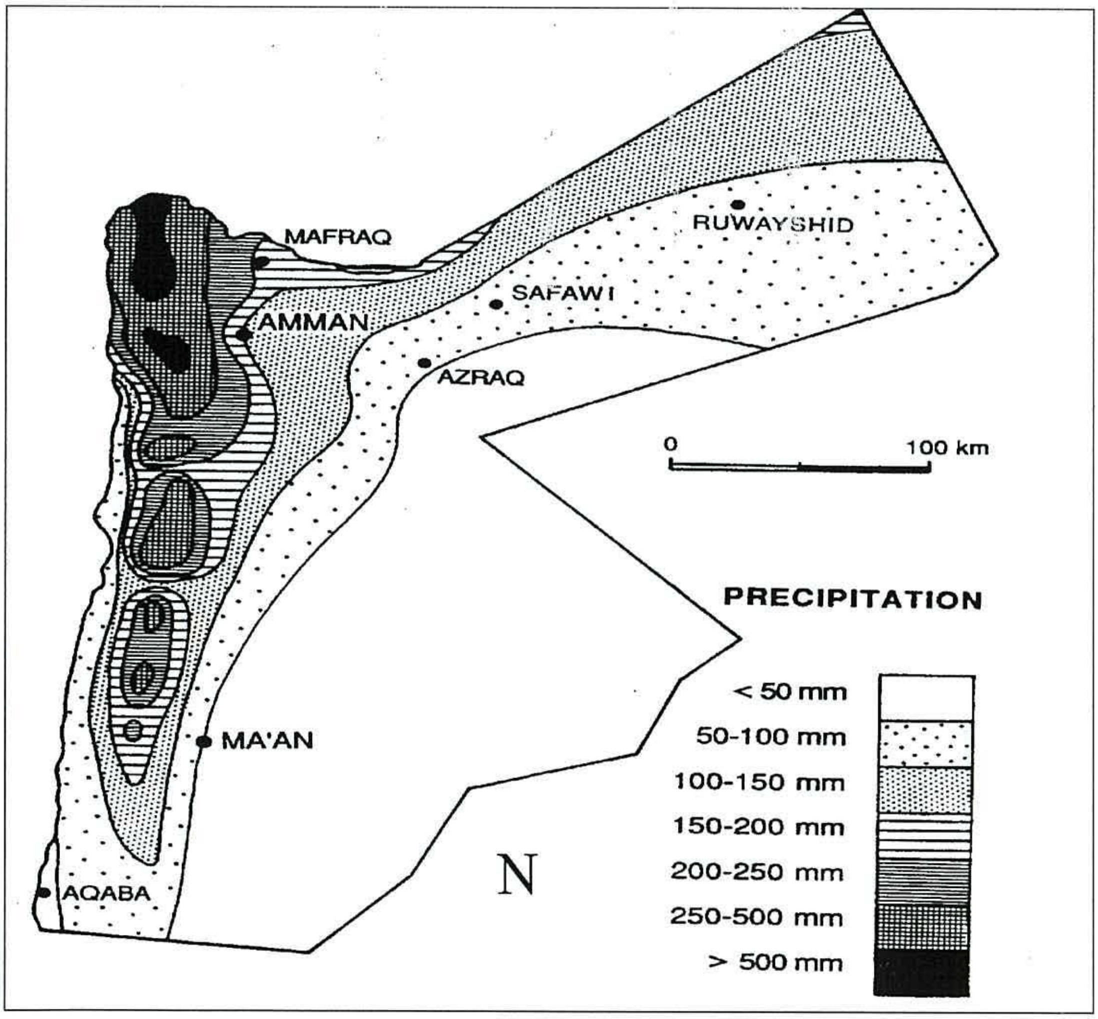

Figure 2.6: Rainfall distribution over Jordan, (Source: Allison et. al., 1998)

2.5.2. Temperature

January is the coldest month in the year, where the average monthly temperature can fall to below zero degrees. The hottest months are July and August with an average temperature of 28 °C. The mean annual temperature is about 15 °C. (Ashour, 1998). The temperature gradually increases from January to July and starts to decrease from August to December. Summer temperatures rarely rise above 40 °C while winter temperatures seldom drop to 0 °C. The north-western part of the Badia programme area near the Syrian border is characterised by a marked variation in temperature, both in terms of its diurnal nature and annual change. This reinforces the fact that the area lies close to the transition from the Mediterranean conditions to a more continental climate further east, which is characterised by more extremes in both diurnal and annual terms.

Daily temperatures vary in a cycle, the highest daily variation taking place during late spring and early summer. The lowest temperature occurs between 4 and 6 am while the highest occurs between 14:00 and 16:00 hours in the afternoon.

2.5.3 Relative Humidity

The maximum average monthly relative humidity is about 61% in December and January. Then it starts to decrease to reach 38% in May. The monthly average relative humidity ranges from 38 to 48% in summer and from 58 to 61% in winter, (UNDP, 1994) as shown in Figure 2.7.

2.5.4 Wind Speed and Direction

Wind is an important factor as it affects the variation in rainfall and evaporation in the Badia. The wind direction is NW in summer between 5:00 and 15:00 hours, while it shifts to a NE direction during summer nights. It is SW in winter days and during the winter nights it turns to SE direction, (Swarieh and Dweik, 1996). The annual average wind speed is 14.2 km/h. This generalisation simplifies the situation, in reality only June to

August fit completely into the summer pattern and November through February fit the winter pattern, while the intervening months are transitional from one pattern to the other.

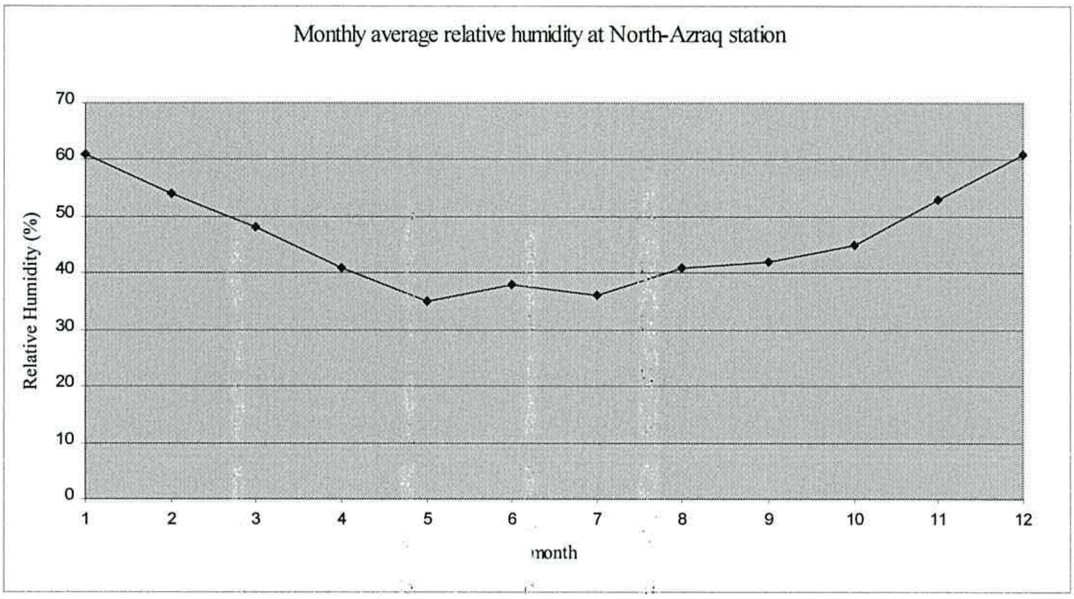

Figure 2.7: Monthly average relative humidity for North Azraq station, (Source: UNDP, 1994), (1=January; 12=December).

2.5.5 Evaporation

Evaporation is defined as the water vapour that returns to the atmosphere from surface and ground soil, water, ice and snow, (Wanielista et. al.1997). Evaporation rate varies with weather conditions. Factors that affect it are cloud cover, wind speed, temperature and relative humidity.

Class A pan is used to measure the open pan evaporation rate in the Badia programme area. Two stations are used for this purpose; Safawi station which is about 35 km NE of *Marab* Hassan and Azraq North which is 10 km SW of the*Marab*.

The average daily evaporation measured at Azraq North station is 11.5 mm. The evaporation rate normally increases from January to July (4.2-19.2 $mm.day^{1}$), and starts to decrease from 17.4 mm/day in August to 4.3 $mm.day^{-1}$ in December, (UNDP, 1994). Generally speaking about 8,500 million m^3 of rain falls in Jordan each year of which about 85-92% is lost by evaporation (Al-Homoud et. al. 1995).

2.6 GEOLOGY

2.6.1 Rock Types

According to Garrad et al. (1985), the arid lands of Jordan can be divided into three major lithological/ecological units; basalt in the north (that is known as basalt plateau), limestone/chalk/flint in the centre and sandstone/granite in the south.

As the catchment area is part of the first category, basalt lava flows are the dominant rock type in the area, which covers an area of about 11,000 km^2. It forms a small part of the huge basalt plateau, which is known as "Harrat Ash-Shaam" basalt plateau. It covers 45,000 km^2 in southern Syria, eastern Jordan and northwestern Saudi Arabia, (UNDP, 1994).

The exposed basalts are classified as one super-group named the "Harrat AshShaam" basaltic super-group. The Harrat Ash-Shaam can be sub-divided into five major groups known as Bishriyya, Rimah, Asfar, Safawi and Wisad, (Ibrahim, 1997) and (Al-Homoud et al. 1995). Table 2.1 gives a brief description of the "Harrat Ash- Shaam" basaltic super-groups and sub-groups.

The basalt is composed of Neogene "plateau basalt", Quaternary Recent "basaltic lava flow" and "Shield Volcanoes". All these basalts erupted from magmatic sources, which originate from the Upper Earth Mantle. Figure 2.8 shows the geologic map of the Badia programme area, which lies in the basalt plateau.

Plateau basalt and shield basalts are generated through fissure effusions from a system of dyke feeders that have a NW-SE trending direction. Basaltic lava flows are generated from volcanic eruptions. They occur as wadi-filling lava flows around their point source feeders, (Schaffer, 1995).

Table 2.1: Harrat Ash-Shaam Basaltic Super-Group, (Source: Ibrahim, 1997)

Group	Formation	Age (Ma)
Bishriyya	Fahda Vesicular Basalt Wadi Manasif Basalt	1.45-0.1
Rimah	Aritayn Volcaniclastic , Hassan Scoriaceous	2.94-2.01
Asfar	Mahadda Basalt Madhal olivine Phyric Basalt Hashimyya Aphanitic Ushayhib Pyroxine Phyric Ufayhim Xenolithic Basalt	3.41-1.96
Safawi	Salman Basalt Abed Olivine Phyric Basalt Ali Doleritic Basalt	9.3-8.45
Wisad		10.53-9.37

2.6.2 Superficial Deposits

Marab Hassan is located in the Al-Bishriyya sheet area, the superficial deposits found in this area are; alluvium and wadi sediments (A1), alluvial mudflat and siltflat (Alm), alluvial fans (alf) and calcrete and soil.

- Alluvium and Wadi Sediments

They consist of stone or boulder-coating deposits along with gravel, sand and silt derived from diverse bedrock lithologies. These sediments fill the wadis and incised terraces comprising gravel and boulder at the base and fine to coarse grained sand at the top.

- Alluvial Fans (Alf)

  Alluvial fans are developed in two places to the south-east of Jebal Al-Aryyatien and south of wadi Al-Arttayien, where the ground is level or where there are shallow depressions. Water accumulates during flooding and fine silts and clays are deposited to form mudfalts.

- Alluvial Mudflats and Siltflats (Alm)

  Mudflats were developed in the low topographic areas when the ground was level and flat. Mudflats probably formed as a result of regional and local faults which produced small depressions where mud accumulated from standing water fed by ephemeral wadis discharging into mudflats, (Sunna, 2000). The major mudflat in the area is *Marab* Hassan. From the 1:50,000 geological map it appears that the *Marab* has formed as a result of the formation of the faults. The major fault in the area is the Fuluq Fault, which is directed in NW-SE direction. It crosses the southwest corner of Al-Aryyatien area, and forms the northern and northeastern border of the Azraq basin. *Marabs* are normally composed of yellowish brown to yellow, soft clay and silty clay with rock fragments, (Ibrahim, 1997).

- Soils and Calcrete (Ct)

  The soil is between 0.5-2 m in depth, and consists of yellow-brown to red-brown calcareous clays with residual basalt blocks. The soil is cemented by lime crust to form calcrete. The soil types within *Marab* Hassan catchment area will be discussed in detail in section 2.8 of this Chapter.

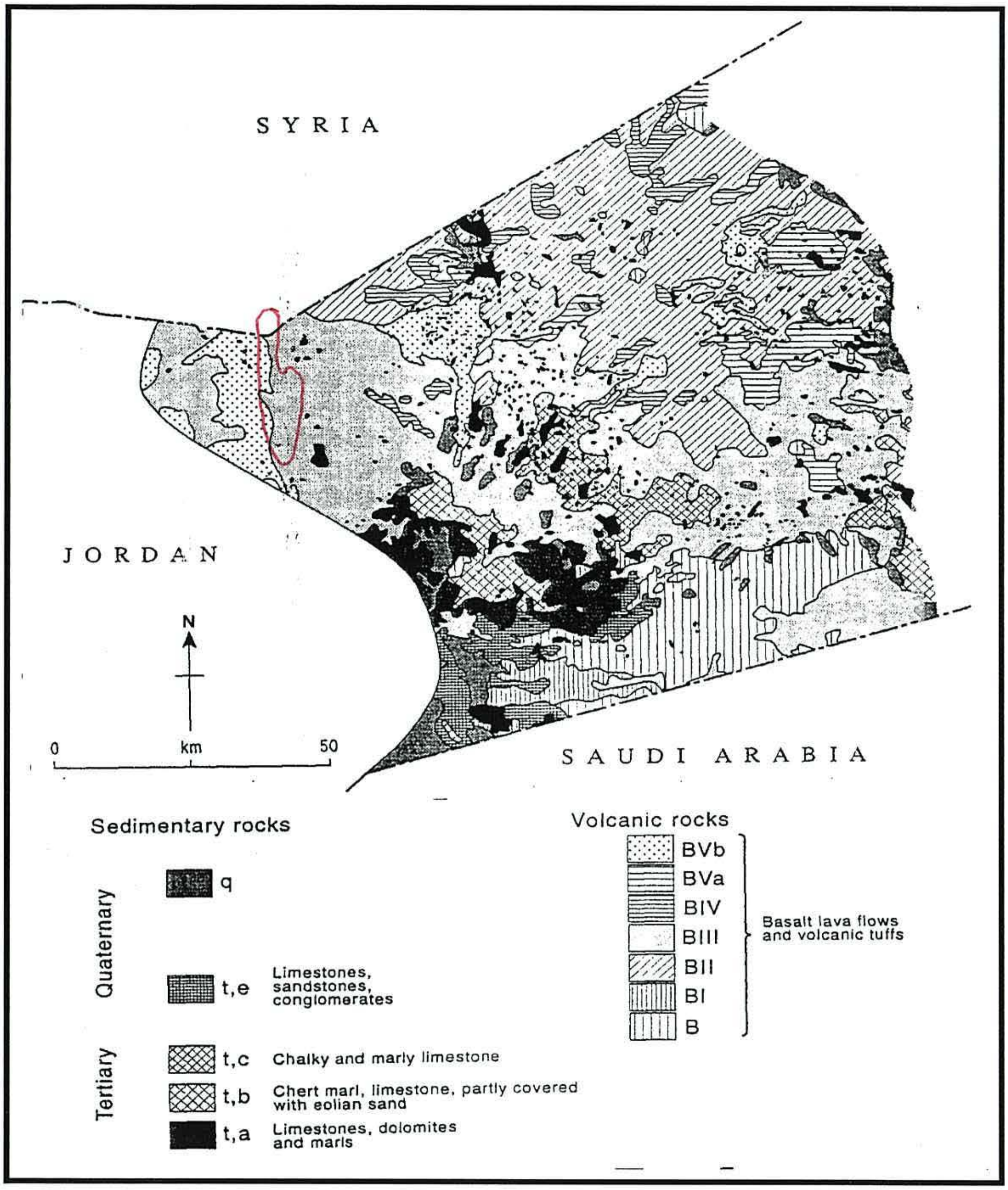

Figure 2.8: Geological map of the Badia programme area, (the red line represents the catchment's boundary), (source: Allison et al., in press)

2.7 GEOMORPHOLOGY

The landscape development of the Badia area is linked to the age and the characteristics of the lava flow. It is concluded that there have been wet and dry climates in the Middle East throughout different periods of time, as will be discussed in detail in chapter three. The warmer and wetter conditions have helped to create a more active weathering environment than at present resulting in the dissection of the upper and exposed parts of the lava flows, (Allison et. al., in press). Fine-grained sediments with light brown to orange colour are present almost everywhere at the ground surface. It is likely that some of the fines close to the ground surface have been discharged into the area from other environments, (Kirk, 1997). But, as the age of the basalt lava flowbecomes younger the degree of basalt disintegration at the ground surface declines. The implication of that is important when it comes to the long-term geomorphologic evolution of the area and the origin of the substrate upon which recent agricultural development relies.

The wadi systems in the programme area are extensive with the general flow direction from north to south and southwest, with much of the water entering the Azraq basin. Some of the wadi systems extend for many kilometres. Wadi Hassan stretches from the north at the foothills of Jebal Al-Arab in Syria until reaching*Marab* Hassan, after which the flow leaves into the Azraq basin.

The geomorphological evolution of the area can be related to the age of the volcanic basalt lava flows. A particularly good example is the degree of wadi connectivity; the drainage network evolution and the extent to which the overland flow moves slowly down the wadi courses, where the *Marabs* are formed. The *Marab* is characterised by fine texture drainage systems, which compose fine-grained sediments and areas where infiltration rate is relatively small. Maximum infiltration occurs along major streams and in the area within the basin surrounding the mudflat and is characterised by medium and coarse textured drainage.

Landsat TM images analysis of the whole Badia programme area has resulted in its sub-divisions into twelve geomorphological zones. The catchment area is located in zones 6 and 7, according to Figure 2.9. Zone 6 is located in the Syrian part of the catchment; it is the land round Jebal Al-Arab, consisting of basalt outcrops and distinct volcanic centres in places.

Most of the catchment lies in zone 7 where a high density of wadis and many small *Qa*'a and *Marab* deposits become more common in the south. The Wadi systems radiate from the higher ground of Jebal Al-Arab (zone 6). This northern part of this zone is characterised by the presence of lichen growth on the basalt boulders, which is an indication of the moisture availability, as the rainfall is more in this part than the southern part. Some boulders in this area have been removed and the lands have been used for agriculture. *Marab* Hassan (shown in Figure 2.4 is an example of the deposits in the area. It is located at the end of the catchment, where the three Wadis join together. It has an area of 3.5 km^2, the soil is loamy soil with the sand, silt and clay percentages are 42.9, 35.4 and 21.8 respectively. The soil-mapping unit for it is NAT as will be discussed in section 2.8.

The *Marab* has originated from the volcanic activity of Tall Hassan that is located a few hundred metres from the *Marab*, as well as from the existence of the major faults (structural systems) that control the whole area. Part of the catchment area has been buried because of the volcanism, and the volcanic cone resulted in the blockage of the original outlet of *Marab* Hassan (the eastern outlet), then the wadi filled and formed a temporary lake at *Marab* Hassan site, while a new outflow channel was formed. After that the old channel was partially re-established by headwater erosion and at high flood stage in Wadi Hassan a proportion of the flow spills down this original channel.

After heavy storms the *Marab* floods and the floodwater stays there for a number of days (5-7). This indicates that the *Marab* has a good potential for agriculture. It has been used for growing barley for many years. The farmer on the *Marab* is relying on rainfall only, so it is rain-fed agriculture. The uses of the *Marab* as well as the best water management techniques are to be discussed later in Chapter Eight in detail. The details will also include discussion about the possibilities of water harvesting in the area, as the water harvesting techniques were practised and evidence was found in the north western part of the Badia programme area, (Al-Sallaq and Farah, 1993).

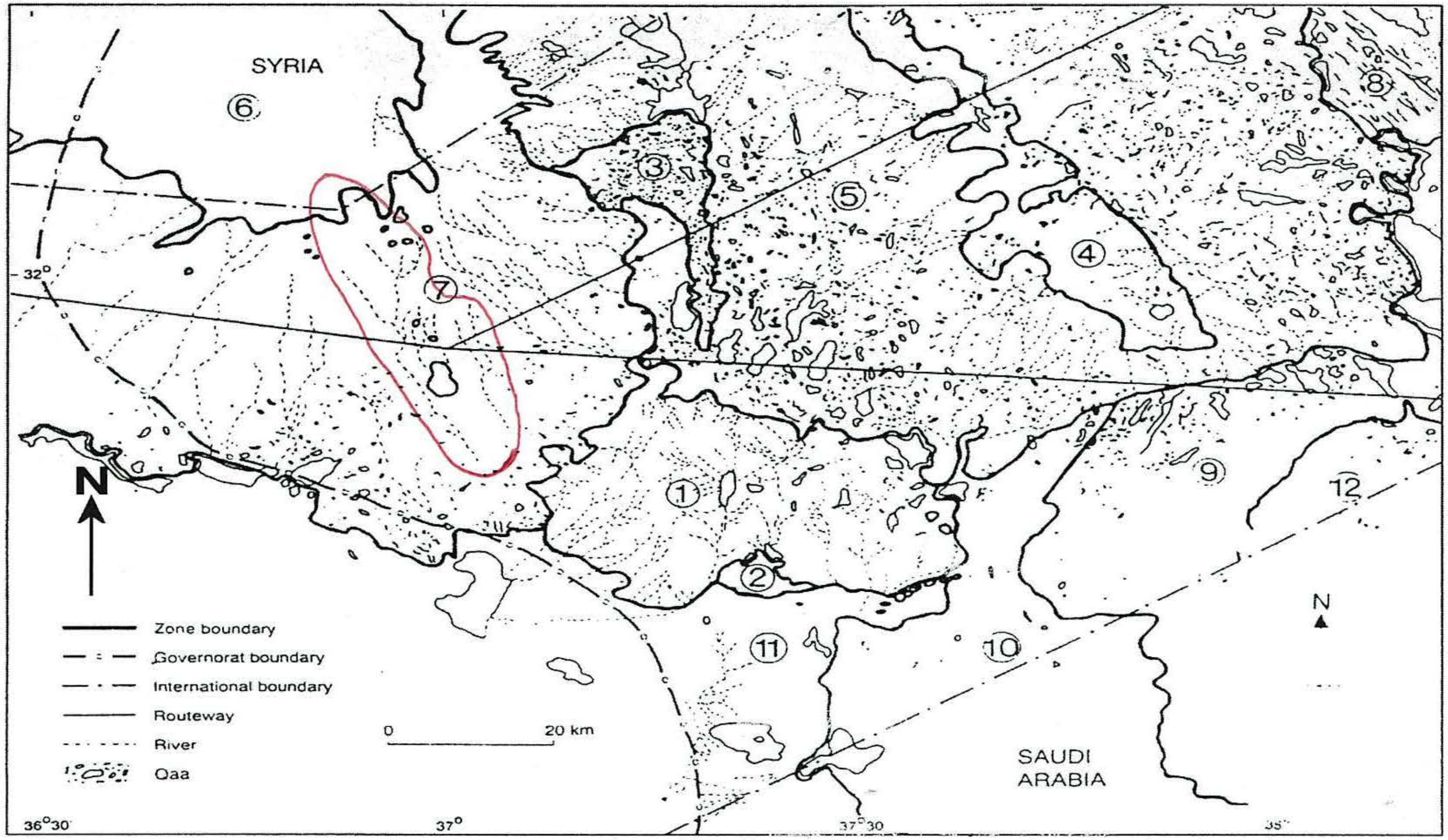

Figure 2.9: The geomorphologic zones of the Badia programme area, (red line represents the catchment's boundary), (Source: Al-Homoud et. al., 1995).

2.8 SOIL

According to the United State Department of Agriculture (USDA) classification system the dominant soils of the area are either Aridisols or Entisols. Aridisols are those enriched with calcium carbonate or gypsum and having aridic moisture content. When gypsum is predominant the soil is classified as Gypsiorthids. While, if it is enriched with calcium carbonates the soils are classified as Calciorthids. If the amount of calcium carbonate is not sufficient to develop calcic horizons, the soil is classified as Camborthids, (Ashour, 1998). Entisols have no distinct subsurface horizons within 1 m of soil surface. The major Entisols groups identified in the area are toriorthens and torrifluvents, which are generally layered soils with a very mixed particle size, (Al-Zubi, 2000).

Most of the soils in the eastern Badia are thin, poorly developed and closely linked with the underlying geology and topography. On summit areas soil is often completely absent. In topographic lows soils and the sediments within which they have formed can be as much as 2m deep.

Historical and archaeological records suggest that agriculture has been prevalent in the eastern Badia since Roman times, (Kirk, 1998b). Clearance of the basalt boulders has always been a necessary preparation for the cultivation. In the past ten years the clearance has extended, especially in the northwestern part of the programme area and the land has been used for cultivation of plants like tomatoes, cucumbers and watermelon, (Allison et. al., in press). The cultivated land mainly depends on groundwater for irrigation between April to October, after that it becomes rain-fed.

Six soil types (mapping units) are found in *Marab* Hassan catchment area. They are NAT, SHA, UBI, ZUM, BIS, and FAR as shown in Figure 2.10. Table 2.2 gives some information about each type. In Figure 2.10, the depiction of soil types is based on surveys of Jordan; therefore the map ends at the Jordan/Syria border (in other words no equivalent soil data for Syria has been made available). However, the hydrologic analyses did include the Syrian part of the catchment.

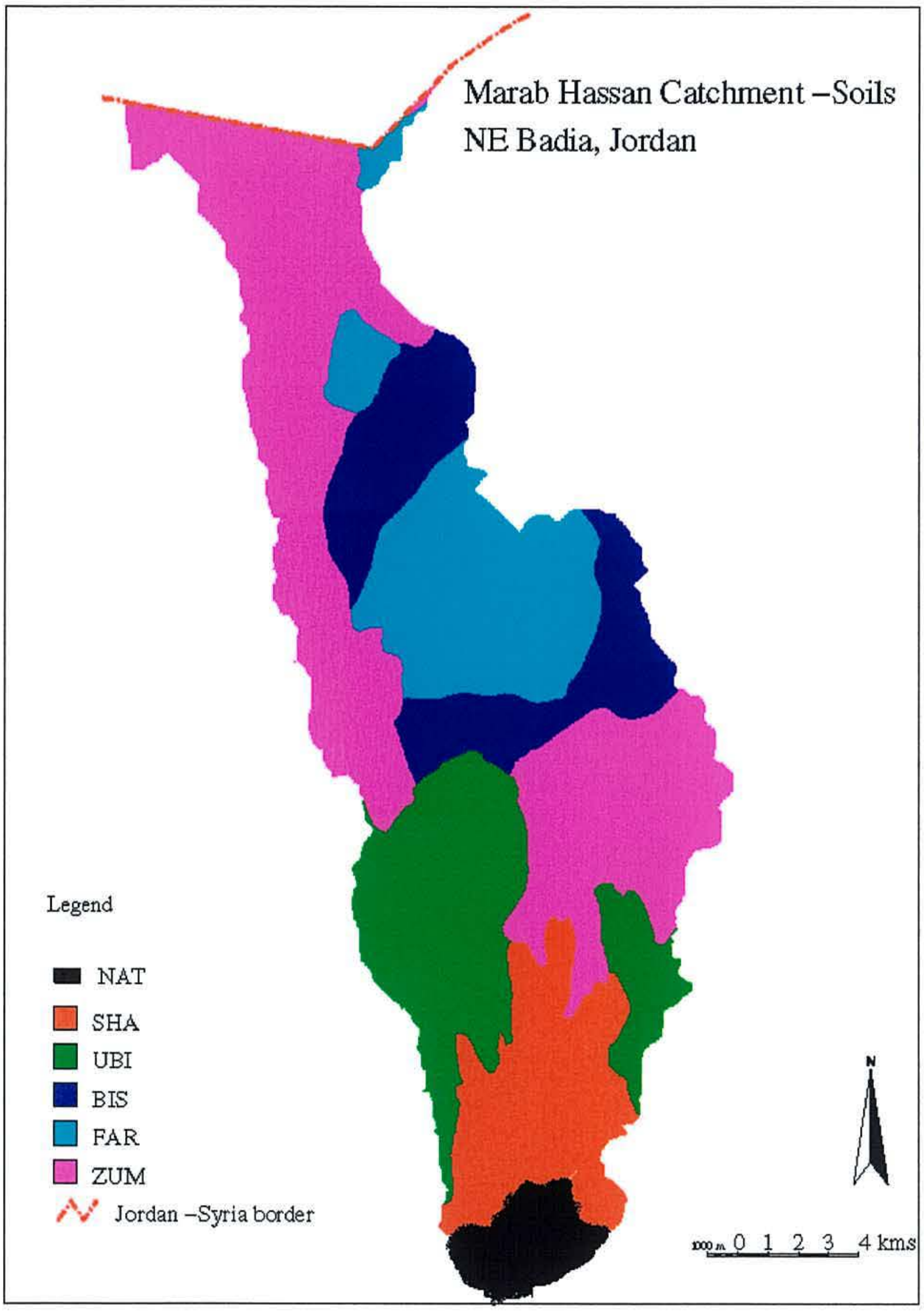

Figure 2.10: Soil types in *Marab* Hassan catchment area.

Table 2.2: Description of the soil types in the catchment area, (Source: Hunting, 1993)

Soil Type	Description
NAT	Depositional basins, wadis and alluvial fans draining basalt flows: extensive *Qa*'s with surrounding terraces remnants and alluvial fans: small deltaic fans at mouths of wadis: sand sheet mantles some fans and wadis: aridic moisture and thermic temperature regimes: altitudes 600 to 1000 m: relative relief < 10m.
SHA	Undulating Quaternary basalt flow, boulder covered with occasional cones: incised wadis, alluvial fans and many drainage basins: aridic moisture regime, aridic-xeric in some wadis and channels: thermic temperature regime: altitude 600-1000m: relative relief 25-50m.
UBI	Ash and lava cones and ridges including craters: well marked radial drainage: steep stony upper and midslopes, gentle lower slopes and concave depositional footslopes: altitude 500 to 1000m: relative relief 50-100m.
ZUM	Undulating, occasionally rolling, plain of Quaternary lavas with rocky interfluves and broad alluvial basins: loess mantle on gentle slopes: xeric-aridic transitional moisture regime, aridic in east: boulder covered slopes: altitude 600 to 1150m: relative relief 25-50m.
BIS	Undulating to rolling dissected lava plain of Quaternary basalts: well-incised parallel drainage system: moderately steep sided hills, convex interfluves and narrow incised valleys: slopes and crests boulder covered: xeric-aridic transitional moisture regime: altitude 800 to 1200m, relative relief 50-100m.
FAR	Volcanic massifs with central cone and steep to moderately steep boulder lava slopes with occasional small ash cones: xeric-aridic transitional moisture regime: altitude 650-1200m, relative relief 100m.

An aridic soil moisture regime prevails in most of the Badia programme area, except some of the northern part near the foothills of Jebal Al-Arab, where the xeric aridic soil moisture regime dominates. A soil moisture regime that has no water available for plants for more than half the cumulative time that the soil temperature at 50 cm below the surface is >5 °C, and has no period as long as 90 consecutive days when there is no water for plants while the soil temperature at 50 cm is continuously >8 °C, is regarded as an aridic moisture regime. A xeric aridic soil moisture regime is found in the northwestern part of the programme area, a regime that is common to the Mediterranean climates that have moist cool winters and warm dry summers. A limited amount of water is present but does not occur at optimum periods of plant growth[1].

Regarding the soil temperature, the hyperthermic soil temperature regime is dominant. The average annual temperature of the soils of this regime is 22 °C or more and >5 °C

[1] Reference: Glossary of soil science terms (http://www.soils.org)

difference between mean summer and mean winter soil temperature at 50 cm below the surface. Figure 2.11 shows the soil moisture and the temperature regimes in the Badia programme area.

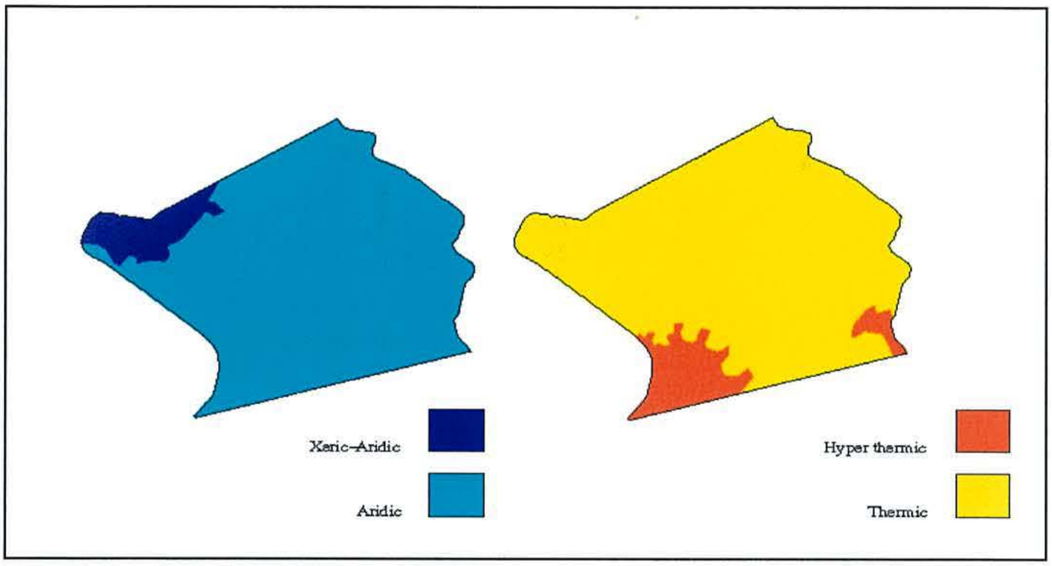

Figure 2.11: Soil moisture regimes and temperature in the Badia programme area, (Source: Ashour 1998)

2.7 GROUNDWATER

Groundwater basins often do not coincide with surface water divides. It is also possible that various aquifer systems at different depths are separated by aquicludes and could have a southwest flow direction. There are different groundwater basins in Jordan. One of them is the Azraq basin, where *Marab* Hassan catchment area lies. It is considered as one of the major ground water basins in Jordan. It covers an area of 12,710 km^2 and it supplies water for the three major Jordanian cities (Amman, Zarqa and Irbid), (Al-Kharabsheh, 2000). Figure (s) 2.12(a) and 2.12(b) show the major groundwater basins in Jordan and the flow directions respectively.

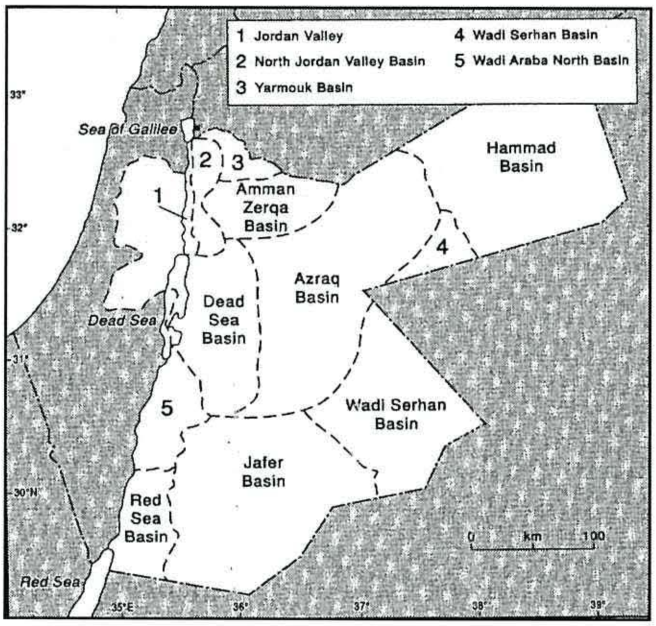

Figure 2.12 (a): Groundwater basins in Jordan, (Source: Al-Homoud et al. 1995)

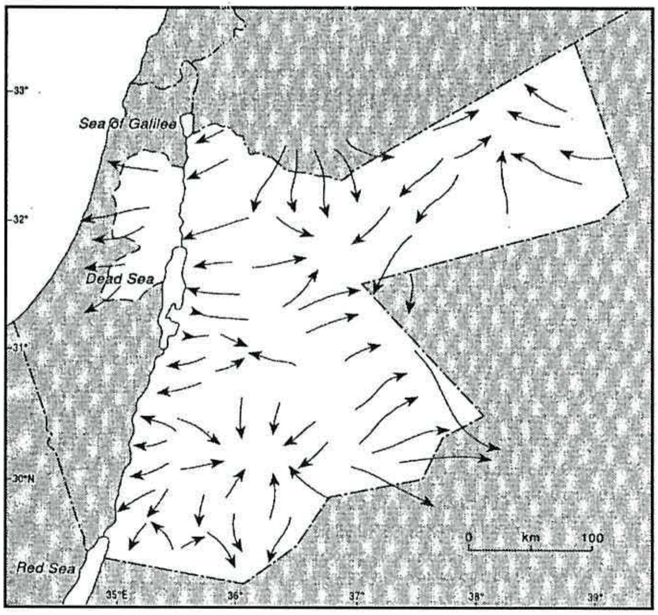

Figure 2.12 (b): Groundwater flow direction, (Source: Al-Homoud et al. 1995)

A number of major aquifer systems can be identified in Jordan. These are important in the programme area and are as follows, (Dottridge, 1998)

The upper aquifer complex consists of:

•Neogene-Quaternary alluvial sediments.

•Neogene-Quaternary basalts.

•Lower Tertiary marly and chalky limestones with cherts (the Rijam aquifer or B4).

The middle aquifer complex:

- Upper Cretaceous limestone, sand limestones (the Amman-Wadi Sir aquifer or B2, A7).
- Middle Cretaceous crystalline to chalky limestone (the Hummar aquifer or A4).

The lower aquifer complex

- Lower Cretaceous sandstones (the Kurnub aquifer).
- Lower Mesozoic-Paleozoic (the Disi aquifer).
- Jurrasic and older

In the Badia programme area the well-known aquifers are the upper and the middle. The lower aquifer is little known and occurs at depths of 1.3 to 3.4 km. The middle aquifer occurs at depths of 400 to 700 metres. The upper aquifer complex covers most of the programme area. Depth of water table in the upper aquifer varies with topography, as in the north near the Syrian border the depth reaches more than 350m but is less than 100m deep towards Azraq. The upper aquifer complex is unconfined and forms the major aquifer of the Azraq basin. The aquifer consists of four different members, which cause large differences in the chemical and physical characteristics of the groundwater, (Al-Kharabsheh, 2000). Groundwater occurrence in the area is complex due to the variety of lithologies present.

As shown in Figure 2.12 (b) the groundwater flow is radial towards the Azraq topographic depression (*Qa* Azraq), mainly in the fissured basalt and the Rijam limestone. The piezometric levels vary between 560m above sea level near the Syrian border to 500m above sea level in the centre of the basin.

Recharge in the Northeast Badia (i.e. in the basalt aquifer) is from infiltration from the wadis after the flood events, up-flow from the deep aquifers, and in the north, via flows between and below the basalt sheets arising from Jebal Al-Arab where the rainfall is relatively high. Some recharge via runoff occurs from Wadi Ruwaished in the northeast. Discharge is by human extraction, evapotranspiration and lateral outflow. Groundwater storage is likely to be moderate since the saturated formations are not thick. Different studies have estimated the volume of the average recharge of the whole Azraq basin between 22 and 36 million m^3/year, which is approximately 3 to 5 percent of the rainfall, (Dottridge, 1998).

The recharge is important, as part of the water balance for the area, in order to be able to calculate the amount of water that is coming in and going out of the system. The water balance assesses the surface water availability after calculating the components of the equation to check how much of this water is contributing to the recharge, as well as the surface runoff that is essential for the agricultural activities that take place in the *Marab* area. In *Marab* Hassan catchment area the estimated surface water is 2.8 million m^3/year and the estimated recharge is 7 million m^3/year, (Abu Sleem, 1995). These figures are estimated based on an annual average rainfall of 86.5 mm/year and runoff coefficient of 3.2%.

The salinity ranges between a few hundred to 4000 ppm (Al-Homoud et al. 1995). In general the basalt waters are of good quality and can be distinguished from water derived from the marl sequences. But, recently there have been signs of water deterioration due to over extraction. The water quality makes it suitable for drinking or irrigation as the Total Dissolved Solids (TDS) is below 270 mg/l in the northwestern part of the Badia programme area. TDS values increase towards the east, this is because of the existence of the Fuluk fault. This helps in increasing the permeability of the soil and the leads to mixing the upper aquifer's water with the middle aquifer, (Dottridge, 1998). Generally structure is a major control of regional flow pattern, either directly by fractures that facilitate infiltration, or indirectly the formation of areas of relative uplift and subsidence, which control the aerial distribution, and thickness of permeable strata and their regional dip.

There is a groundwater well in *Marab* Hassan that occurs in the middle aquifer complex. The depth of the well is 174 m, with a static water level of 69.55 m and a dynamic water level of 81.72 m, (both are below ground level) (BRDP, 1998). The water quality in this well is quite good that matches with the standard level in terms of the total dissolved solids (TDS) of 2816 ppm and the salinity reaches 420 ppm, which falls within the standard range of 200-500 ppm. The pumped water from the well is used for watering the livestock and domestic uses, as the local people bring their tanks and fill them every few days. The future use of the groundwater may include using it for supplementary irrigation over summer months, especially if the proposed water management schemes take place in the *Marab* area as will be discussed later in Chapter Eight.

Figure (s) 2.13 and 2.14 show the major geological divisions of the Badia and a cross section of the main aquifers of the Badia, respectively. In Figure 2.13 the Badia programme area is located between points A (Azraq) in the west and B (Ruwayshid) in the east.

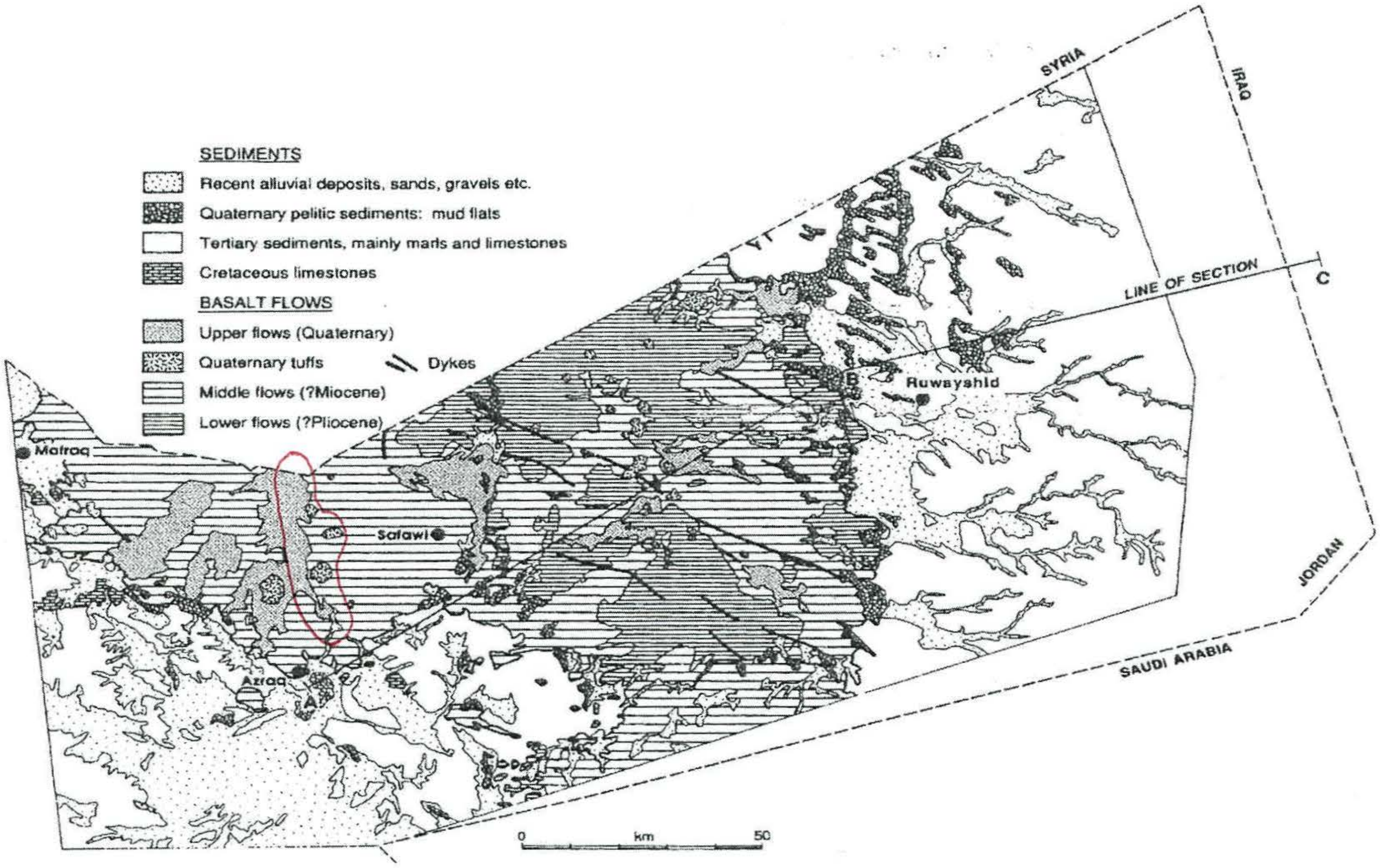

Figure 2.13: Major geological divisions of the Badia (red line represents the catchment's boundary), (Source: Allison et. al., 1998)

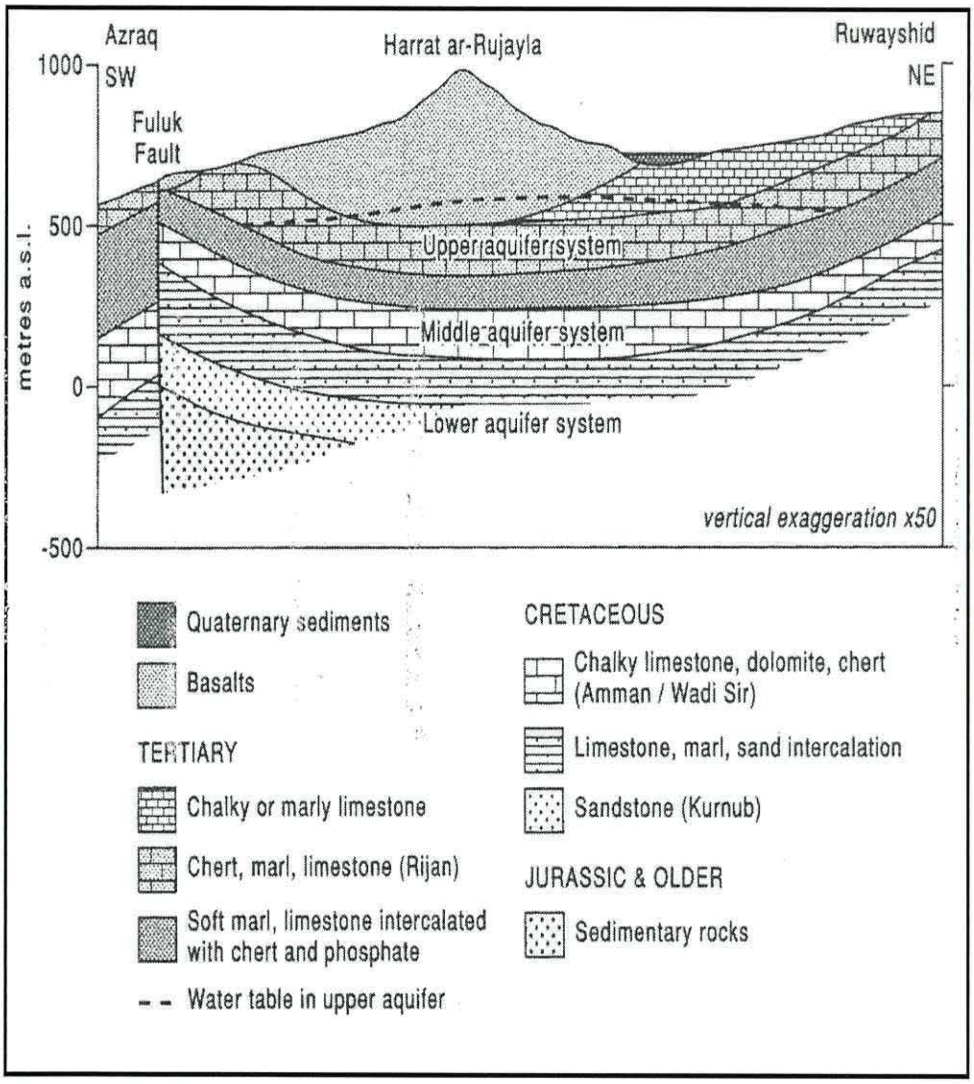

Figure 2.14: Cross section of the main aquifers of the Badia, (Source: Allison et al. 1998)

2.10 SURFACE WATER

Surface water resources in the Badia area are quite limited, as the wadis are ephemeral. In the past none of the wadis were gauged, but recently in 1996, gauges have been installed in Wadi Hassan, however due to vandalism and calibration errors in the gauges, no reliable records are available. The gauges were re-installed in 2000 but because of calibration errors the records were not reliable. The gauging sites were inspected and surveyed by the author and a surveyor from the Royal Jordanian Geographic Centre. Also, the rating curves (shown in Appendix C) were prepared at the Ministry of Water Resources in Jordan.

The major characteristic of the flood in the area is that it comes in a shape of flash flood, which is a characteristic of arid zones. Flash floods occur due to high intensity rainfall that is mainly thunder type as will be discussed later in Chapter Four. Total flows in the programme area have been estimated from rainfall data of an average of 27 million m3 per year for the whole programme area, (Dottridge, 1998). Although, some of the surface water flows through the *Marabs* in the area and helps in supporting their natural vegetation or the rain-fed cultivation that takes place in them, most of the water runs into the mudflats (*Qa's*) and is lost by evaporation.

It has been reported that flood frequency and magnitude have declined markedly in the recent years, as some dams have been constructed in the Syrian part of the upper eaches of the wadis. A Jordanian dam was built in the 1980s on Wadi Rajil, which is one of the major wadis in the area, that has a catchment area of more than 2500 km2. Wadi Rajil's reservoir has only filled up once, in 1994/95.

The surface water has a great potential to be harvested and used for agriculture. A very successful example that has been visited in 2001 is the farm (Abu Sitta farm that has an area of 6,000 donum) on Wadi Al-Ghrabi to the northwest of Azraq, where the wadi flows are captured by small dam and pumped into two storage reservoirs, which have capacities of 1.5 million m^3 and 0.5 million m^3. The water is used for irrigating almost 100,000 olive trees that cover an area of 3,000 donum, as well the other 3,000 donum that are cultivated with barley. The water in the mentioned reservoir lasts all the year through as a supply of water providing that the rainy season is a good one, (Abu Sitta, 2001). According to Abu Sitta (2001) the farm has been going very well for fifteen years now and thepossibility of achieving similar projects elsewhere in the Badia is feasible.

2.11 CONCLUSIONS

Chapter Two has reviewed the importance of the *Marabs* in the Badia area, and the characteristics of *Marab* Hassan catchment area, including the catchment's location; the climatological elements that affect the catchment (i.e. rainfall, temperature, evaporation and relative humidity), the geology and the geomorphology of the catchment, the catchment's soil, and finally the ground and surface water resources in the catchment. The next Chapter will describe the field and laboratory work that was carried out in order to measure the soil physical characteristics, especially for the *Marab* soil, that was helpful in detecting the suitability of the *Marab* for cultivation

CHAPTER THREE

FIELD AND LABORATORY WORK

3.1 INTRODUCTION

This chapter describes the field and laboratory work that was performed in Jordan between September 1998 and August 1999, and between November 2000 and February 2001. The fieldwork included taking soil samples at different sites within the catchment area and then analysing them in the laboratory to measure the soil physical properties such as soil moisture content, bulk density, texture, infiltration rate and moisture release characteristics. Also, during the fieldwork the runoff plot experiments were carried out to give an estimate of the amount of losses to be applied to the rainfall in order to calculate the excess rainfall as will be seen in Chapter Five.

3.1.1 Flow and Rain Gauges

Because of vandalism of existing flow gauges that occurred in 1996 and 2000, new flow and rainfall gauges were installed during the fieldwork in 2000/2001 rainy season. The flow gauges were installed at the inlets of *Marab* Hassan. Locations of the rain gauges were selected to cover the catchment area as well as the neighbouring areas. In some places the gauges were installed adjacent to the existing ones in order to double-check the records. The data collection was augmented by a survey about the historical rainfall and flood events in the past, carried out by interviewing the local people who have been living in the study area for a long time, to obtain "indigenous knowledge" through the use of appropriate participatory rural appraisal techniuque. The survey also included interviews with the farmers who have been cultivating *Marab* Hassan as well as two other *Marabs*. Details about the interviews, what types of questions have been asked and the results are discussed in Chapter Eight. The interviews regarding the historical flood and rainfall events are listed in Appendix E.

3.2 Marab Hassan Catchment Soil Physical Properties

For better understanding of the catchment's soil behaviour, and its effect on runoff generation the catchment's soil physical characteristics (moisture content, soil texture, infiltration rate, soil bulk density and water holding capacity) have been measured. The sites for conducting the measurements have been selected based on certain factors, which are, firstly to cover almost all the soil types in the catchment area, also based on accessibility to the selected sites. Figure 3.1 shows the soil sampling sites within the catchment area. Table 3.1 summarises the tests that have been carried out to measure the soil physical properties within Marab Hassan catchment, as well as the number of samples and the soil type where the samples were taken.

Table 3.1: Summary of soil tests in Marab Hassan catchment area.

Test	No. of samples	Soil type	time
Moisture content	12	FAR	1-7/12/98
Moisture content	12	FAR	7-14/1/99
Texture	5	FAR, UBI, NAT, BIS, ZUM	8-21/12/98
Bulk density	2	FAR, NAT	23/12/98, 3-7/1/99
Moisture release characteristics curve	6	FAR, NAT	24/1-11/2/99
Infiltration rate test	4	ZUM, BIS, FAR, NAT	14/2-19/3/99

3.2.1 Soil Moisture Content (W)

Soil moisture content or the gravimetric water content is defined as the ratio of the water present in the voids to the amount of solids in the soil, (Holtz & Kovacs, 1981), as expressed in equation [3.2.1] below.

$$w = \frac{M_w}{M_s} \qquad [3.2.1]$$

Where:

M_w is the weight of water present in a given soil mass

M_s is the weight of dry soil

Gravimetric sampling, speedy moisture tester, tensiometers and neutron probe could be used to measure the soil moisture content. Gravimetric sampling remains the basic technique, (Agnew, 1992) which has been used in this research. This method involves weighing a moist sample, oven drying it at 105°C, reweighing, and calculating the mass of water lost as a percentage of the mass of the dried soil, (Topp, 1993). The method is straightforward and is commonly thought to yield absolute results. On the other hand, it is destructive, laborious, and the weight loss may be due the volatilisation of the organic matter in the soil, which is volatile at 105°C. In spite of these disadvantages the oven drying method is a commonly used, convenient method to obtain an estimate of soil water content.

The samples were taken during the rainy season 1998/1999. For the *Marab* area samples were taken from 12 points where each one is 30m apart. Sampling was done every 10-cm starting from the ground surface to a depth of 40 cm. Then the results were used to create the moisture content verses depth relationship for the *Marab* soil that is helpful for agricultural purposes in calculating the available water capacity of the soil. The tabulated and plotted results for all the points are shown Appendix A. The sampling stopped at 40 cm due to limitations associated with machinery and manual labour. Also, this sampling was done only for the Marab soil (NAT mapping unit), to check the suitability of the Marab soil for agriculture and to be able to build the water balance for the Marab.

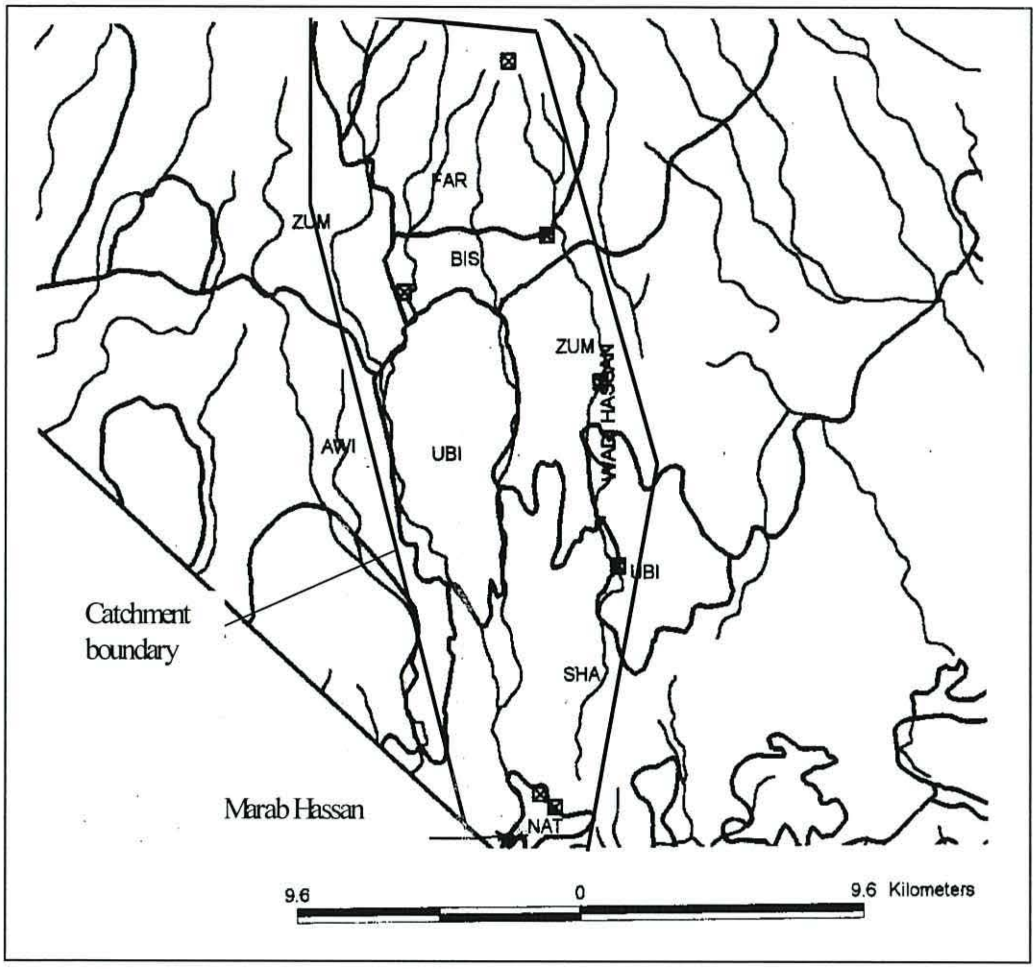

Figure 3.1: Soil sampling sites in *Marab* Hassan catchment area, (the squares refer to the sampling sites within the catchment area)..

3.2.2 Soil Texture

Soil texture refers to the size range of particles in the soil (Hillel, 1982). The traditional method of characterising particle sizes in the soil is to divide them into three separable size ranges known as textural functions, namely, sand, silt and clay. The definitions of sand, silt and clay are based on the particle size, for sand it is between 50 and 2000 μm, for silt 2-50 μm and for clay < 2 μm[1] The mass ratios of these three elements determine the soil classes. Once the percentages of sand, silt and clay are known, the textural triangle is used to determine the soil texture, (Campbell, 1985), as shown in Figure 3.2.

[1] 1 μm = 10^{-6} m = 10^{-3} mm

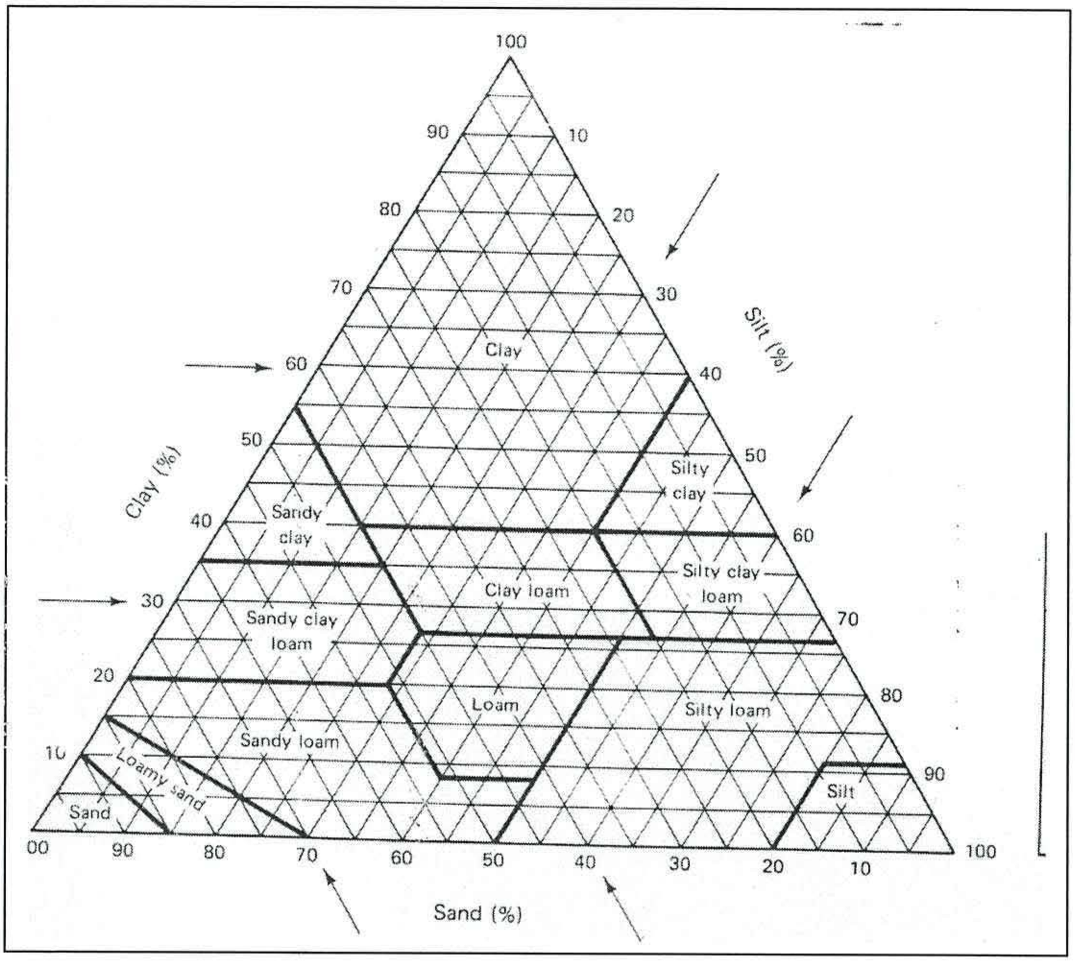

Figure 3.2: The Soil Texture Triangle, (Source: McCuen, 1989).

Bouyoucos Hydrometer method as shown in Figure 3.3 has been used to determine the percentages of sand, silt and clay in the soil samples. This method is based on 'Stoke's law' for measuring the density of the suspension at a given depth as a function of time. With time this density decreases as the largest particles, and then progressively smaller ones, settle out of the region of the suspension being measured. A dispersing agent (Sodium-hexametaphosphate) has been used in this experiment. The function of this agent is to replace the cations adsorbed to the clay with sodium, which has the effect of increasing the hydration of the clay micelles, thus causing them to resist each other rather than consolidate, as they do in the flocculated state. With the standard 'Bouyoucos hydrometer' a settling time of about 40 sec is needed at 20°C to measure the time of concentration of clay and silt (all the sand having settled through), and a time of about 8 hr is needed to measure the clay content alone. Correction factors must be applied whenever there is a difference in temperature.

The use of Stoke's law for measuring the particle sizes is dependent upon certain simplifying assumptions, which are not completely in accord with reality. It assumed that the particles are rigid, spherical and smooth, and have the same density.

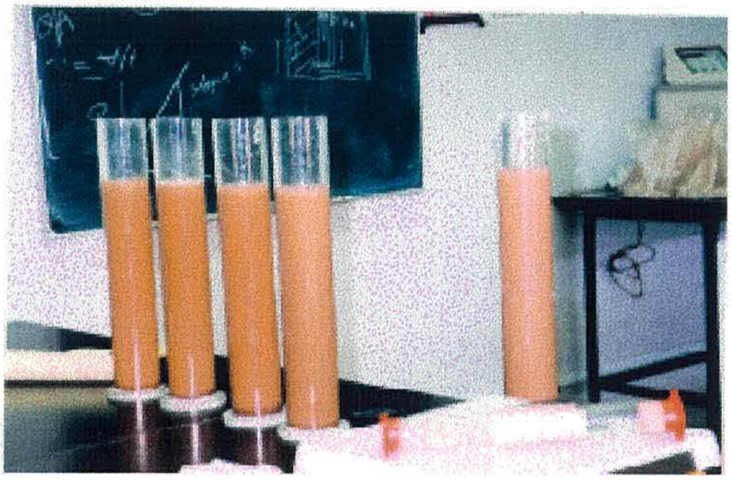

Figure 3.3: Bouyocos Hydrometer method for measuring soil texture.

According to Bouyoucos (1962) and Sheldrick and Wang (1993), the calculations of sand, clay and silt percentages could be expressed as follows:

$$\%sand = 100 - ((hyd.\ reading\ @\ 40\sec /total\ wt.\ of\ dry\ soil)100\%) \qquad [3.2.2]$$

$$\%clay = (hyd.reading\ @\ 2hrs/total\ wt.\ of\ dry\ soil)100\% \qquad [3.2.3]$$

$$\%silt = 100 - (\%sand + \%clay) \qquad [3.2.4]$$

Table 3.2 represents the soil texture results for different soil types at *Marab* Hassan catchment area that have been sampled at depth between 0-25 cm. It shows the percentages of sand, silt and clay for each soil type. The percentage of sand starts from as low as 7.52 for FAR and BIS up to 42.9 for NAT (the *Marab* soil). The clay content for FAR soil is the highest (35.4%), while the lowest (21.8%) is for NAT soil. BIS soil unit has the maximum silt content of 62.6%, in combination with the high clay content, its texture is silty clay loam. The same applies to FAR as it has quite high silt and clay contents and classified as silty clay loam as well.

Silt and clay (these play an important rule in crust formation affecting runoff) mostly dominate the catchment. The crust formation phenomenon will be discussed later in section 5.5.2.

Table 3.2: Soil texture for samples from *Marab* Hassan catchment.

Soil type	% Sand	%Clay	%Silt	Texture
FAR	7.52	35.36	57.12	Silty clay loam
UBI	21.12	32.64	46.24	Clay loam
NAT	42.88	21.76	35.36	Loam
BIS	7.52	29.92	62.56	Silty clay loam
ZUM	32	24.48	43.52	Loam

The same analyses were carried out by Al-Zubi, (2000), who sampled at different depths (0-25, 25-50, 50-75 and 75-100 cm). He concluded that, for ZUM, BIS and FAR the sand fraction decreases with depth, silt fraction also decreases relatively, while clay fraction increases with depth. This means the porosity and permeability decreases with depth, i.e. in terms of relation to runoff it helps in runoff generation, as soil becomes impermeable.

3.2.3 Infiltration Rate

Infiltration is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface. The earliest approach used to calculate the infiltration into soil was by Green and Ampts (1911).

Infiltration measurements characterise a soil's ability to absorb water through the earth's surface. They provide data for models predicting infiltration and surface runoff behaviour following rainstorms, allowing estimates of soil water and groundwater recharge and storage. Since infiltration is a process of water flow in unsaturated soil, infiltration measurements also provide means of obtaining basic soil water properties.

Soil infiltration is influenced by many variables including the rate of the water supply, soil texture, porosity and structure, organic matter content and antecedent moisture conditions, (Agnew and Anderson, 1992). A double ring infiltrometer was used to measure the infiltration in Marab Hassan Catchment. It has been designed to investigate various facets of infiltration behaviour. These techniques use surface areas occupying only a very small fraction of the area of hydrological interest.

Double ring infiltrometers are often used to estimate directly the infiltration that would occur from large areas. The double ring infiltrometer contains two rings, an inner one with a diameter of 26 cm and an outer ring of 53-cm diameter. Both the rings are firmly pressed into the soil to a depth of about 3-7 cm. Then the rings are filled with water, the change in the water depth inside the inner ring (or the rate at which water moves into the ground) is measured and then used to calculate the infiltration rate as we will see later. The test is normally continued until the infiltration rate has become essentially constant. The purpose of filling the outer ring as well is to provide a buffer of infiltrating water which tends to force infiltration below the inner ring to remain completely vertical and one dimensional and to eliminate the edge effect. It is also important to keep the water levels in the two rings very nearly identical to prevent any 'cross gradient' in the soil below rings, which would affect the vertical infiltration.

The test was carried out at different locations within the catchment, the measured values were the accumulated water depth in the soil, and by applying the Kostiakov formula the infiltration rate in the soil was calculated. This empirical formula implies that the infiltration rate (*i*) approaches zero as the time increases, (Youngs, 1991).

$$
\begin{aligned}
D &= at^{b} \\
i &= \frac{dD}{dt} \\
i &= abt^{b-1}
\end{aligned}
\qquad [3.2.5]
$$

where

a and *b* are empirical constants

D is the cumulative water depth (cm or mm)

i is the infiltration rate (mm/hr)
t is time (min or hr)

The Double ring infiltrometer is a simple and straightforward device, but on the other hand, it gives a point measurement that means it could have spatial variability in the results. It is also believed that the bigger are the rings the more accurate are the results. However, use of rings of different sizes makes direct comparison of results impossible.

Figure (s) 3.4, 3.5 and 3.6 show the infiltration curves for ZUM, BIS and FAR mapping units respectively. They are based on the Kostiakov approach of calculation (as expressed in equation [3.2.5] above) using the collected experimental data that were compared with the study done by Al-Zubi, (2000), who has used Horton's approach. This raises the debate about which method to use for calculation, and how accurate it is?

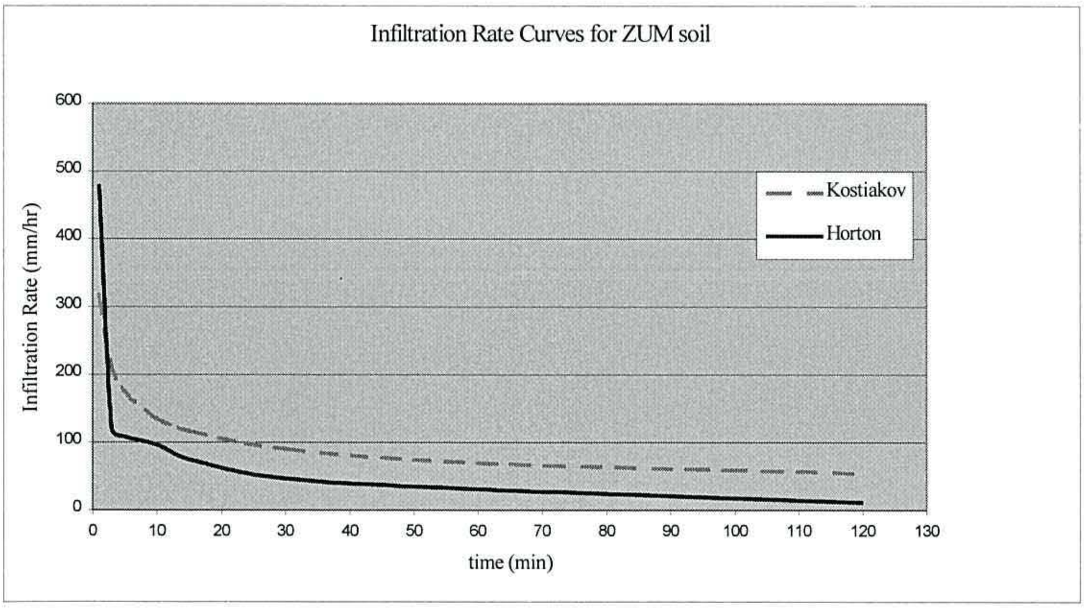

Figure 3.4: Infiltration curves for ZUM mapping unit within *Marab* Hassan catchment, (solid line: from Al-Zoubi, (2000), dashed line: sampled data by author).

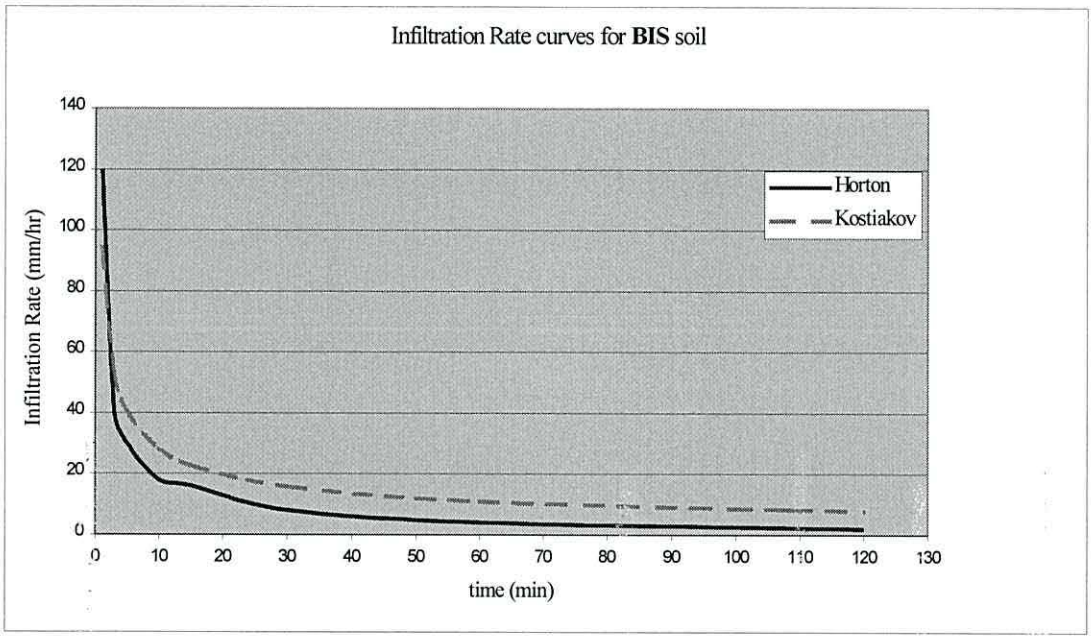

Figure 3.5: Infiltration curves for BIS mapping unit within *Marab* Hassan catchment, (solid line: from Al-Zoubi, (2000), dashed line: sampled data by author).

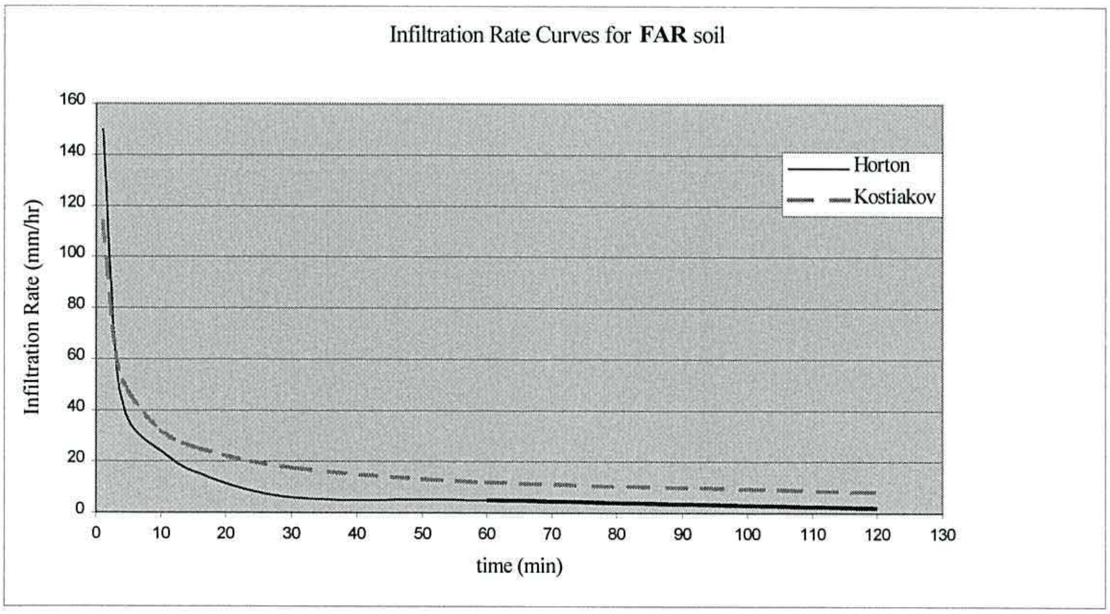

Figure 3.6: Infiltration curves for FAR mapping unit within *Marab* Hassan catchment, (solid line: from Al-Zoubi, (2000), dashed line: sampled data by author).

Horton's formula to calculate the infiltration rate is based on experimental work. He found that the infiltration rate begins with a high rate (f_0) and exponentially decreases with time to fairly steady state rate (f_c), (Chow et al., 1988). The formula is expressed below.

$$f = f_c + (f_0 - f_c)e^{-kt} \qquad [3.2.6]$$

where:

f is the infiltration rate (mm/hr)

f_0 is the initial infiltration capacity

f_c is the final infiltration capacity

e is the base of the Napierian logarithm

k is an empirical coefficient, k as well as f_0 and f_c are functions of soil type, also depend on the antecedent conditions of the soil, (Beven, 2001).

For *Marab* Hassan soil mapping unit (NAT) the infiltration rate was measured also, the developed infiltration curve is shown in Figure 3.7.

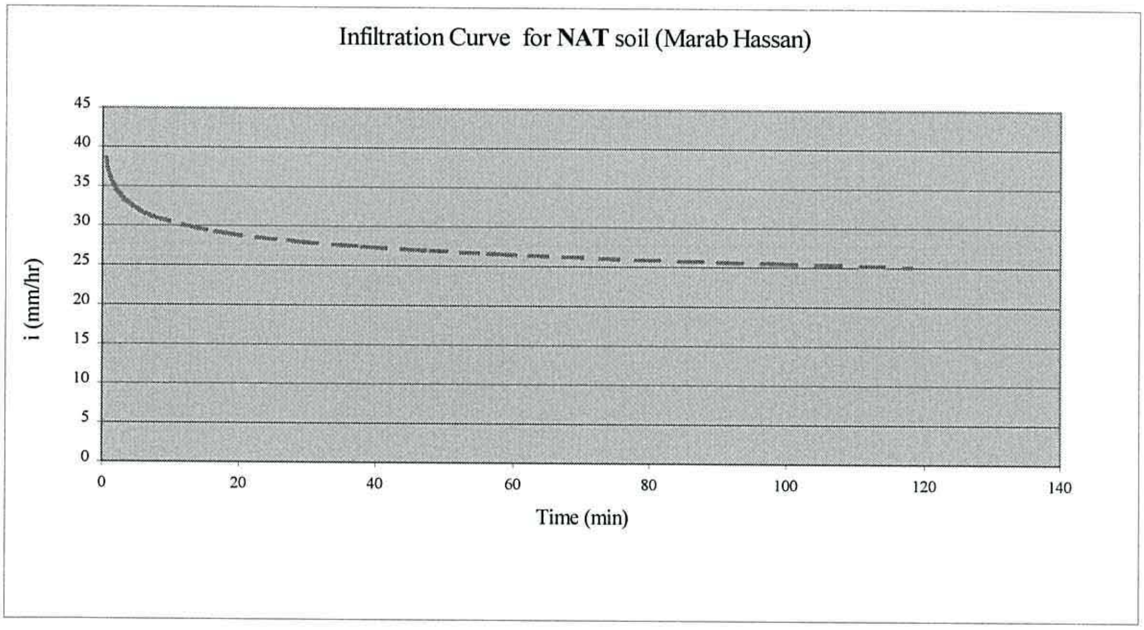

Figure 3.7: Infiltration curve for *Marab* Hassan soil (NAT), (dashed line: sampled data by author).

3.2.4 Soil Bulk Density (γ_d)

Soil bulk density (γ_d) refers to the overall density of the soil, and is defined as the ratio of the mass of oven dried solids to the bulk volume of the solids plus the pore space at some specified soil water content (w), usually at that sampling, (Culley, 1993). It depends on the soil's structure, as well as its swelling and shrinkage characteristics, which are dependent on the clay content and wetness.

The bulk density can be determined either by in situ or destructive sampling techniques. In situ determination involves the measurement of the attenuation of gamma rays through a fixed soil length; with proper calibration. Core, cold, and excavation are the most common methods of determining it destructively. Excavation methods include removal of a volume of soil followed by determination of the volume of the excavation using water, foam, wax or even sand, (Culley, 1993)

The Ottawa sand cone method was used to determine the soil's bulk density for two selected sites in the catchment area. The first site was the upper part of Wadi Hassan near Tall Al-Asfar and the second one was in the *Marab* itself. This test includes using Ottawa sand to determine the bulk volume of the solid plus the pore space. First of all, dry unit weight for the sand (γ_d (sand)) was determined; this was done in the laboratory. Also calibration of the cone is required. Calibration means how much sand is required to fill the cone. Once the sand cone apparatus is installed in the field, a hole is dug and the soil is taken out. This soil is to be kept for determining the soil's moisture content. Then the hole is filled with sand, which is used to know the volume of the hole, as illustrated in Figure 3.8.

Using the following formulae taken from (Das, 1984) gives the description of how the soil's bulk density is calculated.

$$\gamma = \frac{\textit{weight of the moist soil from the hole}}{\textit{volume of the hole}} \qquad [3.2.7]$$

$$\textit{volume of the hole} = \frac{\textit{mass of sand in the hole}}{\textit{dry unit weight of sand}} \qquad [3.2.8]$$

$$\gamma d = \gamma / (1 + w) \qquad [3.2.9]$$

Where

γ_d is the soil bulk density (g/cm^3)

γ is the moist unit weight of the soil in the field (g/cm^3)

w is the soil moisture content

Figure 3.8: Ottawa sand cone test for measuring soil bulk density in *Marab* Hassan.

The measured γ_d for NAT and FAR soil mapping units are 1.30 gm/cm^3 and 1.69 gm/cm^3 respectively.

3.2.5 Moisture Release Characteristics Curve

The relationship between matric potential and water content is called soil moisture release curve, (Campbell, 1985). The matric potential is defined as the amount of work per unit mass of water required transporting an infinitesimal quantity of soil solution from the soil matrix to a reference pool of the same soil solution at the same elevation, pressure and temperature.

The moisture release characteristics curve is used to determine the Available Water Capacity (AWC) for the soil, which is the absolute difference between the Field Capacity (FC) and Permanent Wilting Point (PWP). FC is known as the moisture content of the soil at 48 hours after saturation and subsequently being allowed to drain freely. It is a function of organic matter content, bulk density, field conditions, drainage rates and climate. PWP is the point beyond which plants can not recover because there is not enough water. It depends on potential evapotranspiration, unsaturated hydraulic conductivity of the soil, and the type of the plant.

There are several methods to construct the curve; pressure plate apparatus, sand; sand/kaolin apparatus, solution mixture method, *pF* scale, and filter paper method, (Landon, 1991). Filter paper method is the one that has been used in this research. This method uses Whatman filter papers to absorb water from soil samples at different states of wetness. At equilibration the filter papers and soil samples will be at the same *pF*, so that if the moisture characteristics of the filter paper are known, then the soil moisture suctions can be evaluated.

The Filter paper method was preferred according to the procedure described in Fawcett and Collis, (1967). The soil moisture characteristics curve was prepared by plotting the soil moisture content vs. soil moisture potential expressed as *pF*. AWC is the difference between FC (*pF* 2.5) and PWP (*pF* 4.2). Figures 3.9 and 3.10 show the soil moisture release characteristics curve for *Marab* Hassan soil (NAT) and FAR soil at the upper part respectively.

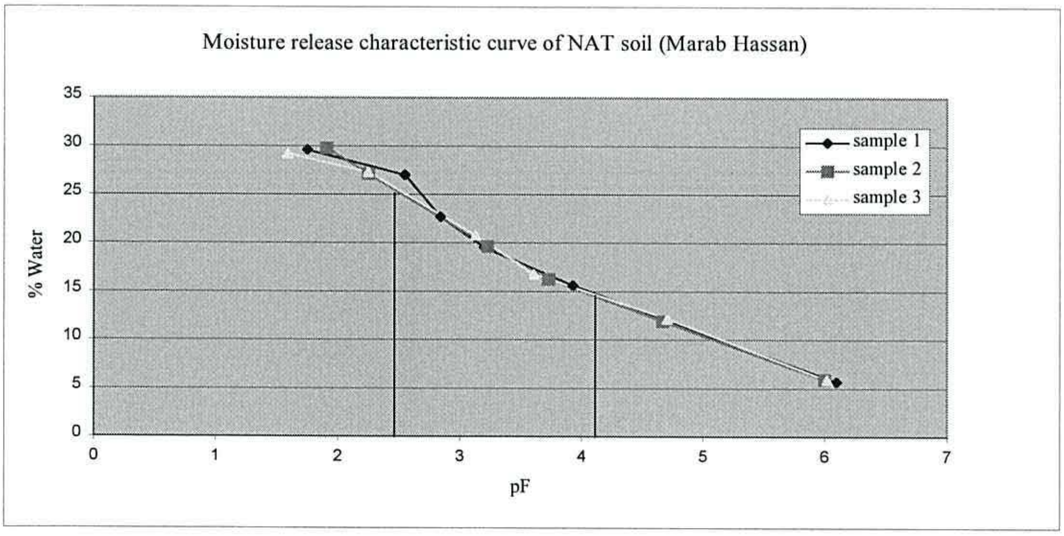

Figure 3.9: Moisture release characteristics curve for *Marab* Hassan soil (NAT).

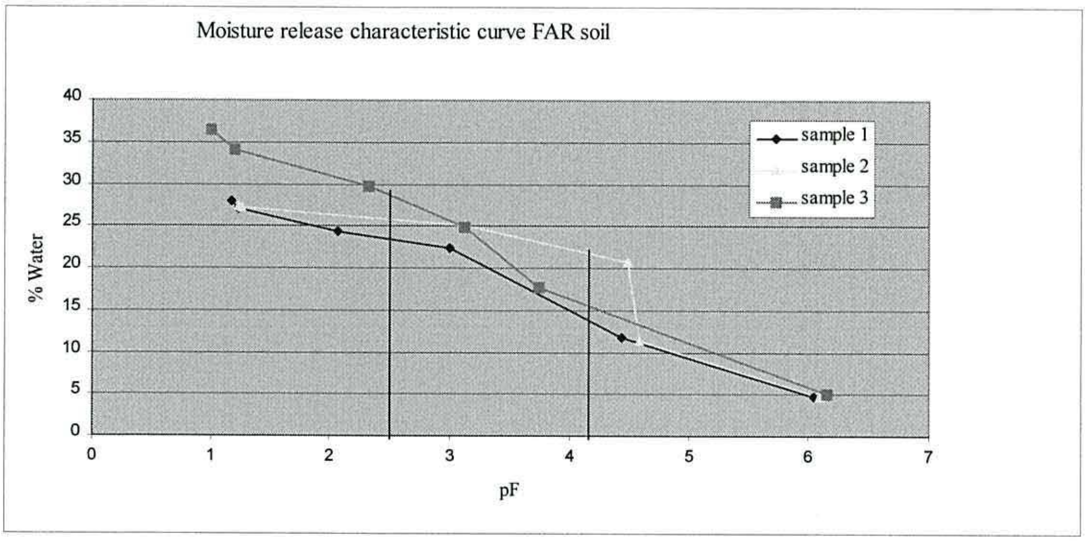

Figure 3.10: Moisture release characteristics curve for FAR soil.

The filter paper method for the *Marab* Hassan soil was carried out, in the soil mechanics laboratory at Jordan University of Science and Technology. From Figure 3.9 the FC for the *Marab* soil (NAT) is 26% and the PWP is 14.5%. The measured bulk density ($_d$) at 30 cm was 1.3 gm/cm3, this means that the available water capacity of the soil at this depth is 45 mm per 30 cm (150 mm/m). This measured value is important as it shows how much water is available for the plant's use and when to irrigate the crop.

A number of attempts have been made to predict the moisture release characteristics from the soil texture. These attempts have not been completely successful, as they only worked for the areas where they were originally developed.

3.3 Runoff Plot Experiments

Runoff plots are plots of 3x3m that were built at three different places in *Marab* Hassan catchment area, according to different soil types and slopes. The slopes of the plots varied from 1 to 2 percent. The sites are the upper and the middle parts of Wadi Hassan as well as the *Marab* area. One of these plots is shown in Figure 3.11. The aim of building such plots is to determine the relationship between rainfall and runoff on a plot basis. This gives an estimate of the runoff coefficient.

Runoff from each plot was collected in an oil drum through a plastic pipe with a gutter at the outlet of the plot. Totaliser rain gauges were placed inside or in the nearest place to each plot. Different factors were taken into account when selecting the site for constructing the plots. The most important factors were safety and accessibility. Factors like the location of the plot, soil type and texture, the presence of stones are affect the amount of collected runoff.

Results of three rainy seasons were collected from the plots, then the results have been used to develop on a plot basis rainfall-runoff relationships, which is very important in estimating the runoff coefficient and the amount of losses in the catchment area.

Figure 3.11: Runoff plot experiment at *Marab* Hassan.

Excess rainfall, known as effective rainfall is the part of rainfall that appears as direct runoff, or mainly it is the rainfall after subtracting all kinds of losses as evaporation and storage (interception, depression and soil storage), (McCuen, 1989). For Marab Hassan catchment area runoff plot experiments were conducted and used in calculating the excess rainfall over the catchment as discussed below.

Results from the three plots with the two soil-mapping units (FAR and NAT) were used to develop the rainfall-runoff relation as these mapping units represent the upper and lower parts of the catchment area respectively. Figure 3.12 shows the developed plot basis rainfall-runoff relationship. It is clearly seen that for rainfall values less than 5mm it is hard to measure surface runoff, while after this limit runoff develops easily.

This 5-mm limit is used later in Chapter Eight as an indication of events that cause floods.

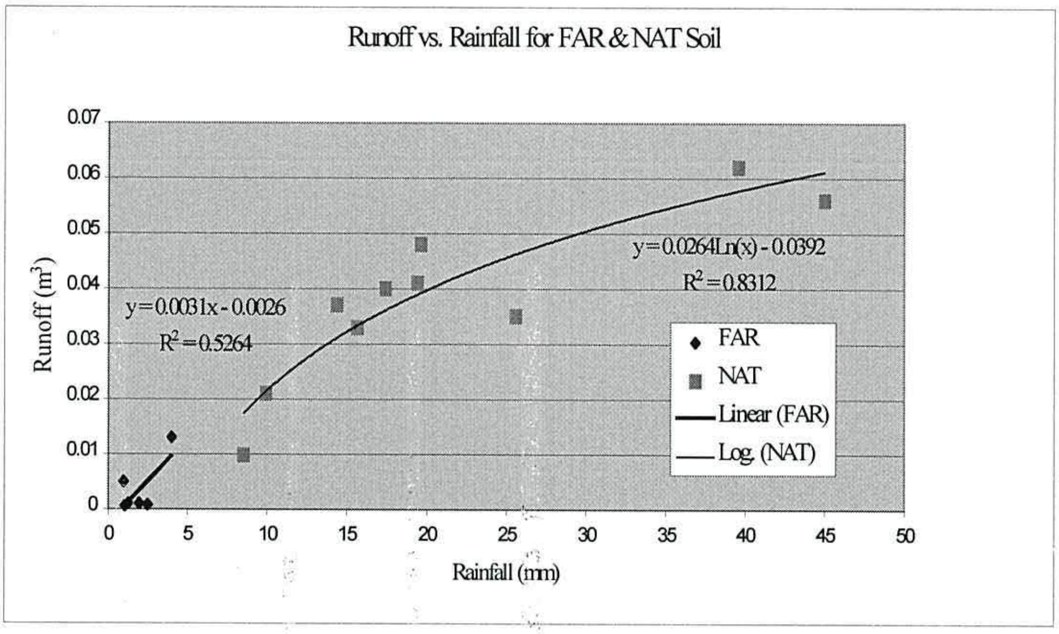

Figure 3.12: Runoff (m^3) vs. Rainfall (mm) on plot basis, for FAR and NAT soils

The rainfall and runoff values in Figure 3.12 were used to develop the loss factor as a function of the rainfall as shown in Figure(s) 3.13 and 3.14. The loss factor values were calculated using the rainfall with the corresponding runoff values, then the calculated loss factor was plotted verses the rainfall as shown in Figure(s) 3.13 and 3.14 below. Figure(s) 3.13 and 3.14 can be used to calculate the excess rainfall over the catchment area from a given rainfall amount, as excess rainfall is the actual rainfall minus the losses.

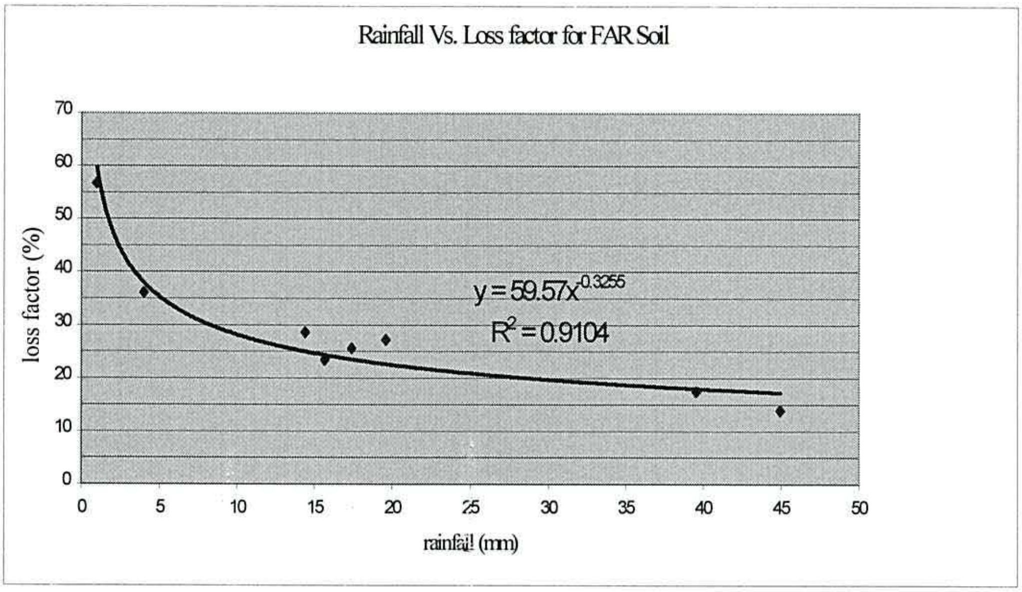

Figure 3.13: Loss factor vs. Rainfall for FAR soil.

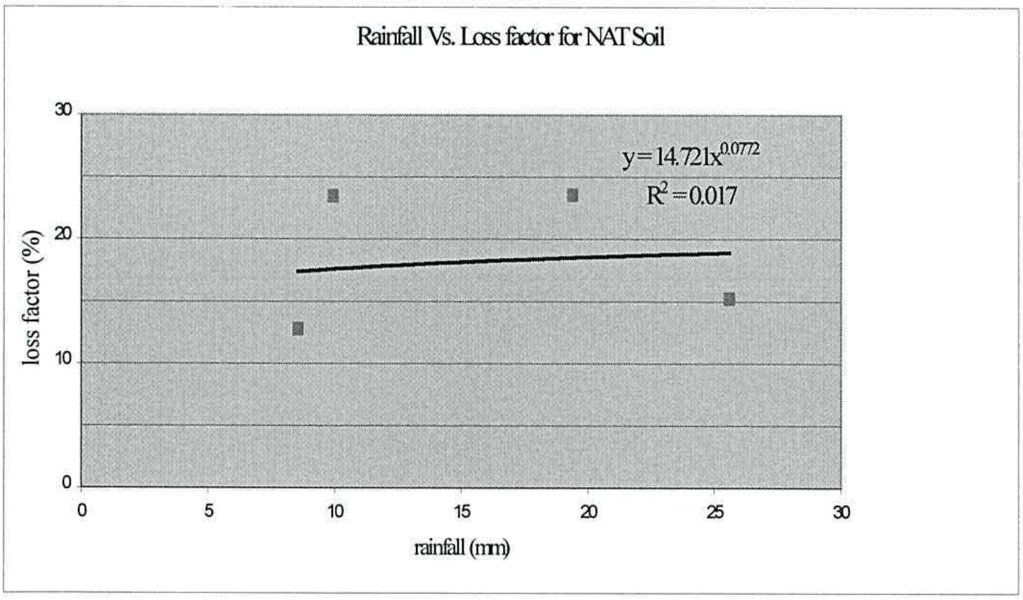

Figure 3.14: Loss factor vs. Rainfall for NAT soil.

3.4 RAINFALL AND FLOW DATA IN THE CATCHMENT AREA

The rainfall data are more available in the catchment area as well as elsewhere in the Badia area compared with the flow data. Monthly rainfall data from five Jordanian and three Syrian rain gauges have been used in this study. Data from these stations have been used in Chapter Four for developing the Double Mass Curves and the departure from the annual average for the stations, a detailed discussion will be given in Chapter Four. Also, rainfall data from fourteen stations distributed over the whole of Jordan as shown in Figure 4.4 were used in Chapter Seven of this thesis to develop the rainfall probability model based on the correlation with the climatic indices. Monthly rainfall data from these stations are available in Appendix B.

Ten new rain gauges have been installed in the catchment area as seen in Figure 4.19. Four of these stations are recording gauges that give continuous records. Data from these gauges were used to develop the rainfall distribution maps for the catchment area are shown in Figure (s) 4.17 to 4.20.

No reliable flow data is available for *Marab* Hassan catchment area, as there was data obtained after the rainy season 1996/97 from the gauge at the *Marab* outlet. But after inspection of it, it was concluded that it is unreliable due to the fact that the weir where the gauge was installed was broken, as well as the fact that the shape of the hydrograph did not look like "a standard" arid zone hydrograph. The obtained hydrograph is shown in Figure 3.14, where the recession limb is over 30 hours of gentle decline followed by an abrupt fall to zero. This could be due to the gauge's type, as it was float type where the water depth is recorded using the pen and the paper roll. A sticking float is the most probable reason of the shape for the hydrograph, especially the recession limb. This leads one to say that the data could not be used in this study. However, various attempts were made to use the actual recorded hydrograph shown in Figure 3.16, but all of them were unsuccessful. The first attempt was to use the actual recorded hydrograph and compare it with the synthetic (theoretical) unit hydrographs, but there was no comparison. The second attempt was to route the flood from the outlet of the wadi across different parts of the Marab (i.e. working backward by taking the recorded hydrograph as the output hydrograph and using the reservoir routing procedure), in order to be able to get the input hydrograph at the inlets, but this also did not work. As a result, a decision was made to discard the recorded hydrograph.

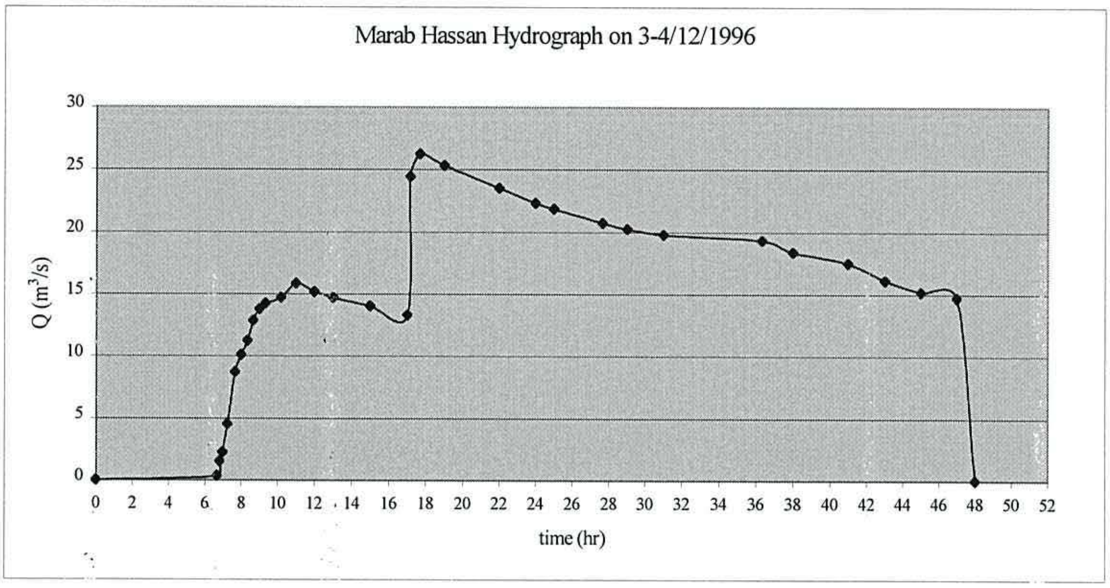

Figure 3.15: Marab Hassan hydrograph on 3-4/12/1996 (at the Marab outlet)

A major problem leading to lack of flow data is vandalism. Firstly, the gauge down stream at the *Marab* outlet was vandalised, then two new flow gauges were installed at the *Marab* inlets, but one of them was vandalised in 1999 and replaced the year after. Two new pressure transducer gauges were installed at two selected sections in the Wadi bed, as shown in Figure 3.16, inside 12in. pipe, (Perforated from the bottom), where the data logger was kept on the top and the sensor on the bottom facing the ground surface. . The two sections were surveyed and the cross sections of them were used to develop the flow rating curves for both of them using Manning's equation. The gauges' sites were selected carefully with assistance from an expert from the Jordanian Ministry of Water Resources. The cross sections and their rating curves are shown in Appendix C. The gauges were installed in the rainy season 2000/2001 but no reliable data were obtained due to calibration errors.

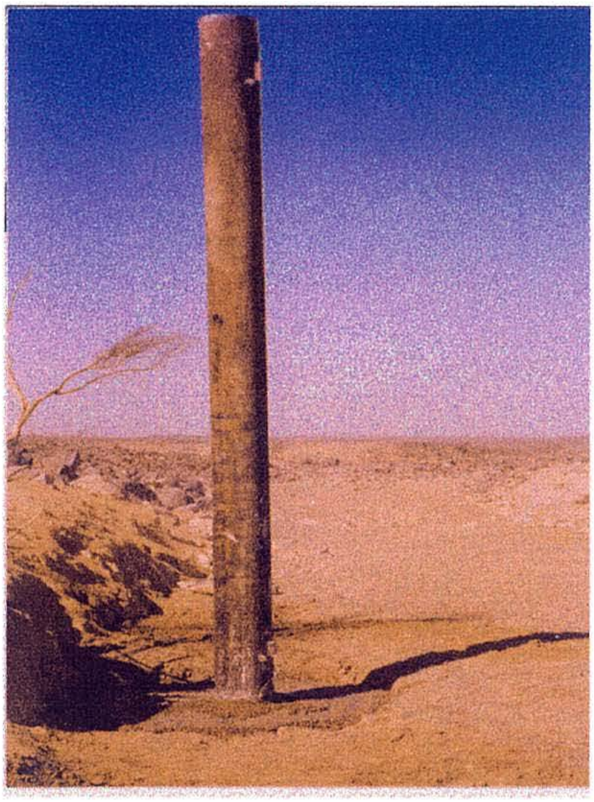

Figure 3.16: Installation of flow gauge at *Marab* Hassan eastern inlet.

To overcome the lack of flow data three crest (stage) gauges were installed at the inlets and the outlet. The design of the crest gauges was obtained from the United States Geological Survey (USGS). The crest gauges measure the maximum water depth after each event so they are not that much helpful, but good enough in giving an idea about the maximum flow depth for design purposes. The design and results of the crest gauges are given in Appendix C.

3.5 Participatory Rural Appraisal

A series of semi-structural individual and group interviews have been held with local people who have been living in the area for long time. The age group of the survey sample was forty and above years old. The questions the people were asked were about the rainfall and the flood events in the last 10 to 20 years. A good feedback was obtained as will be discussed in Chapter Eight. Also some *Marab* owners were interviewed and were asked about the flow patterns in the *Marab*, frequency, etc., as will be described in detail in Chapter Eight. The questionnaires with their answers are listed in Appendix E. the interviews were carried out in two villages within Marab

Hassan catchment area, which are Al-Hashmyya Al-Sharqyya and Deir Al-Kahf. Al-Hashmyya Al-Sharqyya has a total population of 39 people and Deir Al-Kahf total number of population is 817 people (these figures are according to the 1993 census), (Al-Hunaiti, 1998). Three interviews were carried out in Al-Hashmyya Al-Sharqyya (8% of the total population), and seventeen were conducted in Deir Al-Kahf (i.e. this represents 2% of the total population). The interest of meeting old people only has created limitations in the sample size and the number of people who have been interviewed.

This participatory rural appraisal was carried out for two reasons. Firstly, to obtain information about the flood events in the past, because of the lack of runoff data, as well as obtaining detail about the rainfall events in the area (i.e. duration, intensity and frequency). The vandalism of the monitoring gauges has been a serious problem in the Badia area since the establishment of the Badia programme area. The participatory rural appraisal and the involvement of the local people can be emphasised more, as the local people may help in the safety of the gauges, either by getting them paid to guard the gauges, or by increasing their sense of awareness about the importance of having such devices in the area, which is at the end of the day for their benefit and for the sustainable development of the area.

The second reason was to meet the people who have been farming some of the Marabs in the Badia area for long time, in order to discuss with them the crops they grow and the methods of cultivation that they have been using, as well as the frequency of the flood events the Marab receives and how do the deal with the flood in terms of water distribution.

3.6 Conclusion

This Chapter has described the methods used to measure the soil physical characteristics of *Marab* Hassan as well as other parts of the catchment area. It is important to take these characteristics into account when developing any water-harvesting scheme in the *Marab* area, as will be shown in Chapter Eight.

It also discussed the issue of the lack of flow data, and how the installation of the crest gauges and the indigenous knowledge are two useful pieces of information that could be used in design purposes, as well as decision making for any cultivation process that takes place in *Marab* Hassan or any other *Marab*.

Chapter Four will discuss the rainfall data analysis and the use of this kind of data in such an area where rainfall data is the only reliable available data. It will focus on discussing the rainfall synoptic, variability, and types in Jordan and the catchment area.

CHAPTER FOUR

RAINFALL DATA ANALYSIS

4.1 INTRODUCTION

Chapter Three has discussed the measurements that were carried out in the catchment area. Since no runoff data are available the emphasis was to use the available rainfall data to have a better understanding about the rainfall in Jordan and the Badia area, then concentrating on Marab Hassan catchment area. This chapter gives a brief description about the climate of Jordan in the past and the present. Then it moves to talk about the rainfall synoptic and variability in Jordan. The rainfall in the Badia area and the catchment area particularly will be discussed in detail. Finally it describes some quantitative measures that have been made to check the data reliability and consistency.

4.2 THE CLIMATE OF JORDAN IN THE PAST AND THE PRESENT

The climate of Jordan during geological time

The climate of Jordan in the past is believed to be different from today's climate; the following is a description of the climate during different geological eras.

- Pre-Quaternary periods

Geological investigations of sandstone deposits of the Nubian facies in the country showed that Jordan had experienced arid and semi-arid climates during most of the geological periods that extended from the pre-Cambrian to the middle Cretaceous, (Shehadeh, 1991).

- Tertiary

Figure 4.1 shows major oscillations of the coastline between the Tethys (Mediterranean) and the Arabian Nubian masses during geological times. During the Palaeozoic five marine transgressions were experienced, but the last regression in the Permian brought arid and semi-arid conditions in the whole area. Other eastwards transgressions in the Mesozoic expanded the Mediterranean deeper inland. Although, large parts of Jordan were covered by sea during the middle Triassic, deposits of Nubian sandstone indicated that there was regression during the upper Triassic when the sea flooded most of Jordan. Another regression happened during the lower Cretaceous, with large areas in the southern parts of Jordan covered with the Nubian deposits. After that, from the middle Cretaceous to the Oligocene much of Jordan was submerged again, but the eastern and southern parts were arid as it appears from the nature of the sediments there.

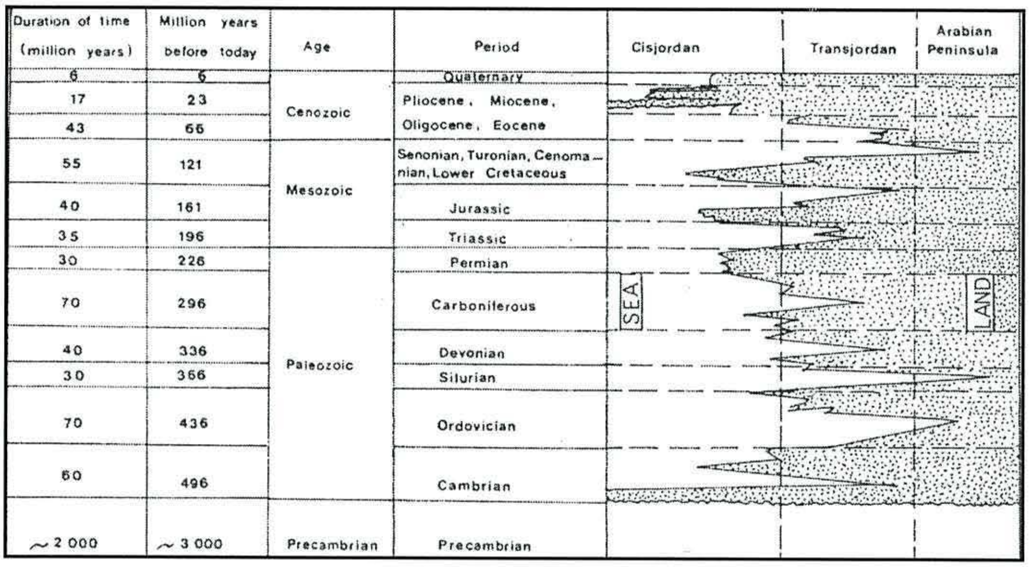

Figure 4.1: Transgressions and regressions in the Middle East, (Source: Shehadeh, 1985)

During the Miocene and Pliocene the climatic conditions are poorly defined, but from the terrestrial deposits of angular, poorly sorted hard chalk, limestone and flint that were covered by the earliest basalt flows in Syria, it is indicated that the area had experienced arid or semi-arid climate conditions, (Shehadeh, 1985).

The climate of the Neogene was characterised by several periods of sufficient rainfall to allow forests to flourish. Generally, periods of abundant rainfall were rare and discontinuous and were frequently interrupted by dry conditions. This generalisation is based on the inter-basaltic clay layers that were found between successive flows of basalt in southern Syria and Northern Jordan, (Shehadeh, 1985)

- Quaternary

The Quaternary period is divided into two periods; the Pleistocene and the Holocene. During the Pleistocene several dramatic climatic oscillations of great significance had occurred. The oscillations were experienced in the Northern Hemisphere in the shape of five major "glacial" and "interglacial" periods. Glacials and interglacials of the high latitudes were associated with 'pluvials' and 'interpluvials' in the middle latitudes. Pluvials were known as periods of widespread long-term rainfall increase of sufficient duration and intensity that had an effect on the geomorphology and landscape. While, during interpluvials, the climatic conditions were dry as today or even drier than present conditions.

The five major glacials are Guns, Mindell, Riss and Wurm. In the Levant the main pluvial 'A' was correlated with Riss or both Riss and Mindell. Pluvial 'B' was only slightly developed and was possibly connected with Wurm. The main characteristics of the climate of the Levant during the Pleistocene can be summarised as follows, (Shehadeh, 1991):

1. Pluvials were increased due to the increase in the number of rainstorms passing from the Mediterranean eastwards.
2. Pluvials were associated with more torrential rain in the rainy season, especially during the transitional seasons (autumn and spring), but summers were no less dry than at present. It is believed that during the pluvials of the Pleistocene, the rainfall was more abundant in the Levant than today, the following evidences support this hypothesis.
    - The levels of the lakes were higher, like the Dead Sea that had levels of 0.305, 76.2, 91.4, 131.1 and 164.6 metre above MSL, whereas today Dead Sea level is –400 metre MSL.
    - Fluctuations of the Mediterranean level like the fluctuations that were experienced in the coasts of Palestine and Lebanon.
    - Stratigraphy of geological deposits that were found in Mountain Carmel in Palestine and the rich fauna in the area indicate that the area used to receive high rainfall.
3. Coastal areas of the Mediterranean used to have strong pluvials, which they decreased rapidly towards the interior as well as from north to south.

4. The Levant highlands had experienced cold climate during the last glacial age, and lowlands had experienced pluvial conditions in the early glacial age. Evidences of support are mentioned below.
   - The snow line used to be 1000 metre higher than today in Lebanese highlands.
   - Evidence of crocodiles in Palestine during the last interglacial and postglacial ages.
   - Deposits of flat and angular limestone rubbles are attributed to frost cracking in the highland caves.
   - Woodland species like oak, beech, elm and hazel were found in the highlands, and believed to belong to the last glacial age.
5. The incised rivers and valleys were much bigger than would be today. In adjacent area such as Saudi Arabia, satellite images have revealed relics of drainage network.

Climate fluctuations of the post-glacial periods

The Levant has experienced climatic fluctuations including rainfall since about 12,000 BC as shown in Figure 4.2. The Mesolithic period ended in 8800 BC and was followed by pluvial conditions lasting well into the third millennium. Evidence of moisture abundance during that period was found in the Jordan valley, (Shehadeh, 1985).

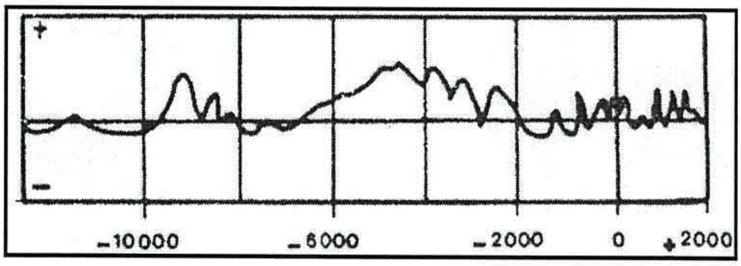

Figure 4.2: Rainfall trends in the Near East since about 12,000 BC, (Source: Shehadeh, 1985).

Another period of uniform rainfall occurred between 2850-2650 BC when most of the cities in Palestine were built, which indicates that the rainfall was relatively abundant during that period. But after that between 2500-1000 BC conditions were getting drier, in comparison with present day conditions, especially between 1800-1300 BC when most of the cities in Jordan and Palestine were abandoned, which shows how arid it was during that time.

Climate fluctuations during Present Epoch

During the first two centuries of the Christian era the climate was moist and rainfall was almost greater than today's rainfall, (Issar et al., 1992). This is clearly indicated by the affluence of the city of Jerash between 130-180 AD. Also, in the Syrian Desert a number of oases were reported and archaeological evidence dated from that period showed that Roman bridges and ruined piers on presently dry wadis, and many well heads on houses indicating springs that do not exist today. But, the moist period ended by the beginning of the 3rd century and the level of the Dead Sea in 333 AD became as low as it is today. This dry period persisted until the end of the 6th and beginning of the 7th century AD.

Climatic fluctuation in the Islamic era

The first two centuries of the Islamic era were relatively moist and more humid than today. This is witnessed by the archaeological findings of many Ummayad palaces, hunting boxes and baths in the Jordanian and Syrian deserts, where no water exists today. Then these two moist centuries were followed by a dry period that had lasted through the 10th and 11th centuries AD, but followed by a moist period during the 12th and 13th centuries. Table 4.1 summarises the climate fluctuations during the Christian and Islamic eras until 1900.

Table 4.1: Short-term rainfall trend of the Christian and Islamic eras (Source: Shehadeh, 1985)

Period (AD)	**Rainfall**	**Period (AD)**	**Rainfall**
1-180	Very moist	1428-1460	Very moist
180-390	Dry	1460-1540	Dry
390-415	Moist	1540-1680	Very moist
415-670	Very dry	1680-1708	Dry
670-925	Very moist	1708-1838	Dry
925-1100	Very dry	1838-1875	Dry
1100-1310	Very moist	1875-1900	Dry
1310-1428	Very dry	1901-	Very dry

Whatever the case, there is a clear indication that conditions were significantly wetter in early-mid Holocene times for much of the Middle East and North Africa than today. In these areas there is a widespread appearance of Neolithic sites across the landscape attesting to a significant expansion of occupation lasting until mid-Holocene times. While the timing of the early-mid Holocene moist period seems to be slightly different for different areas, it is likely that this same impact was also experienced in eastern Jordan and recorded in the events in the eastern deserts up to the onset of a more arid phase which has continued up to the present.

4.3 Climate of Jordan at Present

Synoptic Rainfall in Jordan

The present synoptic climatology of Jordan can be classified as part of the Mediterranean. Winter, summer, autumn and spring synoptic situations will be discussed in the next section.

- *Winter Synoptic Situation*

During winter months (December, January and February) Jordan is affected by a series of depressions that move from the western or southwestern Mediterranean east and northeastwards. The Mediterranean depressions are grouped into three groups according to their areas of formation, (Shehadeh, 1991)

- Depressions of the western Mediterranean basin that are called "Genoa depressions". These depressions do not reach the eastern Mediterranean and have no direct/immediate effect upon the climate of Jordan.

- Khamasin depressions, or frequently called "Saharan depressions" as they form in the area of the Atlas Mountains and move along the southern shores of the Mediterranean. Most of these depressions occur during spring, and they account for 18 percent of the Mediterranean depression. They have an implicit effect on the Jordanian climate, as the ones that affect the Mediterranean depressions earlier will affect Jordan later.

- Central and eastern Mediterranean depressions, which move along three main tracks:
  - Annual averages of 10.5 depressions move to the northeast through northern Syria and southern Turkey.
  - 11 depressions move yearly to the east and few of them reach northern Iraq.
  - Average of 1.5 depressions move to the southeast.
  -

The decrease in the number of depressions moving southwards explains the decrease of rainfall in Jordan from north to south; this is coupled with orographic effects on the mountains in Lebanon.

- Summer Synoptic Situation

Summer is the most sTable season in Jordan. Due to the intensive heating of the landmasses, the following pressure changes occur: the Mediterranean experiences high-pressure centre, while a belt of low pressure extends from North Africa and the Indian Ocean. This brings the eastern Mediterranean within the monsoon belt of Southern Asia, and invites hot and dry northerly continental tropical air masses. In addition two centres of low pressure cut off are formed over the northern Red Sea and Saudi Arabia that brings occasional invasions of very warm air masses and cause a rise in temperature and heat waves, as shown in Figure 4.3.

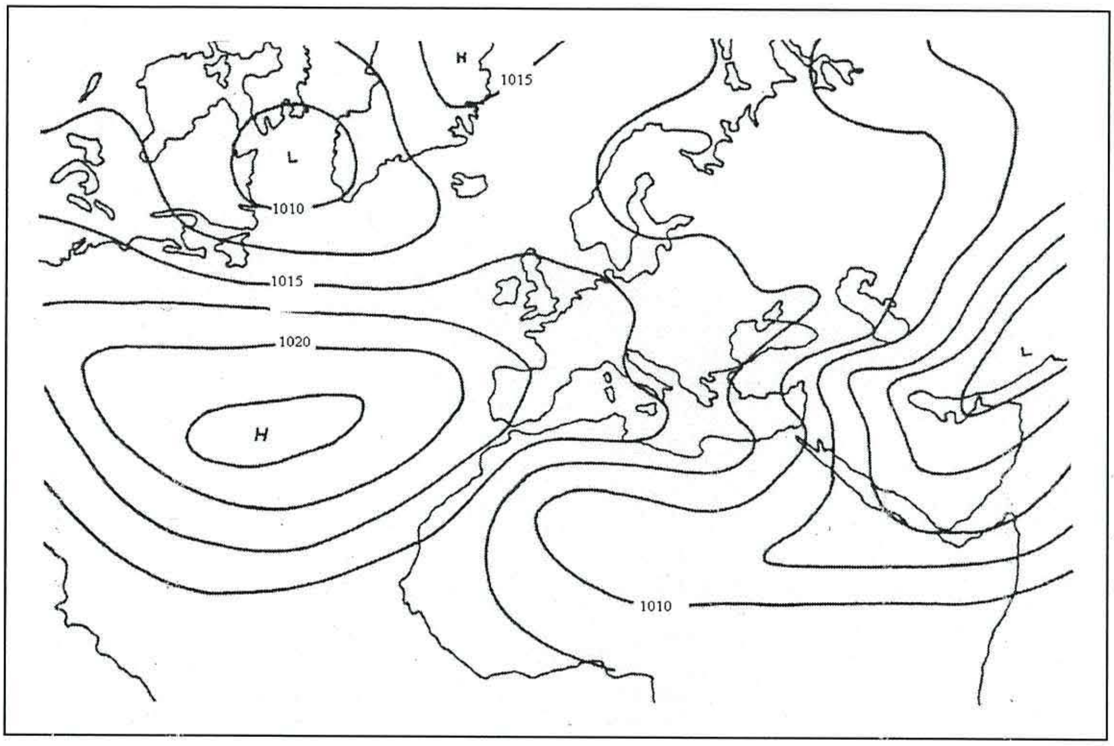

Figure 4.3: Typical pressure system in June, (in millibar), (Source: Shehadeh, 1991).

- Spring and Autumn Synoptic Situations

Spring and autumn are called the transitional seasons in Jordan. Spring is a transitional season between winter and summer and autumn is a transitional season between summer and winter. During spring the high-pressure centre that had centred over North Africa in winter starts to shift northwards, which gives way to the development of low-pressure centres and forms the Khamasin depressions. Also, the Siberian high-pressure extensions over the eastern Mediterranean start to weaken.

For the western and central Mediterranean regions, in autumn a phenomenon called "fall break" occurs. During this fall break the region is invaded by cold polar air masses, which initiate the start of the unsettled weather.

In Jordan the most important cause of the unsettled weather is the "Red Sea Trough". The Red Sea Trough occurs at the northern part of the Red Sea, due to the meeting of the cold north westerly Mediterranean wind with the hot and dry tropical wind that comes from the south or Southeast (Abu Hussain, 1994).

The synoptic situations in autumn, winter and spring of Jordan reveal the fact that the rainfall is more consistent in winter rather than in autumn and spring. As the number and the type of depressions that affect rainfall in each season plays a role in the rainfall variability, as appears when moving from northwest to southeast. This is clear in the developed Double Mass Curves for the rain gauges of the catchment area.

4.4 RAINFALL VARIABILITY IN JORDAN

To study this aspect about the Jordanian rainfall 14 stations were taken into consideration. They are distributed all over the country from north to south and west to east. The stations in the north and the middle are Irbid, Deiralla, Jordan University and Amman airport. The eastern stations those are located in the Badia area are Mafraq, Um Al-Quttein, Deir Al-Kahf, Al-Aryyatein, Safawi, Ruwaished and Azraq, (Um Al-Quttein, Deir Al-Kahf and Al-Aryyatein are not shown in Figure 4.4, but are shown in Figure 4.21). The southern stations are Errabah (near Kerak on the map), Ma'an and Aqaba. Figure 4.4 shows the distribution of the mentioned stations. Monthly rainfall data from 1960 until 2000 for the northern, southern and some on the eastern stations was obtained from the Jordanian Ministry of Water Resources. Except for Al-Aryyatein, Deir Al-Kahf and Azraq the data set starts in 1962, 1963 and 1968 respectively and ends in 1998.

Rainfall over Jordan is known to decrease from north to south and west to east, (Shehadeh, 1985 and Figure 2.6). From the figures it is seen that the annual rainfall varies between 400-500 mm in the northwestern part and less than 50 mm in the southeastern part, (Allison et al., 1998). Percentage wise this means that only 1.3% of Jordan receives the highest rainfall, while almost 63.2% receive less than 50 mm per year, and the remaining 35.5% receives between these two extremes.

The major factors that affect the spatial distribution of rainfall are the physiography and latitude, (Salameh, 1993). Mountainous areas like Amman have higher rainfall than the low lands in the Jordan Valley where altitude drops below sea level. As mentioned previously the rainfall decreases from north to south, this is due to the increased distance from the main tracks of the Mediterranean depressions and the small number of depressions that travel along the southern Mediterranean track. The eastward decrease is caused by the adiabatic heating of the moist winds on the lee slopes of the eastern mountains. The rate of eastward rainfall decrease is very rapid and considerable. Important examples of the spatial distribution of rainfall are Figures 4.5 and 4.6, which show the annual rainfall of the northern stations (Jordan University and Amman airport which is located 10km to the southeast, as well as Irbid in the north and Deiralla in the Jordan Valley, that is 45 km northwest of Amman, and not shown in Figure 4.4), and the southern stations (Errabah, Ma'an and Aqaba) respectively. From both figures it can be seen how much rainfall is changing as we go south and east.

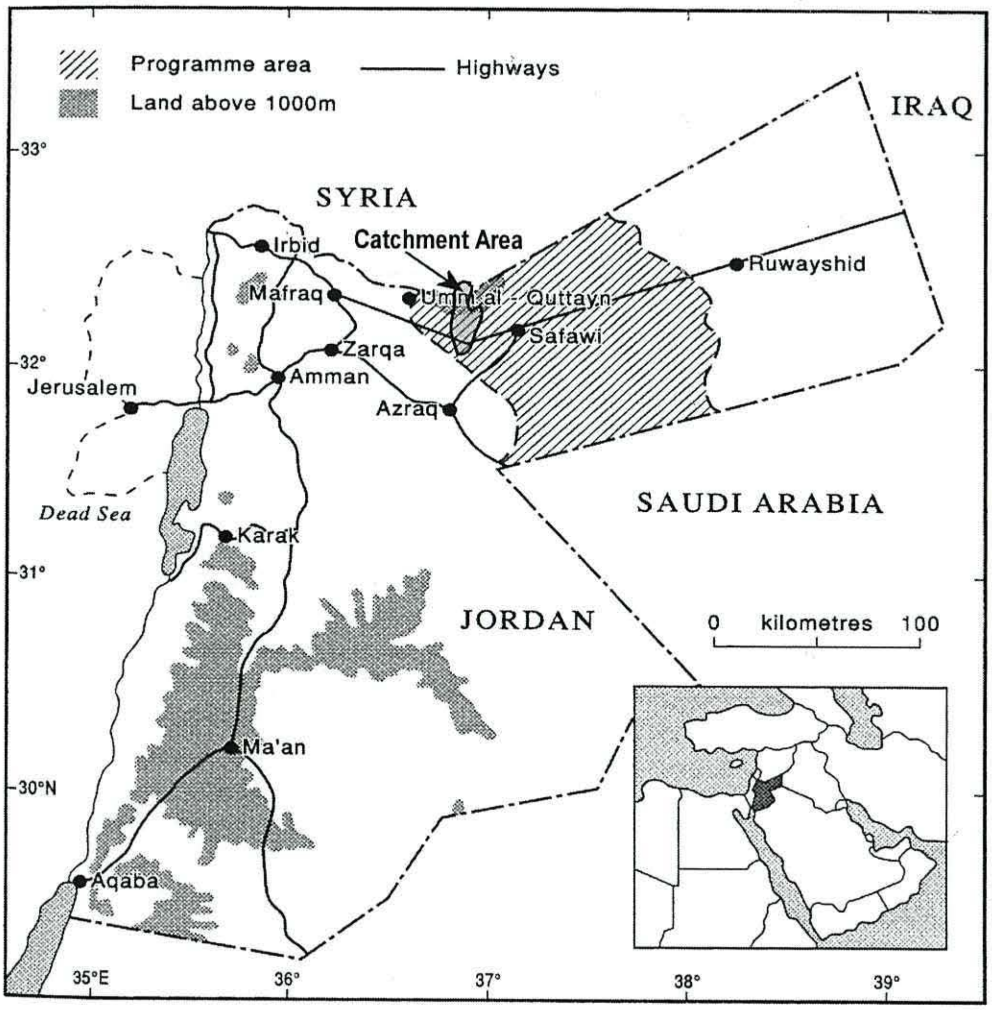

Figure 4.4: The distribution of the rain gauges used in this study, (black circles refer to rain gauges), (Source: Allison et. al., 1998).

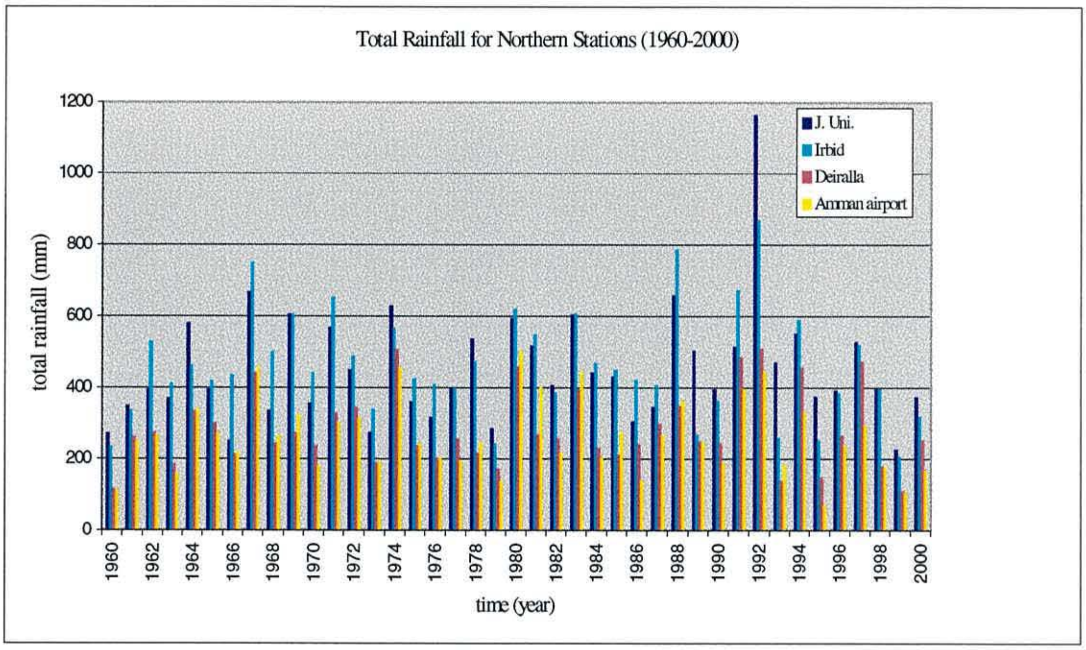

Figure 4.5: Annual rainfall distribution of the northern stations.

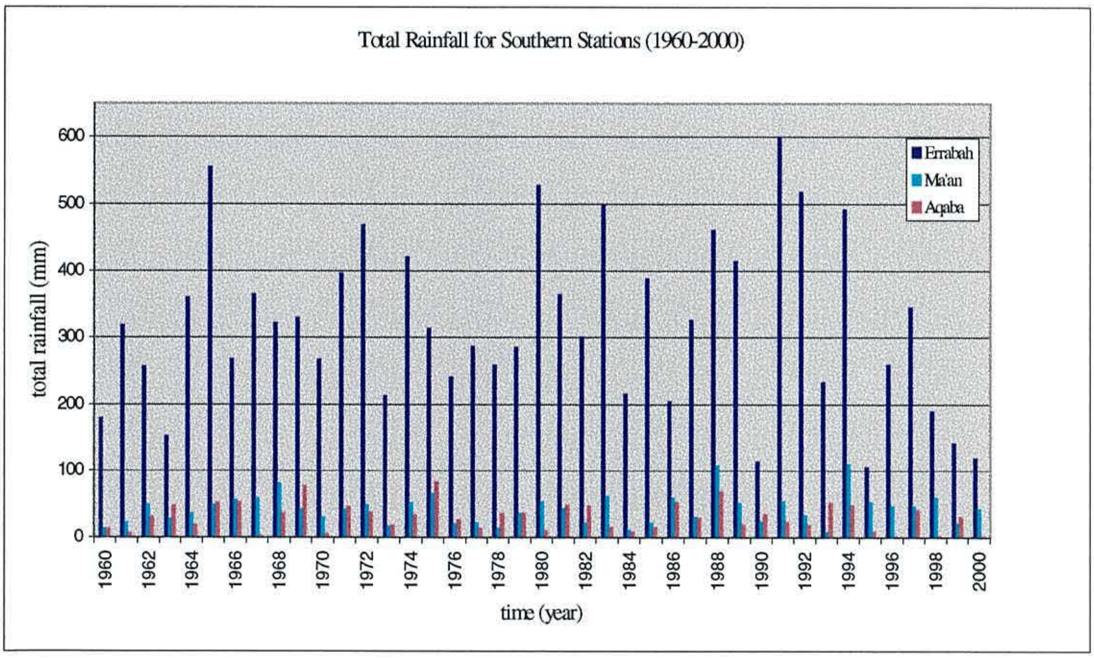

Figure 4.6: Annual rainfall distribution of the southern stations.

Another indication that could be used to identify how much the rainfall is spatially variable is the coefficient of variation[1] for the Jordanian stations. Average annual rainfall for the 14 stations distributed all over Jordan was used and plotted against the coefficient of variation for the corresponding stations as shown in Figure 4.7. The figure shows that as average rainfall increases the coefficient of variation decreases. The coefficient of variation that was calculated using the annual average and standard deviation rainfall values varies from 33% for Irbid in the northern part of Jordan to 67% for Aqaba in the south.

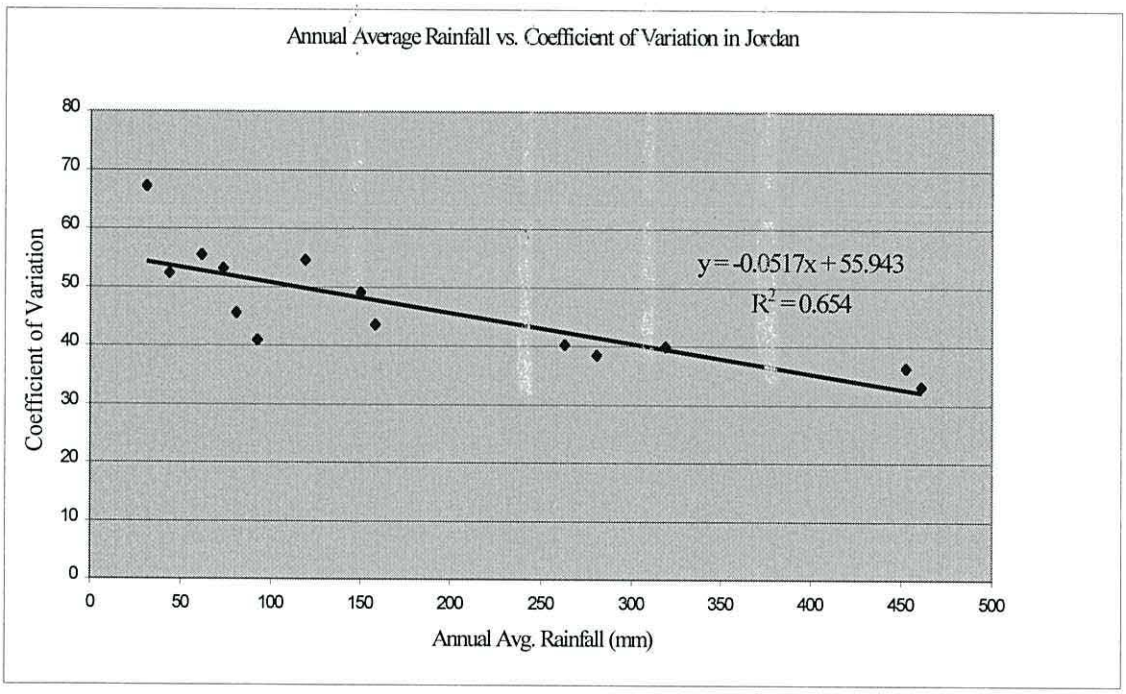

Figure 4.7: Relationship between average annual rainfall and its coefficient of variation in Jordan.

Jordanian rainfall is characterised by its seasonality, i.e the variability of rainfall at different seasons or the temporal variability at different times of the year. The rainy season in Jordan is from September to May, but most of it falls during the winter months from December to February (DJF) in the northern and central parts of the country. While autumn (SON) and spring (MAM) rainfalls contribute less. Figure 4.8 shows the average annual and seasonal rainfall distribution for all the stations.

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[1]Coefficient of Variation is a relative measure of dispersion found by expressing the standard deviation as a percentage of the arithmetic mean.

It is clearly shown that the winter rainfall is more than 50% of the annual rainfall in all cases. This is mainly becasue the winter rainfall is more persistent and associated with cold fronts rather than the thunderstorm activity that dominates in autumn and spring.

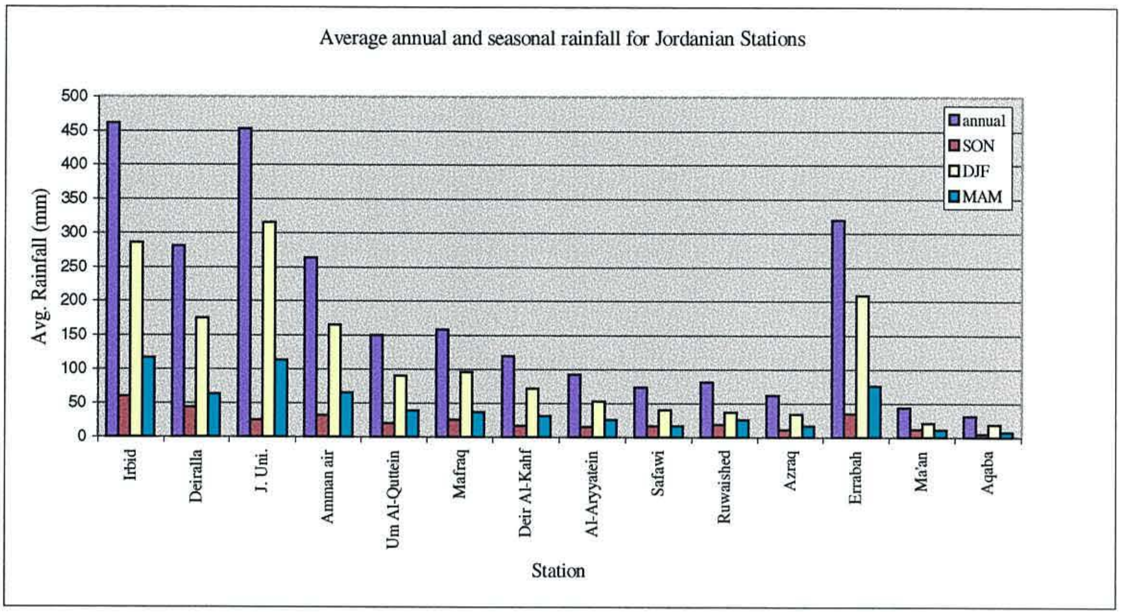


Figure 4.8: Average annual and seasonal rainfall distribution for all the stations, (Figure 4.4 shows the location of the stations).

The seasonal coefficients of variation values are higher than the annual ones, because of the nature, the spatial and temporal distribution of the seasonal rainfall. For example autumn's coefficient of variation for most of the southern stations is higher than 100% as it reached 144% for Aqaba. Having values greater than 100% means that the standard deviation value is higher than the average value, which indicates that the rainfall is more variable and sporadic. Also it is a sign of the thunder type of rainfall that occurs in the beginning and the end of the rainy season (i.e. autumn and spring). Perhaps it also indicates that even annual totals can be greatly influenced by very few extreme events (i.e. big storms) while other years can have zero rainfall.

In Jordan the autumn rainfall is named as the early rainfall and the spring one is known as the late one. This is according to the people who have been interviewed as part of this study. The full questionnaire results will be discussed in Chapter Eight.

4.5 Rainfall Types in the Northeastern Badia

There are different synoptic situations that affect the weather systems in Jordan as discussed earlier. In the Badia as well as other areas different types of rainfall have been reported. Rainfall is divided into four major types; which are

- Convective storms

Convective storms result as warm air rises into cooler overlying air as shown in Figure 4.9. A common example of this type is summer thunderstorms, (Raudkivi, 1979). This kind of storm is noticeable in the Badia area at both the beginning (October and November) and the end of the rainy season (March, April and May). This type of thunderstorms is localised and may be undetected by gauges, also they may occur at random locations due to the excessive heating of the earth surface. Then the air adjacent to the surface becomes warmer than the air mass above it, which causes the warm air to be lifted above, (Brooks et. al., 1991). As a result condensation occurs and then rain falls with high intensity and short duration over limited areas (i.e. small areal coverage). Often this kind of storms is not detected by widely spread rain gauges, and runoff occurs as a flash flood that only may be sustained for few kilometres before it disappears into the bed of the wadi.

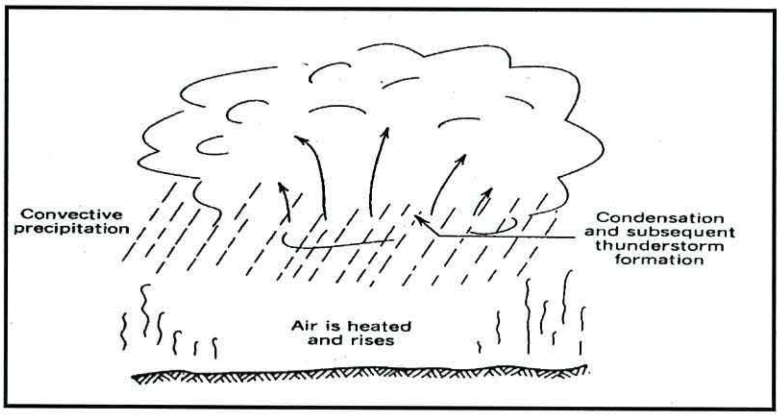


Figure 4.9: Convective storm type of rainfall, (Source: Wanielista et. al., 1997).

- Orographic storms

Orographic rainfall occurs when general atmospheric circulation forces an air mass up and over mountain ranges. As shown in Figure 4.10, when the air mass is lifted, a greater volume of the air mass reaches saturation, which results in more rainfall as the elevation increases. The Northern part of the catchment near the Syrian Jebal Al-Arab gets this kind of rainfall, as well as the Jordanian part adjacent to the Syrian border. Also this effect explains why much of the moisture coming from the Mediterranean falls as precipitation in Lebanon. This will be mentioned in detail later.

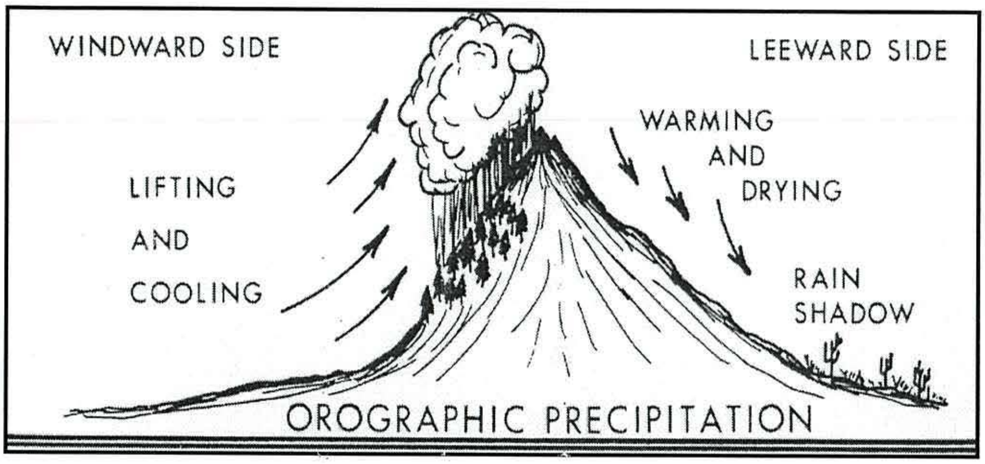


Figure 4.10: Orographic type of rainfall (Source: Brooks et. al., 1991).

- Cyclonic storms (Frontal systems)

Frontal rainfall occurs when two air masses of different temperature and moisture content are brought together by general circulation. The movement of air from high to low pressure area is called a front. They are two types, cold and warm fronts. Cold fronts are formed by cold air mass replacing warm air, while warm fronts are formed by warm air advancing over cold air. Figure 4.11 shows cyclonic types of storms. Cold fronts usually move faster than warm ones, with associated rainfall falling in a heavier intensity and a shorter duration than the warm fronts. This type of rainfall is well known in the Badia as well as the rest of the country during winter months between December and February.

In spite of the prevailing thunderstorms in the area which occur in October, November, and March to May, cyclonic rainfall reaches the area particularly in December, January and February (WAJ, 1989). This is also emphasised by local people who participated in answering the Participatory Rural Appraisal (PRA) questionnaire about rainfall in the area, as listed in Table 8.4. This leads to classify the area as an arid zone without a defined rainy season, (Rodda, 1985). This kind of category may receive rainfall in autumn, winter, spring and rarely showers in summer, but generally the summer is dry. In the northern part of the catchment orographic rainfall is important especially in Jebal Al-Arab in the Syrian part of the catchment. Details about this will be shown later in the chapter.

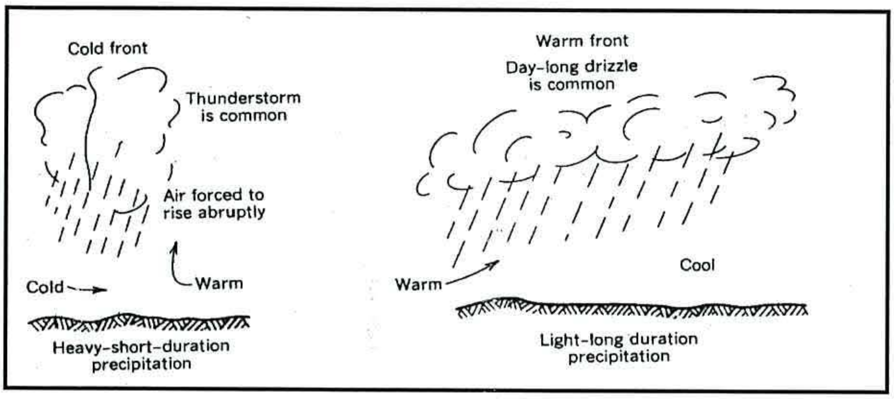


Figure 4.11: Frontal systems type of rainfall, (Source: Wanielista et. al., 1997).

- Tropical cyclones

A tropical cyclone is an intense cyclone with its source in the tropics where the surface water temperature is generally greater than 29 °C and the wind speed is 75 mph and more. In North America it is called hurricane while in the Far East it is called typhoon. Tropical cyclones have high rainfall intensity and they can cause considerate damage. This kind of rainfall is not relevant to the Badia area, but it is worth mentioning as another type of rainfall.

4.6 Rainfall Variability in the Northeastern Badia

Rainfall in the Badia area is characterised by its irregular intensity and duration. It decreases from north to south and west to east. The maximum rainfall amount occurs in the northwestern part of the catchment near the Syrian border. The altitude of the station and its distance eastward affect the rainfall amount, (Kirk, 1997). There are some trends in rainfall in the Badia area that can be summarised as shown in Figure 4.12. From this figure it can be clearly seen that for most of the stations rainfall starts falling in October, with a rapid increase until December when the peak rainfall occurs, before they start decreasing again until March, then dropping off quickly in April to an almost negligible amount in May. Mafraq station that is located in the northwestern edge of the Badia programme area receives the highest average annual rainfall, of 158mm. Mafraq, Deir Al-Kahf and Al-Aryyatein show a similar pattern. These three stations give confidence to the idea that the frontal systems that continue over the hills to the east of the rift valley will tend to give rainfall only as they are forced over the higher ground of Jebal Al-Arab. The amount of winter rainfall for these stations depends on two major factors; the station's altitude and its distance eastwards. Mafraq has the highest rainfall, as it is the most westerly one. As mentioned before the orographic nature of Jebal Al-Arab affects the rainfall amounts. For example, the average annual rainfall for Um Al-Quttein is 150mm while for Deir Al-Kahf that has a higher elevation it is 119mm. This is due to the orographic effect of Jebal Al-Arab as Deir Al-Kahf lies in the rain shadow in the Southeastern side of the hills and therefore receives less. Because of the orographic effect the four stations mentioned are experiencing almost the same trend.

The remaining three (Safawi, Ruwaished and Azraq) which lie at lower elevations are dominated by other regional climatic patterns. These stations' rainfall bears no relation to the rainfall at the Northwesterly part. For example, Ruwaished got the highest rainfall in October, April and May compared with other stations. This could be due to the thunder type of rain that falls at the beginning at the end of the rainy season, which seems to be more localised rather than having a specific trend.

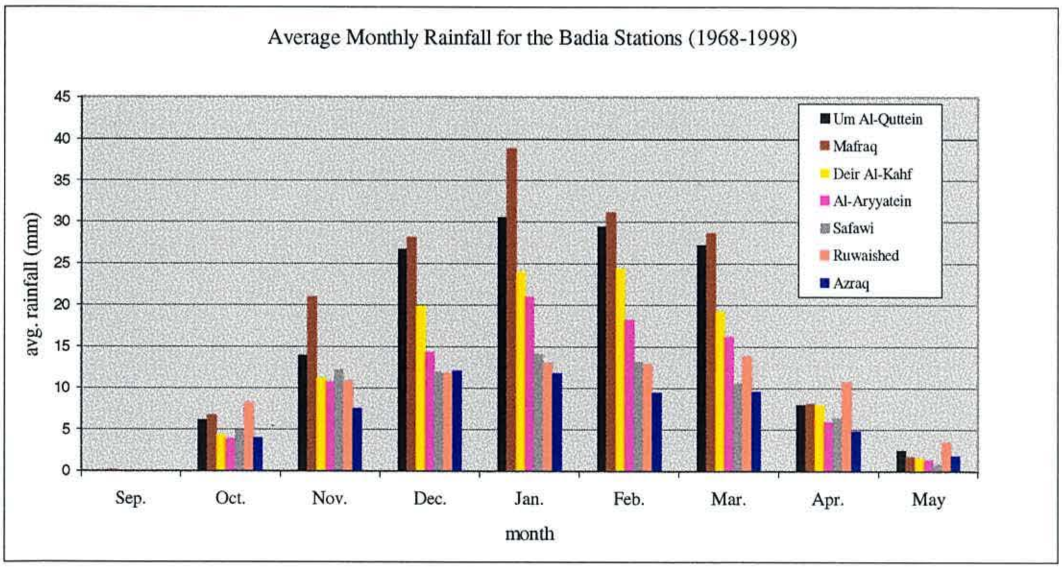


Figure 4.12: Average monthly rainfall for the Badia stations, (location of stations is shown in Figure 4.19, apart from Mafraq and Ruwaished that are shown in Figure 4.4).

The long-term change in the annual rainfall for the Badia area has been considered. For the stations that lie on the foothills of Jebal Al-Arab (Mafraq, Um Al-Quttein, Deir Al-Kahf and Al-Aryyatein) there is a considerable reduction in the average annual rainfall in the last 20 years, i.e. in the 1980s and 1990s. Other stations (Safawi, Ruwaished and Azraq) as well showed a reduction in the average annual rainfall. Figure(s) 4.13 and 4.14 show the annual change in rainfall for Jebal Al-Arab station and the other stations respectively. Looking at the average rainfall for the whole period of record (1960-2000) and comparing it with the average of the last two decades, i.e. the 1980s (1980-1989) and 1990s (1990-2000) separately. It is clearly seen that the rainfall at all stations except Mafraq has decreased significantly in the 1990s. Table 4.2 shows the long-term annual average, the 1980s and 1990s average and standard deviation value for the Badia stations. From the Table it can be seen that during the 1980s most stations were wetter than either the 1990s or before the 1980s.

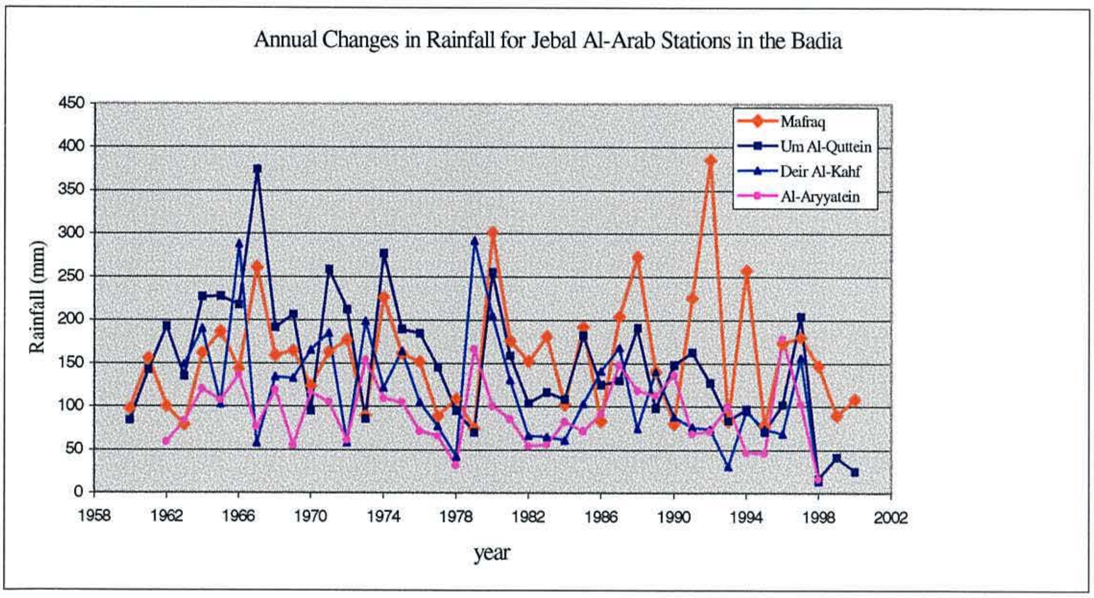


Figure 4.13: Annual changes in rainfall for Jebal Al-Arab stations in the Badia.

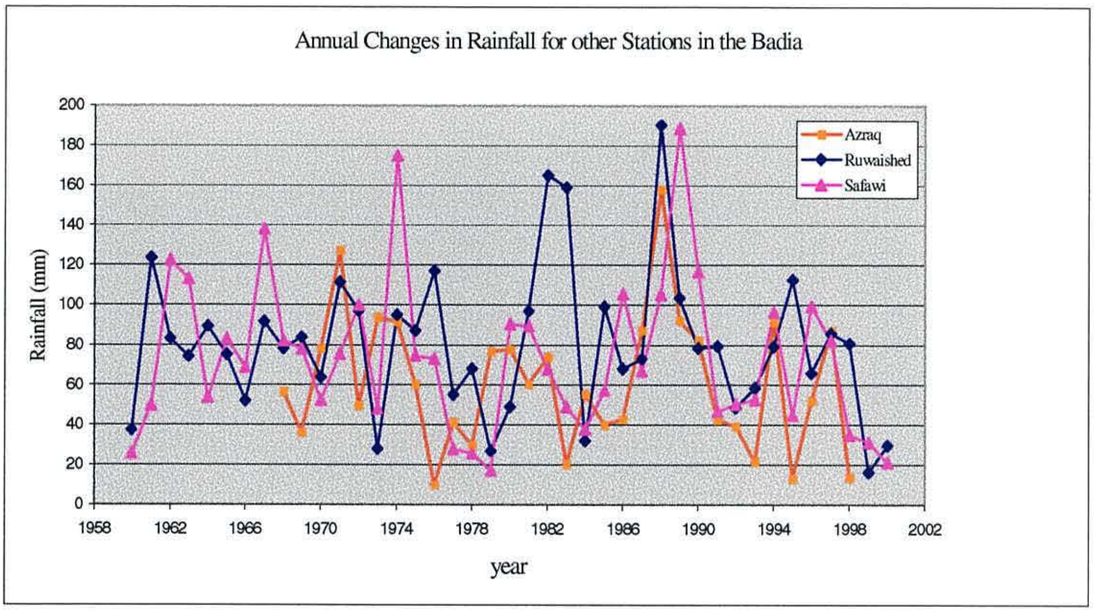


Figure 4.14: Annual changes in rainfall for other stations in the Badia.

Table 4.2: Change in the rainfall of the Badia stations in 1980s and 1990s.

Station	Long-term avg.	S.D	80s avg.	80s S.D	90s avg.	90s S.D	% change (80s)	% change (90s)
Mafraq	158.1	68.9	180.50	68.4	164.2	95.9	14.2	3.9
Um Al-Quttein	150.0	73.6	146.70	50.1	97.8	59.2	-2.2	-34.8
Deir Al-Kahf	119.0	65.0	115.20	49.6	74.8	40.2	-3.2	-37.1
Al-Aryyatein	92.3	37.7	91.60	30	85	50.5	-0.8	-8.0
Safawi	73.5	39.1	85.80	42.9	61.4	31.7	16.7	-16.5
Ruwaished	80.7	36.7	103.60	52.4	66.8	27.3	28.4	-17.2
Azraq	61.4	34.0	70.90	38.1	49.2	31.2	15.5	-19.8

4.7 DROUGHT IN THE CONTEXT OF THE BADIA

From the above analysis it can be concluded that the area has become significantly drier in the last decade. This leads to emphasise more attention to the concept of "drought"; what does it mean, how to trace it and what are its impacts? In the literature there are at least 150 different definitions for drought, (Eden and Twist, 1995).

- Meteorological drought that is defined as a period of abnormally dry weather sufficiently extended for the lack of water to cause serious hydrologic imbalance in the affected area, (Huschke, 1959).

- Agricultural drought which is known as a climatic excursion involving a shortage of precipitation sufficient to adversely affect crop production or range production, (Rosenberg, 1979).
- Hydrologic drought is a period of below average water content in streams, reservoirs, ground-water aquifers, lakes and soils (Yevjevich et al., 1977).

These three categories can be defined as environmental indicators, while the socio-economic drought, which associates drought with supply and demand for an economic good, is known as a water resources indicator.

There is a relationship between the different drought categories. A meteorological drought in terms of the lack of precipitation is the primary cause of a drought. Also the most variable in terms of location: in UK a few weeks is known as drought; while in Saudi Arabia five or more years is considered as a drought. It usually first leads to an agricultural drought due to the lack of soil moisture. If rainfall deficiencies continue a hydrological drought in terms of surface water deficits develops. The groundwater is normally the last to be affected, but also the last to return to normal water levels, (Hisdal and Tallasken, 2000). Figure 4.15 shows the sequence of drought impacts associated with meteorological, agricultural and hydrological drought.

Drought can be measured by different indices. A drought index is a single number characterising the general drought behaviour at a measurement site, (Hisdal and Tallasken, 2000). One of the indices used is the Standardised Precipitation Index (SPI) or the standardised rainfall anomaly is one of the measures used to measure the strength of the drought. SPI is defined as the ratio between the difference between the actual rainfall and the average values and the standard deviation, it is formulated as below, (Agnew, 2000).

$$SPI = \frac{X_{ik} - \bar{X}_i}{\sigma_i}$$

Where

X_{ik} is the kth observation rainfall for the ith station.

$\bar{X}_i$ is the average rainfall for the ith station.

σ_i is the standard deviation for the ith station.

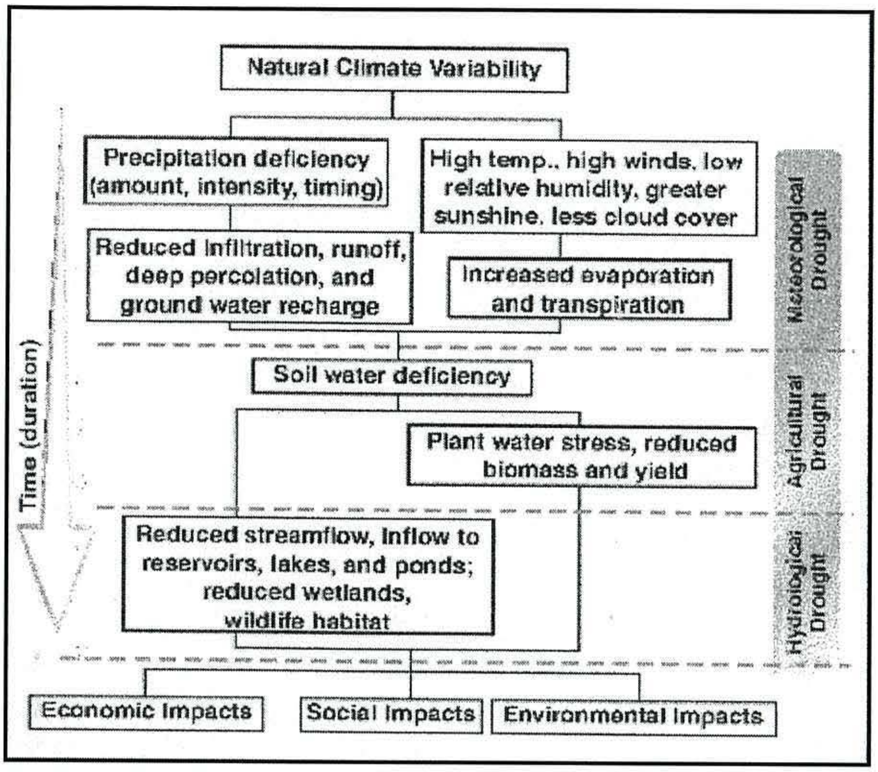


Figure 4.15: The sequence of drought impacts associated with drought, (Source: Hisdal and Tallasken, 2000).

The index has the advantage that is easily to calculate, needs moderate data requirement and it is independent of the magnitude of the average rainfall and therefore comparable over climatic zones. Actually there is a lot of debate about choosing the SPI limit that is considered as a drought limit. Some take it as below average rainfall i.e. if SPI <0 it is meant to be a mild drought, others have selected different limits for SPI. For example, for SPI of values <-1 it is considered as a moderate drought, while a value of <-2 denotes an extreme drought, (Mckee et. al., 1995). While, according to Agnew (2000) for a drought to be moderate SPI has to be <-0.84, and for SPI of <-1.65 it is known as extreme drought.

SPI for the whole of Jordan is calculated using the same 14 rain gauges mentioned previously. The annual rainfall values for the stations were taken for the period between 1960 and 2000, the developed SPI plot is shown in Figure 4.16. From Figure

4.16 it is clearly seen that the SPI values are following a systematic pattern, i.e. the values have started with below zero (i.e. below average rainfall) and they have kept the same pattern for 4 years, then the pattern has changed to a positive sign, which indicates above average rainfall and so on so forth. But, it was clear that in the last 3 years between 1998 and 2000 there was a drought. According to Agnew's classification, in 1999 the country has suffered from "a moderate" drought.

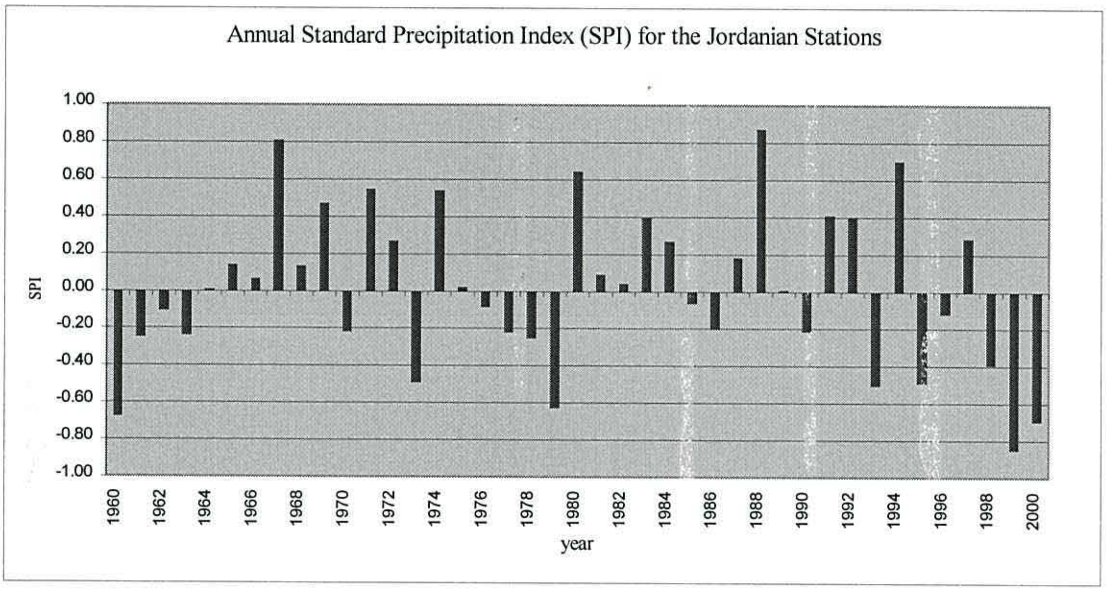


Figure 4.16: SPI for the Jordanian stations.

Detecting the dry years is as important as detecting the wet ones, or even more important. Detailed analyses have been conducted in chapters Six and Seven regarding this issue and its importance to the water resources management of the study area.

4.8 Rainfall Distribution in the Badia Area

Rainfall in Marab Hassan catchment as well as the rest of the Badia area is variable in time and space. From analysing the annual and continuous rainfall data for the stations inside and outside the catchment, it is obvious that rainfall records are variable between stations, also they are variable for the same station in different years. Isohyetal rainfall maps for the Badia area were produced using "Inverse Distance to the Power" and "Modified Shepard's" gridding methods in *SURFER* software for monthly, seasonal and annual data for the 2000/2001 rainy season. These methods produce different interpretations; therefore *SURFER* output needs to be examined with reference to regional data. The Inverse Distance to a Power gridding method is a weighted average interpolator, where data are weighted during interpolation such that the influence of one point relative to another declines with distance from the grid node. One of the characteristics of this method is that it generates bull's-eyes around the position of observations within the gridded area. Modified Shepard's uses an inverse distance weighted least squares method. As such, Modified Shepard's Method is similar to the Inverse Distance to a Power interpolator, but the use of local least squares eliminates or reduces the "bull's-eye" appearance of the generated contours. Inverse Distance to a Power showed better results than Modified Shepard's one, so the results from the first one will only be used in this study. The annual and seasonal (SON, DJF and MAM) distributions are shown in Figures 4.17, 4.18, 4.19 and 4.20 respectively.

Contouring (i.e. creating the rainfall distribution maps) for the area is deceptive due to limitations in the *SURFER* software itself and with the limited rainfall data. The annual rainfall distribution of the Badia area (shown in Figure 4.17) is more reliable in terms of plotting as all the stations appear in the Figure have contributed with their annual total rainfall, which eliminates the edge effect of the *SURFER* software. While, the seasonal distributions (shown in Figures 4.18 to 4.20), have been affected by the software assumptions that created the edge effect.

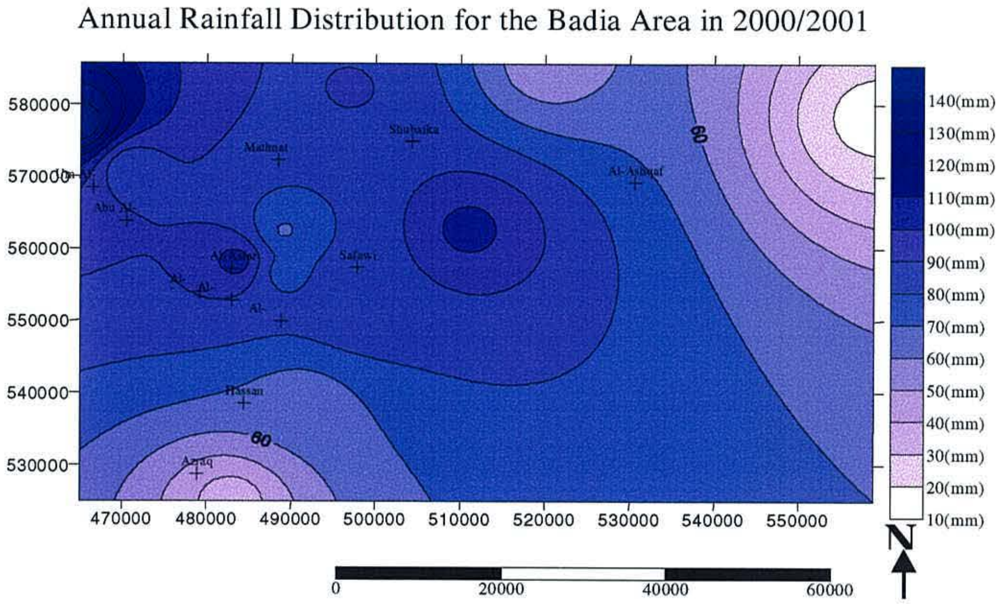


Figure 4.17: Annual rainfall distribution for the Badia area in 2000/01

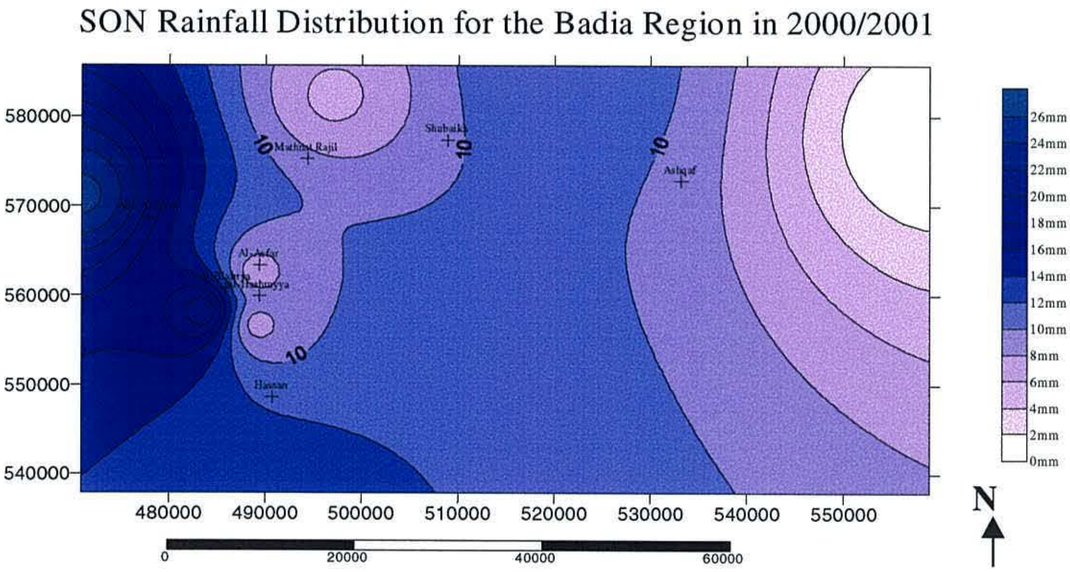


Figure 4.18: SON rainfall distribution for the Badia region in 2000/01.

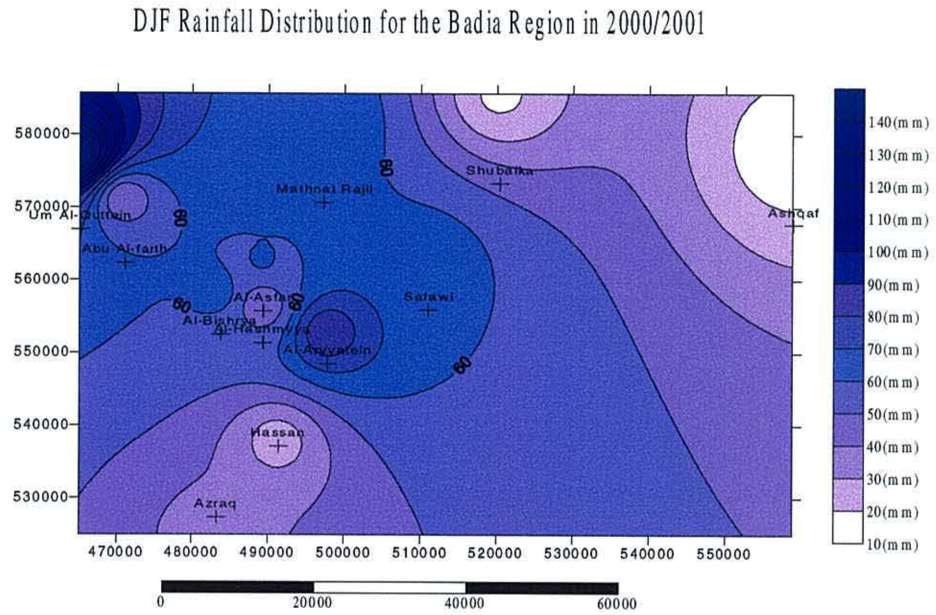


Figure 4.19: DJF rainfall distribution for the Badia region in 2000/01.

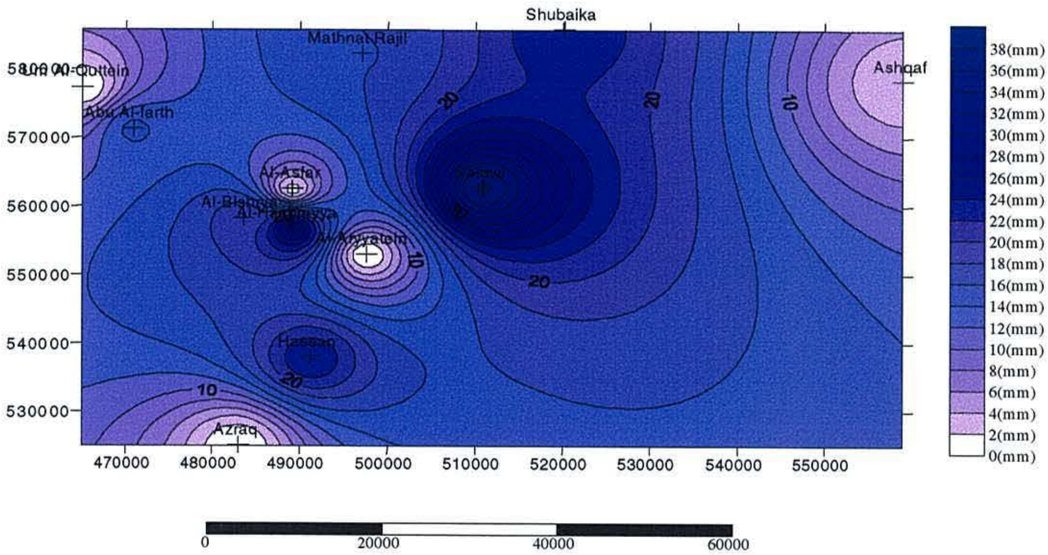


Fig. 4.20: MAM rainfall distribution for the Badia region in 2000/01.

4.9 Rainfall in Marab Hassan Catchment

Inspite of the prevailing thunderstorms in the area which occur in October, November, March to May, cyclonic rainfall may reach the area particularly in December, January, February and March (WAJ, 1989). In the northern part of the catchment orographic rainfall is important especially in Jebal Al-Arab in the Syrian part of the catchment.

Rainfall is characterised by irregular intensity (i) and duration, as shown in Table 4.3. The intensity values shown in the Table were obtained from the four continuous recorders that have been installed in and adjacent to the catchment area, which are Um Al-Quttein, AL-Aryyatien, Safawi and Azraq. The intensity values are ranked from 1 to 4, with 1 represents low intensity event and 4 is a very intensity event, (i=1-1.5 mm/hr=1 (low), i=1.5-3 mm/hr=2(medium), i=3-5 mm/hr=3(high), i> 5 mm/hr=4(very high)). This ranking system is based on the PRA interviews with the local people, as will be discussed in Chapter Eight. As was claimed by the local people the high and very high intensity events are responsible for the floods in the catchment area.

Rainfall decreases from north to south and west to east. The maximum rainfall amount within the study area occurs in the northern of the catchment near the Syrian border. The altitude of the station and its distance eastward affect the rainfall amount, (Kirk, 1997). Here the orographic effect of Jebal Al-Arab affects the rainfall amounts. For example, Um Al-Quttein has lower elevation than Deir Al-Khaf does, but it receives more rainfall because Deir Al-Khaf lies in the southeastern side of the hills in the rain shadow.

To define and analyse the rainfall patterns that dictates the Badia's climate it is first necessary to study collected rainfall data from a number of stations elsewhere in Jordan as well as in Syria. Availability and accuracy can be problematic according to various reasons. For example, in Lebanon the civil conflict makes continuous records for the required period difficult to obtain.

Table 4.3: Rainfall intensity (mm/hr) with ranking (*1-4*) from PRA.

Date	Um Al-Quttein	Al-Aryyatein	Safawi	Azraq
01/12/00	0.73(*1*)			
08/12/00		8.24 (*4*)		
09/12/00	11.00 (*4*)	27.70 (*4*)		1.65 (*2*)
10/12/00		4.30 (*4*)		
12/12/00	2.44 (*2*)	4.50 (*4*)		
13/12/00		23.10 (*4*)	22.50 (*4*)	
19/12/00	0.92 (*1*)			
20/12/00		1.78 (*2*)		13.85 (*4*)
24/12/00	0.92 (*1*)			5.70 (*4*)
25/12/00	1.60(*2*)			
24/01/01	1.00 (*1*)			
25/01/01	3.20 (*3*)	1.50 (*2*)	1.00 (*1*)	
04/02/01	0.80 (1)	1.00 (*1*)		
07/02/01	1.22 (1)		2.40 (*2*)	1.86 (*2*)
08/02/01		0.36 (*1*)		
14/02/01	1.24 (*1*)			
15/02/01		0.21 (*1*)		
20/02/01	0.80 (*1*)			
21/02/01	1.64 (*2*)			
24/03/01			5.00 (*3*)	11.00 (*4*)
04/04/01			0.73 (*1*)	1.57 (*2*)
05/04/01			1.23 (*1*)	

Rainfall in Marab Hassan catchment as well as the rest of the Badia area is variable in time and space. From analysing the annual rainfall data for the stations inside and outside the catchment, it is obvious that rainfall records are variable among stations, also they are variable for the same station in different years. The stations are three Syrian stations, which are (Imtan, Kirbat Awwad and Salkhad), and five Jordanian that are (Um Al-Quttein, Deir Al-Kahf, Al-Aryyatien, Safawi and Azraq), as shown in Figure 4.21 that shows the distribution of the rain gauges within the catchment area. Figures 4.22 to 4.29 show the rainfall histograms for both Jordanian and Syrian stations. From the graphs it can be seen that the rainfall records are variable spatially and temporally. For some years the values were below the average while for others they are above the average.

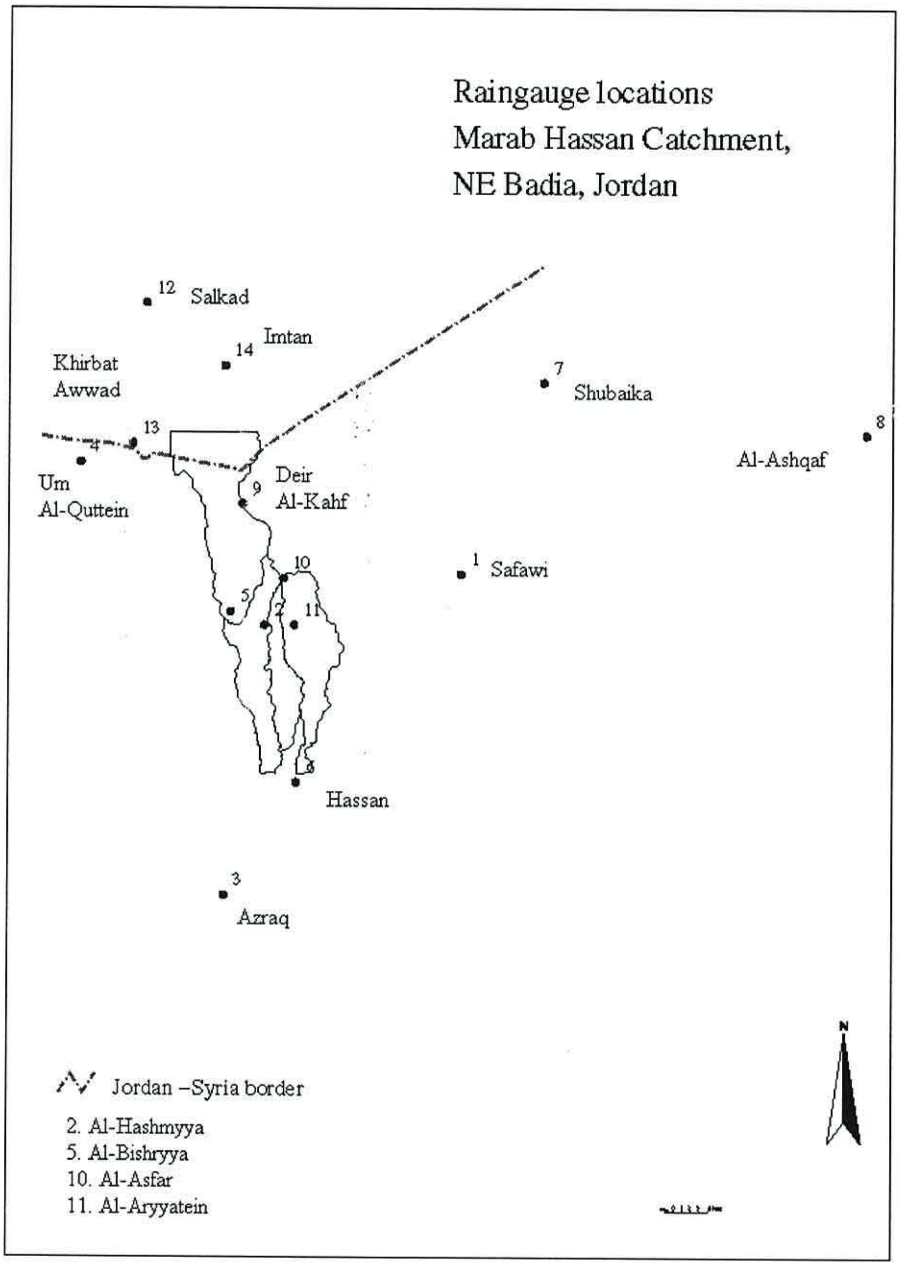


Figure 4.21: Rain gauge distribution within and adjacent to Marab Hassan catchment.

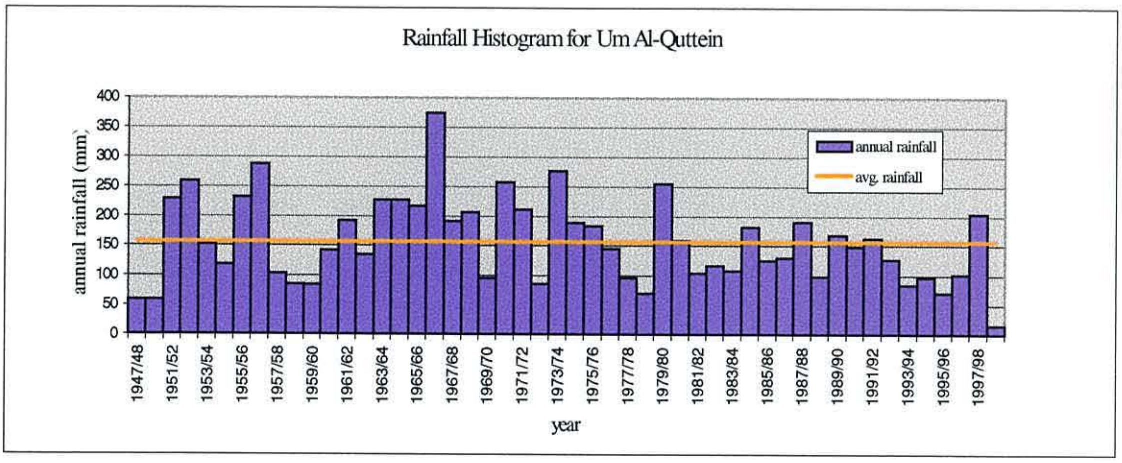


Figure 4.22: Annual rainfall histogram for Um Al-Quttein station.

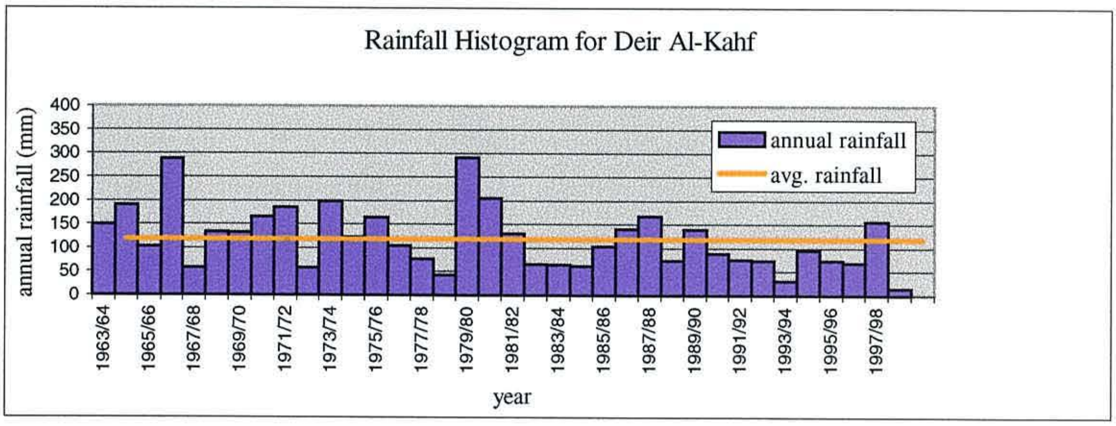


Figure 4.23: Annual rainfall histogram for Deir Al-Kahf station.

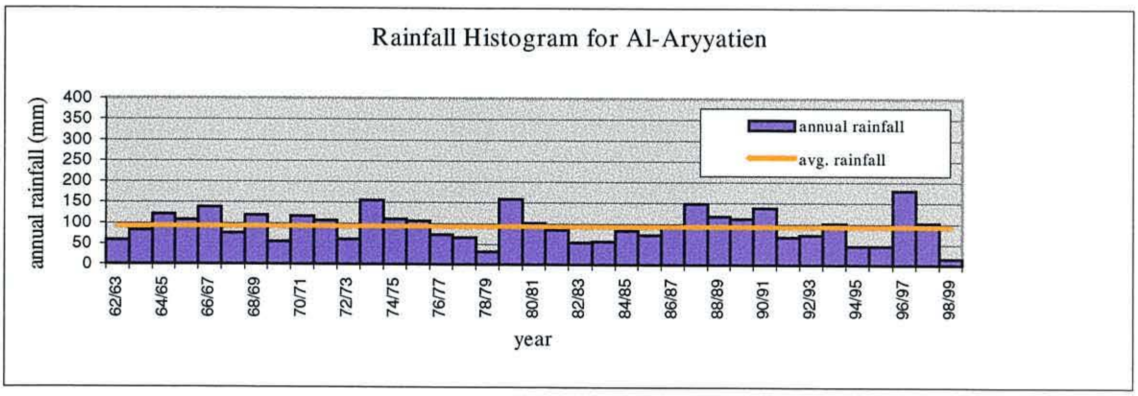


Figure 4.24: Annual rainfall histogram for Al-Aryyatien station.

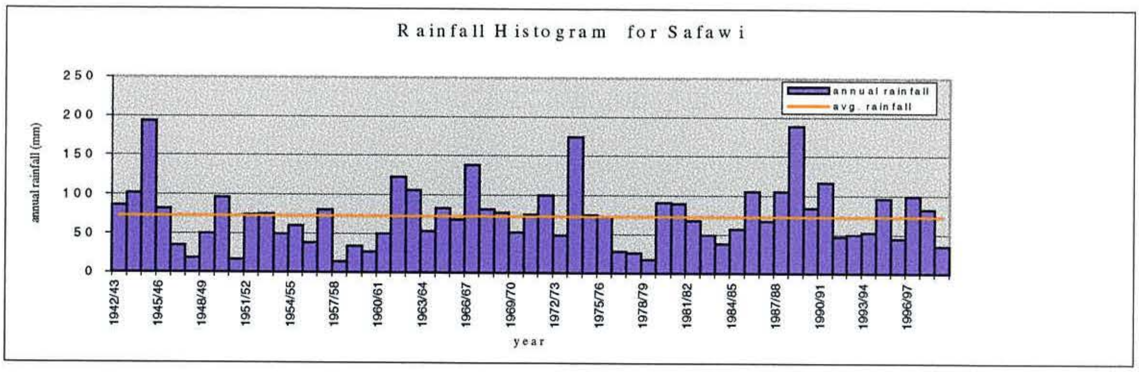


Figure 4.25: Annual rainfall histogram for Safawi station.

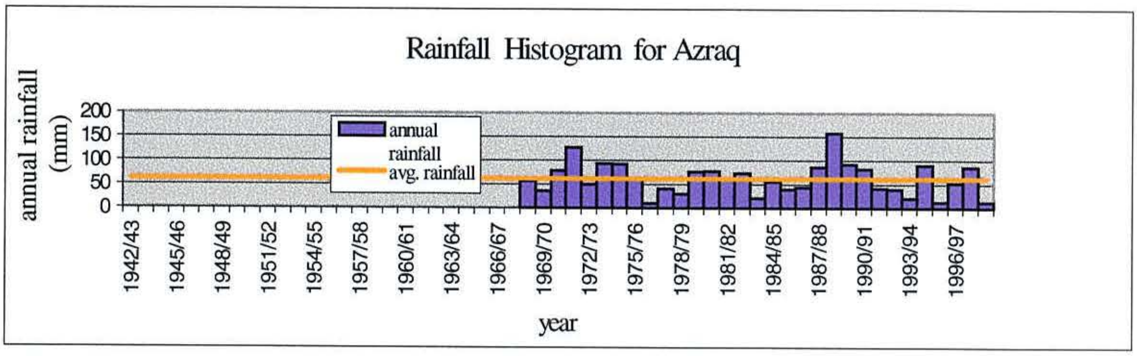


Figure 4.26: Annual rainfall histogram for Azraq station.

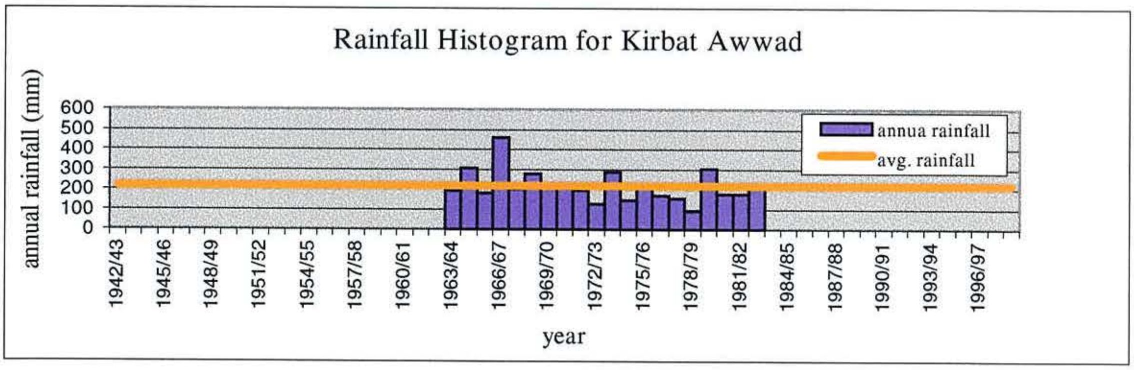


Figure 4.27: Annual rainfall histogram for Kirbat Awwad station.

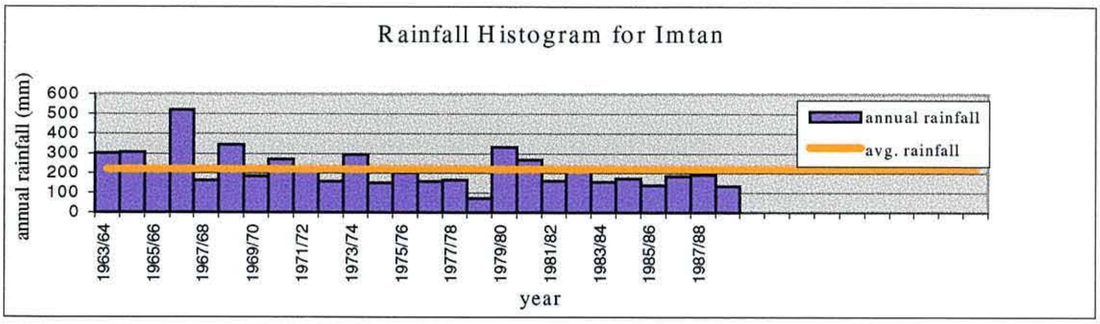


Figure 4.28: Annual rainfall histogram for Imtan station.

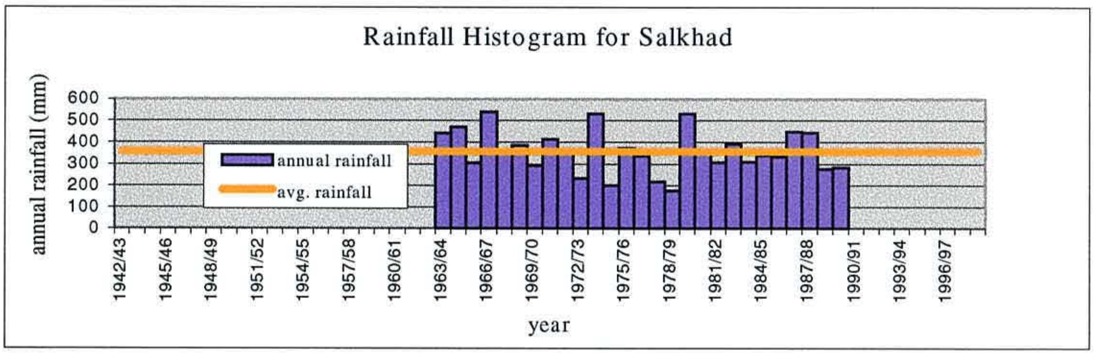


Figure 4.29: Annual rainfall histogram for Salkhad station.

4.10 Reliability of Rainfall Records

4.10.1 Double Mass Curves

Consistency of rainfall records is checked using "Double Mass Analysis" method. Double mass analysis tests the consistency of the record at the station by comparing its accumulated monthly or annual rainfall with the concurrent accumulated values of mean rainfall for a group of surrounding stations. Once the curve is plotted a change in slope indicates that there is a change in the rainfall regime. This change could be due to a change in the gauge's location, a change in local environment at the station, or the absence of the observer for some reason, (Bras, 1990).

Seven gauges have been used in the analysis; four of them are in Jordan and three in Syria. For the Jordanian stations the period of analysis was between 1963 and 1999, and for the Syrian the period of analysis was from 1962 to 1983. This is because the data were only available for all the stations for this period. For two Jordanian stations

(Safawi and Um Al-Quttien) the records are available from early 1940s till 1999, while for the other two (Deir Al-Kahf and Al-Aryyatein) the recording is from the early 1960s till now. For the Syrian stations (Imtan, Kirbat Awwad and Salkhad) the records are only available from 1962 till 1983, due to limited access to data.

The annual double mass curves for both Jordanian and Syrian stations have been developed, as shown in Figures 4.30 and 4.31 respectively. From the figures it is clearly seen that the double mass curve is a good approach that has been used to describe the rainfall pattern. They give a clear indication of the storms origin and movement, as the pattern establishes in Syria and then moves from Northwest to Southeast. Also, they show a broad consistency in data for the Syrian stations that appear to have a constant relationship for most of the months, as a result of relatively large weather systems (i.e. cold fronts) most of the time. The annual double mass curves also indicate the gauges' consistency and confirm the data reliability.

Monthly and annual double mass curves were developed for the mentioned stations. Figures 4.32 and 4.33 show the double mass curves at the middle of the rainy season (January) for the Jordanian and Syrian stations respectively. The relationship is well defined in December, January and February, which indicates the cold fronts effect compared with the beginning of the season (October and November) and the end of the season (March till May). At the beginning of the rainy season (October) the pattern is different as the curves seem to be scattered especially for the Jordanian stations as illustrated in Figure 4.34. While for the Syrian stations the pattern is better defined as shown in Figure 4.35. These give an indication that the cold fronts are established earlier in Syria and do not penetrate to Jordan, i.e. in Jordan the pattern establishes later and stops earlier than in Syria. Also, they indicate that the thunder effect is more dominant in Jordan compared with Syria, as the curves for the Jordanian stations at the beginning and end of season show more scattered pattern, which indicates that it rained in some places and did not in others.

Figure 4.36 shows the double mass curves for the Jordanian stations in May (the end of the rainy season). It can be seen that the curves are patchy, which is due to the localised rainfall pattern that seems to happen at these times of the year. This has been confirmed from both the rainfall distribution maps, as well as the local people who have been interviewed during the questionnaire that took place during the fieldwork in Jordan. For the Syrian stations at the beginning (October) as shown in Figure 4.35 and the end of the season (May) the pattern is more consistent compared with the Jordanian stations as shown in Figure 4.37. The monthly double mass curves for the Jordanian and Syrian stations that are not shown in this section are shown in Appendix B.

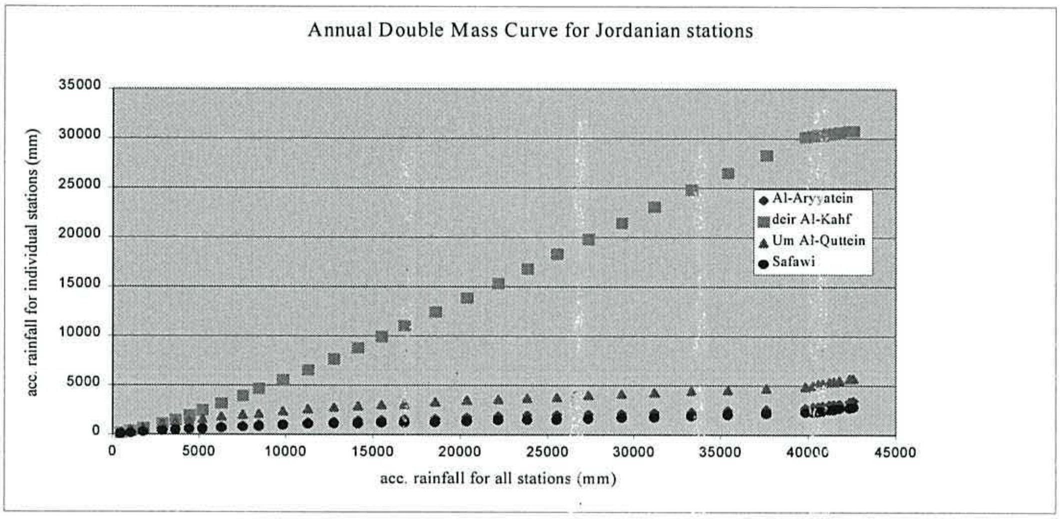


Figure: 4.30: Annual double mass curves for Jordanian stations.

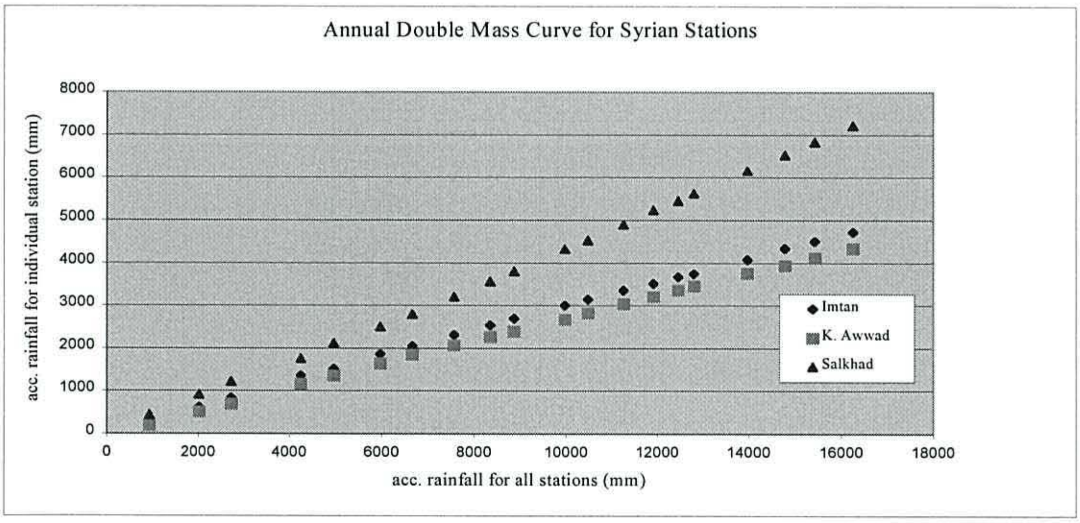


Figure 4.31: Annual double mass curves for Syrian stations.

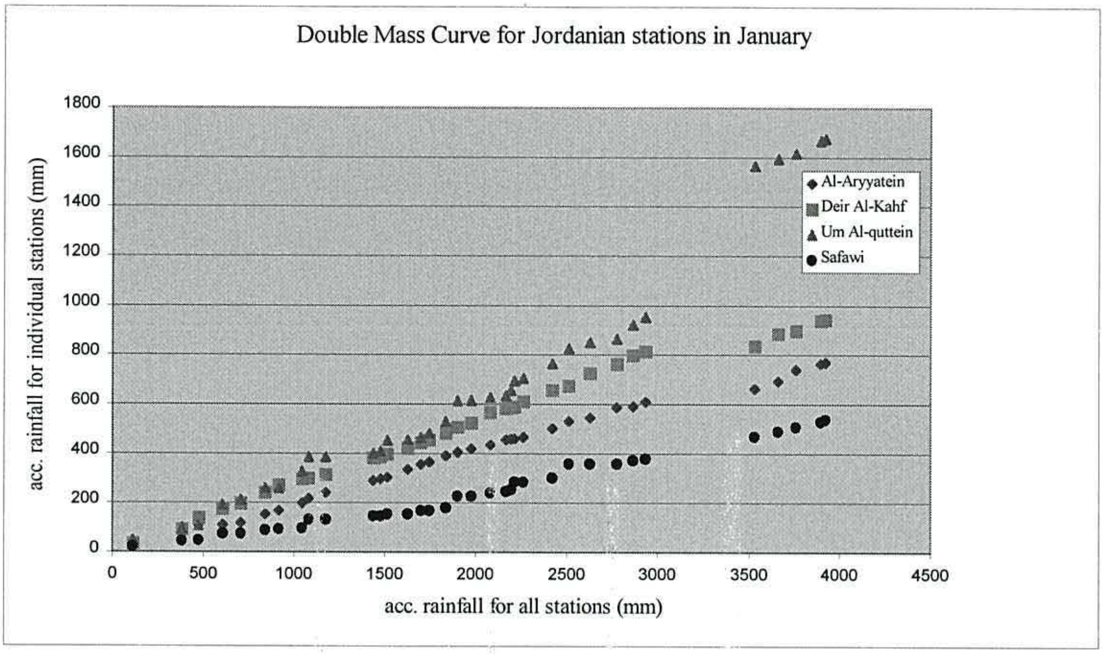


Figure 4.32: Double mass curves for Jordanian stations in January.

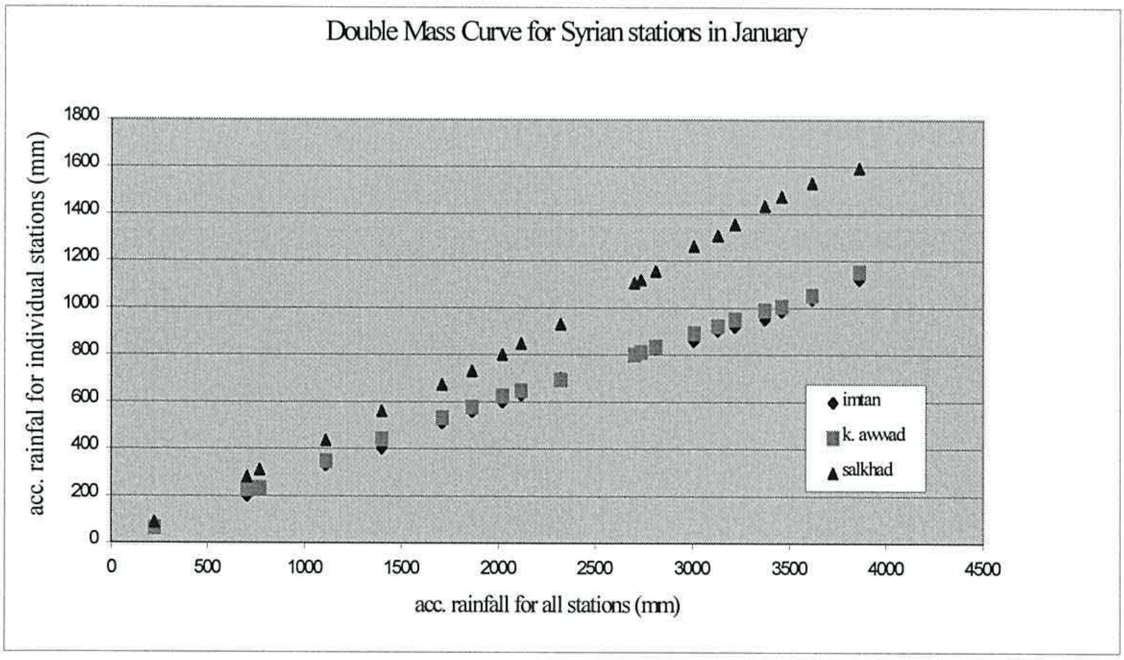


Figure 4.33: Double mass curves for Syrian stations in January.

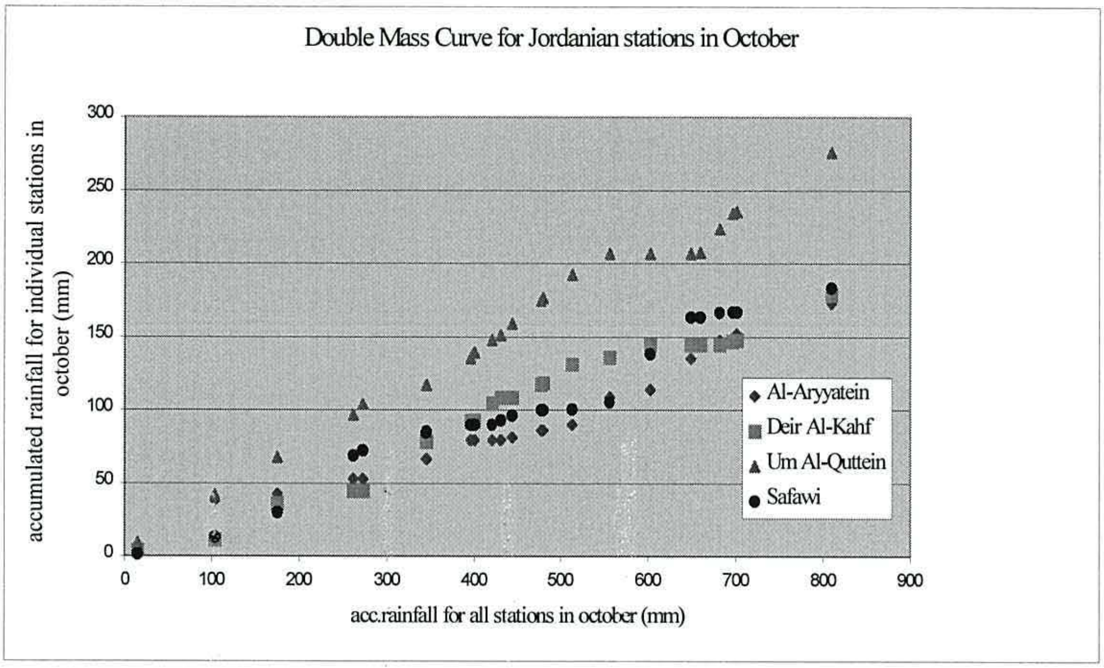


Figure 4.34: Double mass curves for Jordanian stations in October.

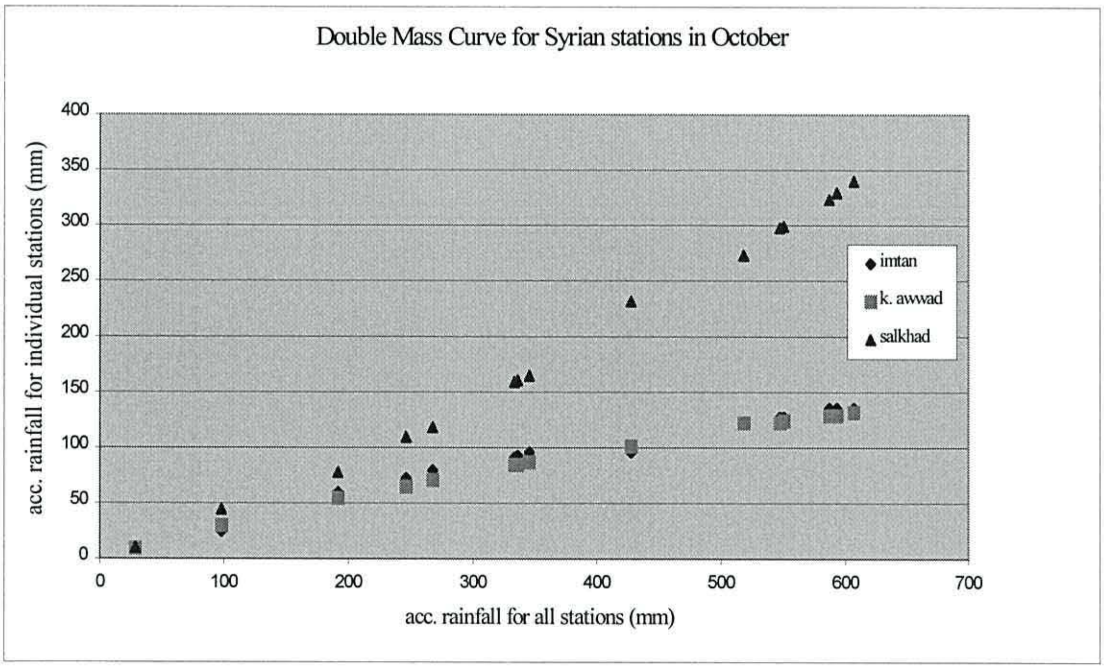


Figure 4.35: Double mass curves for Syrian stations in October.

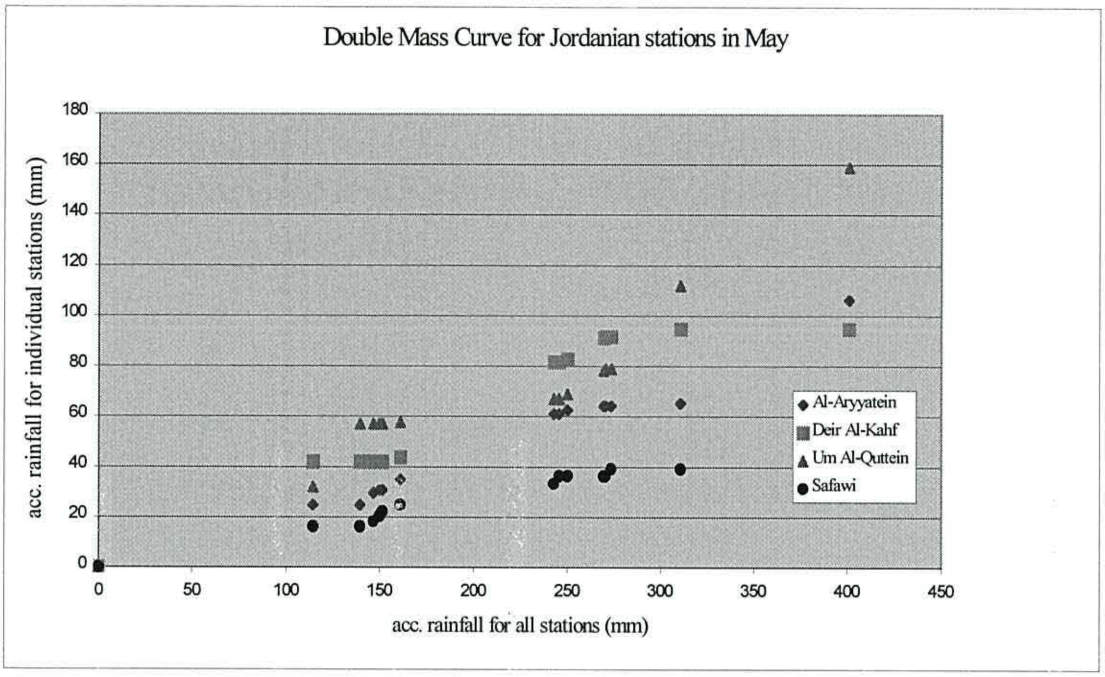


Figure 4.36: Double mass curves for Jordanian stations in May.

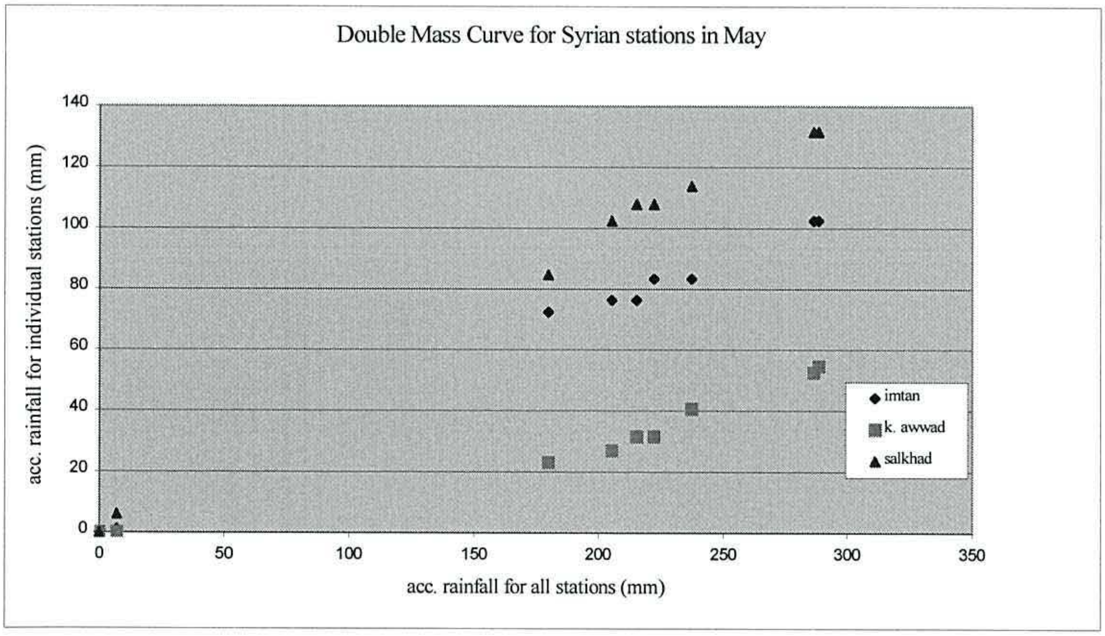


Figure 4.37: Double mass curves for Syrian stations in May.

4.10.2 Departure from Annual Average Rainfall

Departure from the annual average rainfall means how much the rainfall amount is away from the average value. It is calculated by subtracting the rainfall value from the average value for each station. Also cumulative departure from the average could be calculated by adding the departure values together keeping negative and positive signs. The departure from the annual rainfall and cumulative departure from the annual average curves have been plotted for all the stations. For Um Al-Quttein and Safawi that have the longest records (1947-1999) the curves have been developed, and then for all the station the same curves have been developed but by only taking the data set from 1963 till whatever time each gauge has got records. It can be clearly seen that the plotted cumulative departures are fluctuated above and below the zero. Also for the cumulative departure from the average curves the fluctuation is found and in some times it indicates that there is a rainfall deficit, which means that the year is a dry year, it gives some indication of batches of dry or wet years. Quantitative measures such as the departure from annual rainfall method and qualitative approaches like participatory rural appraisal have been used to define the dry years in the northeastern part. Figures 4.38 to 4.44 show the departure and cumulative departure from the annual average rainfall for both Jordanian and Syrian stations.

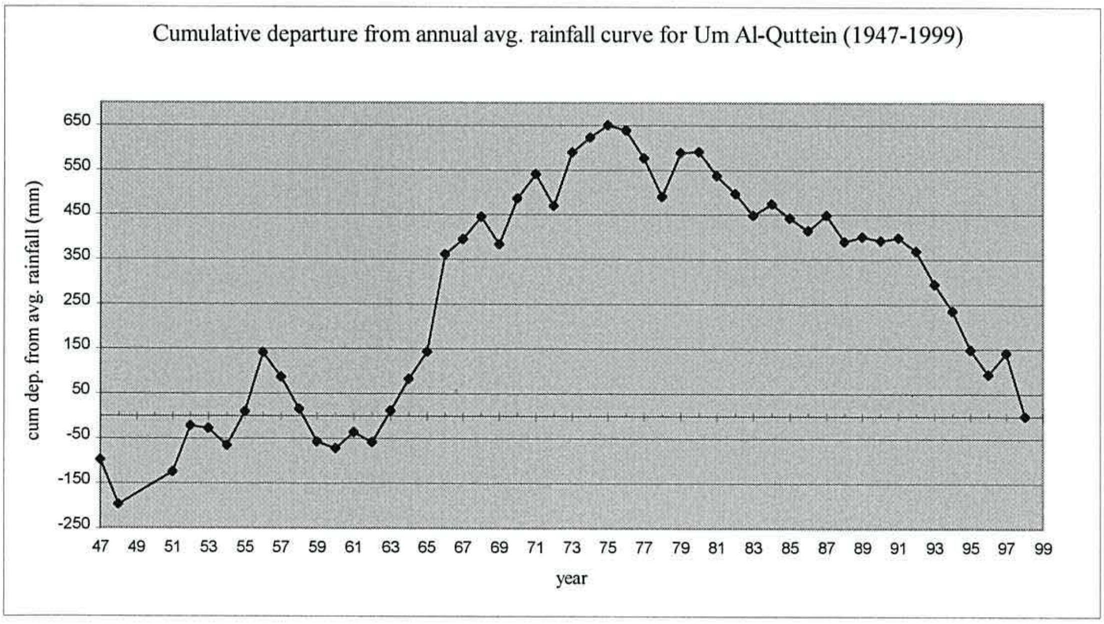


Figure 4.38: Cumulative departure from annual rainfall for Um Al-Quttein station.

Figure 4.38 shows the cumulative departure from annual rainfall for Um Al-Quettein. From the figure it is shown that phases of dry and wet years were experienced in the area between 1947 and 1999. For example, the turning point at 1948 indicates an entry in a wet phased that lasted until 1957 where a dry phase started and lasted until 1961, then in 1963 a new wet phase started and ended in1975, which was a new entry of a long dry phase.

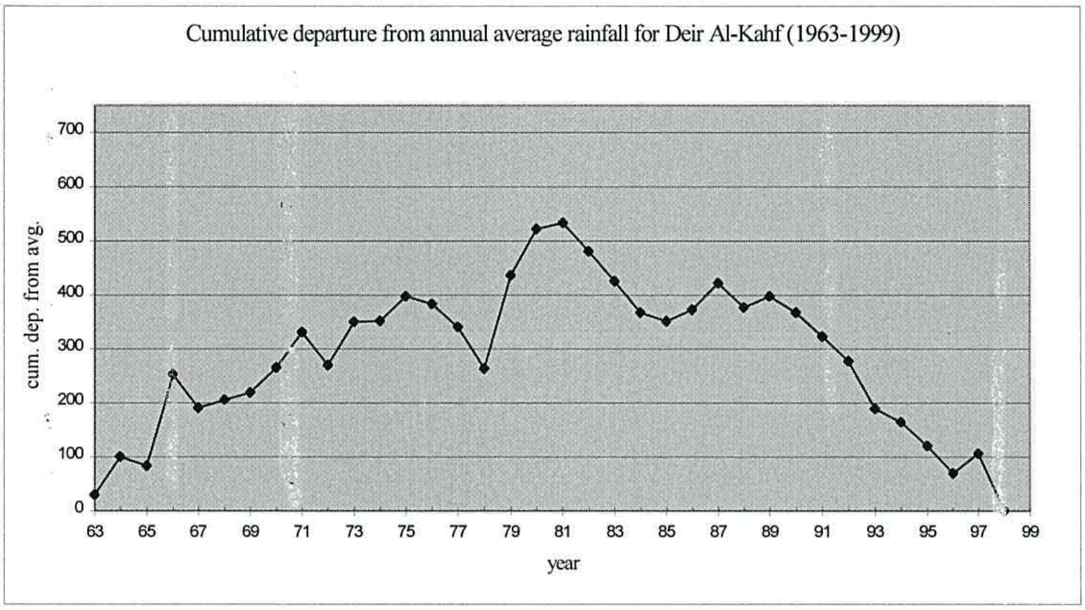


Figure 4.39: Cumulative departure from annual rainfall for Deir Al-Kahf station.

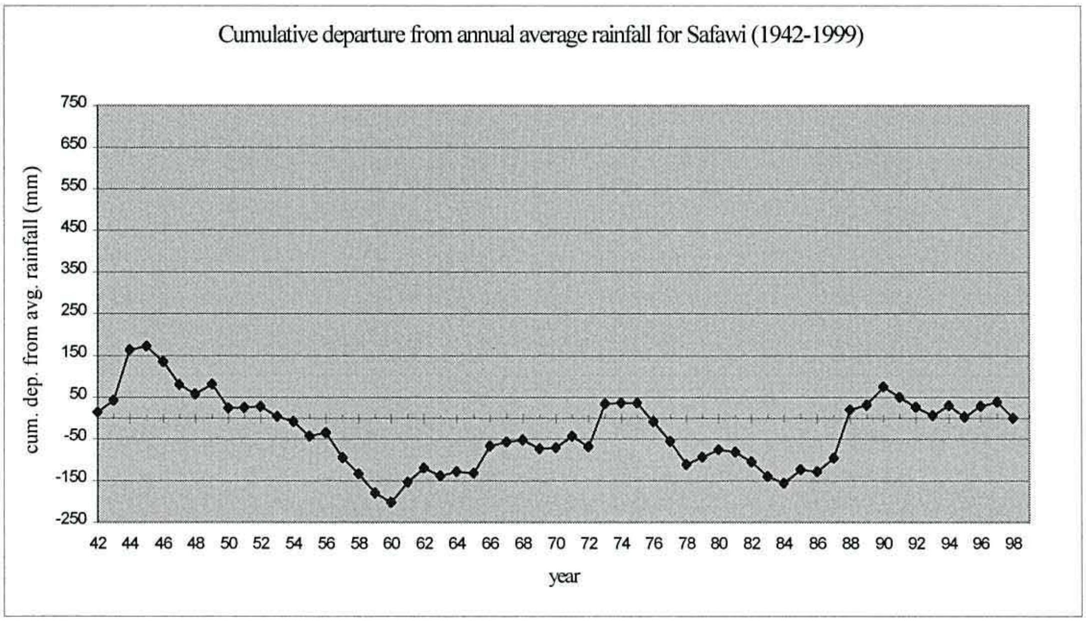


Figure 4.40: Cumulative departure from annual rainfall for Safawi station.

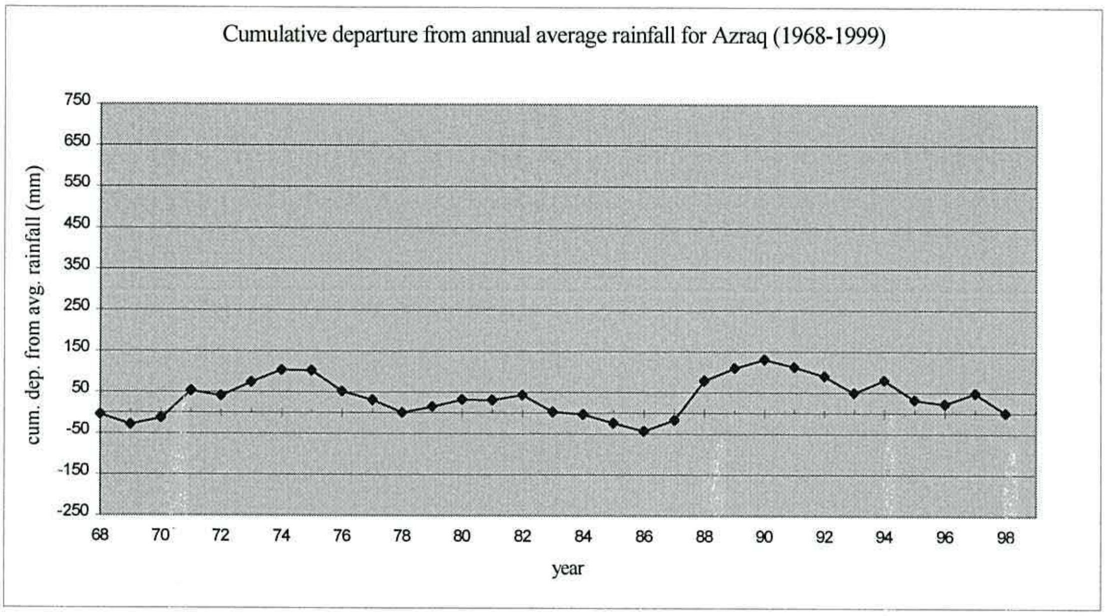


Figure 4.41: Cumulative departure from annual rainfall for Azraq station.

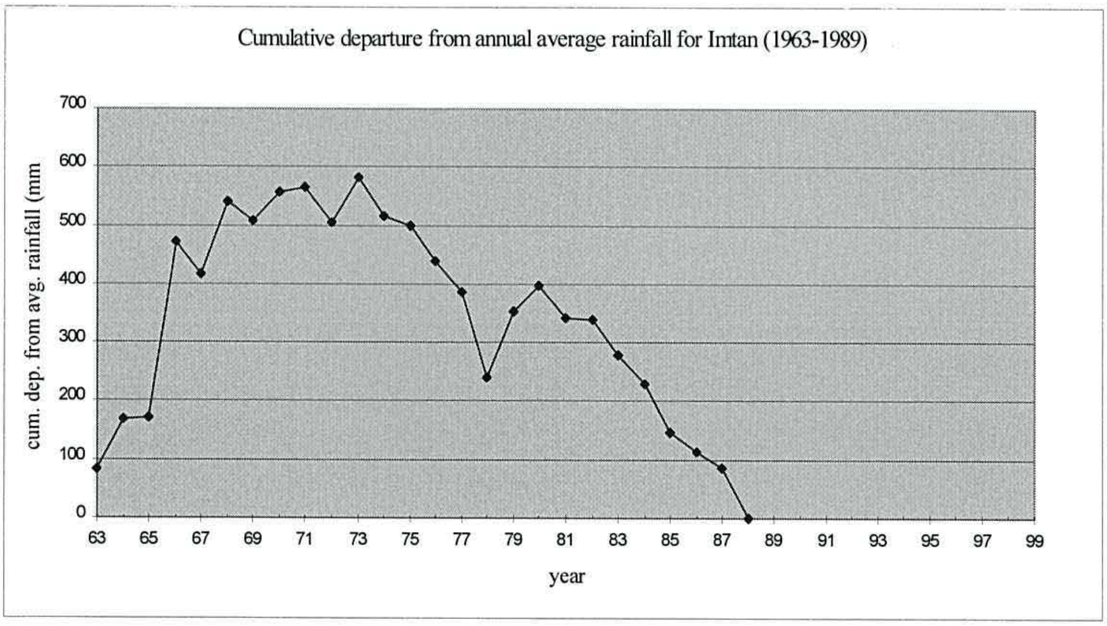


Figure 4.42: Cumulative departure from annual rainfall for Imtan station.

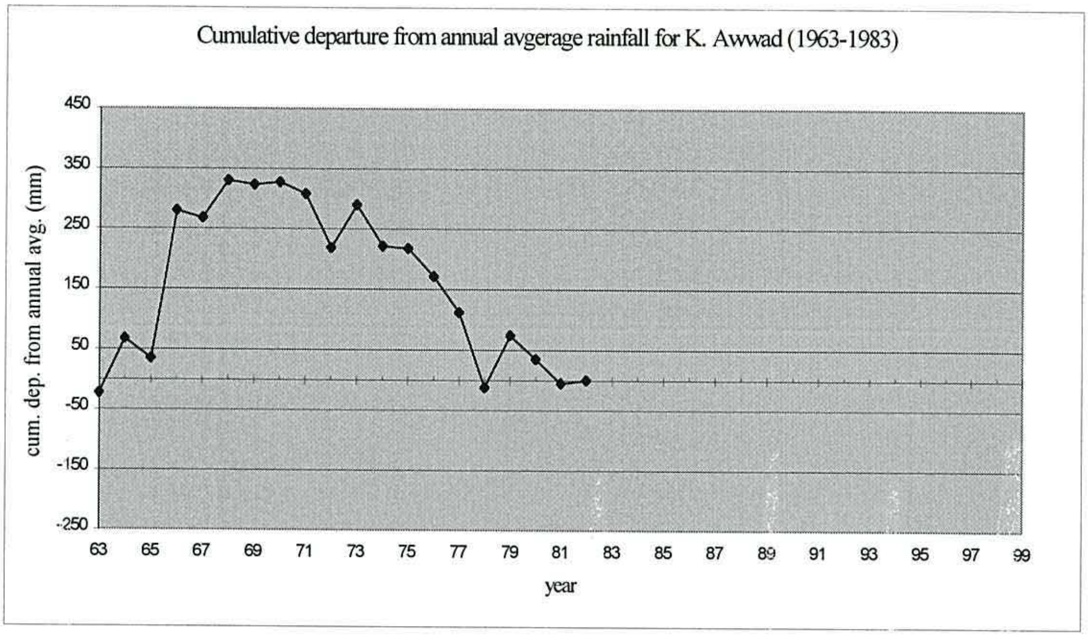


Figure 4.43: Cumulative departure from annual rainfall for Kirbat Awwad station.

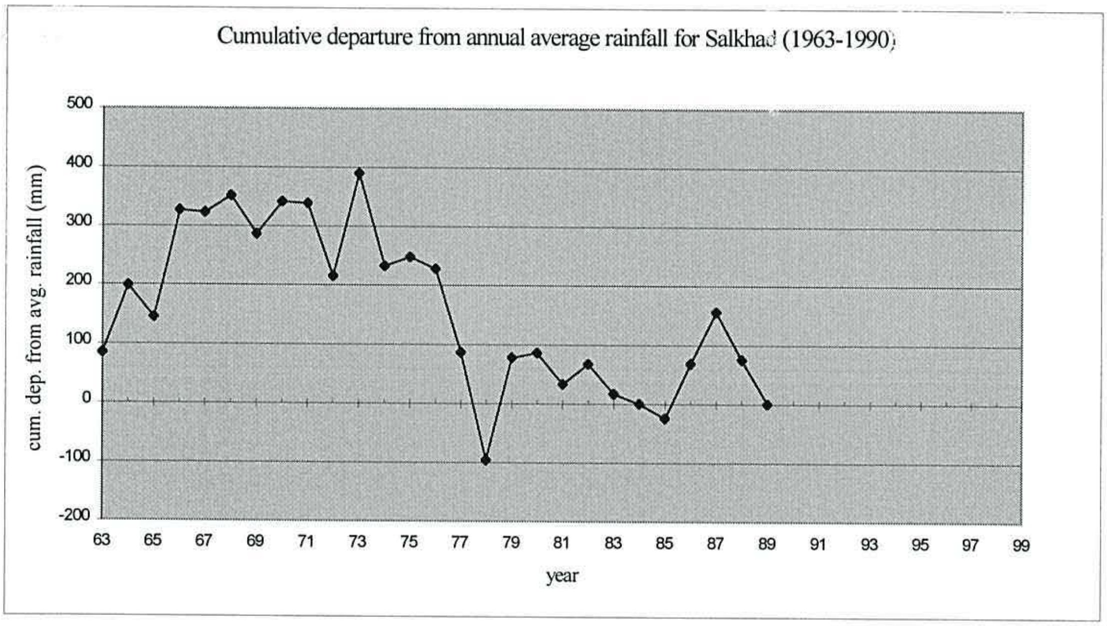


Figure 4.44: Cumulative departure from annual rainfall for Salkhad station.

4.11 CONCLUSION

Chapter Four has discussed the rainfall in Jordan in the past and present times, also it described the rainfall variability in Jordan. The rainfall in the Badia area in terms of types, variability in time and space and the long-term trend was also discussed in detail. Finally *Marab* Hassan catchment rainfall was described with some quantitative measures that were used to check the gauges consistency and the reliability of the rainfall. The double mass analyses with the aid of the PRA (as will be discussed in Chapter Eight) have checked the rainfall patterns. It can be concluded that rainfall is more reliable in the northwest with longer winter season, as going southeast the rainfall decreases and the season becomes shorter.

The rainfall intensity in the area is variable, according to the event type and timing. Those events with high and very high intensity (Section 4.10) are responsible for the flood events in the catchment area. This indicates the spatial and temporal variability of rainfall in the Badia area.

From the quantitative analyses and the PRA approach it is concluded that there three types of rainfall in the Badia area, which are convective type that is experienced at the beginning and the end of the rainy season (i.e. October and November, and March until May respectively). The second type is the orographic rainfall that is associated with Jebal Al-Arab stations in the northwest. Finally, the cold front type of rainfall that occurs in the middle of the rainy season, (December to February).

Chapter Five will talk about the runoff generation in general, with an emphasis of describing some of the synthetic approaches that have been used to develop the catchment's unit hydrograph.

CHAPTER FIVE

CATCHMENT RUNOFF AND RAINFALL-RUNOFF MODELLING

5.1 INTRODUCTION

Rainfall and runoff are the most important means that control all the issues that are related to water resources development and planning. This chapter concentrates on the relationship between the rainfall and runoff for the catchment area of Marab Hassan itself. Sections 5.2, 5.3 and 5.4 describe the catchment runoff, sources and types of runoff and factors that affect it. Arid lands runoff and runoff generation in general is discussed in section 5.5. Rainfall-runoff modelling methods are discussed in section 5.6. Sections 5.7, 5.8 and 5.9 talk about the general aspects of hydrologic modelling, the unit hydrograph theory and Muskingum flow routing technique respectively. Synthetic unit hydrograph approaches with their applications to Marab Hassan catchment area are discussed in detail in sections 5.10 and 5.11. Finally, excess rainfall calculation using an experimental approach of runoff plots is described in section 5.12.

5.2 CATCHMENT RUNOFF

Runoff is a key factor in water resources management. In the literature runoff is defined in different ways, some of which are mentioned below.

- Runoff can be defined as the final phase of the hydrologic cycle and is the returning surplus of precipitation to the ocean. This definition clearly means that runoff is the water remaining from precipitation after the losses from evaporation, transpiration and seepage into the groundwater. (Foster, 1948)
- According to (Ward & Robinson, 1990) runoff may be variously referred to as a stream or river discharge or catchment yield, and is normally expressed as a volume per unit time.
- The above leads to the definition of the catchment yield as that volume of water available from a stream at a given location over a specified period of time, (Raudkivi, 1979).

- Colman, (1953) stated that precipitation is the source of water yield, and the amount of water released as a surface runoff is that proportion of the rainfall remaining after certain demands are satisfied, including absorption and storage by the soil and evaporation from land, vegetation and water bodies.

5.3 Sources and Types of Runoff

The main source of all runoff types is rainfall, snow or hail, (Foster, 1948). Runoff can be categorised in many ways, some of which are mentioned below. According to (Ward & Robinson, 1990) the runoff can be grouped into three main groups, as shown in Figure 5.1.

- Direct runoff that is the sum of channel precipitation, surface runoff and rapid throughflow (shallow subsurface flow). Direct runoff represents the major runoff contribution during storm periods and most floods.
- Baseflow or base runoff is the sum of groundwater runoff and delayed throughflow.
- Throughflow is the water that infiltrates and moves laterally through the upper soil horizon towards the stream channels, either as unsaturated flow or usually as shallow perched saturated flow above the main groundwater level.

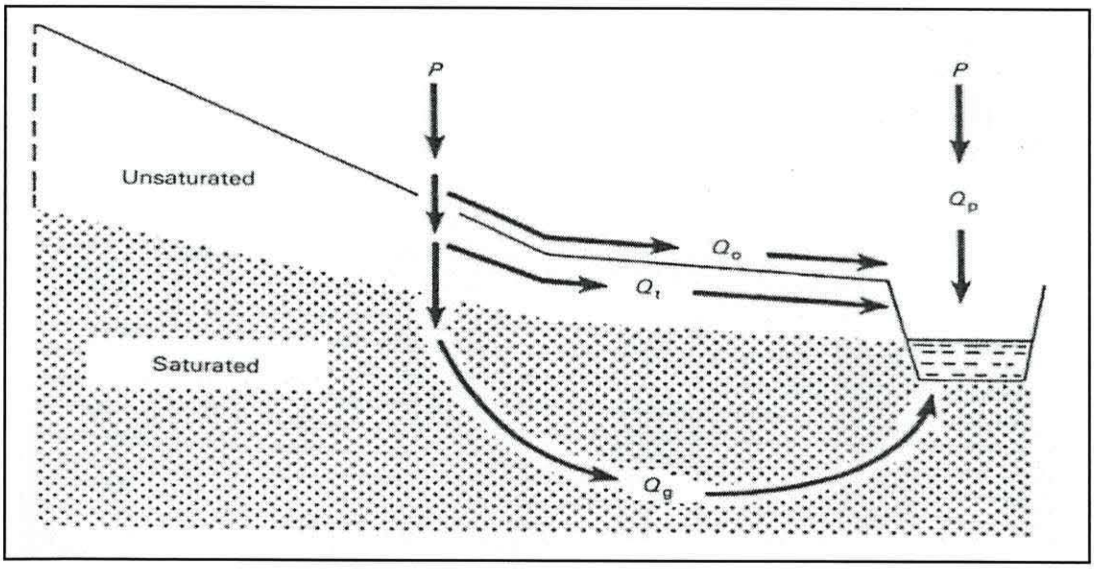


Figure 5.1: Flow paths of the sources of stream flow: Q_p is direct precipitation onto the surface, Q_o is overland flow, Q_t is throughflow and Q_g is groundwater flow, (Source: Ward and Robinson, 1990).

There is another classification by the United States Department of Agriculture (USDA, 1972), which classifies runoff into four classes.

1. Channel runoff that occurs when rain falls on a flowing stream or on the impervious surfaces of a streamflow measuring installation.
2. Surface runoff that can only occur when the rainfall rate is greater than the infiltration rate.
3. Subsurface flow, this type of flow occurs when infiltrated rainfall meets an underground zone of low transmission, travels above the zone to the soil surface downhill and appears as a seep or a spring.
4. Baseflow occurs when there is a fairly steady flow from natural storage. The flow comes from lakes or swamps, or from an aquifer replenished by infiltrated rainfall or surface runoff, or from bank storage, which is supplied by infiltration into channel banks as stream water level, rises and which drains back into the stream as the water level falls.

In flood hydrology the first three types are combined together as direct runoff, and all the types do not regularly appear in all catchments. Climate is one indicator of the probability of all the types. In arid zones the flow on smaller catchments is all sub-surface flow, as most of the water infiltrated in the ground before any surface runoff forms. While in humid regions it is generally more of the surface type as the ground surface is almost saturated that helps to generate runoff faster.

5.4 Factors Affecting Runoff Generation

Runoff is affected by the physical characteristics of the catchment and climate, (Wilson, 1990; Raudkivi, 1979). The primary physical characteristics of the catchment are: area or size, shape, altitude, slope and aspect, soil type, geology, drainage or channel stream, water storage capacity and vegetation cover.

Langbein et al. (1947), considered the climatic factors and soil-vegetation complex as variables that exercise their principal influence on the volume of runoff. The topography of the catchment is a sensibly permanent or constant characteristic, (Potter, 1953), which influences mainly the concentration or time distribution of the discharge from a drainage basin, (Langbein et al., 1947).

First of all, the definition of the catchment has to be known. The catchment is an area within a closed curve lying in the land surface, such that all the surface runoff is produced by precipitation falling on this area (Raudkivi, 1979). Another definition made by Wilson, (1990) is that the catchment area is the whole land and water surface area contributing to the discharge at a particular stream or river cross-section, from which its clear that every point on the stream channel has a unique catchment of its own.

5.4.1 Constant characteristics of the catchment

The morphology of the catchment as illustrated in Figure 5.2 is important in shaping the runoff response, (Jones, 1997).

a) The size of the catchment affects the runoff amount as well as the lag time between rainfall and peak runoff. The larger the catchment the higher the peak discharge or runoff, (Open University, 1995; Jones, 1997), as shown in Figure 5.2(a).

b) Catchment shape affects the runoff hydrograph and this can be accumulated if the rainstorm does not cover the whole catchment at once, or if it moves over it from one end to another, (Wilson, 1990). From Ward & Robinson, (1990) consider that the shape is important particularly in association with the nature of the channel network. As shown in Figure 5.2(b) where a high bifurcation ratio is associated with a long, narrow catchment, flood peaks may be low and attenuated especially with a storm moving upstream with a low bifurcation ratio will generate higher and sharper flood peaks. Bifurcation ratio is more or less related to the drainage density and the number of streams in the network.

c) The slope of the catchment is a major control of peak flow but it is a factor, which is difficult to interpret meaningfully, (Chorley, 1971). As shown in Figure 5.2(c) the steeper the slope the faster the runoff generation, because this affects the time needed for the water to flow, (i.e. the greater the slope the less the time), which means that the higher the peak of the hydrograph, (Wanielista et. al., 1997; Jones, 1997).

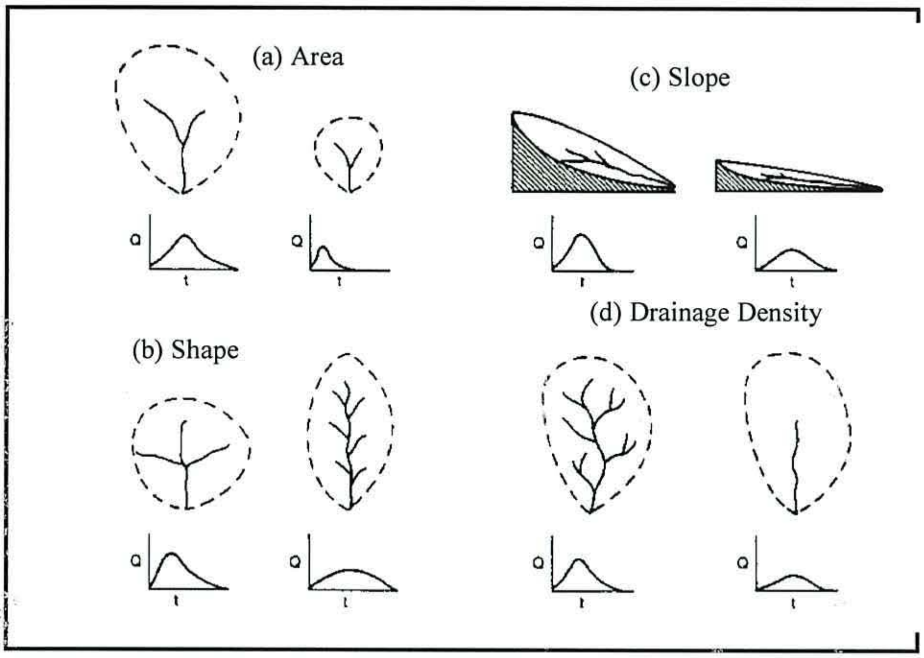


Figure 5.2: Catchment morphology ((a) Area, (b) Shape, (c) Slope, (d) Drainage Density) and its effect on runoff, (Source: Jones, 1997).

d) Stream channel slope.

The slope of the channel affects the velocity of the flow, (Linsley et al., 1988). Which influences the runoff volume as it appears in the formula.

$$Q = V.A \qquad [5.4.1]$$

Where:

Q is the discharge (runoff volume/time)

A is the cross-sectional area of the channel.

V is the flow velocity.

The above formula is a general one, but it can be specified by the way that the velocity is calculated. Manning's formula can be used to calculate the discharge for ungauged catchment by knowing the cross-sectional area of the stream channel (A), its slope (S), the roughness or Manning's coefficient (n) and the hydraulic radius (R), (Wilson, 1990) and (Foster, 1948).

$$Q = \left[AR^{2/3}S^{1/2}\right]/n \qquad [5.4.2]$$

R equals the cross-sectional area of the stream channel divided by the wetted perimeter.

Values of Manning's coefficient can be taken from tables like Table 5.1 below, or can be calculated, depending on selecting the base value for n and then correcting it for five factors. The five factors are; the degree of regularity of the surface, the character of variation in the size and shape of cross sections, the presence of obstacles and their characteristics, the effect of vegetation on flow and finally the degree of channel meandering, (McCuen, 1989).

Table 5.1: Typical values of Manning's coefficient, (Source: Wilson, 1990)

Type of Channel	n
Smooth timber	0.011
Cement-asbestos pipes, welded steel	0.012
Concrete-lined (high quality formwork)	0.013
Brickwork well-laid and flush-joined	0.014
Concrete and cast iron pipes	0.015
Rolled earth brickwork in poor condition	0.018
Rough-dressed stone paved, without sharp bends	0.021
Natural stream channel, flowing smoothly in clean conditions	0.030
Standard natural stream or river in stable condition	0.035
River with shallow meanders noticeable aquatic growth	0.045
River or stream with rocks and stones, shallow and weedy	0.060
Slow flowing meandering river with pools, slight rapids, very weedy and overgrown	0.100

Note that there is a divergence between Manning's original concept of roughness as a function of the bed size, and current usage, which tends to use Manning's "n" as a lumped parameter and "builds in" considerations of channel meanders and vegetation.

e) Catchment topography, i.e. the altitude and the aspect (the slope direction) of the catchment both affect the amount and type of precipitation, which plays and important role in runoff generation as will be discussed later. Catchment topography for the whole catchment is considered as a constant parameter, while it can be variable from one point to another within the catchment.

f) The geology of the catchment plays an important role in the amount of runoff as well as its type. One of the major geological features is the permeability of the rocks. An impermeable catchment will produce higher peak discharges and lower flows at other times. In a permeable catchment, with a greater base flow contribution, there is less variation in discharge (Open University, 1995). The occurrence of the faults within the system also affects the groundwater recharge.

5.4.2 Variable characteristics of the catchment

Variable characteristics of the catchment are soil type, vegetation cover and climate of the catchment. The effects of these parameters appear in different ways, (Ward and Robinson, 1990).

i) Soil type affects the soil permeability. This affects the surface runoff amount, an impermeable catchment will produce a higher runoff amount, and while in a highly permeable one most of the rainfall will contribute to the groundwater. Linsley et al., (1988) show that low permeability soil encourages surface flow, while a thick soil mantle, even though permeable may retain so much water as soil moisture that little or non of it can reach the groundwater.

ii) The vegetation cover is an important factor in determining the catchment water yield. Vegetation cover and land use affect the infiltration rate, so as a result the runoff within the catchment will be affected. The type of land cover determines the runoff volume. For example, in a forest area the runoff volume is less than in a grassland area. This is because of the interception of raindrops by the forest trees leaves, tree roots and litter that prevent it from reaching the ground. A study done by the author proved that the land cover has a clear effect on runoff volume. This study was on Cwm Pennant catchment (of an area of 32 km^2) in Wales. It was noticed that the runoff volume is decreased by about 30 % when the author assumed that the grassland is changed by forest.

According to Colman, (1953) the role of vegetation cover with regards to the water yield is paradoxical. On the one hand it increases the usable water yield by holding down erosion, facilitating water to flow by reducing the evaporation from the soil surface. On the other hand, it reduces the total yield by facilitating the return of water to the atmosphere through interception and transpiration.

iii) Climatic factors that directly affect the catchment yield are those related to rainfall and evaporation.

First of all, the precipitation affects the yield from different aspects. Rainfall intensity and duration also affect the runoff. Runoff occurs only if the rainfall intensity (depth of rainfall/unit time) exceeds the infiltration loss, (Raudkivi, 1979). Since intensity is depth/time it cannot be considered separately from the duration. The same depth of the rainfall delivered over two different durations will produce different runoff rates, (Wilson, 1990). Besides intensity and duration, average annual rainfall influences the runoff amount, which is more or less rainfall dependent, that is, actually depends on the climate of the catchment. For example, in temperate maritime zones like the UK rainfall occurs throughout the year, and the evaporation rate in summer is greater than that in winter, so this affects the runoff amount during the summer time, (Open University, 1995). While, in arid and semi-arid regions where the rainfall is low and the evaporation is high, the runoff occurs from storms of high intensities and short duration, (FAO, 1981).

Rainfall distribution and direction of the storm movement also affect the catchment yield, especially the peak runoff. Rainfall near the outlet will result in a peak near the start of the storm; also storms moving downstream toward the gauging station generally produce a greater peak relative to movement in the opposite direction, (Wanielista et al., 1997).

Evaporation rate is an important factor in water resources evaluation especially in the calculation of the catchment water balance. Evaporation is a function of solar radiation, wind speed, relative humidity and temperature. It can be said that all these factors affect the runoff indirectly through the evaporation. Evaporation is relatively more important in the long-term water balance.

As a conclusion both the constant and variable characteristics of the catchment affect its yield. It cannot be said that any one is more important than the others, but all of them have an integrated effect on the catchment water yield. These characteristics can be used, as we will see later on in catchment runoff modelling, in what is called physically based catchment model.

5.5 Runoff Generation in Arid Lands

5.5.1 General Description

Aridity is a climatic phenomenon due to the lack of moisture. According to Agnew & Anderson, (1992) there are several classifications of the arid lands depending on different climatic definitions.

Classical approach: - it uses a combination between the rainfall and plant growth to define an arid area. A 100mm of rainfall is considered a boundary condition for deserts and 600mm for semi-arid regions.

Climatic indices: - like the ones employed by Köppen, (1931) and Thornthwaite, (1948). Köppen's classification relates the temperature and rainfall and puts them into an index. For arid boundary the index value is less than 1, and for semi-arid boundary it ranges between 1 and 2, as shown in the formulae below:

$$\text{Aridity Boundary} = \frac{P}{T} < 1$$

$$\text{Semi-arid boundary} = 1 < \frac{P}{T} < 2$$

P = mean annual rainfall (cm)

T = mean annual temperature (°C)

Thornthwaite's classification takes into account the moisture available to the plants as an index of aridity, determined by a water balance calculations for rainfall and evaporation.

Arid boundary: Im < -66.7

Semi arid boundary: -33.3 > Im > -66.7

$$\text{Im} = 100\left[\left(\frac{P}{P_e}\right) - 1\right] \qquad [5.5.1]$$

P = mean annual rainfall (mm)

P_e = mean annual potential evapotranspiration (mm)

UNESCO's classification considers the same factors as Thornthwaite's, but it represents them in a different manner to end up with an arid and hyper-arid boundary of an index less than 0.2 and for semi-arid boundary for a value range between 0.5 – 0.2.

$$\text{Arid hyper-arid boundary: } \frac{P}{ET_p} < 0.2$$

$$\text{Semi-arid boundary: } 0.2 \leq \frac{P}{ET_p} < 0.5$$

P = mean annual rainfall (mm)

ET_p = mean annual potential Evapotranspiration (mm)

According to Chow (1964) arid means dry or parched and the primary determinant of aridity is the lack of rainfall. Another definition of aridity is that stated by Yair and Lavee (1985). They defined the aridity as a lack of moisture, but it is essentially a climatic phenomenon based upon the average climatic conditions over the region.

Precipitation in arid zones results largely from storm lines and convective cloud mechanisms, producing storms typically of short duration, with relatively high intensity and limited areal extent. However, low intensity frontal type rains are sometimes experienced usually in the winter season. Where most of the precipitation occurs at this time of the year, as in Jordan and in the Negev desert, relatively low intensity rainfall may represent the greater part of annual rainfall (FAO, 1981). Rainfall in arid lands is infrequent and highly irregular but when it does occur it is a very significant event (Heathcote, 1983). In spite of irregularity and low intensity of rainfall in arid lands, rainfall events can generate runoff because of the nature of the desert surface conditions.

Arid land rainfall is mainly characterised by variability of both space and time as we discussed before. The phenomenon of localised nature of convective storms is common, and it is believed that it is the major mechanism that generates floods in arid areas.

Another characteristic of rainfall events in arid zones is the general independence of events. Rain that falls during a specific period of time is not affected by the rainfall that occurred during previous periods, i.e. intervening periods between events are so long that leave no residual baseflow as well as establishing a soil moisture deficit. This characteristic is noticeable in Jordan especially at the beginning and the end of the rainy season, where the rainfall is associated with thunder storms.

5.5.2 Arid Lands Runoff

Much of the rain falling on the desert surfaces is absorbed by the porous mantle of the soil and rock waste, or is lost by evaporation. Since, desert rainfall is naturally infrequent and often short lived, these initial losses are proportionally greater than in humid areas. So that "in general" percentage runoff tends to decrease with decreasing annual rainfall and is less than 10% in most arid zones (Chow, 1964). This means that many rains do not cause any runoff. Also, runoff may disappear within the catchment especially if the storm is short.

Within the arid zones runoff typically occurs in the form of short, isolated flows generated by direct storms (Agnew & Anderson, 1992). Generally speaking runoff occurs in arid zones when the conditions are favourable, such as on soil of low permeability and/or steep slopes. Runoff generation in arid zones is affected by different factors; some of them are mentioned below.

The first important factors are the rainfall characteristics, as the rainfall intensity and duration are very important. The rainfall intensity may be more important than the total amount of rainfall. Generally speaking the lower the rainfall intensity the larger will be the time to the soil to reach saturation, so the longer the time needed to initiate runoff generation (Scoging, 1989), also the runoff will tend to increase with the duration of the fall. In other words the thunder type of rainfall as discussed in Chapter Four is very important and most of the time it causes runoff, compared with the frontal type of rainfall that does not contribute that much to runoff generation.

Another factor important in arid lands is the surface property. One of the major characteristics of arid lands is the crust formation. Crust is formed by raindrops, which destroy the surface soil aggregates and gradually form a continuous crust with a much lower hydraulic conductivity, so this increases the runoff generation, (Kirk, 1997). The crust is very thin (1 mm) and can be described as a membrane on the soil surface (Morin & Benyamini, 1977; Agassi et al. 1996). Also, in the absence of the dense vegetation the nature of the surface is an important factor in controlling the amount and character of runoff (Chow, 1964). Crust dominates most of *Marab* Hassan catchment area, where after rainfall the soil particles form a solid layer that acts like an impermeable membrane, which enables runoff generations and reduces infiltration.

The geology and soil properties of the area affect the runoff. For example, if the area is characterised by fractures which play an important role in seepage losses. The soil type, its storage capacity, antecedent moisture content and infiltration properties have an effect on runoff generation in arid zones (Scoging, 1983). These properties affect the transmission losses through the wadi bed and sediment transport as well. Transmission losses have a significant influence on water yield and shape and the size of the runoff hydrograph. Transmission losses can be calculated based on the type of relationship between the runoff volume and different parameters, from which the hydraulic conductivity of the channel alluvium is an important factor (Lane, 1982).

According to Reid and Frostick (1989) the rate of transmission losses depend upon the porosity and depth of the channel fill, as well as the hydraulic conductivity of its least permeable layer in relation to the length of the flood period. Most of the rainfall in arid regions is lost by evaporation, so because of high evaporation losses the degree of slope exercises a stronger control on the amount of runoff than in humid areas (Chow, 1964; Scoging, 1989). On desert hill slopes there is still relation with the slope mantle, as runoff is very rapid in contrast with plains, which are usually mantled with fine detritus that initially absorbs much of the rainfall.

5.6 Rainfall-Runoff Modelling

Hydrologists and engineers have always been interested in the flow rates resulting from rainfall. Not only in measuring the flow, but also in the process of transforming the rainfall into stream flow hydrographs. The classic problem in proceeding with the hydrograph generation is the lack of flow records. Even in the cases of gauged catchments the records may not be reliable, as has been seen previously in the catchment of *Marab* Hassan. Since rainfall records are more available than flow records, synthetic approaches can be used to develop hydrographs as will be discussed later.

The origins of rainfall-runoff modelling in the broad sense can be found in the second half of the 19th century (Todini, 1988) arising in response to different types of engineering problems such as: design of engineering structures and water supply systems, river regulation schemes and studying the potential impacts of changes in land use and climate (Jones, 1997). In the last three decades many rainfall-runoff models have been developed, tested and the results published (Naef, 1981).

James (1972) stated that catchment modelling combines both science and arts. Science helps through searching the literature to determine the theoretically or empirically derived equations that represent the water movement processes. Arts offer integrating these equations into a trial computer programme until it works and revising the equations until they faithfully model recorded flows for the catchment.

5.6.1 Rainfall-Runoff Relationship

Before dealing with runoff alone, the relation with its major cause, the rainfall has to be known. In hydrologic analysis it is often necessary to develop relationships between rainfall and runoff, possibly using some of the factors affecting runoff as parameters. The importance of such relationships lies in their application to the interpolation or extrapolation of runoff records from generally longer records of rainfall, (Chow, 1964).

In the literature there are many different methods dealing with rainfall-runoff relationships. Some of these methods are mentioned below.

5.6.1.1 Rainfall-runoff correlation

According to (Law, 1953) the basis of this method is to find a correlation between the measured runoff from the catchment and the rain which has fallen upon it in the same period, as indicated from the readings from one or more rain gauges. Rainfall is plotted against Runoff to see the type of correlation.

1. If the scatter is small a line between points can be easily drawn through the mean value.
2. If the scatter is wide the statistical theory ' regression' is quite useful, (Wanielista et al., 1997).

The relation in this case could be:

Runoff = a + b (Rainfall) [5.6.1]

Where

a is the interception with y-axis when rainfall equal 0

b is the slope (in case of linear relationship), because it could be non-linear.

Wilson, 1990 reported that this type of linear correlation could be found in humid and tropic climates. But application of such relation is restricted; it can nevertheless be a useful method for estimating total annual runoff of completely ungauged catchments if they are in similar climates and in similar size and characteristics.

5.6.1.2 Antecedent precipitation index (API) Method

Another method that can be used to find the correlation between rainfall and runoff is the Antecedent Precipitation Index method (API). It uses week of the year and storm duration as parameters in order to develop a relationship between rainfall and storm runoff, by a graphical method of coaxial correlation, (Wilson, 1990; Betson et al., 1969; Sittner et al., 1969 and Chow, 1964). It is called coaxial because of a range of factors that have been incorporated in a diagram in order to predict the runoff volume, (Chorley, 1971).

The derivation of rainfall-runoff relationship for a catchment area can be a fundamental problem. Although, it is easy to have rainfall data, flow records may be difficult and not easy to obtain. For example, Shaw (1990) stated that determining the water yield from a catchment could be completed satisfactorily by using relationships between totals of monthly or annual rainfall and runoff. In a sense, rainfall-runoff relationships are much easier to establish on an annual, seasonal or monthly basis than for individual events.

5.7 General Aspects of Hydrological Models

Hydrological models are a class of mathematical models used to describe the response of the catchment to climate input (Strzepek and Yates, 1996). According to Shaw (1990), hydrological models are divided into two groups, deterministic and stochastic models. Beside these two groups; Ward and Robinson (1990) see that there are other types as conceptual or empirical, linear or non-linear and finally lumped and distributed. Other groups like event or continuous (sequential) models measured or fitted parameters models can be added to the series (ESCAP, 1997).

- A deterministic model can be defined as that the type of model in which a given input of rainfall must produce a fixed output in a certain physical environment (Jones, 1997). This physical environment is the catchment where the physical processes in it are involved in the transformation of rainfall to stream flow or runoff (Shaw, 1990; Ward & Robinson, 1990).
- Stochastic models take into consideration the chance of occurrence of probability distribution of the hydrological variables like rainfall, evaporation and runoff (ESCAP, 1997; Strezepek & Yates, 1999). In other words a model is considered stochastic if for a given set of initial and boundary conditions, it may have a range of possible outcomes, often each outcome is associated with an estimated probability, (Beven, 2001).
- Conceptual models can be called process models because they attempt to model the physical, chemical and biological processes acting within the catchment system. In these models the processes are represented in a very simple manner, including some calculated elements (Jones, 1997).
- Black box models are formulated from a consideration of the relationships between system inputs and outputs only, with no concern for the processes those work within the system. They are used for flood estimation and for some simple catchment yield estimation.
- Lumped models are so called because they deal with the catchment as one unit and assume that it is subjected to uniform rainfall (Linsley et al. 1988). They are designed for medium to large catchments or for long time periods and often referred to as 'water balance models'. Parameters for this type of model are not usually meant to represent the physical characteristics of the catchment.

- Distributed models more or less mean physically based models, which firmly based on our understanding of the hydrological processes that control the catchment response (Beven, 1985) by dividing it into sub catchments, simulate each separately and then combine them to obtain the catchment response.

Almost all the mentioned kinds of modelling techniques are suitable for temperate climate, where the flow records are generally available and easy to get, whereas rainfall-runoff modelling in arid zones has never been an easy task to conduct. It always faces different kinds of problems; like the lack of data, inaccessibility to monitoring sites because of the rough terrain conditions, as well as damage and vandalism of the gauges. Also, the rarity of events, i.e. ephemeral flows that occur just for few days of the year make it difficult to stage the discharge. Adding to this the remote locations of the gauges with the low population density and the harsh environment make monitoring the flow extremely difficult. All the mentioned problems were experienced with Marab Hassan catchment area. Because of such difficulties in modelling "a straightforward" model, different synthetic approaches were used to develop the hydrograph for the catchment. The ones used are Snyder's, Soil Conservation Service method (SCS) and Geomorphologic Instantaneous Unit Hydrograph (GIUH) approaches. All of these approaches use some geomorphologic characteristics of the catchment area, though the GIUH is much more data intensive which makes its use more complex.

5.8 UNIT HYDROGRAPH THEORY

It is important to discuss what is meant by the unit hydrograph, as the next sections will be dealing with different synthetic approaches to develop the unit hydrograph for the catchment area of Marab Hassan. Sherman first introduced the concept of Unit Hydrograph (UH) in 1932. Sherman defined the unit hydrograph as follows.

> *"If a given one day rainfall produced a 1in. depth of runoff over a given drainage area, the hydrograph showing the rates at which the runoff occurred can be considered a unit graph for that watershed".*

Chow et al. (1988) described the assumptions behind the unit hydrograph theory as:

1. Excess rainfall intensity is constant within the effective duration.
2. Excess rainfall is uniformly distributed throughout the whole catchment area.

3. The time base of the direct runoff hydrograph is constant for a given duration of rainfall. This assumption implies that regardless of the rainfall intensities, storms with the same duration produce direct runoff hydrographs with the same time base.
4. The hydrograph resulting from excess rainfall reflects the unique catchment characteristics.
5. The ordinates of all direct runoff hydrographs with the same time base are proportional to the total amount of direct runoff presented by each hydrograph.

A unit hydrograph can be developed from streamflow data if the data is available, by assuming a specific shape of the hydrograph based on the catchment conditions. Using the streamflow records, baseflow (and other groundwater flows if present) are subtracted from the streamflow. The resulting hydrograph is the runoff hydrograph, (Wanielista et. al., 1997).

When the streamflow data are not available the unit hydrograph can be developed using synthetic approaches. A synthetic hydrograph is the one that can be developed with minimum use of streamflow data or even without the existence of the data. Catchment characteristics like area, stream length, slope, etc. are mainly used to develop the synthetic hydrograph. Different approaches like rational method, SCS, Snyder, Clark and Santa Barbara can be used to develop the synthetic unit hydrograph, (Wanielista et. al., 1997; Chow et. al., 1988; Bras, 1990; McCuen, 1989). Two approaches that are SCS and Snyder were used to develop the unit hydrograph for the catchment area of Marab Hassan.

5.9 MUSKINGUM FLOW ROUTING

Flow routing is the process to determine the time and volume of the flow at a point of the watercourse from a known or assumed hydrograph at one or more points upstream, (Chow et al., 1988). There are two types for flow routing; hydrologic and hydraulic routing. Hydrologic routing is based on the continuity equation [5.9.1] i.e. the change in storage with time (*dS/dt*) equals the difference between inflow (*I*) and outflow (*O*). Muskingum routing technique is an example of this method of routing. It estimates the outflow hydrograph based on that the inflow values related to each other using certain coefficients called Muskingum coefficients (C_0, C_1, C_2) as expressed below, as presented in (McCuen, 1989).

$$\frac{dS}{dt} = I - O \qquad [5.9.1]$$

Knowing that the storage S equals eqn. [5.9.2], then substituting it in [5.9.1] the result is eqn [5.9.3], which is Muskingum routing formula.

$$S = K[xI + (1 - x)O] \qquad [5.9.2]$$

where K is the storage constant (see 5.9.7) and x is a constant expressing the relative importance of inflow and outflow.

$$O_2 = C_0 I_2 + C_1 I_1 + C_2 O_1 \qquad [5.9.3]$$

The coefficients (C_0, C_1, *and C2*) are calculated using the following formulae.

$$C_0 = -\frac{Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t} \qquad [5.9.4]$$

$$C_1 = \frac{Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t} \qquad [5.9.5]$$

$$C_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t} \qquad [5.9.6]$$

The value of K is estimated by the travel time through the reach as shown in equation [5.9.7], and x ranges between 0 and 0.5 with 0.2 as an average value and commonly used. t is to be *x 0.5 t/K 1-x*

$$K = \frac{0.6L}{V_0} \qquad [5.9.7]$$

where:

L is the reach length

V_0 is the average velocity

The Muskingum routing method has been used to route the flow from each sub-catchment within Marab Hassan catchment, to reach the Marab inlets and then the individual hydrographs for each sub catchment were routed inside the Marab as a channel routing until reaching the Marab outlet. The velocity values used in routing were established based on channel geometry as well as stream order. The Marab characteristics of flow length, slope and flow velocity were used in the routing.

Routing was applied to the unit hydrographs of Marab Hassan catchment to account for storage and translation effects. The routed hydrograph had the same total area but with a decrease in the peak flow (Q_p) and an increase of the time to peak (t_p). Marab Hassan catchment was divided into three main sub-catchmnets with sub-catchment three also divided into two sub- areas, upper and lower. The routing procedure was applied to upper sub-catchment three as it was routed through the lower part and then the lower part's hydrograph was combined with the upper routed one. Then the combined unit hydrographs were routed through Marab Hassan as well as the unit hydrographs of sub-catchments one and two. The three routed unit hydrographs were combined to give the catchment's unit hydrograph as will be discussed later in this chapter and in Chapter Six.

5.10 Synthetic Unit Hydrographs

For catchment such as Marab Hassan where flow records are not available, the synthetic approaches can be used to derive the unit hydrographs. Snyder (1938) presented the procedure of the first synthetic unit hydrograph. He developed his procedure by studying several basins located in the Appalachian Mountains region. In his model discharge properties were determined empirically from the drainage basin's physical characteristics, as will be described later. Another synthetic unit hydrograph approach that is widely used is the SCS synthetic hydrograph as will be discussed later. Both of these approaches were applied on Hassan catchment, due to different problems such as the lack of data mainly because of vandalism as well as other factors as mentioned in Section 5.7 previously.

5.10.1 Snyder Synthetic Unit Hydrograph

Synder (1938) presented the first synthetic unit hydrograph procedure. He developed his procedure by studying several basins of areas 10-10,000 square miles located in the Appalachian Mountains region. In his model, discharge properties were determined empirically from the drainage basin physical characteristics such as area, slope and length and length from the centroid to the catchment outlet.

This method provides computation of the lag time, peak flow, and hydrograph time base. These points could be used to plot the unit hydrograph. The following is a summary how to calculate each of these parameters, (Veissman et al. 1977, Chow et al. 1988, and Snyder, 1938).

1.Determination of the Lag time (t_l) of the catchment area:

Lag is defined as the time from the centre of mass of the rainfall to peak of runoff (Snyder, 1938). It is assumed to be constant for a particular catchment.

$$t_l = C_1 C_t (l l_c)^{0.3} \qquad [5.10.1]$$

t_l is the lag time (hr)

l is the main stream length (km)

l_c is the length from the centroid to the catchment outlet (km)

$C_l = 0.75$

C_t is a coefficient representing variations in the catchment's slopes and storage, it ranges between 1.8-2.2 with an average of 2.

2. Determination of the Peak flow (Q_p) and time to peak (t_p)

$$Q_p = C_2 C_p A / t_1 \qquad [5.10.2]$$

$$t_p = t_l + D/ \quad 2 \qquad [5.10.3]$$

Where

Q_p is the peak flow (m^3/s)

t_p is the time to peak (hr)

D is the duration of excess rainfall (hr)

$C_2 = 2.75$

C_p is a coefficient accounting for flood wave and storage conditions, effective area contributing to the peak flow and drainage area. Values for C_p range from 0.4 to 0.8. Larger values of C_p are generally associated with smaller values of C_t.

A is the catchment area (km^2)

3. Determination of the Time base (T) of the Hydrograph

To determine T is a controversial aspect as different equations can be used to calculate T as shown below. Snyder, (1938) and Veissman et al, (1977) suggested it to be as in equation [5.10.4]:

$$T = 3 + \frac{t_1}{8} \qquad [5.10.4]$$

where

T is the time base of the synthetic unit hydrograph (days)

Equation [5.10.4] gives a high T value for small areas, so generally as a rule of thumb use the time base as 3-5 times the peak time when plotting the unit hydrograph (Veissman et al. 1977). While, Chow et al, 1988 suggested that the time base can be determined using the fact that the area under the unit hydrograph equals a direct runoff of 1 cm (**1in.** in Imperial units), so T may be estimated as

$$T = \frac{c}{Q_{pa}} \qquad [5.10.5]$$

where

$c = 5.56$ (1290 for the English system)

$$Q_{pa} = \frac{Q_p}{A} \qquad [5.10.6]$$

5.10.2 SCS Unit Hydrograph

The United States Soil Conservation Services (SCS) developed this method. It uses the triangular shape hydrograph to approximate the unit hydrograph, (Haan et al., 1982).

The following procedure was used to develop SCS unit hydrograph, (Wanielista et al, 1997, McCuen, 1982 and Viessman et al, and Haan et al, 1982).

1. Determination of the Lag time (t_l)

$$T_c = 0.02 L_c^{0.77} S_c^{-0.385} + \left| \frac{2nL_0}{\sqrt{S_0}} \right|^{0.467} \quad [5.10.7]$$

$$t_1 = 0.6 T_c \quad [5.10.8]$$

T_c is time of concentration (min), which is the time required for a particle of water to travel from the farthest point of the catchment to the point where the design is to be made, (McCuen, 1982).

L_c is length of stream (m)

S_c is average of channel reach (m/m)

L_0 is overland flow length (m)

S_0 is slope along that path

n is manning roughness coefficient

t_l is the lag time (min)

Equation [5.10.8] takes into account both the overland and channel flows. This is simply because the runoff doesn't start as a channel flow, but it starts as a shallow overland flow then takes the shape of defined channels. The overland flow phase has a maximum travel time, and it is hardly to maintain overland flow for a distance longer than 100-150 m. Therefore, L_0 is used as 150 m and S_0 is taken from the slope map of the catchment area, as an average value of 3° or 0.052 m/m.

2. Determination of the peak flow (Q_p) and time to peak (t_p)

$$t_p = D/2 + 0.6 T_c \quad [5.10.9]$$

t_P is the time to peak (min)

D is the excess rainfall duration (min)

$$Q_p = 16.7AQ/t_p \qquad [5.10.10]$$

A is the catchment area (m^2)

Q is excess rainfall (10 mm)

t_P is the time to peak (min)

3. Determination of the time base (T) of the hydrograph.

The same assumption that has been used before in calculating the time base for Snynder's synthetic unit hydrograph was used here to calculate time base for SCS unit hydrograph. It is mainly based on the fact that that the total volume under the unit hydrograph equals 10 mm.

5.11 Application of Synthetic Unit Hydrographs to Marab Hassan Catchment

5.11.1 Marab Hassan Catchment Snyder Unit Hydrograph

Equation [5.10.5] was used in calculating the time base for the hydrographs of Marab Hassan catchment area. Marab Hassan catchment was divided into three sub-catchments as shown in Figure 5.4, These characteristics were determined by the aid of Geographic Information System (GIS) as will be discussed later.

Table 5.2: Marab Hassan sub-catchments characteristics

Sub-catchment	A (km^2)	l (km)	l_c (km)	S_c (m/m)
1	88.95	33.00	19.15	0.0120
2	43.10	23.54	10.34	0.0144
3 upper	147.62	27.12	14.64	0.0147
3 lower	77.70	19.92	15.48	0.0100

Snyder Synthetic Unit Hydrographs were developed for Marab Hassan sub-catchments 1, 2, upper 3 and lower 3 using the sub-catchments characteristics in table 5.2 above using $C_t = 0.48$ *and* $C_p = 0.4$. Then the upper 3 unit hydrograph was routed through the lower 3 using Muskingum routing method as mentioned before. After that the routed upper 3 was combined with the lower 3. Finally the three sub-catchments 1,2 and combined 3 were routed through Marab Hassan, as shown in Figure 5.3, using the

Marab characteristics (slope, flow velocity and length), assuming the flow is a shallow channel flow with a 30 cm depth and 500 cm width.

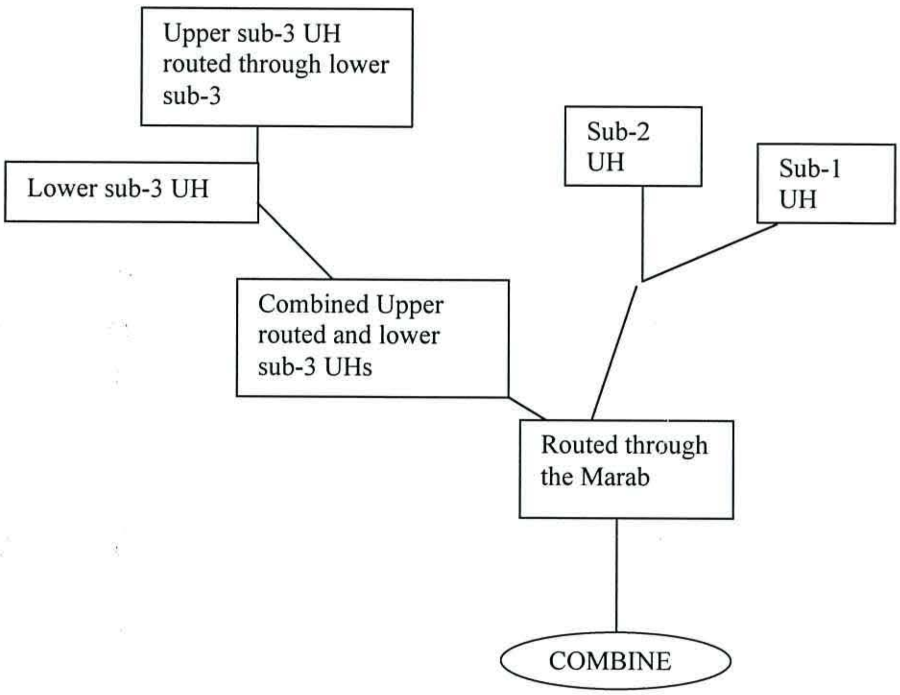


Figure 5.3: Illustration of Muskigum routing procedure.

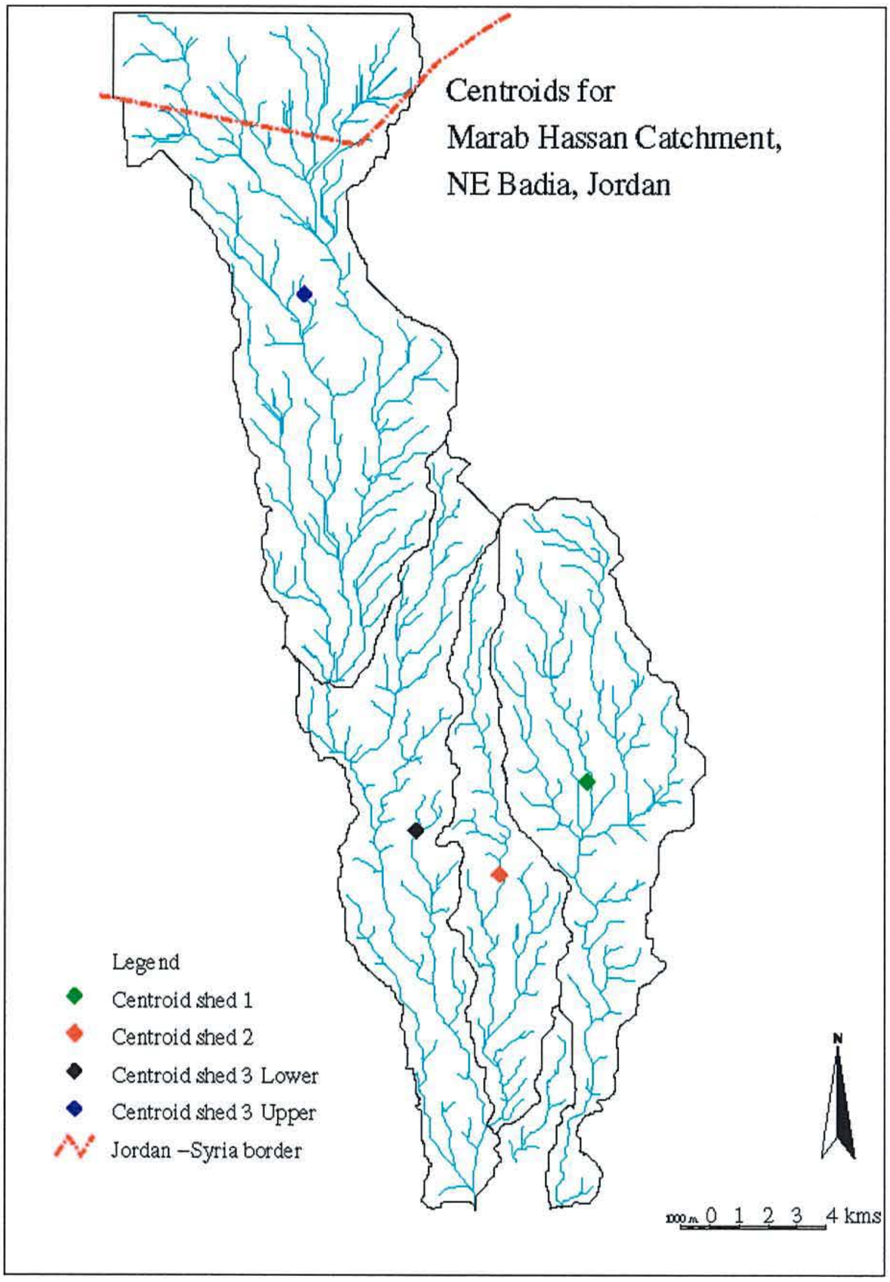


Figure 5.4: Marab Hassan sub-catchments used in developing Snyder's Unit Hydrographs.

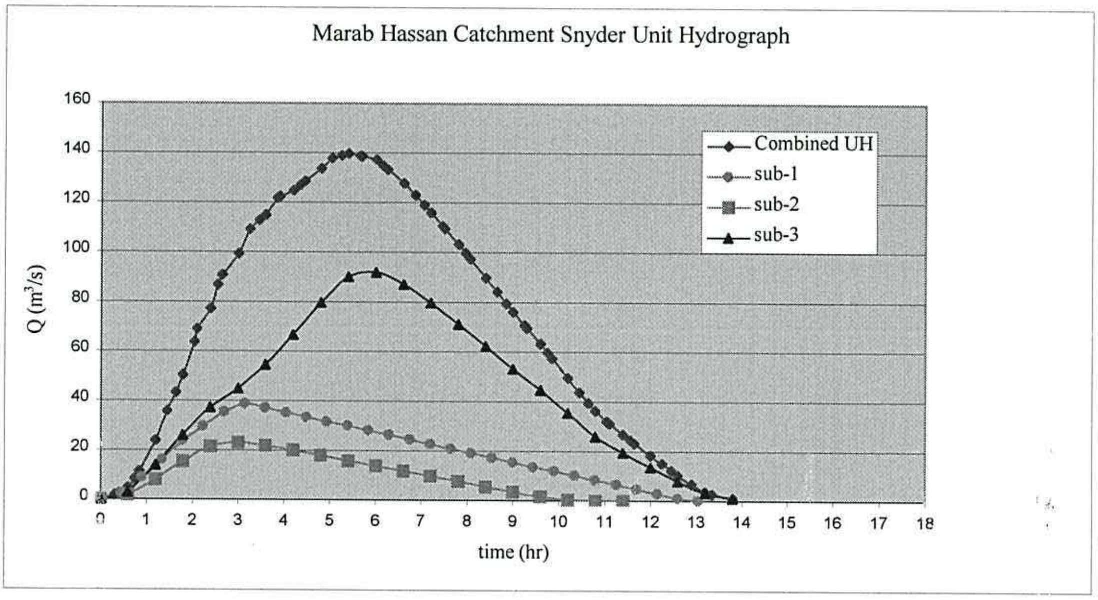


Figure 5.5: Marab Hassan catchment Snyder Unit Hydrograph (for 1 hour rainfall).

From the Figure 5.5 above Table 5.3 is listed to show the major characteristics of the hydrographs i.e. peak flow *(Q_p)*, time to peak *(t_p)* and the time base *(T)* for each sub-catchment.

Table 5.3: Marab Hassan sub-catchments Snyder Unit Hydrographs characteristics.

Sub-ID	$Q_p(m^3/s)$	t_p(hr)	T(hr)
1	38.45	3.15	13.05
2	23.08	3.00	11.40
3	91.88	6.00	13.80
Combined	139.6	5.40	13.80

From the table above it is clearly seen that the peak flow values *(Q_p)* seem to be highly affected by the catchment area A, as sub-3 is the biggest among the three, and then comes sub-1 and finally sub-2. Regarding the time to peak, as it is a function of the stream length l as well as the length from the centroid l_c to the outlet. It is again with sub-3 being the longest; it is obvious that it will have the highest lag time (that is the time needed for the flow to travel from the furthest point to the outlet) and the highest time to peak value. But with the values of $C_t = 0.48$ and $C_p = 0.4$ that have been selected by iterations and literature review, it is possibly that the developed hydrographs may not be reliable. A shortcoming of the Snyder technique is the non-availability of regional coefficients, based on calibration with runoff data.

The general shape of the developed hydrographs they do not appear to match the "standard" arid zones hydrographs, which normally have steep rising and recession limbs, (Reid and Frostick, 1989).

5.11.2 MARAB HASSAN SCS UNIT HYDROGRAPH

The same divisions used to develop Snyder's unit hydrographs were used again here to develop the SCS unit hydrographs for the catchment area. The same routing procedures were used to route the unit hydrographs within the streams and the Marab. Figure 5.6 shows the developed SCS unit hydrograph for Marab Hassan catchment. Table 5.4 also summarises SCS unit hydrograph characteristics for Marab Hassan catchment area.

Table 5.4: SCS unit hydrographs characteristics for Marab Hassan catchment area.

Sub-ID	Q_p(m3/s)	t_p(hr)	T(hr)
1	60.62	4.05	8.10
2	36.67	3.60	7.80
3	130.13	5.19	9.29
Combined	205.73	4.45	9.60

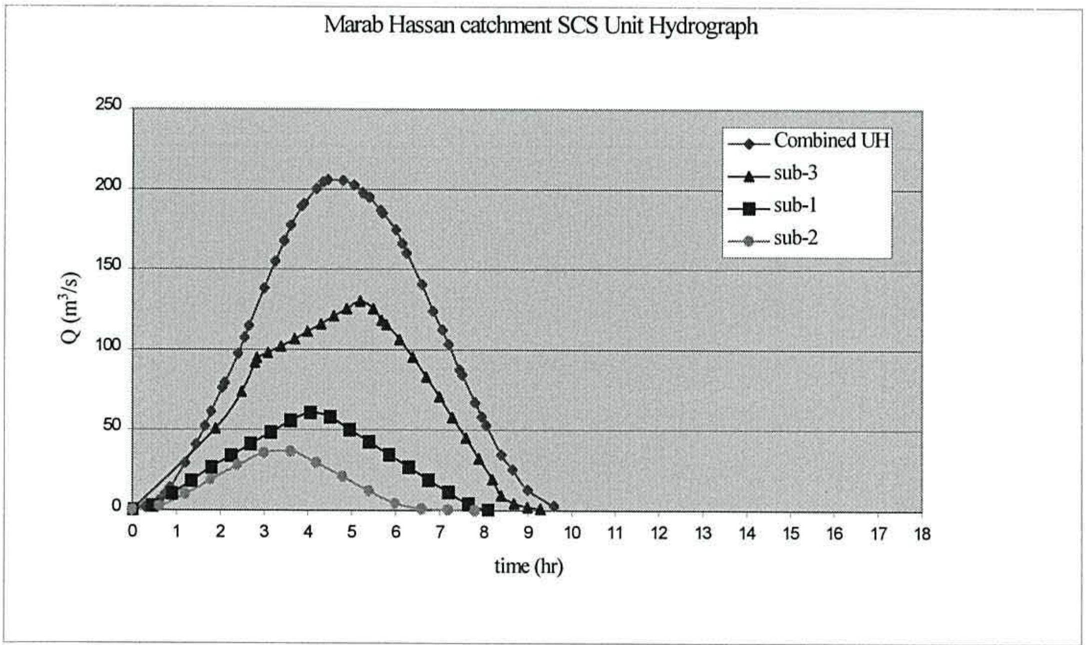


Figure 5.6: Developed SCS unit hydrograph for Marab Hassan catchment area, (for 1 hour rainfall).

From the plots and the table it is clearly seen that sub-2 has the minimum peak flow (Q_p) compared with sub-1 and sub-3. This is because of the peak flow is a primarly function of the catchment area (A

The time to peak depends on the time of concentration (i.e. the time needed for the flow to travel from the furthest point on the catchment boundary to the outlet), which is mainly dependent on the catchment characteristics i.e. stream length, channel slope, and the overland flow component. As will be shown in the derived slope map for the catchment area (Figure 6.4) almost all the catchment's slopes are between 0-2% which are gentle, so this leads us to say that slope effects on the time to peak are similar. Therefore, the factor that has a major effect on the time to peak is stream length. Sub-3 has the maximum stream length, so it has the highest time to peak value, second comes sub-1 and finally sub-2.

Figure 5.7 compares SCS with Snyder's unit hydrograph. The SCS looks better but still not convincing in terms of comparing with the arid zones typical hydrograph. Both of them are empirical methods that deal with the catchment as one unit "lumped model" which doesn't take into account the individual streams that feed into the system, as it just considers the mainstream length. The lack of actual flow records makes it difficult to test the reliability of the developed hydrographs; as if the records are available the unit hydrographs for the selected rainfall duration would have been generated from real data using S-graph method. This reason why the synthetic methods are not considered reliable, instead a Digital Elevation Model (DEM) based approach was adopted.

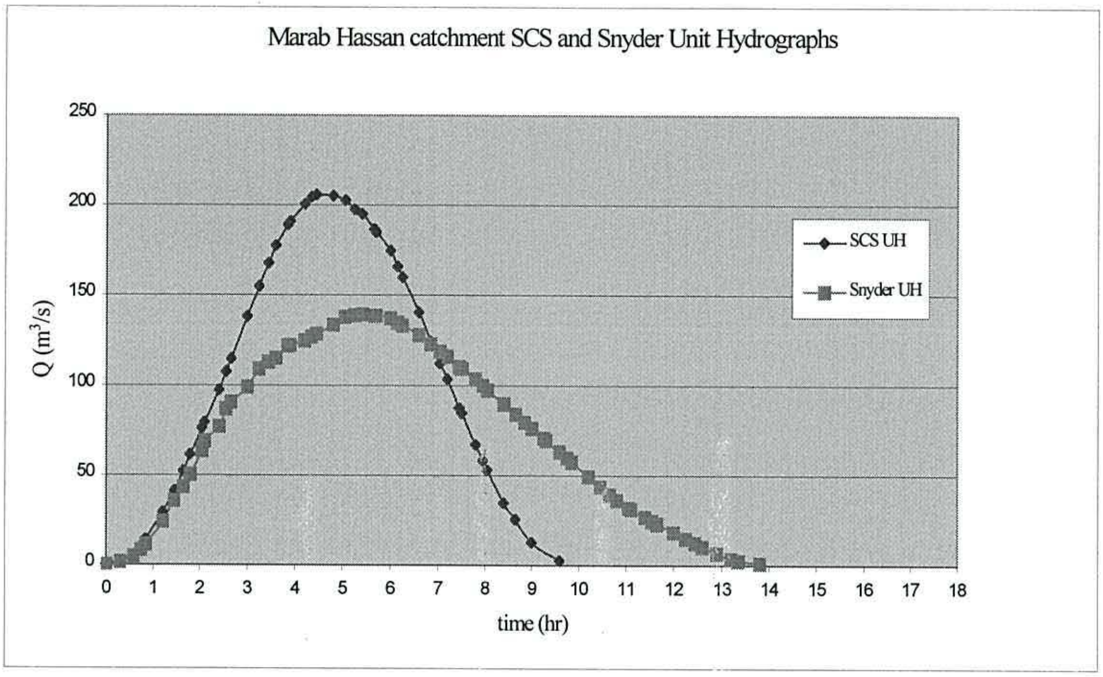


Figure 5.7: SCS and Snyder Unit Hydrograph.

5.12 CONCLUSIONS

The factors affecting runoff generation have been discussed in this Chapter. Then the rainfall-runoff relationship was described, with an emphasis on the unit hydrograph concept and some synthetic approaches for developing the unit hydrograph. Two approaches (SCS and Snyder) were discussed with their application to Marab Hassan catchment area. The traditional synthetic methods have difficulty with parameter estimation in arid zones due to the lack of actual runoff data to calibrate the coefficients.

Chapter Six will discuss the application of another approach for developing the unit hydrograph of Marab Hassan catchment area. This approach is called the Geomorphologic Instantaneous Unit Hydrograph (GIUH), which is based on the use of the catchment characteristics (i.e. stream order, length and area) to develop the unit hydrograph. The Geographic Information System (GIS) was used as a tool to extract the catchment characteristics from the Digital Elevation Model (DEM).

CHAPTER SIX

USE OF A GEOGRAPHIC INFORMATION SYSTEM IN RAINFALL-RUNOFF MODELLING

6.1 INTRODUCTION

The original intention of the modelling aspect was to develop a rainfall-runoff model to the catchment area and then to calibrate it using rainfall and runoff data. But due to circumstances of the gauges' failure, vandalism and lack of runoff data and runoff events, the calibration part was not possible. The actual approach was shifted to develop synthetic unit hydrographs for the catchment as was done in Chapter Five, using Snyder and SCS unit hydrographs. In this chapter a Geographic Information System (GIS) is used to develop the Geomorphologic Instantaneous Unit Hydrograph (GIUH), using the catchment's geomorphologic characteristics like the stream network, stream length, stream order. These characteristics are determined from the Digital Elevation Model (DEM) for the catchment using GIS. The use of GIS in an arid area such as *Marab* Hassan catchment has proved its efficiency in terms of extracting the catchment's characteristics that are important in runoff determination (i.e. using the synthetic approaches).

The first two sections of this chapter discuss the use of the DEM and GIS in hydrologic modelling, as well as the GIS functions that have been used. The third part discusses the concept of the GIUH, and the fourth part consider the application of GIUH to *Marab* Hassan catchment area, with some comparison with the other two approaches from the previous chapter (i.e. Snyder and SCS).

6.2 GIS ROLE IN HYDROLOGIC MODELLING

Geographic Information Systems (GIS) can be defined as computer based tools that display, store, analyse, retrieve, and generate geographically referenced data. GIS is being more and more involved in hydrology and water resources and has proved a very useful tool. However, its use is still not widespread. Unfortunately, most existing standard GIS packages do not include procedures that are necessary for hydrologic modelling. Nevertheless, there are some hydrologically oriented GIS, which have made use of cell-based analysis, (Smadi, 1998).

GIS has been used in hydrology as well as many other sciences in the last couple of decades. The capabilities available in GIS enable the user to handle and analyse hydrological data more efficiently, (Nelson et. al., 1997), moreover, different scenarios of analysis can now be modelled in a relatively short time. GIS has useful applications in the hydrological modelling of ungauged catchments, as it tends to provide and manipulate the topographic database that is necessary to define the catchment characteristics.

ARC/INFO from Environmental Systems Research Institute (ESRI) is popular software that has been used by hydrologists. The majority of the functions used are within the GRID spatial modelling software (a part of *ARC/INFO*), (DeBarry, 1999). GRID was used to create the maps in this study.

Maidment (1993) summarised the different levels of hydrologic modelling in association with GIS as follows:

- Hydrologic assessment.
- Hydrologic parameter estimation
- Hydrologic modelling inside GIS.
- Linking GIS and hydrologic models.

He also suggested that the major limitation for applying hydrologic modelling directly within GIS is the time variability of the hydrologic processes.

6.3 Extracting Catchment Characteristics from the Digital Elevation Model

Digitised maps for *Marab* Hassan catchment area were obtained from the Royal Jordanian Geographic Centre (RJGC). They include topographic, wadi spreads, villages and built up areas, roads, streams and soil maps. They are at 1:50,000 scale except for the soil map which has a scale of 1:250,000.

Digital Elevation Models (DEM) are the primary input to most surface hydrologic models. A DEM is defined as a raster representation of a continuous surface, usually referring to the surface of the earth, (ESRI, 1992). Raster data are made up of individual cell grids of a specified dimension that tend to deform the actual size and shape of an object, and cause a stair-step formation along linear edges. *Marab* Hassan catchment Digital Elevation Model was built up from the 10-metre contour interval topographic map. The accuracy of the DEM is decided by the resolution (i.e. the distance between sampling points). The command used to create *Marab* Hassan catchment 30 metres resolution DEM is called Topogrid that is listed in Appendix D. Topogrid generates hydrologically correct DEM. *Marab* Hassan catchment DEM is shown in Figure 6.1. The DEM includes all the sub-catchments including the Syrian part of upper sub-catchment 3.

DEM is a function of the map scale as well as the contour interval. The map scale affects the DEM resolution as the resolution may be modified according to the scale, (Vieux, 2001). Also the contour interval affects the DEM resolution, the larger the contour interval the less the number of features appear on the map, which will affect the DEM output. As the DEM is the major input for all the hydrologic features (i.e. flow direction, accumulation, etc) so implicitly the factors that affect the DEM affect these features as well.

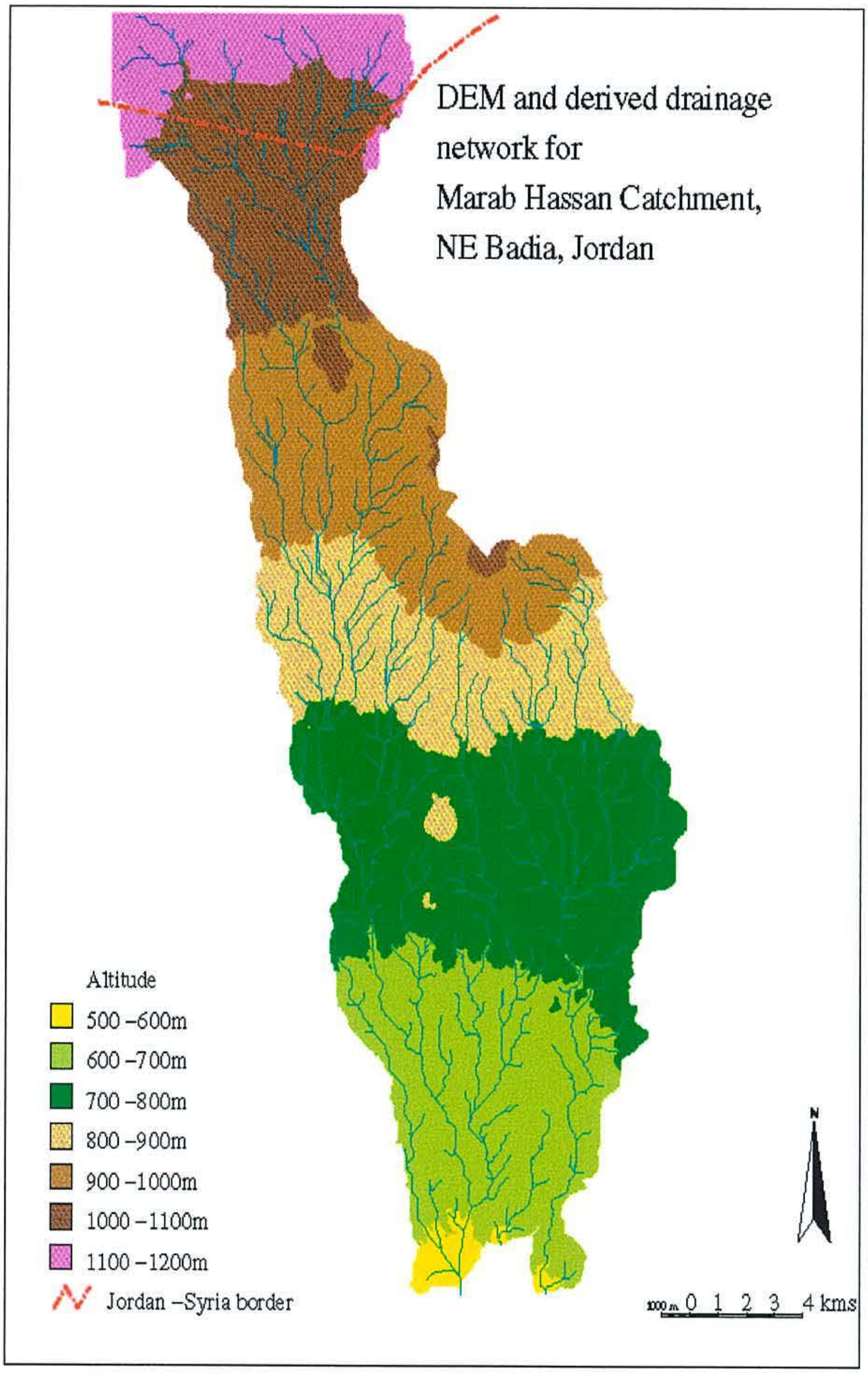
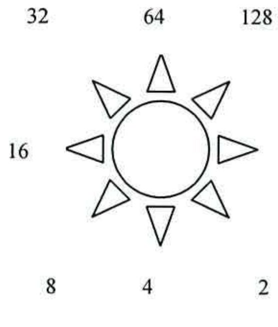


Figure 6.1: DEM and derived drainage network for *Marab* Hassan catchment.

Grid based DEMs are one of the most widely used data structures as they are easy to deal with and they have easy algorithms for the computers to handle. However, they have several disadvantages; they cannot easily control sudden changes in elevation, the size of the grid mesh (i.e. resolution) affects the results obtained and the computational efficiency, and the definition of the specific catchment areas may be imprecise in flat areas, (Vieux, 2001). Starting with the DEM, hydrologic features of the terrain (i.e. flow direction, flow accumulation, flow length, stream network, drainage areas, as well as the slope and aspect, etc.) can be determined.

6.3.1 Flow Direction

The ability to determine the direction of the flow from every cell in the grid is one of the keys to deriving the hydrologic characteristics about the surface. This is done with the *FLOWDIRECTION* function (command is listed in Appendix D). The function creates a grid of flow directions from each cell to the steepest down slope. Within this flow direction grid, each cell is assigned a direction within which water would flow through it. The water flows towards their steepest downslope neighbours along one of eight directions labelled as E = 1, SE = 2, S = 4, SW = 8, W = 16, NW = 32, N = 64 and NE = 128



6.3.2 Flow Accumulation

Once the flow direction grid has been generated a flow accumulation grid is created. The *FLOWACCUMULATION* command that is shown in Appendix D counts for all the upstream cells flowing to a given cell. Cells, which are part of the stream network, have larger flow accumulation value, while cells near the catchment boundaries and where overland flow dominates will have a lower flow accumulation value. This command calculates accumulated flow as the accumulated weight of all the cells flowing into each down slope cell in the output grid. If no weight is applied it is assumed to be 1 for each cell, and the value of cells in the output grid will be the number of cells that flow into each cell.

6.3.3 Flow Length

The flow Length function calculates upstream or downstream distance along a flow path. Also it can be used to calculate the cumulative travel time of flow from one cell to the outlet by providing the time of flow over one metre distance, the full command for generating the flow length is described in Appendix D.

6.3.4 Stream Network Derivation

The stream network was derived from the DEM using the flow accumulation function as input. By applying a threshold value of flow accumulation using GRID a stream network could be defined. The mechanism of creating the stream network from the DEM is simply based on connecting each cell to the neighbouring one in the direction of principal slope. The derived stream network for *Marab* Hassan catchment matches quite well the actual one, as shown in Figure 6.2. The derived stream network was used in all the analyses. Two commands can be used to develop the stream network as shown in Appendix D.

The difference between the actual and the derived stream networks exists because the actual one is originally created from the digitised maps, which do not depict all the channels due to the scale of the map. While the derived one is developed using the DEM for the catchment area and utilises topographic features to define channels. As the Digital Elevation Model may have some errors due to the reasons mentioned in Section 6.3 this caused the difference between the actual and derived stream networks.

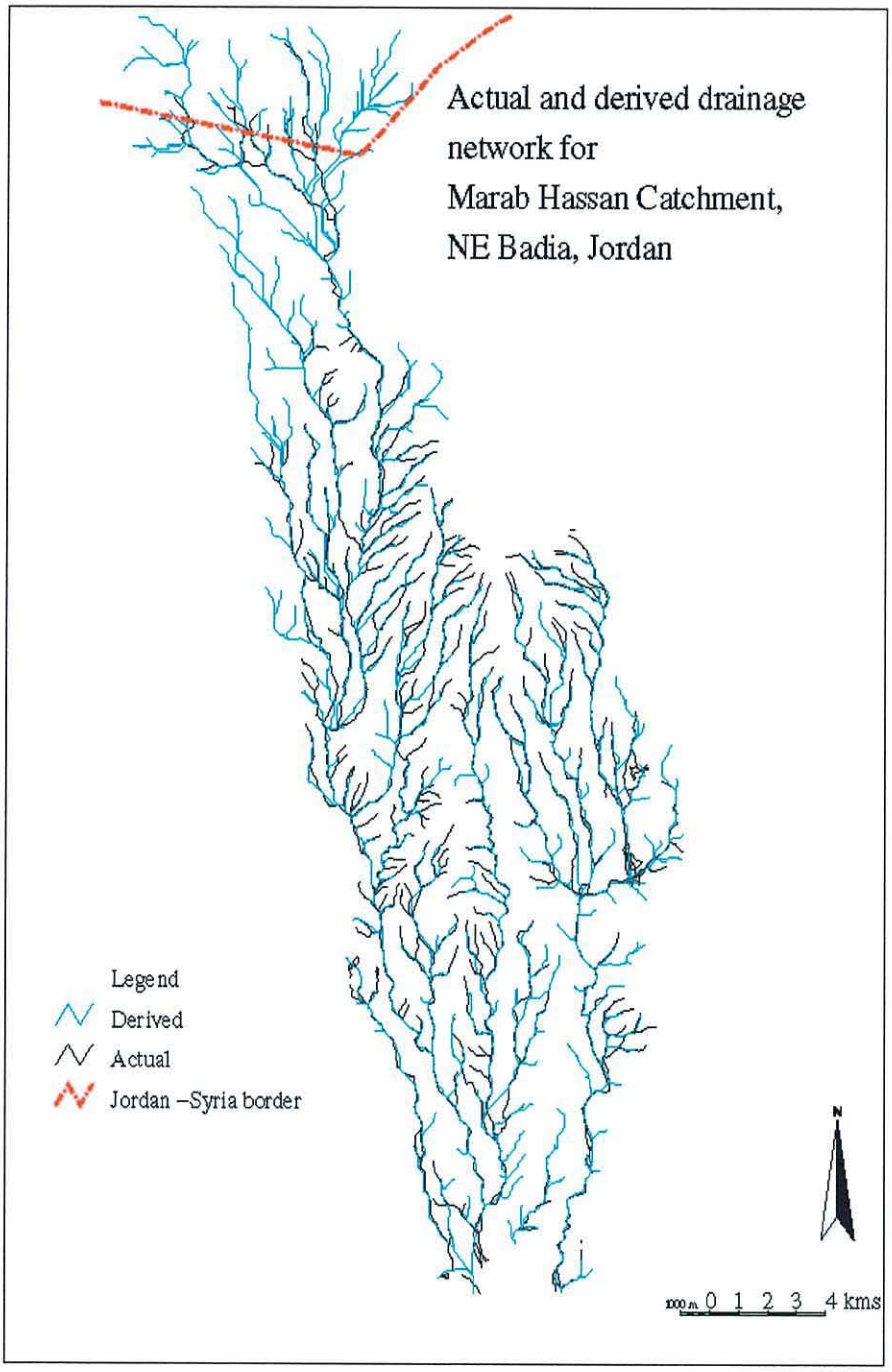


Figure 6.2: Derived and actual stream network for *Marab* Hassan catchment.

6.3.5 STREAM ORDERING

Stream ordering is a way of appointing a numeric order to the links in a stream network and mainly based on the number of tributaries. Starting by giving the stream that has no upstream junction order one, then as two streams of order one join, the results will be second order. Basically, when two streams of order *w* join, the result will be a stream of *w+1* order, and so on until reaching the outlet. But, when two streams of different orders join, the resulting one takes the higher of the two stream orders, (Strahler, 1964; Beven, 2001; Xiong and Wang, 1993). The Strahler ordering method has been used to create the stream orders network for *Marab* Hassan catchment as follows. Figure 6.3 represents the Strahler ordering method for *Marab* Hassan catchment.

The stream order is created from the DEM, which is function of the scale of the map and the contour interval. The scale affects the resolution of the DEM, therefore the features that are developed from the DEM like the stream order will also be affected by the same factors.

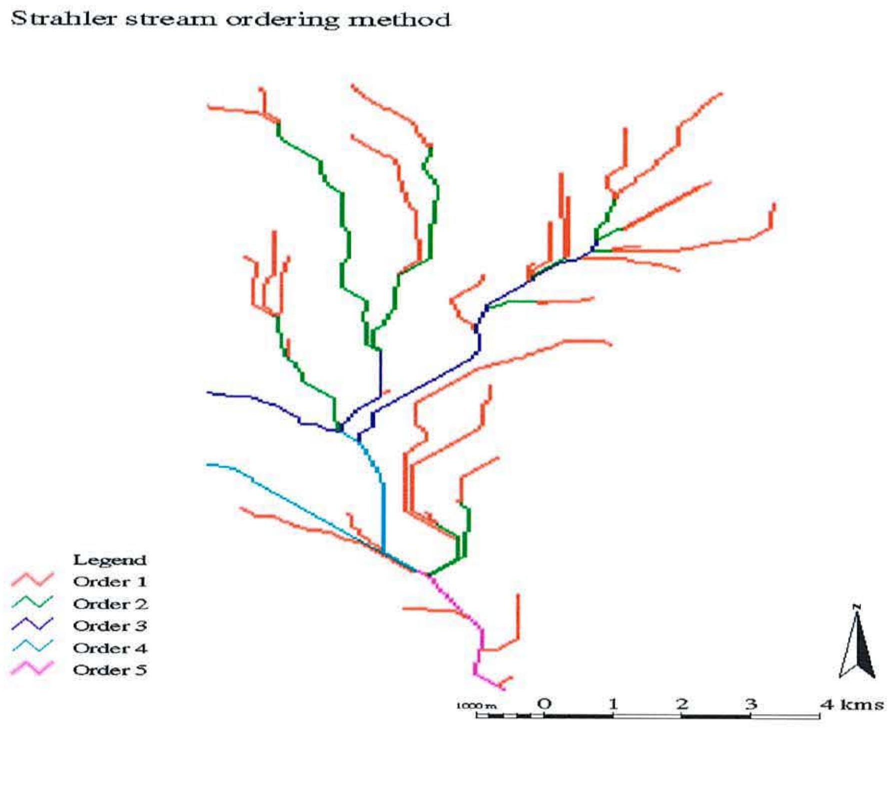


Figure 6.3: Strahler stream ordering method.

6.3.6 Catchment Delineation

Catchment boundaries are a key requirement for nearly all surface hydrologic modelling The catchment or watershed area is known as the up slope area contributing flow to a given location. Two techniques were used to define catchments. To delineate the major sub-catchments for *Marab* Hassan catchment area (sub-1, 2, upper 3 and lower 3) the *WATERSHED* and *SELECTPOINT* functions were used in combination. The commands used for catchment and sub-catchments delineation are listed in Appendix D.

The sub-catchments within each sub-catchment that will be used in the Geomorphologic Instantaneous Unit Hydrograph (GIUH) as will be seen later in the chapter were defined using the *SNAPPOUR* function. Snappour function snaps selected points to the cell of heighest flow accumulation within a specified neighbourhood. The selected points become the lowest point on the boundary of the watershed and are therefore referred to as pour points. A pour point is the point at which the water flows out of an area. After selecting the pour points catchments (watersheds) could be delineated from a DEM using the *FLOWDIRECTION* as input, as shown in Appendix D.

For each sub-area the individual stream length, order and minimum stream length (which is the length from the sub-area outlet to the major outlet of the whole catchment) are determined using GRID functions as follows in Appendix D.

6.3.7 Slope and Aspect

The slope and aspect maps were also created from the DEM, using GRID function. Aspect is the direction of the slope. Slope and aspects maps for *Marab* Hassan catchment are shown in Figures 6.4 and 6.5 respectively. The commands that have been used to develop the slope and aspect maps for *Marab* Hassan catchment are described in Appendix D. Figure 6.4 shows the slope map for the catchment area, it is clearly seen that the catchment's slope is mostly between 0 and 4 percent, except for the volcanic cones that have steep slopes of more than 4 percent. For example the slope reaches up to 10 to 20 percent at Al-Aryyatein cones in the middle of the catchment.

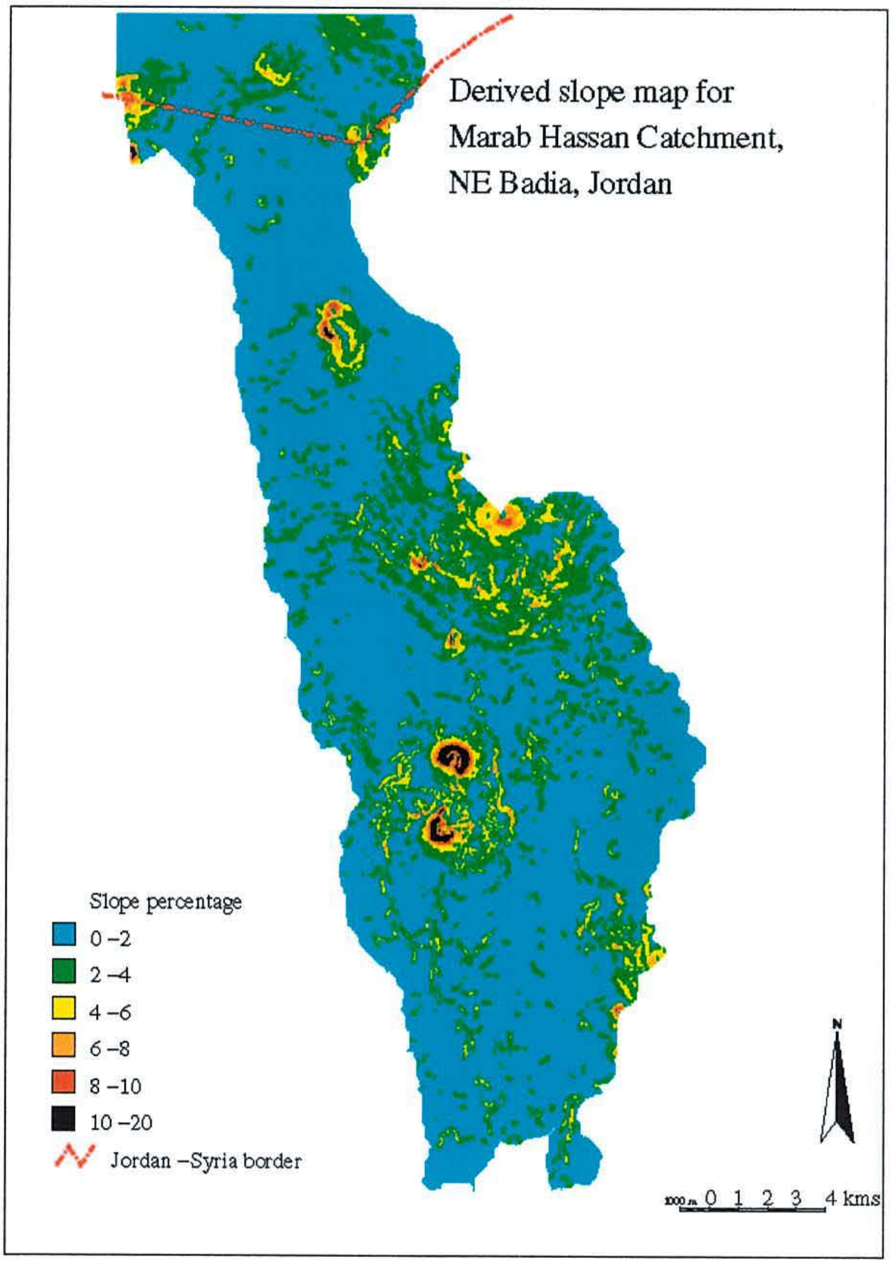


Figure 6.4: Derived slope map for *Marab* Hassan catchment

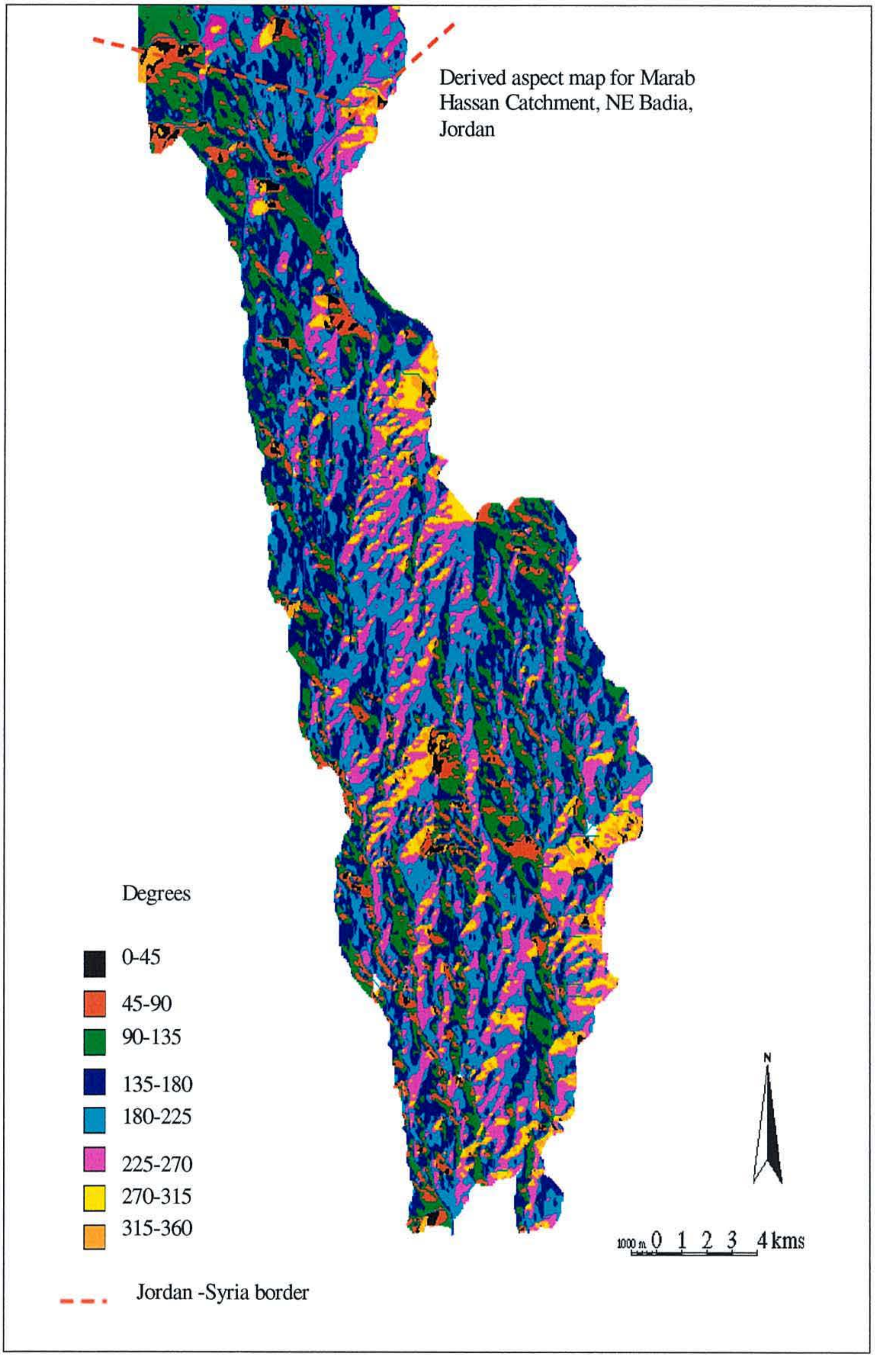


Figure 6.5: Derived aspect map for *Marab* Hassan catchment area.

6.4 The Concept of the Geomorphologic Instantaneous Unit Hydrograph (GIUH) and Its Application to *Marab* Hassan Catchment

Iturbe introduced the idea of Geomorphologic Instantaneous Unit Hydrograph (GIUH) in 1979, and it has been used since that time by many hydrologists. The GIUH relates the geometry of the stream network to the Instantaneous Unit Hydrograph (IUH) of the catchment (Jain et al., 2000). IUH is expressed as a function of Horton's laws: law of stream areas (R_A), law of stream numbers (R_B), and law of stream lengths (R_L); the stream length (L_w) and the streamflow velocity (v). Rodriguez-Iturbe and Valdes, (1979); Whittow (1984) and Snell and Sivapalan (1994) expressed Horton's laws as follows:

Law of stream areas (R_A, range: 3-6): This ratio is calculated from the average areas of the different stream orders within the catchment, starting with the mean area of the highest stream order and ending up with the 1st order average area, this ratio is represented below.

$$R_A = \frac{\overline{A_w}}{\overline{A_{w-1}}} \qquad [6.4.1]$$

where

$\bar{A}_w$ is the average area of basins of stream order w

$\bar{A}_{w-1}$ is the average area of basins of stream order $w-1$

Law of stream lengths (R_L, range: 1.5-3.5): The same story applies to the ratio of stream lengths, but stream lengths average is used here instead.

$$R_L = \frac{\overline{L_w}}{\overline{L_{w-1}}} \qquad [6.4.2]$$

where

$\bar{L}_w$ is the average length of stream segments of order w

$\bar{L}_{w-1}$ is the average length of segments of order *w-1*

Law of stream numbers (R_B, range: 3-5): It is also known as bifurcation ratio, as it takes into account the number of streams in each order to calculate the ratio. The ratio of the number of segments of order N_w to the number of segments of N_{w+1} is termed as bifurcation ratio, and it is expressed as follows.

$$R_B = \frac{N_w}{N_{w+1}} \qquad [6.4.3]$$

where

N_w is the number of segments of stream order *w*

N_{w+1} is the number of segments of stream order *w+1*

The relationship between the above ratios and the stream order is recognisable, as the laws of stream areas and stream lengths tend to formulate an ascending order relationship. Figures 6.6 and 6.7 show the relationships between stream order and stream catchment areas, and of stream lengths respectively for *Marab* Hassan sub-catchments. For the law of stream numbers the relationship is descending, (Figure 6.8).

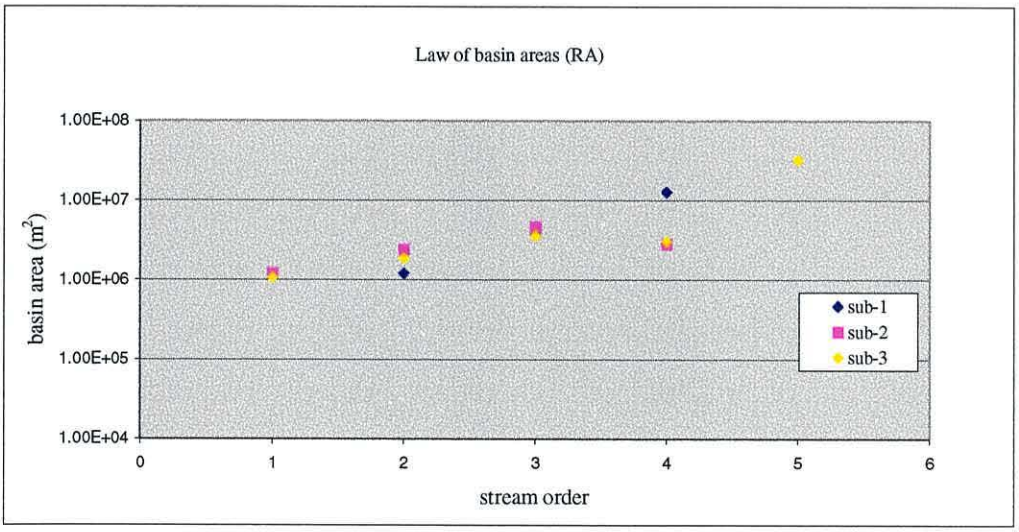


Figure 6.6: *Marab* Hassan catchment law of stream areas.

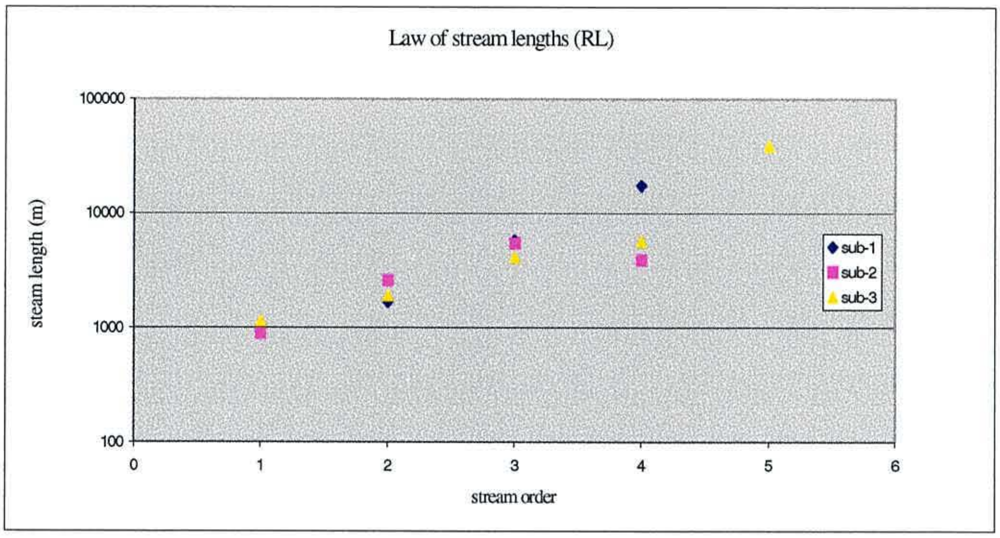


Figure 6.7: *Marab* Hassan catchment law of stream lengths.

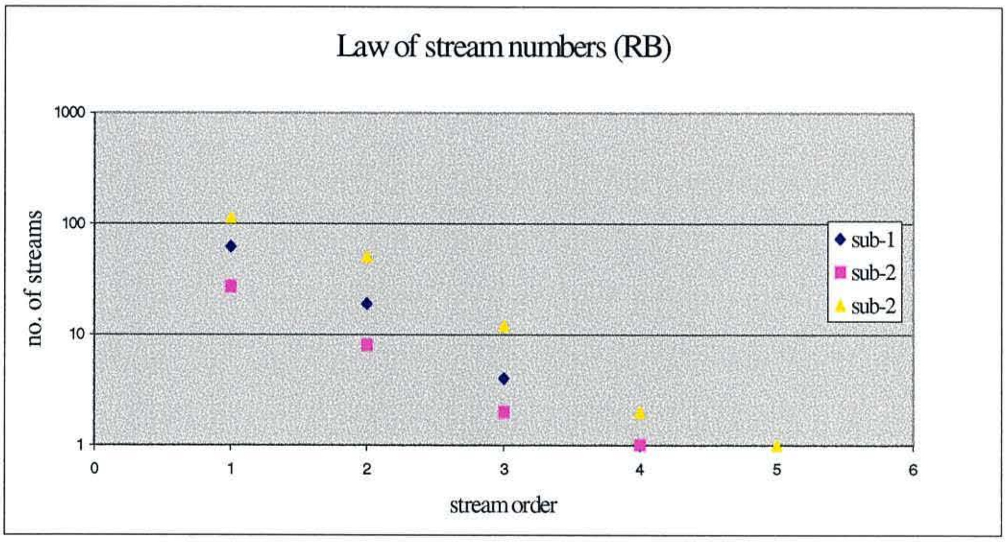


Figure 6.8: *Marab* Hassan catchment law of stream numbers

The most important characteristics of the GIUH are its peak flow (Q_p) and time to peak (t_p). Equations to calculate them for a 3rd order stream catchment are given below as developed by Rodriguez-Iturbe and Valdes, (1979), for higher orders the equations can be derived with the same framework, i.e. similar procedure but applying a different formula. Compare, in Section 6.3, the limitations of the DEM in resolving in first order streams. Note that this is a general problem with maps whose scales do not allow the depiction of all the channels.

$$Q_p = 1.31(R_L)^{0.43}\frac{v}{Lw} \qquad [6.4.4]$$

$$t_p = 0.44(R_L)^{-0.38}(\frac{R_B}{R_A})^{0.55}(\frac{Lw}{v}) \qquad [6.4.5]$$

Where:

Q_p is the peak flow (hr^{-1})

t_p is the time to peak (hr)

R_L is the law of stream lengths

R_A is the law of stream areas.

R_B is law of stream numbers

L_w is the stream length (km)

v is streamflow velocity (m/s)

For 4th order catchments the above equations will be:

$$Q_p = 1.31(R_L)^{-0.57}\frac{v}{Lw} \qquad [6.4.6]$$

$$t_p = 0.44(R_L)^{0.62}(\frac{R_B}{R_A})^{0.55}(\frac{Lw}{v}) \qquad [6.4.7]$$

For 5th order catchments the above equations will be:

$$Q_p = 1.31(R_L)^{-1.57}\frac{v}{Lw} \qquad [6.4.8]$$

$$t_p = 0.44(R_L)^{1.62}(\frac{R_B}{R_A})^{0.55}(\frac{Lw}{v}) \qquad [6.4.9]$$

The procedure for developing Marab Hassan catchment area GIUH is listed below:

1. The stream order grid was created for the catchment area using the Strahler stream ordering method as mentioned before, (Figure 6.9).
2. The catchment area was divided into three sub-catchments, and each sub-catchment was subdivided into further sub-catchments according to the stream order, as presented in Figures 6.10 and 6.11. Sub-catchments with order 2 and above were considered in calculations, for simplicity. For each sub-catchment, the stream length (L_w), the stream order, and area (A) were known, as shown in figures 6.6, 6.7 and 6.8.
3. Each stream order was assigned a velocity value (v) according to the sections' geometry. Values used are 2.36, 4.16, 4.65 and 5 m/s for 2nd, 3rd, 4th and 5th orders respectively. These velocity values were calculated using Manning's equation (equation 5.4.2).
4. Using the above equations the peak flow (Q_p) and time to peak (t_p) values were calculated for each sub-catchment. To calculate the time base for the hydrograph, an approximation was made that the hydrograph shape is triangular and the total volume of the runoff under the hydrograph is 10 mm. Tables 6.1, 6.2 and 6.3 list the calculated hydrograph characteristics for each sub-catchment and its subdivisions.
5. The time base (T) for the hydrographs was calculated based on the assumption that the total volume under the hydrograph is 10 mm.
6. Muskingum routing method was used to route the individual hydrographs for each sub-catchment to reach the major outlet, at which they combined to perform the GIUH for each major sub-catchment of the three. Then after reaching the *Marab* the three GIUHs were routed again as done before for Snyder's and SCS unit hydrographs.

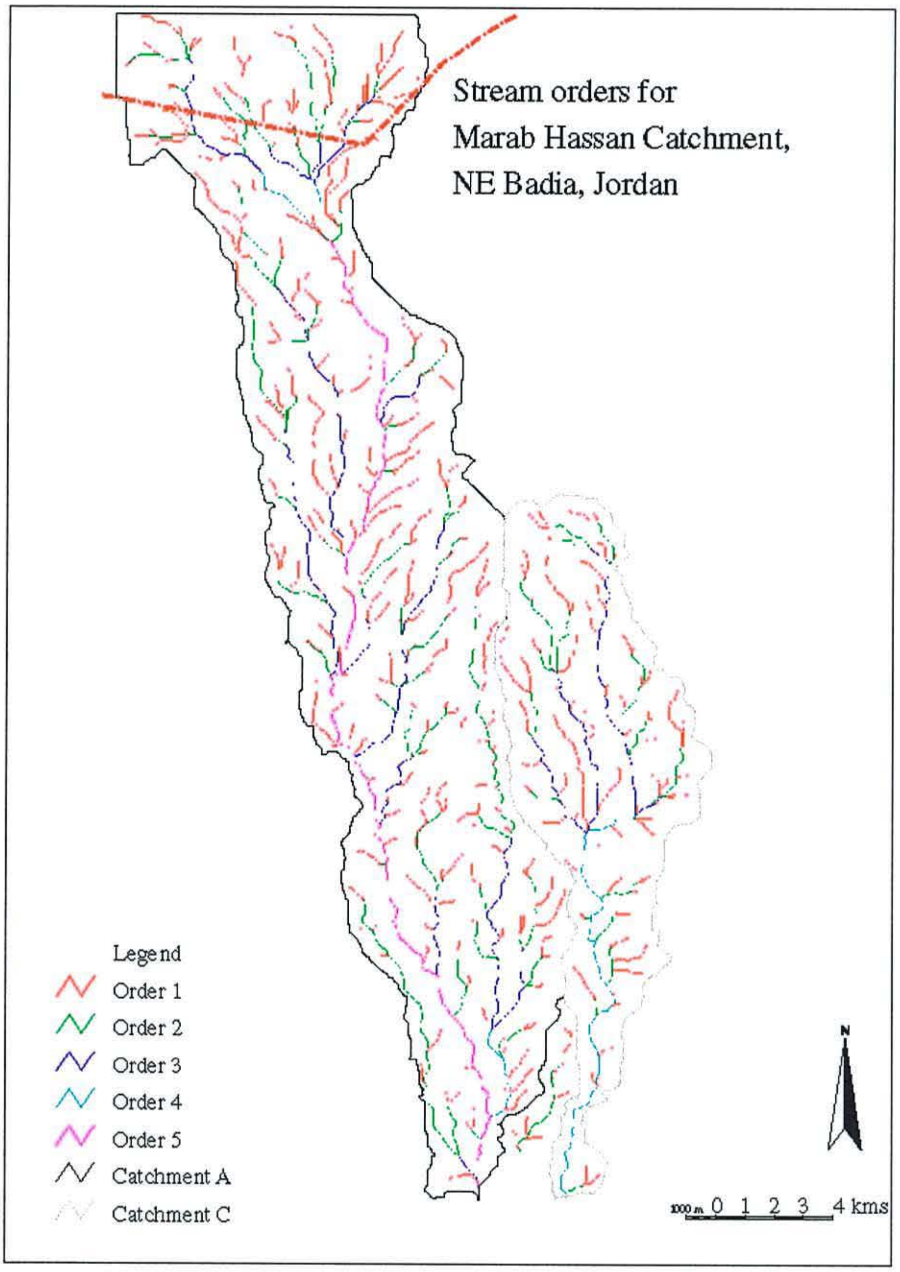


Figure 6.9: *Marab* Hassan catchment stream orders and sub-catchments, (developed based on DEM that is originally based on 1:50,000 topographic maps with 10m contour interval).

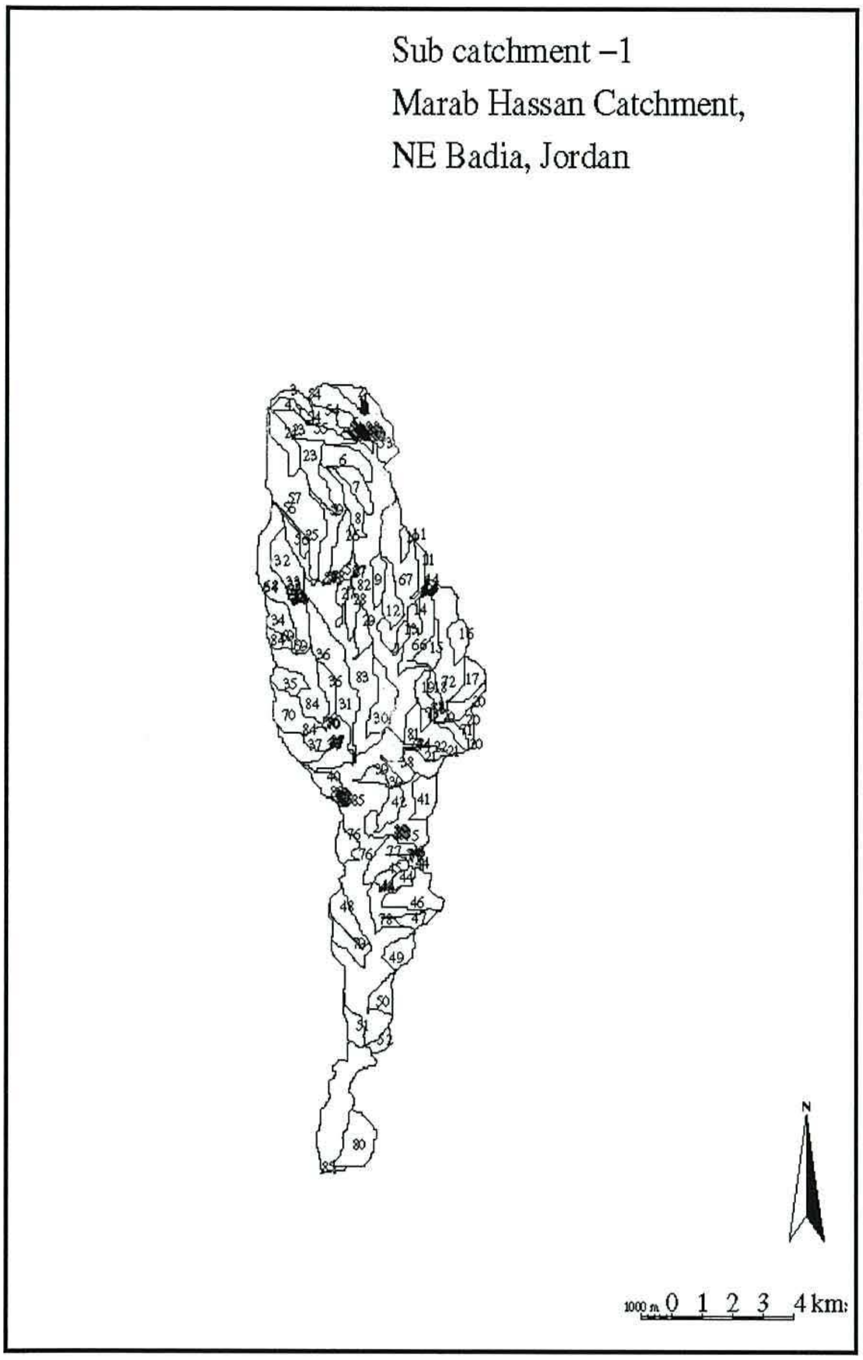


Figure 6.10: sub-1 sub-areas with numbers that are used in GIUH.

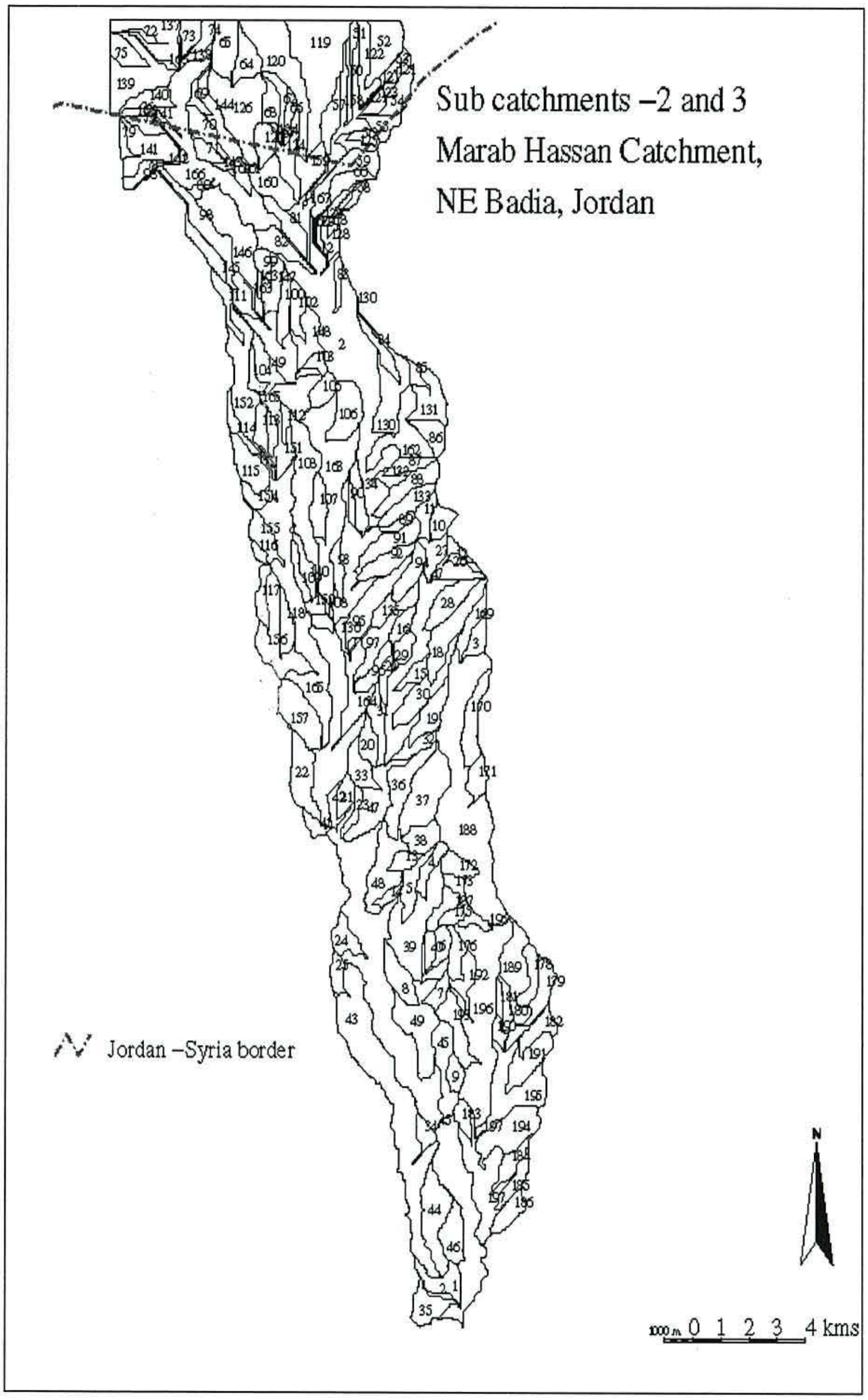


Figure 6.11: sub-2 and 3 sub-areas with numbers, used in GIUH.

Table 6.1: Sub-1 subdivisions GIUH characteristics

sub-area	A (m^2)	Stream length (m)	Stream length (km)	Qp (hr^{-1})	Qp (m3/s)	tp (hr)	T (hr)
stream order 2 areas							
53	2220300	2955.99	2.96	1.63	10.05	0.48	1.23
54	639900	1861.873	1.86	3.33	5.92	0.31	0.60
55	1137600	1506.837	1.51	3.18	10.05	0.24	0.63
56	601200	1453.675	1.45	3.32	5.54	0.23	0.60
57	3533400	4304.041	4.30	1.12	10.99	0.7	1.79
59	1555200	2955.808	2.96	1.63	7.04	0.48	1.23
66	1243800	1661.102	1.66	2.89	9.98	0.27	0.69
67	1902600	3277.204	3.28	1.47	7.77	0.48	1.36
68	977040	1706.543	1.71	2.81	7.63	0.27	0.71
70	1318500	1202.756	1.20	4	14.65	0.19	0.50
72	1795500	2109.153	2.11	2.27	11.32	0.35	0.88
73	145800	396.8377	0.40	12.01	4.86	0.06	0.17
75	1795500	1678.675	1.68	2.86	14.26	0.27	0.70
76	587700	358.4924	0.36	13.35	21.79	0.06	0.15
77	1107000	1230.807	1.23	3.91	12.02	0.2	0.51
78	1013400	1405.477	1.41	3.4	9.57	0.23	0.59
79	729900	694.7056	0.69	6.97	14.13	0.11	0.29
80	730800	641.9849	0.64	7.51	15.25	0.1	0.27

Sub-area	A (m^2)	stream length (m)	stream length (km)	Qp (hr^{-1})	Qp (m^3/s)	tp (hr)	T (hr)
Stream order 3							
81	1442700	1212.168	1.21	6.99	28.01	0.11	0.29
82	5727600	10770.66	10.77	0.79	12.57	0.99	2.53
83	3778200	6717.275	6.72	1.26	13.22	0.62	1.59
84	3642300	4301.438	4.30	1.97	19.93	0.4	1.02

Sub-area	A (m^2)	stream length (m)	stream length (km)	Qp (hr^{-1})	Qp (m^3/s)	tp (hr)	T (hr)
Stream order 4							
85	12689100	17457.05	17.46	0.19	6.70	4.02	10.53

Table 6.2: Sub-2 subdivision GIUH characteristics

Sub-area	A (m^2)	Stream Length (m)	Stream length (km)	Qp (hr-1)	Qp (m^3/s)	tp (hr)	T (hr)
order 2 areas							
187	1165500	1581	1.58	2.58	8.36	0.34	0.77
188	9393300	9656	9.66	0.42	11.03	2.10	4.73
189	2417400	2775	2.78	1.47	9.88	0.60	1.36
190	340200	560	0.56	7.29	6.89	0.12	0.27
191	1387800	1286	1.29	3.17	12.24	0.28	0.63
192	795600	1294	1.29	3.16	6.97	0.28	0.63
193	1358100	1920	1.92	2.13	8.02	0.42	0.94
194	2182500	1550	1.55	2.63	15.97	0.34	0.76

Table 6.2: Continued

order 3 areas	A (m^2)	Stream length (m)	Stream length (km)	Qp (hr^{-1})	Qp (m^3/s)	tp (hr)	T (hr)
195	2781900	3282	3.28	2.19	16.95	0.41	0.91
196	6514200	7606	7.61	0.95	17.12	0.94	2.11

order 4 areas

Sub-area	A (m^2)	Stream length (m)	Stream length (km)	Qp (hr^{-1})	Qp (m^3/s)	Tp (hr)	T (hr)
197	2782800	3614	3.61	1.17	9.01	0.76	1.72

Table 6.3: Sub-3 subdivision used in GIUH.

order 2 areas

sub-area	A (m^2)	Stream length (m)	Stream length (km)	Qp (hr^{-1})	Qp (m^3/s)	tp (hr)	T (hr)
119	4827600	3314	3.31	1.50	20.18	0.39	1.33
120	3324600	3767	3.77	1.32	12.22	0.45	1.51
122	1059300	662	0.66	7.53	22.16	0.08	0.27
126	3359700	2840	2.84	1.76	16.38	0.34	1.14
124	1207800	1964	1.96	2.54	8.52	0.23	0.79
138	374400	340	0.34	14.66	15.25	0.04	0.14
137	1791900	938	0.94	5.32	26.46	0.11	0.38
139	2605500	2268	2.27	2.20	15.91	0.27	0.91
141	1880100	1744	1.74	2.86	14.93	0.21	0.70
144	1312200	2418	2.42	2.06	7.52	0.29	0.97
128	777600	1229	1.23	4.06	8.76	0.15	0.49
130	2022300	1908	1.91	2.61	14.68	0.23	0.77
131	1515600	1283	1.28	3.89	16.36	0.15	0.51
146	2991600	3776	3.78	1.32	10.97	0.45	1.51
147	939600	999	1.00	4.99	13.03	0.12	0.40
145	1697400	1707	1.71	2.92	13.77	0.20	0.68
148	1271700	1205	1.21	4.14	14.62	0.14	0.48
149	1066500	925	0.93	5.39	15.97	0.11	0.37
152	2695500	4781	4.78	1.04	7.81	0.57	1.92
151	1139400	1220	1.22	4.09	12.93	0.15	0.49
156	2376900	2610	2.61	1.91	12.61	0.31	1.05
157	1985400	1531	1.53	3.26	17.96	0.18	0.61
150	356400	871	0.87	5.72	5.67	0.10	0.35
135	983700	2496	2.50	2.00	5.46	0.30	1.00
27	815400	1354	1.35	3.68	8.34	0.16	0.54
26	1097100	809	0.81	6.16	18.78	0.10	0.32
28	1332000	1000	1.00	4.99	18.45	0.12	0.40
29	1019700	1112	1.11	4.48	12.70	0.13	0.45
30	1553400	2120	2.12	2.35	10.15	0.25	0.85
32	676800	1419	1.42	3.51	6.61	0.17	0.57
33	979200	750	0.75	6.65	18.08	0.09	0.30
36	1792800	2026	2.03	2.46	12.26	0.24	0.81
37	2728800	2038	2.04	2.45	18.54	0.24	0.82
39	3185100	3361	3.36	1.48	13.13	0.40	1.35
45	1552500	2678	2.68	1.86	8.03	0.32	1.07
44	2252700	2064	2.06	2.42	15.12	0.25	0.83

Table 6.3: Continued

43	8258400	10688	10.69	0.47	10.70	1.27	4.29
Order 3 areas							
Sub-area	A (m^2)	Stream length (m)	Stream length (km)	Qp (hr^{-1})	Qp (m^3/s)	tp (hr)	T (hr)
158	2105100	3970	3.97	2.21	12.95	0.27	0.90
159	1101600	1336	1.336	6.58	20.13	0.09	0.30
160	1592100	1973	1.973	4.46	19.70	0.13	0.45
166	5573700	5727	5.727	1.53	23.76	0.39	1.30
163	8653500	11257	11.257	0.78	18.77	0.76	2.56
162	2101500	2453	2.453	3.58	20.92	0.17	0.56
165	6448500	8759	8.759	1.00	17.98	0.59	1.99
47	5511600	9680	9.68	0.91	13.90	0.66	2.20
48	2049300	3314	3.314	2.65	15.10	0.22	0.75
49	2674800	3166	3.166	2.78	20.63	0.21	0.72
164	1585800	3287	3.287	2.67	11.78	0.22	0.75
Order 4 areas							
Sub-area	A (m^2)	Stream length (m)	Stream length (km)	Qp (hr^{-1})	Qp (m^3/s)	tp (hr)	T (hr)
166	397000	3568	3.57	0.91	1.00	0.65	2.21
167	714600	2361	2.36	1.37	2.72	0.43	1.46
197	2799000	3614	3.61	0.89	6.95	0.65	2.24
order 5 areas							
sub-area	A (m^2)	Stream length (m)	Stream length (km)	Qp (hr^{-1})	Qp (m^3/s)	tp (hr)	T (hr)
2	32207400	39125	39.13	0.029	2.61	20.36	68.46

The peak flow, time to peak and time base values in the tables above were used to develop the individual unit hydrograph for each subdivision. Then each one was routed through the channel reaches, after that all of them were combined to form *Marab* Hassan Geomorphologic Instantaneous Unit Hydrograph (GIUH) as shown in Figure 6.12.

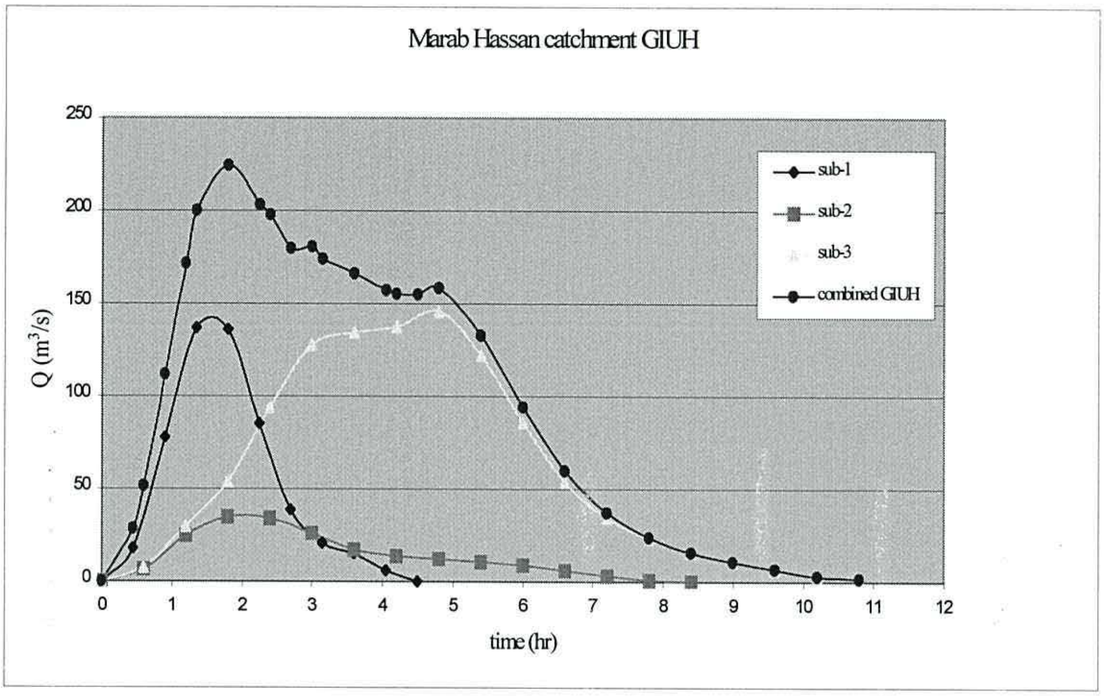


Figure 6.12: *Marab* Hassan catchment GIUH.

Table 6.4: *Marab* Hassan catchment GUIH characteristics

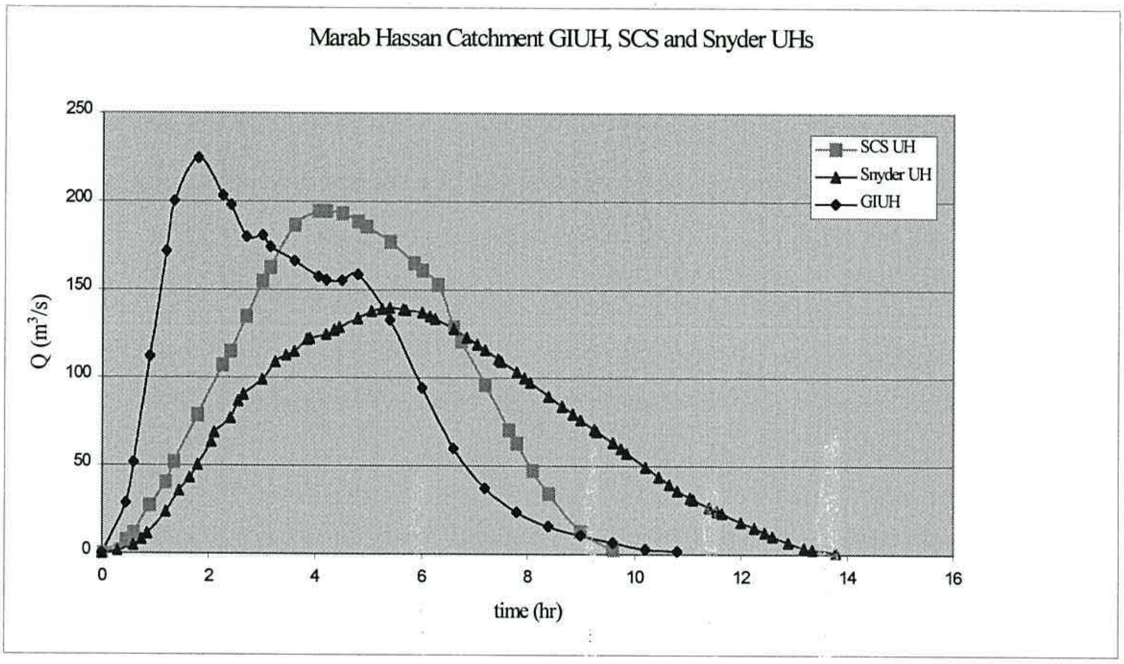
Sub-ID	Q_p (m^3/s)	t_p (hr)	T (hr)
1	137	1.58	4.5
2	34.65	1.80	8.4
3	145.95	4.80	10.8
Combined	224.22	1.80	10.8

From Figure 6.12 and Table 6.4 it is clearly seen that the shape of the hydrographs is looking better than the SCS and Snyder's. With sub-2 having the minimum peak flow rate and sub-3 having the maximum and sub-1 is somewhere in between, it can be concluded that as sub-2 got only eight 2nd order sub-catchments, two 3rd and only one 4th order sub-catchment that contribute to the flow. It is obvious that the total number compared with the other two sub-catchments 1 and 3 is less than the total number for sub-1 (eighteen 2nd, four 3rd and one 4th) and sub-3 (thirty-seven 2nd, twelve 3rd, three 4th and one 5th) affects the amount of the peak flow. Time to peak is a function of both stream length and velocity, as velocity increases the travel time decreases for areas with the same stream length. For sub-1 being longer than sub-2 but shorter than sub-3 and the majority of sub-areas of stream order 2 were routed through order 3, which has a flow velocity of 4.16 m/s, the total time to peak for it almost the same as sub-2. Most of the delay in sub-2 comes from a fairly long sub-area (sub-188) that is 2nd order and then routed again within sub-196 that is shorter but the total effect makes the time to peak to the whole catchment almost the same as sub-1. While for sub-1 the sub-areas contributing to the travel time are 3rd order with fairly high velocity (4.16 m/s) compared with 2.36 m/s for the 2nd order streams, and then these areas were routed through the 4th order sub-area which again has a fairly high flow velocity (4.65 m/s), so the combined effect is having a reasonable time to peak compared with SCS and Snyder as shown in Figure 6.13.

Sub-3 is the biggest in area and number of streams (thirty-seven 32nd, twelve 3rd, three 4th and one 5th). This number of areas is contributing well to the peak flow, that makes it the highest among the three. Also having 37 sub-areas of stream order 2, (v=2,36 m/s) affects the time to peak, as well as the time base of the hydrograph. Sub-3 has the longest time to peak and time base.

From the previous discussion it can be concluded that the flow velocity is one of the key factors that affect the GIUH characteristics. Generally speaking the higher the velocity value, the higher the peak flow and the lower the time to peak, (Rodriguez-Iturbe and Valdes, 1979; Al-Wagdany and Rao, 1998). The same time we should bear in mind that the velocity is not easy to estimate, as it needs to be selected carefully. The ratios used (Horton's laws, (Whittow, 1984)) seem to have almost the same effects on all the catchments.

Figure 6.13 compares the three unit hydrographs for the whole catchment, what if the hydrographs for each sub-catchment are taken and compared separately? Are the individual sub-catchments going to behave the same way? Figures 6.14 to 6.16 answer the question. From the figures it seems that the GIUH for the individual sub-catchments are the most favourable. This is due to the various reasons mentioned previously. The individual sub-catchments unit hydrographs before routing through the *Marab* are shown in Appendix C.



Figure[1] 6.13: *Marab* Hassan catchment GIUH, SCS and Snyder unit hydrographs.

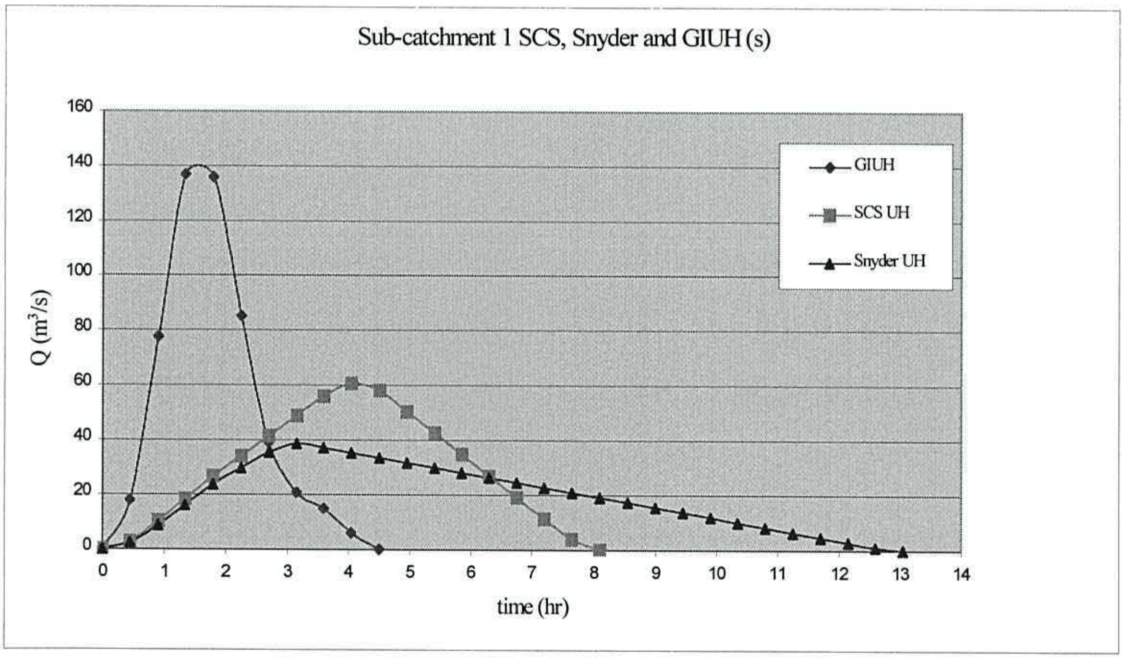


Figure 6.14: Sub-catchment 1 GIUH, SCS and Snyder unit hydrographs.

[1] SCS and Snyder are 1 hour unit hydrographs, while GIUH is instantaneous, i.e. it needs to develop the 1 hour GIUH.

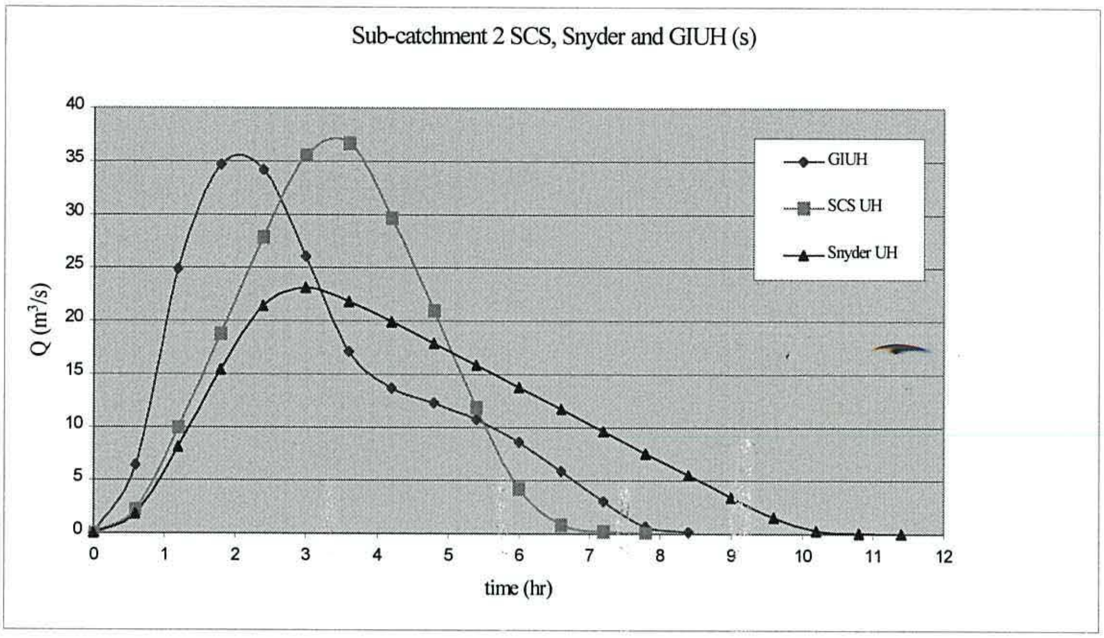


Figure 6.15: Sub-catchment 2 GIUH, SCS and Snyder unit hydrographs.

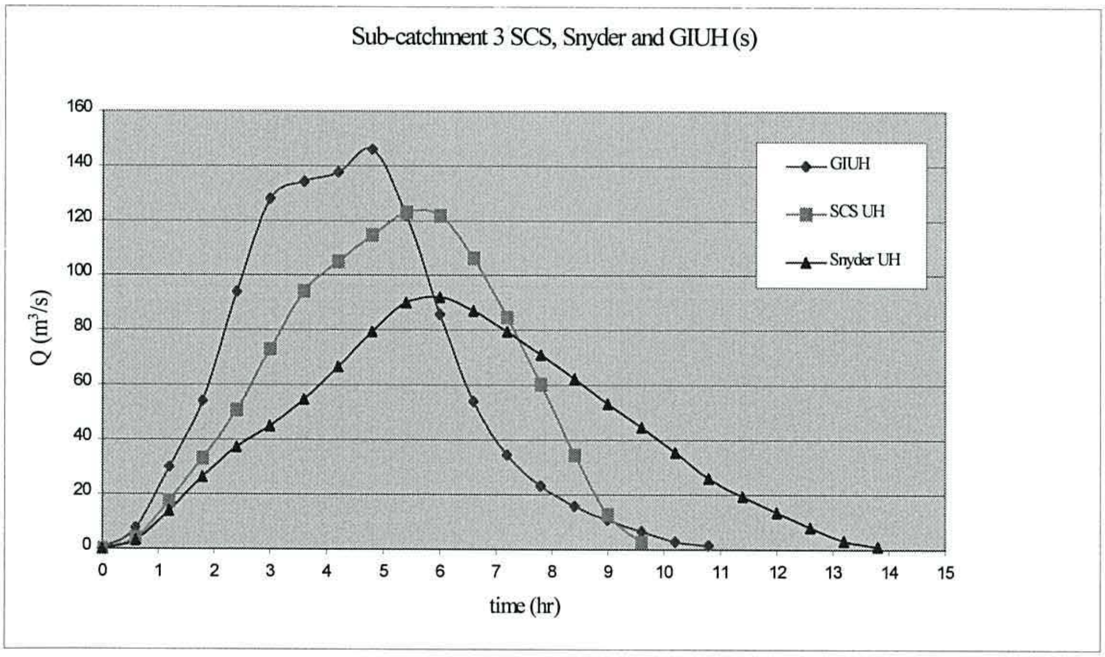


Figure 6.16: Sub-catchment 3 GIUH, SCS and Snyder unit hydrographs.

One more important thing that should be taken into account not just with the GIUH approach, but with every modelling approach is the effect of the drainage density (i.e. the ratio of the total length of the stream channels in a catchment to its area). This becomes an important issue, as the drainage network used in the analysis originated from the DEM, which means that some streams could be missed and not included in the system and this has an effect on the whole modelling processes. An approach given by Hickok, Keppel and Raffey (that was meant to be similar to the SCS), (Gray, 1970) has been applied to Marab Hassan catchment. In this approach the travel time was given as a function of the drainage density, which made the approach not applicable to *Marab* Hassan catchment area due to limitations of GIS/DEM in detecting the drainage density.

The areas with stream order one were not taken into account while developing the GIUH. This is because of the flow in these areas is mostly overland flow that cannot be dealt with as channel flow. Therefore, because of limitations associated with the GIUH equations, (as they are only considered for channel flow), areas with stream order one were excluded from the calculations. However this may have affected the results, especially the peak flow and the time to peak as well, as they might be under estimated.

6.5 Conclusions

The lack of data (due to reasons mentioned previously) is the major constraint on modelling arid zones. This problem has been associated with the catchment since the start of the project more than four years ago. It proved impossible to collect reliable flow or stage data during the project period.

All synthetic unit hydrograph methods including GIUH are dependent on the selection or estimation of some parameters like Manning's n and Muskingum routing coefficients. Therefore, comparing the three is not a comparison of three independent methods, rather it is a comparison of partially inter-dependent methods.

For all the mentioned reasons synthetic approaches were followed to model the catchment area, and from all of them the GIUH approach seems to be the most reliable one for the reasons mentioned earlier. Also, GIUH appears to be the most sophisticated and detailed methodology. The Geomorphologic Instantaneous Unit

Hydrograph shape is judged to be more realistic than the SCS and Snyder's. However the SCS hydrograph seems broadly satisfactory, especially as it includes less work (i.e. time and effort), while Snyder is found not applicable to the catchment without regional coefficients.

CHAPTER SEVEN

THE DETECTION OF THE INFLUENCE OF GLOBAL CLIMATIC PHENOMENA IN JORDANIAN RAINFALL

7.1 INTRODUCTION

The objective of this study is to integrate possible correlation between the Jordanian seasonal and annual rainfall and several climatic phenomena comprising the El- Niño Southern Oscillation (ENSO), North Atlantic Oscillation and Indian Ocean Sea Surface Temperature (tabulated values of the indices are listed in Appendix F), in order to develop a rainfall probability model, based on the significant correlation coefficients. If the model can be developed and verified it will be useful for water resources management in the area.

7.2 EL-NIÑO SOUTHERN OSCILLATION (ENSO)

El-Niño is a Spanish word, which means a small boy or more specifically the Christ child. It occurs around December, therefore the connection with Christmas and Christ child. It refers to the warm currents that migrate from the western pacific to the east reaching the coast of South America, causing a rise in the sea temperature (Glantz, 1998). The changes in the ocean circulation have been linked to the seesaw changes in atmospheric pressure in the Pacific known as Southern Oscillation (SO). The Southern Oscillation Index (SOI) is the pressure difference between the eastern equatorial Pacific and Indo-Australian areas. Generally, when pressure is high over the Pacific Ocean, it tends to be low in the eastern Indian Ocean, and vice versa. It is measured by taking the difference in sea level pressure between Tahiti in the east, and Darwin in the west. High negative values of SOI represent an El-Niño or a warm event. It is known as ENSO, which is El-Niño Southern Oscillation.

El-Niño's return period varies, ranging from two to seven years, (Mackenzie, 1998). The intensity and the duration of the event are also variable and hard to predict.

Typically, it lasts from 14 to 22 months, but it can be much longer or shorter. It begins early in the year and peaks in other sites between the following November and January. But it may last for longer as in the 1994 El-Niño started around April1991 and ended around January 1994, (Bigg, 1995). During the last century 23 El-Niño events happened. It is believed that the major ones were the 1982-83 and 1997-98 events, as they were called "the El-Niños of the century". The duration of any El-Niño event is considered as a measure of its strength.

High positive values of the SOI indicate a La-Niña or cold event (the Spanish word for girl). La-Niña is a counterpart of the El-Niño and represents the other extreme of the ENSO cycle. During La-Niña the sea surface temperatures in the equatorial Pacific drop well below the normal levels and depart to the west while the trade winds are usually intense rather than weak. La-Niña years often but not always follow El-Niño years, but sometimes La-Niña may begin on its own without an immediately proceeding El-Niño, (Philander, 1998). It occurs roughly half as often as El-Niño. The most recent strong La-Niña was in 1988/89; a moderate one occurred in 1998/99, which weakened back to natural conditions before reforming for a shorter period in 1999/2000. This last event finished in autumn 2000. The effects of the El-Niño and La-Niña on global climate are mirror images in each other. For example, drought is a common occurrence in the south-western United States during La-Niña, in contrast to the wet years associated with El-Niño, (Glantz, 2001). Table 7.1 shows the El-Niño and La-Niña years.

ENSO is known to be one of the largest sources of natural variability in the climate system. Once it is established there is a tendency for the phenomenon to exhibit a quasi-biennial (i.e. occurs every two years) characteristics, i.e. to change from one phase to the other during the life cycle, (Allan et al., 1996). ENSO occurrences are global climate events that are linked to various climatic anomalies. Anomalies denote the departure of an element from its long-term average value for the location concerned. Not all anomalies even in ENSO years are due to ENSO. In fact, statistical evidence shows that ENSO can account for about 50% of the international rainfall variance in Eastern and Southern Africa. Many researchers are studying the relationship between ENSO (El-Niño and La-Niña) events and weather anomalies around the globe to determine whether links exist understanding these teleconnections can help in forecasting drought, floods, and tropical storms, (Glantz, 2001). There appears to be an association between ENSO events and the increased likelihood of droughts in different parts of the world like northern Australia, south-eastern Africa, Indonesia, the Philippines, northern Brazil and Central America.

As well as SOI, ENSO Sea Surface Temperature (SST) Index could be used to indicate the event's phase, either El-Niño or La-Niña, (Kiem and Franks, 2001). During El-Niño episodes, the equatorial SSTs are abnormally warm from the date line eastward to the South American coast. Warm means high positive values for SST. As a conclusion El- Niño events are associated with high SST values and low SOI values, while during La-Niña events the SOI values are high and the SST values are low. The two indices are shown in Figure 7.1. Once SST began it is clearly seen that there is a correlation between SST and SOI, i.e. if one is high the other is low and vice versa. SST is the most important parameter for ENSO monitoring, and it is the key-predicting factor in all ENSO forecasting schemes, as will be seen later in the next sections.

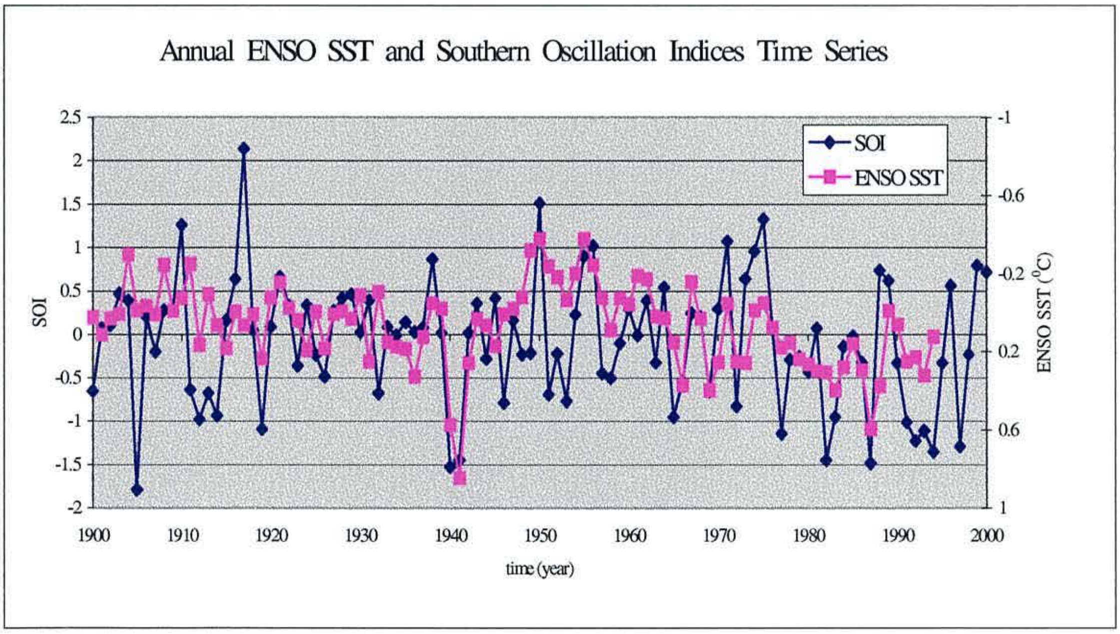


Figure 7.1: Annual ENSO SST and SOI Time Series.

Table 7.1: El-Niño and La-Niña years, after NOAA[1]

El-Niño years	La-Niña years
1902-1903	1904-1905
1905-1906	1909-1910
1911-1912	1910-1911
1914-1915	1915-1916
1918-1919	1917-1918
1923-1924	1924-1925
1925-1926	1928-1929
1930-1931	1938-1939
1932-1933	1950-1951
1939-1940	1955-1956
1941-1942	1956-1957
1951-1952	1964-1965
1953-1954	1970-1971
1957-1958	1971-1972
1965-1966	1973-1974
1969-1970	1975-1976
1972-1973	1984-1985
1976-1977	1988-1989
1982-1983	1995-1996
1986-1987	1998-1999
1991-1992	1999-2000
1994-1995	
1997-1998	
2001/2002[P]	

[P] indicates predicted, as it is predicted that El- Niño will start in early spring and will peak sometimes late this year, (Daly, 2002).

7.3 ENSO's Link with Sunspot and Lunar Cycles

Actually, El-Niño and La-Niña are subjected to external forcing by the sun's varying activity to such a degree that it explains nearly all of ENSO's irregularities and makes long-range forecasts beyond the 1-year limit possible. Sunspots are regions of the sun's surface of intense magnetic disturbance 100-1000 times the average for the sun, (Bryant, 1991).

Sunspots generally occur in groups, which are bipolar; i. e. the first spots forming in any hemisphere of the sun are of one magnetic polarity, while subsequent spots are of opposite polarity. This sequence has reversed polarity in the opposite hemisphere every 11 years. For example, if sunspots developing in the Northern Hemisphere of the sun in the first 11 years show a north-south polarity, there will be evidence of a south-north polarity in the following cycle. Thus, the sun has a 22 years magnetic cycle, consisting of two 11 years sunspot cycle. Also from further inspection it appears

[1] NOOA: National Oceanic and Atmospheric Administration (http://www.noaa.gov/climate.html)

that the peaks become higher every 80-90 years. But most scientists only infer a link between climatic variables and the 11 and 22 years cycles.

Although there are no strict physical arguments that could explain in detail how solar activity causes ENSO events, it is quite possible to develop working hypotheses that suggest potential connections. Strong solar eruptions cause the highest velocities in the solar wind and create shock waves that compress and intensify magnetic fields in the sun's plasma moving outward to the boundary of the solar system. The solar wind strengthened by solar eruptions weakens cosmic rays. So one would deduce that shrinking cloud cover, stronger irradiance and changing trade winds, caused by the modulating effect of solar eruptions on cosmic rays, improve the conditions for the birth of El-Niños.

Southern Oscillation could also be affected by the lunar cycle that tends to be 18.6 years, as it represents the fluctuation in the orbit of the moon. The 18.6-year lunar cycle is associated with either floods or drought in different parts of the world. There is now proof that numerous droughts and subsequently heavy rainfall periods are cyclic, not only in semi-arid parts of the globe but also in temperate climates, (Bryant, 1991). This cyclicity is not random but matches well with the 18.6 years lunar cycle in regions like North America, Argentina, north China, the Nile Valley and India. There is also evidence that the sunspot 11 years cycle represents the rain in some countries (Gates, 1993).

There is no clear link so far between the occurrence of ENSO and climate change (global warming), as El-Niño has occurred many years ago before people started adding carbon dioxide to the atmosphere that caused the global warming. Whether climate change is causing El-Niños in recent years to become stronger or longer lasting is an open question. Still there is no clear evidence for that.

7.4 North Atlantic Oscillation (NAO)

The ENSO is not the only atmospheric pattern that is known to impact the weather and climates worldwide. A similar phenomenon called the North Atlantic Oscillation (NAO) occurs over the Atlantic Ocean. The NAO is characterised by an oscillation, or mass exchange, between a low-pressure region over Iceland and a broad high pressure belt centred at about 40°N in the North Atlantic. The high-pressure region is sometimes termed the Azores, Lisbon or Gibraltar high. Many previous studies have used the Azores. More recently Hurrel from the National Centre for Atmospheric Research has used Lisbon, (Hurrel, 1995). In this study the index will be taken as the difference between Iceland and Gibraltar.

For spring, summer and autumn the pressure systems remain weak and ineffectual while for winter the NAO index becomes active and develops one of two phases, positive or negative. The positive (warm) NAO index phase shows a stronger than usual Azores high pressure and deeper than normal Icelandic low. This increased pressure difference results in more and strong winter storms crossing the Atlantic Ocean on more northerly track. As a result warm and wet winters are experienced in Europe, droughts in the Middle East, and cold and dry winters in northern Canada and Greenland, while, the eastern United States have mild and wet winter conditions, (Creilson, 2000).

During the negative (cold) NAO phase both the Azores and the Icelandic are weak, i.e. the pressure difference is negative. This results in fewer and weaker winter storms crossing the Atlantic on more west-east way. They bring moist air to the Mediterranean and cold weather to northern Europe. The United States East Coast experiences more cold air outbreaks and hence snowy winter condition. Greenland will have milder winter conditions, (Weter, 2000).

The variations in the rainfall climatology in the Middle East are related to climate anomalies in other parts of the world. For example wintertime North Atlantic Oscillation index and the Middle East temperature anomalies have been found negatively correlated, (Jedlovec and Chang, 1997). An example about that is the study that was done by Cullen and deMenocal, (1997), which indicated that the Turkish winter temperature is correlated with the NAO_{SST} index with $r=-0.56$; exceeds 99.9% confidence interval. Turkish winter rainfall showed a high correlation with the NAO_{SST} index between 1930-1994 of $r=-0.70$ and exceeds 99.9 confidence interval. The effect on NAO on the Jordanian rainfall will be discussed later in the chapter.

7.5 Indian Ocean Sea Surface Temperature Anomalies

The Indian Ocean has its own El-Niño like phenomenon that does not always occur at the same time as the El-Niño in the Pacific Ocean. It is characterised by an east to west displacement of warm water that affects parts of the world, (Webster, 1999). This movement is known as the Indian Ocean Dipole. Even a strong event in the Indian Ocean is weak compared to an average El-Niño, (Geerts, 1998). This index is based on the ocean's Sea Surface Temperature SST variations.

The Indian summer monsoon is crucial for agriculture, but during the Indian Ocean "El-Niño", the southwesterly summer monsoon is much weaker and less moisture is less advected to India, i.e. drought conditions are experienced. The Indian Ocean Sea Surface Temperature Anomalies have been correlated with the Jordanian rainfall as will be seen later.

7.6 Jordanian Rainfall and Climatic Cycles

Global patterns described by satellite observations have made it possible for scientists to link weather systems and climatic anomalies in one region of the globe to another and lead the notion on teleconnection associated with inter-annual variabilities like ENSO, (Gurney et al., 1993). The large distance in space and the difference in timing between anomalous events make it difficult for one to believe that events like El-Niño and La-Niña could possibly have connections with for example, droughts in southern Africa, (Glantz, 2001).

In the next section we will test the correlation between ENSO SST and SOI and the Jordanian Rainfall. Throughout the analysis of annual rainfall for the Jordanian stations it was clearly seen that there are periods of above and below average rainfall during the El-Niño and La-Niña years. In 1972-73 El-Niño events that started in April 1972 and ended in March 1973, drought was experienced in Jordan between September and December 1972. Another example is the impact of 1986 El-Niño that started in August 1986 and ended in February 1988, is a drought that took place between April and May, while for the La-Niña event heavy snow occurred in the country between December 1988 and February 1989. The event started in May 1988 and ended in June 1989. (Glantz, 2001). While, during the 1991-92 El-Niño event heavy rain occurred in December 1991 as well as snows in January and February 1992. The event is believed to have lasted for a long time as it started around April 1991 until January 1994 as mentioned before, (Bigg, 1995). It should be noticed that in some years drought occurs without the occurrence of an El-Niño event. Figure 7.3 illustrates the annual regional rainfall index (ARRI) for the Jordanian stations vs. the SOI between 1960-1989. From the figure it is clearly seen that the amount of rainfall in El-Niño years is almost below the average for most of the stations, while in some La-Niña years the opposite scenario occurs.

The same analysis was done between the rainfall and the ENSO-SST anomalies, North Atlantic Oscillation and Indian Ocean Sea Surface Temperature anomalies (IO SST) indices.

7.7 Correlation between the Rainfall Index and the Climatic Indices

The main aim of this exercise is to test the correlation between the Jordanian rainfall and the climate indices, which are ENSO SST index, SOI, North Atlantic Oscillation (NAOI) and Indian Ocean SST anomalies, then to build up rainfall probability model (based on using a set of rainfall data between 1960 to 2000), which will be used to predict the future rainfall based on the climate indices values. This kind of model could be helpful in water resources management for the whole of Jordan, especially for the agricultural sector, as predicting the status of the following year's rainfall (i.e. above or below average) in advance is essential.

7.8 Data

The data used in the analysis included monthly rainfall data for 11 Jordanian stations distributed all over the country, between 1960 and 2000. The first 30 years from 1960-1989 were used to build up the model and the last 11 years were used to verify it. The concept of hydrological year from September to August of the following year was used for both the rainfall and the other indices. The first 30 years (1960-1989) data set was obtained from the University of Manchester database centre, while the last 11 years was obtained from the Jordanian Ministry of Water Resources. The monthly rainfall data was used to calculate the Average Regional Rainfall Index (ARRI) as will be described in the methodology section.

Monthly global SST ENSO index values were obtained from the University of Washington web site. The index is taken as the average SST for the region of 20° North and South the equator minus the average SST poleward of 20°. The monthly records of SOI were taken from the Climatic Research Unit web site at the University of East Anglia, in United Kingdom. SOI as explained earlier is the pressure difference between Tahiti and Darwin. Both indices are time series for long period of records starting from mid 1880s until 2001 for the SOI and till 1995 for the SST ENSO index. Obviously the corresponding years for the rainfall data were used in the analysis.

Monthly North Atlantic Oscillation index (NAOI) values were obtained from the web site of the Climatic Research Unit at the University of East Anglia in United Kingdom. This index is based on the pressure difference between Iceland and Gibraltar. The obtained time series is from 1821 until 2000. The corresponding values of the rainfall records were used. The values were averaged on seasonal and annual basis to be correlated with the ARRI.

Indian Ocean Sea Surface Temperature Anomalies were obtained from the University of Washington web site. Monthly values (in hundreds of degrees Celsius) between 185 and 1992 were obtained.

7.9 Methodology

Average Regional Rainfall Index (ARRI) was calculated using the 11 Jordanian stations, between 1960-1989. This index was calculated on monthly, seasonal and annual basis. The annual ARRI is illustrated in Figure 7.2. The seasonal index was calculated by considering 3 seasons; Autumn that includes September, October and November (SON); Winter including December, January and February (DJF) and Spring with March, April and May (MAM). Summer season; June, July and August (JJA) was excluded, as it is rare to have rainfall in Jordan during this season.

$$ARI = \frac{R - \bar{R}}{\sigma_R} \qquad [7.9.1]$$

$$ARRI = \frac{1}{n}\sum_{i=1}^{n} ARI_i \qquad [7.9.2]$$

Where:

ARI is the average rainfall index for individual stations

ARRI is the average regional rainfall index for all stations at the same time.

R is the, monthly, seasonal or annual rainfall of the station.

$\bar{R}$ is the average monthly, seasonal or annual rainfall for the same station.

σ_R is the standard deviation of the monthly, seasonal or annual rainfall values.

Monthly ENSO SST, SOI, NAOI and Indian Ocean SST anomalies were taken based on hydrologic year from September to the following August. Each year was divided into four seasons SON, DJF, MAM and JJA and the average index values were taken. A set of seven ENSO SST and SOI seasons is used to develop the correlation with ARRI. These seasons are SON^{-}♦, DJF^{-}, MAM^{-}, JJA^{-}, SON, DJF and MAM. Two different techniques were used to create statistical links between the selected ARRI and the climatic indices between 1960-1989.

Method one is to correlate monthly rainfall index (the ARRI) and the monthly SOI, NAOI and Indian Ocean SST anomalies using Time Series Cross Correlation analysis, using *MINITAB* release 13.1 statistical software. This kind of analysis deals with the data set as continuous time series with no gaps, (Grubb, 2002). The data length was 360 observations including the months of zero rainfall. Time series cross correlation is used to compare two different time series at a various lag (k), i.e. one series is delayed with respect to the other, (Abraham and Ledolter, 1983). The cross correlation function is written as in the following equation, Chatfield, 1984).

♦ refers to the previous year

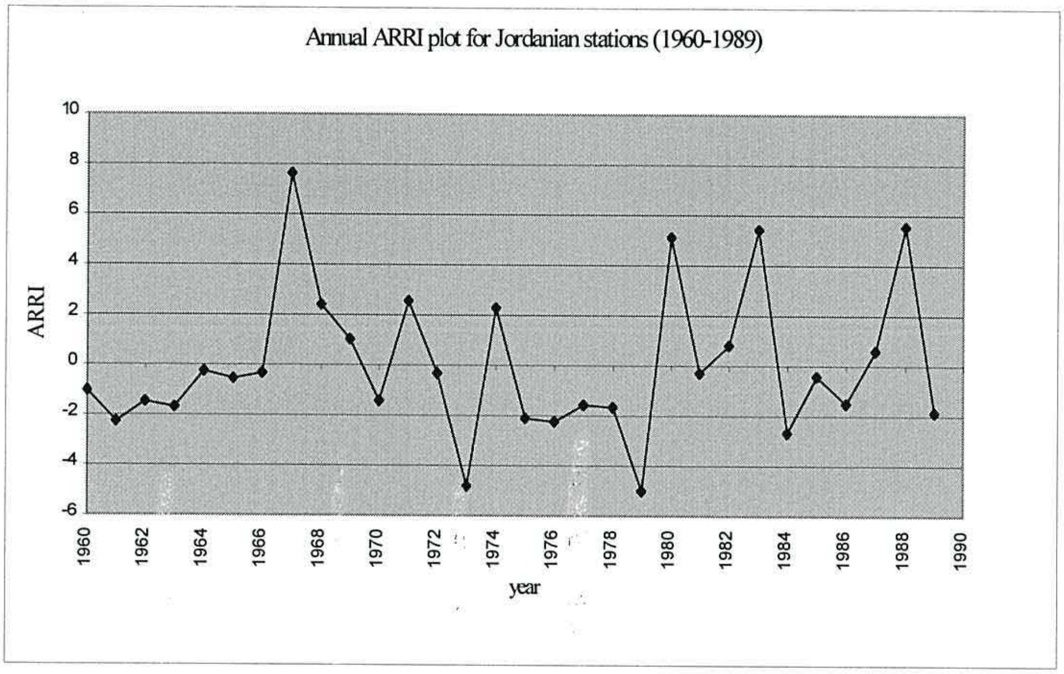


Figure 7.2: Annual ARRI for Jordanian stations (1960-1989).

$$r_{xy}(k) = \frac{C_{xy}(k)}{S_x S_y} \qquad [7.9.3]$$

Where

$r_{xy}(k)$ is the cross correlation coefficient at lag k.

S_x, S_y are the standard deviations for x and y series.

$C_{xy}(k)$ is cross covariance at lag k.

$$C_{xy}(k) = \begin{cases} \sum_{t=1}^{n-k} (x_t - \bar{x})(y_{t+k} - \bar{y}), & k = 0,1,2,\ldots \\ \sum_{t=1}^{n+k} (y_t - \bar{y})(x_{t-k} - \bar{x}), & k = -1,-2,\ldots \end{cases} \qquad [7.9.4]$$

$$S_x = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(x_t - \bar{x})^2} \qquad [7.9.5]$$

$$S_y = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(y_t - \bar{y})^2} \qquad [7.9.6]$$

As the time series has to be continuous all the months from September to August for the 30 years period have to be included. This means that months with 0 rainfall from June to September were taken into account. Including the 0 rainfall has affected the cross correlation results. It made them unreliable and excluded them from building the rainfall probability model. This is because that the 0 rainfall in these months is always there regardless the values of the SOI, NAOI and Indian Ocean SST anomalies. This means that SOI, NAOI and Indian Ocean SST anomalies do not affect the rainfall and the rainfall in these months does not depend on the index values. To avoid the inconvenience of using the 0 rainfall months the annual rainfall ARRI and seasonal SOI time series were cross-correlated again. Then the annual ARRI and annual SOI, NAOI and Indian Ocean SST anomalies were correlated. The summary of this technique's results is shown in Table 7.2. The Table shows the ARRI correlation with three of the climatic indices (SOI, ANOI and Indian Ocean SST anomalies).

Table 7.2: Summary of Cross Correlation Results

	SOI		NAOI		Indian Ocean SST anomalies	
Monthly	(-8) months	0.123	(-9) months	-0.104	no sig. Correlation	
MA Residuals						
6 months	(-8) months	0.189	(-11) months	0.123	(-1) month	-0.105
12 months	(-8) months	0.165	(-11) months	0.13	(-9) month	-0.100
18 months	(-8) months	0.163	(-11) months	0.127	(-18) months	-0.110
Seasonal	(-18) seasons	0.196				
4 seasons Moving Avg.	(-18) seasons	0.231				
Annual	(-4) years	0.255	(-9) years	0.268		
	(-7) years	0.236	(-10) years	-0.311		
	(-8) years	0.280				
3 years MA Fits	(-4) years	0.392	(-3) years	-0.267		
	(-5) years	0.458	(-4) years	-0.252		
	(-6) years	0.530	(-10) years	-0.257		
	(-7) years	0.561				
	(-8)years	0.495				

From Figure 7.3 it can be seen that both the annual rainfall ARRI and annual SOI do not have a definite trend, so the moving average for both of the series was calculated. Moving Average smoothes the data by averaging consecutive observations in a series and provides short-term forecasts. 3 and 4 years moving average were created for both rainfall and SOI. Then the moving average fits and residuals (the difference between the actual and the moving average values) were cross-correlated. The moving average fits showed higher correlation coefficients compared with the residuals. Both 3 and 4 years moving average fits were highly correlated at –4, -5, -6, -7 and –8 years with the maximum correlation of (0.561) at –7 years for the 3 years moving average fits, and (0.758) at –6 years for the 4 years moving average fits. The detailed results are shown in Table 7.2. The problem with the cross correlation technique is that, as it lags the X and Y values by time k, this creates "an apparent" forward correlation which seems to be illogical in terms of that the previous SOI should affect the current rainfall not the other way around. This seems to be a mathematical "artefact" of the method rather than a real phenomenon, but makes it necessary to treat the results with caution.

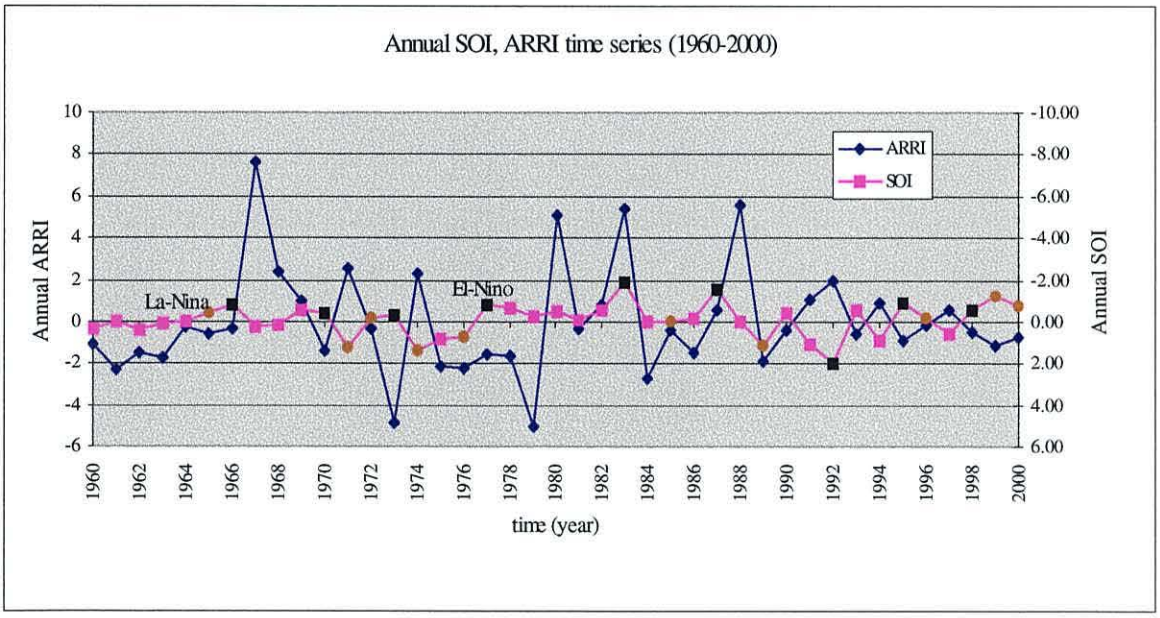


Figure 7.3: Annual SOI, ARRI Time Series, (1960-2000) (the black square refers to El-Niño year and the brown dot refers to La-Niña year)

Method two was to develop a linear correlation between the seasonal SOI and NAOI the corresponding seasonal ARRI for the current year. The results of this approach did not show significant results. Then this approach was modified by taking the seasonal

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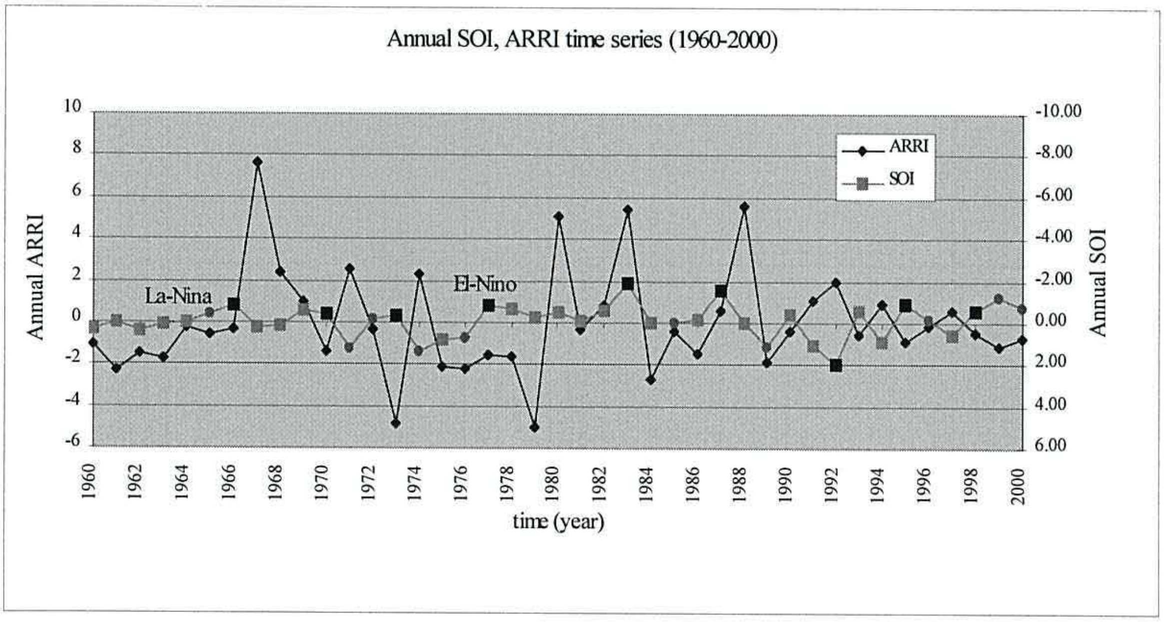

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ENSO SST and SOI for both current and previous years, and the current annual ARRI. The ENSO SST and SOI indices taken for the correlation are the previous autumn SON$^-$, the previous winter DJF$^-$, the previous spring MAM$^-$, the previous summer JJA$^-$, the current autumn SON, the current winter DJF and the current spring MAM. The correlation also was done between the annual ARRI and the annual ENSO SST and SOI for both previous and current years. The obtained linear correlation coefficients from this approach will be discussed in the following section, as well as the application of these results. Table 7.3 shows the linear correlation results between the annual ARRI and all the climatic indices that have been tested.

The linear correlation coefficient C_c that measure the degree of association between two variables x and y was calculated using the following equation, (Gujarati, 1995).

$$C_c = \frac{\sum x_i y_i}{\sqrt{(\sum x_i^2)(\sum y_i^2)}} \qquad [7.9.7]$$

The linear correlation between the seasonal North Atlantic Oscillation Index NAOI, the seasonal Indian Ocean SST anomalies and annual ARRI was also developed. Same as done for ENSO SST and SOI, the seven seasons used for correlation are the pervious autumn SON$^-$, the previous winter DJF$^-$, the previous spring MAM$^-$, the previous summer JJA$^-$, the current autumn SON, the current winter DJF and the current spring MAM. These seven seasons have been correlated with annual ARRI. The results are summarised in Table 7.3.

Table 7.3: Linear Correlation Results Summary.

	ENSO SST	**SOI**	**NAOI**	**Indian Ocean SST Anomalies**
SON$^-$	0.282*	-0.296*	-0.039	-0.04
DJF$^-$	0.309*	-0.019	-0.082	0.088
MAM$^-$	0.331*	-0.362*	0.307*	0.04
JJA$^-$	0.352*	-0.178	-0.302*	-0.046
SON	0.255*	-0.185	0.021	0.23*
DJF	0.313*	-0.051	0.108	0.13
MAM	0.344*	-0.096	-0.204	0.09
Annual	0.129	-0.104	-0.061	2.03
(-1) Annual	0.361*	-0.286*	-0.059	0.007

* significant at 90% or higher significant level

7.10 Interpretation of Results

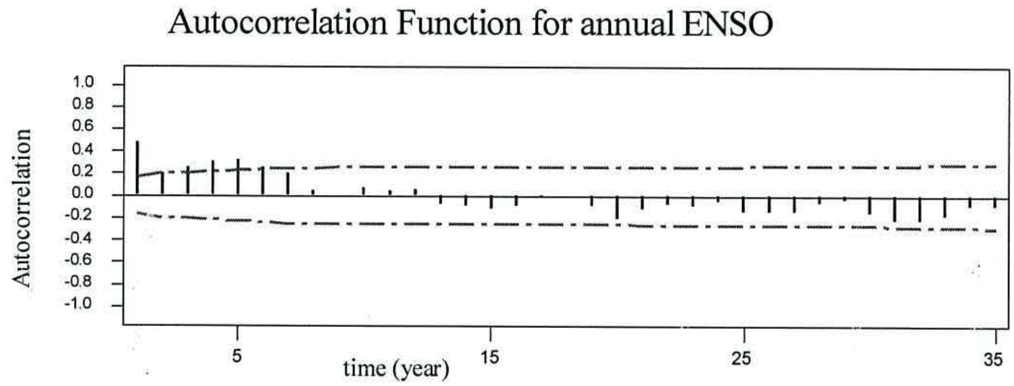
Calculating the corresponding correlation coefficients has developed the statistical links between the annual ARRI and the climatic indices; the values are listed in Table 7.3 above. These correlation coefficients provide quantitative measures of the effects of the climatic indices (ENSO SST, SOI, ANOI and Indian Ocean SST anomalies) on the Jordanian rainfall. The significance level of the correlation coefficients has to be checked using t-test. The level of significance for the correlation under the null hypothesis of no-correlation is verified using the two-tailed test using the student distribution. This test is based on calculating a t value and then comparing the calculated value with standard values in the t-distribution standard Table, (Montgomery and Runger, 1994). The t value is a function of the correlation coefficient (C_c), the number of data points in the sample (N) as in the equation below, (Osman et al., 2001). For the C_c to be significant at a certain level (normally 90%, 95% or 99%), the calculated t value has to be greater than or equal the standard t at this level. In other words we reject the null hypothesis of no correlation and prove that the rainfall and the climatic index are correlated. For example, if a C_c value is significant at 95% level, this means that the ARRI and any of the indices are correlated 95% of the time.

$$t = C_c \frac{\sqrt{N-2}}{\sqrt{1-C_c^2}} \qquad [7.10.1]$$

The significant C_c values obtained from the linear correlation between ARRI and the climatic indices will be used to develop the scatter diagrams between the climatic indices and the rainfall index ARRI. The following sections will be dealing with each index separately.

7.11 ENSO SST-ARRI

The ENSO SST values are autocorrelated. The autocorrelation is the self-correlation of one series with some agreed upon time lag, (Nazim, 1988). *MINITAB* was used to estimate the autocorrelation for ENSO SST as shown in Figure 7.4. It is shown that the values are highly correlated at year 1 and year 4, i.e. these are the most significant values. The plot shows the cyclic pattern of the ENSO SST that supports the fact that the El- Niño occurs everyone to seven years.



Lag	Corr	T	LBQ	Lag	Corr	T	LBQ	Lag	Corr	T	LBQ	Lag	Corr	T	LBQ
1	0.48	5.72	33.36	10	0.07	0.56	95.40	19	-0.08	-0.63	102.68	28	-0.06	-0.41	124.80
2	0.20	2.01	39.45	11	0.04	0.32	95.66	20	-0.21	-1.60	109.90	29	-0.03	-0.20	124.94
3	0.25	2.40	48.66	12	0.06	0.47	96.22	21	-0.11	-0.81	111.85	30	-0.15	-1.08	128.94
4	0.31	2.81	62.41	13	-0.07	-0.52	96.91	22	-0.07	-0.54	112.75	31	-0.21	-1.55	137.35
5	0.32	2.81	77.80	14	-0.09	-0.68	98.14	23	-0.08	-0.60	113.84	32	-0.21	-1.50	145.60
6	0.26	2.16	88.03	15	-0.12	-0.92	100.38	24	-0.05	-0.38	114.28	33	-0.18	-1.27	151.74
7	0.20	1.62	94.19	16	-0.09	-0.66	101.57	25	-0.13	-0.99	117.35	34	-0.09	-0.62	153.25
8	0.05	0.41	94.61	17	-0.01	-0.04	101.58	26	-0.14	-1.04	120.80	35	-0.08	-0.58	154.58
9	0.01	0.05	94.61	18	0.00	0.02	101.58	27	-0.14	-1.03	124.25				

Figure 7.4: Annual ENSO SST index autocorrelation.

Figure 7.5 shows the time series of the ARRI between 1960 and 2000 and the ENSO SST index for the period 1960-1994. From the figure it is seen that the rainfall index ARRI responds to the changes in ENSO SST index. It is indicated that the dry years are most of the time associated with the cold phase of the ENSO (La-Niña) that is indicated in the figure by zero or very negative values in the inverted scale. The probability is 67% of having a dry condition (below the average rainfall) during La-Niña years. Likewise the wet years are associated with the warm phase of the ENSO (El- Niño), which is denoted by high positive values of the inverted scale. It is noticed also that during the consecutive events of La- Niña and El- Niño or vice versa the following year is remarkably wet. For example, the 1964/65 La- Niña followed by 1965/66 El- Niño resulted in the annual ARRI of 7.62 for the 1966/67. The ARRI for 1970/71 was 2.54, which came after 1969/70 El-Niño followed by a La- Niña in

1970/71. In Figure 7.5 the black squares indicate El-Niño years and the brown circles refer to La-Niña years.

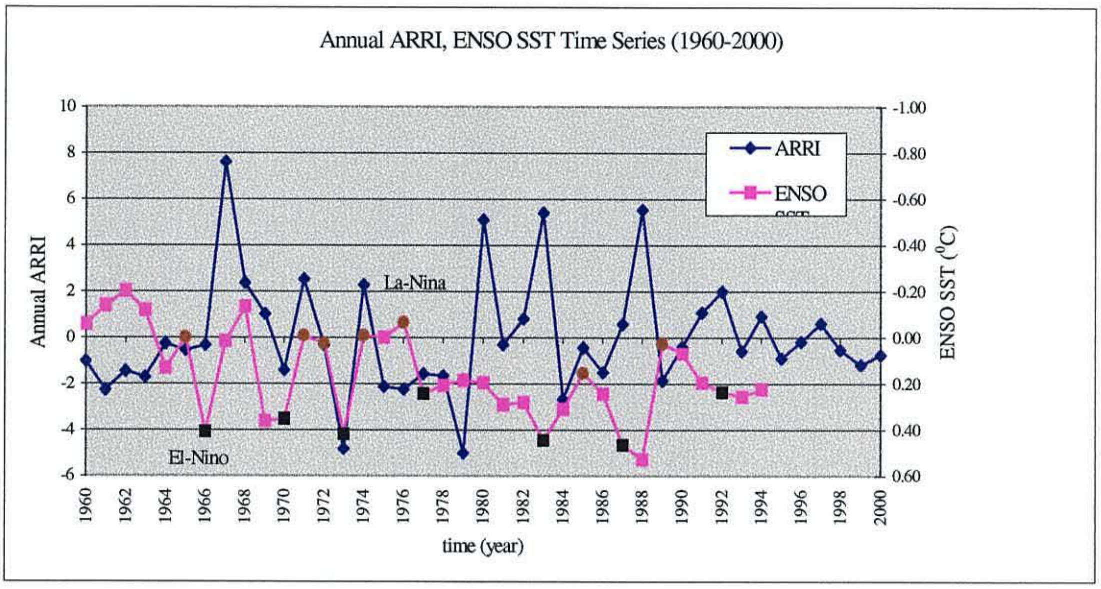


Figure 7.5: Annual ARRI and ENSO time series (the black square refers to El-Niño year and the brown dot refers to La-Niña year)

From Table 7.3 above it is clearly seen that the ARRI is correlated with the ENSO SST most of the time. Correlation is found with all the previous and current seasonal indices, as well as the previous (-1) year annual ENSO SST. But here we will deal with the previous indices that are correlated with the current rainfall, i.e. SON^-, DJF^-, MAM^-, JJA^- and the (-1) year. This is to have the opportunity to be pro-active rather than reactive for the management purposes. This means that the correlation must be known in advance to be able to predict the future rainfall based on the index's status. This is known as the probabilistic rainfall prediction model.

The development of the model has involved the following steps:-

- Plotting the scatter diagrams for the previous seasonal SON^-, DJF^-, MAM^-, and $JJA^-$and the pervious annual ENSO SST with the ARRI.
- For ARRI values <0, the corresponding year is considered as being dry. For ARRI values >0, the year is regarded as considered as being wet.
- For ENSO SST different limits have been assigned to identify the ENSO phase for each season. These limits have taken into account the number of data points in each region, as they approximately have to be equal.

- Starting with JJA⁻ and MAM⁻ ENSO SST, values >0.2, the corresponding ENSO condition is regarded as being warm, while vales <0.2 are considered to be forming a cold phase.
- For SON⁻ three phases have been identified, for ENSO SST >0.2 the phase is regarded as warm, for values <0 it is considered as cold phase, a normal phase is taken for the values between these two limits (0<ENSO SST<0.2).
- For DJF⁻ three phases also have been identified, for ENSO SST >0.26 the phase is regarded as warm, for values <0.06 it is considered as cold phase, a normal phase is taken for the values between these two limits (0.06<ENSO SST<0.26).
- For (-1) year ENSO SST, values >0.27 indicate warm conditions, while values <0.27 represent a cold phase.

According to the above rules the JJA⁻ and MAM⁻ ENSO SST and annual ARRI scatter diagrams are divided into four windows, as shown in Figures 7.6 and 7.7. For each window in the scatter diagram, the conditional probability of having a dry or a wet year, given a certain ENSO SST condition (warm or cold) is found by dividing the number of data points in the corresponding window by the total number of data points that are associated with the ENSO SST conditions. In Figures 7.6 and 7.7 below the conditional probability is a shown as a percentage in the corresponding window.

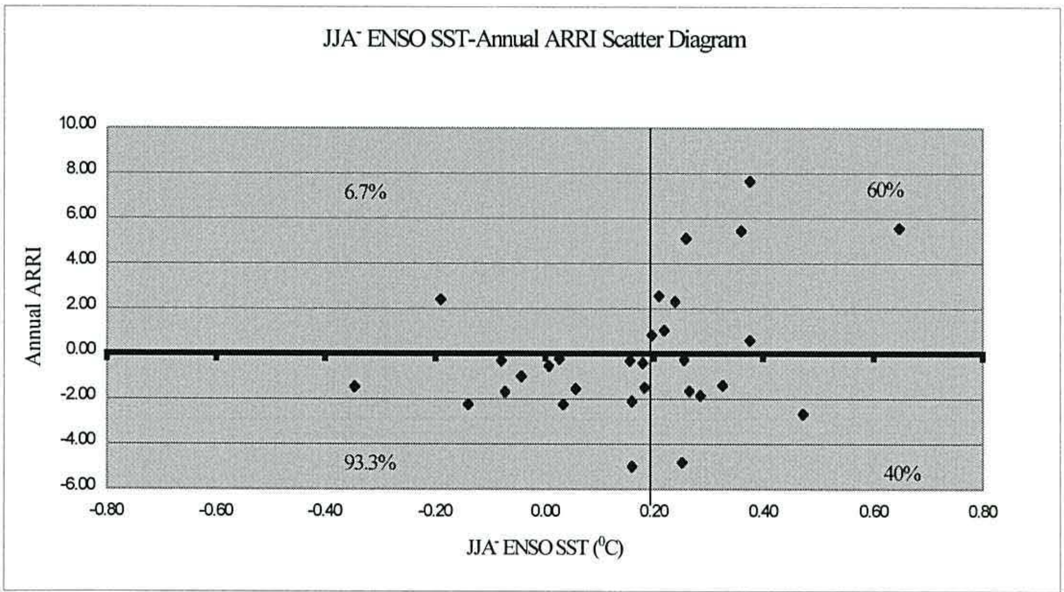


Figure 7.6: Scatter plot of the data showing the Jordanian Annual ARRI and JJA⁻ ENSO SST index, for the years 1960-1989. The coefficient of correlation is 0.352

The derived probabilistic models for Jordan using JJA⁻ and MAM⁻ seasonal ENSO SST and annual ARRI are listed in Tables 7.4 and 7.5 below. The scatter diagrams and the probabilistic models Tables for SON⁻ ENSO SST and Annual ARRI are attached in Appendix F.

Table 7.4: Probabilistic Model for Jordanian Annual Rainfall using JJA⁻ seasonal ENSO SST

JJA⁻ SST category	Probability of Rainfall year Category	
	Dry	Wet
Cold	93.3	6.7
Warm	40	60

Table 7.5: Probabilistic Model for Jordanian Annual Rainfall using MAM⁻ seasonal ENSO SST

MAM⁻ SST category	Probability of Rainfall year Category	
	Dry	Wet
Cold	82.4	17.6
Warm	46.2	53.8

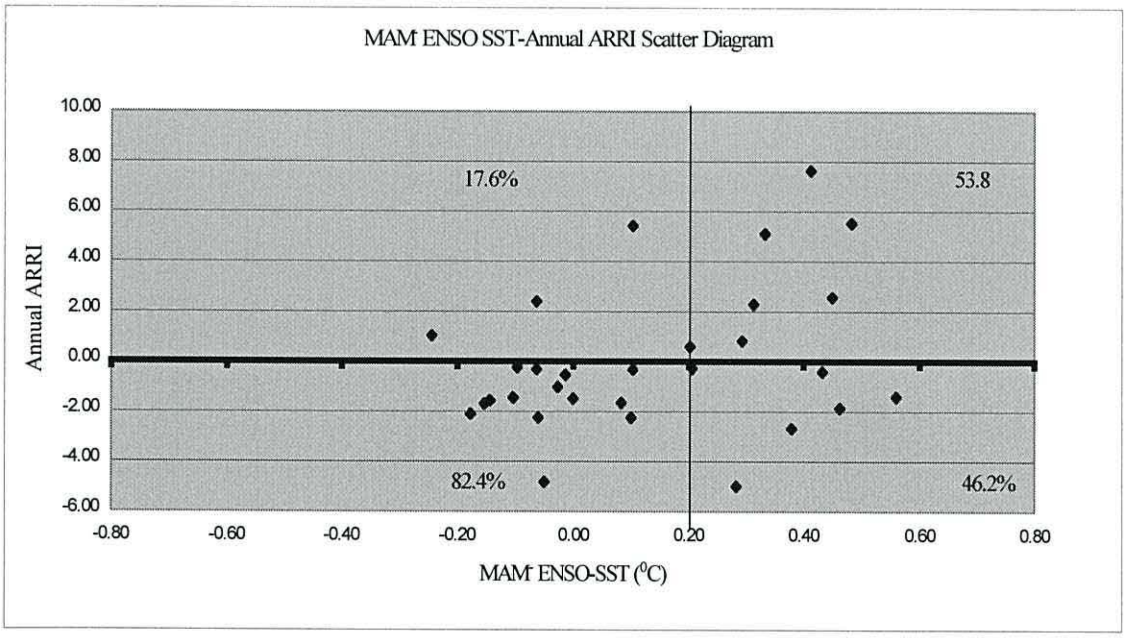


Figure 7.7: Scatter plot of the data showing the Jordanian Annual ARRI and MAM⁻ ENSO SST index, for the years 1960-1989. The coefficient of correlation is 0.362.

7.12 Verification and Performance of Rainfall Probability Model

To verify the adequacy of the probabilistic models developed in the previous section, a set of ARRI and JJA⁻ and MAM⁻ ENSO SST values for the year 1990-1995 is used. The ENSO SST data are not available online after 1994, and therefore were used even though the ARRI is available until 2000.

The rainfall probability models that have been developed using seasonal JJA⁻ and MAM⁻ ENSO SST and Annual ARRI both performed quite well. As shown in Table 7.6 below, the seasonal JJA⁻ ENSO SST model predicted with the knowledge of the ENSO SST as the input three dry and three wet years. Since the verification period has three dry years and three wet years, then the model predictions are only correct in four out of six years, (i.e. the model's efficiency* is 66.7 percent).

Table 7.6: verification of the Probabilistic Model using JJA⁻ ENSO SST

Year	JJA⁻ ENSO SST	Predicted ARRI	(Observed ARRI) class	Evaluation
1990	0.00	Dry	(-0.43) dry	T
1991	0.04	Dry	(1.07) wet	F
1992	0.26	Wet	(2.00) wet	T
1993	0.28	Wet	(-0.59) dry	F
1994	0.37	Wet	(0.91) wet	T
1995	-0.10	Dry	(-0.9) dry	T

Where T refers to a true Prediction and F to a False Prediction.

The seasonal MAM⁻ ENSO SST model predicted with the knowledge of the ENSO SST as the input five dry years and one wet year. Since the verification period has three dry years and three wet years, then the model predictions are only correct in four out of six years, (i.e. the model's efficiency is 66.7 percent). The verification of the probabilistic model using MAM⁻ ENSO SST is listed below in Table 7.7.

Table 7.7: Verification of the Probabilistic Model using MAM⁻ ENSO SST

Year	MAM⁻ ENSO SST	Predicted ARRI	(Observed ARRI) class	Evaluation
1990	-0.24	Dry	(-0.43) dry	T
1991	-0.03	Dry	(1.07) wet	F
1992	0.18	Dry	(2.00) wet	F
1993	0.12	Dry	(-0.59) dry	T
1994	0.23	Dry	(0.91) wet	T
1995	0.11	Dry	(-0.9) dry	T

* Efficiency: is the years of true prediction out of the total number of years.

From the Tables above it is indicated that the use of ENSO SST index improved the rainfall prediction. However, the model efficiency was 66.7 percent in both cases, i.e. JJA^- and MAM^-. This could be an indication that there are other factors that might have an effect on the Jordanian rainfall, rather than the ENSO SST index. This denotes that the efficiency could improve if we take the combined effect of the JJA^- and MAM^- ENSO SST index is considered as will be seen later in this section.

As shown previously in Table 7.3 the previous seasonal SON^-, DJF^-, MAM^- and JJA^- ENSO SST indices were all significantly correlated to the annual ARRI. All of them have been tested with developing the rainfall probability model, but results showed that SON^- gave a very poor efficiency of 16.7 percent. While, DJF^- gave 33.3 percent efficiency, which makes it not very significant. Another reason to discard the DJF-based model is that as shown in the scatter diagram for DJF^- ENSO SST and the annual ARRI in Figure 7.8 below. The Figure is confusing, as for ENSO SST values of less than 0.26 (i.e. during the normal and cold phases) the result is always the same, in other words the prediction is always a dry year. The probabilistic and verification Tables for both of the SON^- and DJF^- ENSO SST indices, as well as the scatter diagram for SON^- ENSO SST and annual ARRI.

The story with the (-1) annual ENSO SST index is somehow different. The scatter diagram shown in Figure 7.9 below was created the same way as mentioned before. From the diagram it appears that if the (-1) annual ENSO SST >0.27 there is a 60 percent chance to have a wet year. While, for the index values <0.27 it is highly likely to get a dry year. Table 7.8 shows the rainfall probability model based on using the previous year's ENSO SST index, i.e. the (-1) annual ENSO SST index and the annual ARRI.

Table 7.8: Probabilistic Model for Jordanian Annual Rainfall using (-1) annual ENSO SST

(-1) annual SST category	Probability of Rainfall year Category	
	Dry	Wet
Cold	80	20
Warm	40	60

The built model was verified using the annual figures for ENSO SST and ARRI between 1990 and 1995. The model gave 50 percent efficiency, as it predicted six dry years, while the actual figures were that three dry years and three wet years. This prediction means that prediction might not be true 50 percent of the time; no significant improvement on chances, (the prediction did improve the null hypothesis).

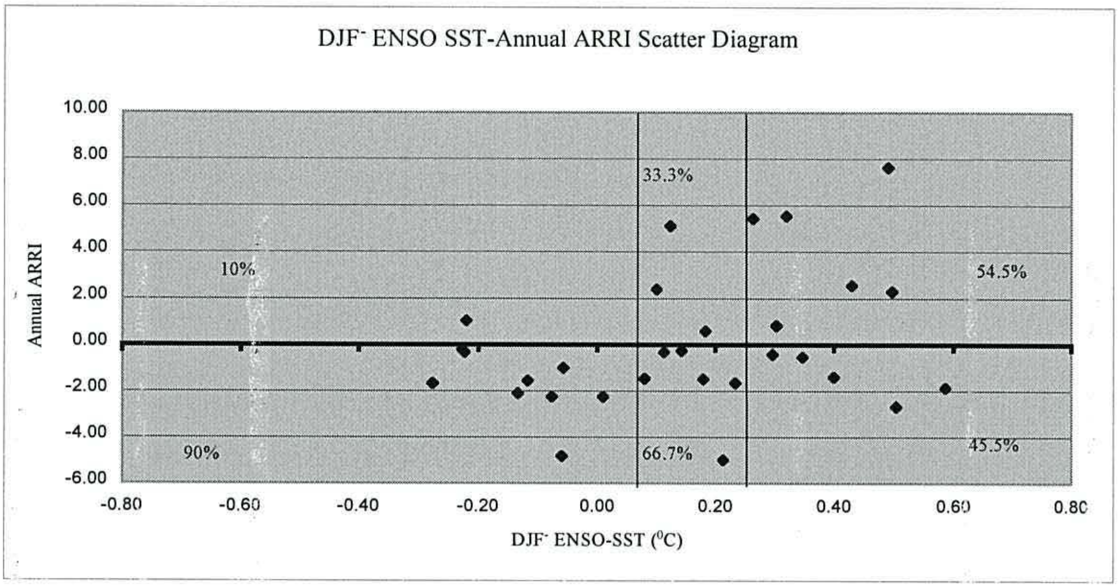


Figure 7.8: Scatter plot of the data showing the Jordanian Annual ARRI and DJF⁻ ENSO SST index, for the years 1960-1989. The coefficient of correlation is 0.309

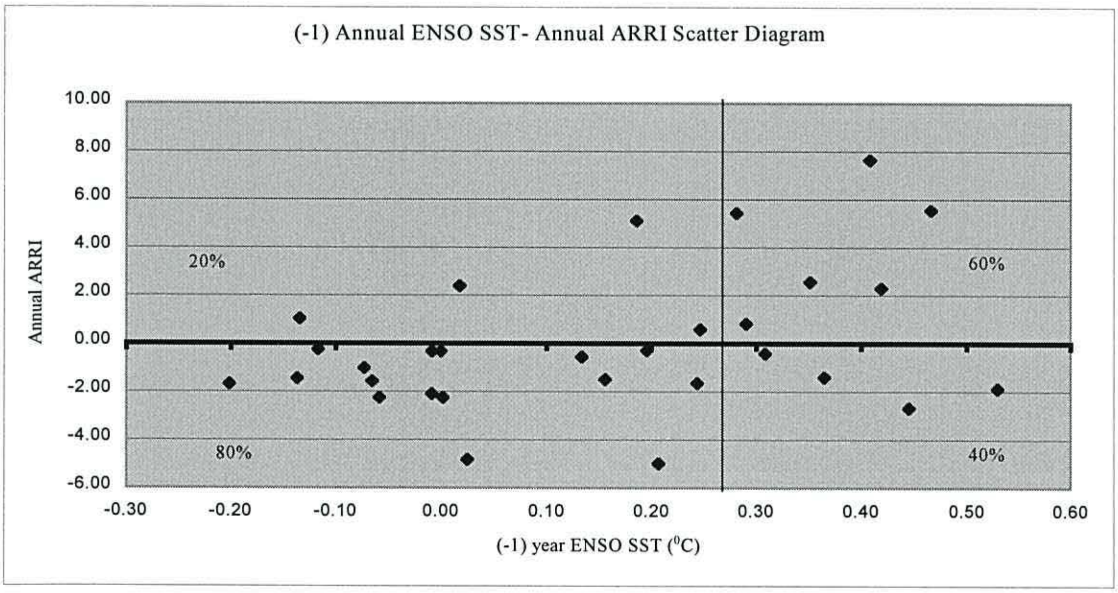


Figure 7.9: Scatter plot of the data showing the Jordanian Annual ARRI (-1) annual ENSO SST index, for the years 1960-1989. The coefficient of correlation is 0.361

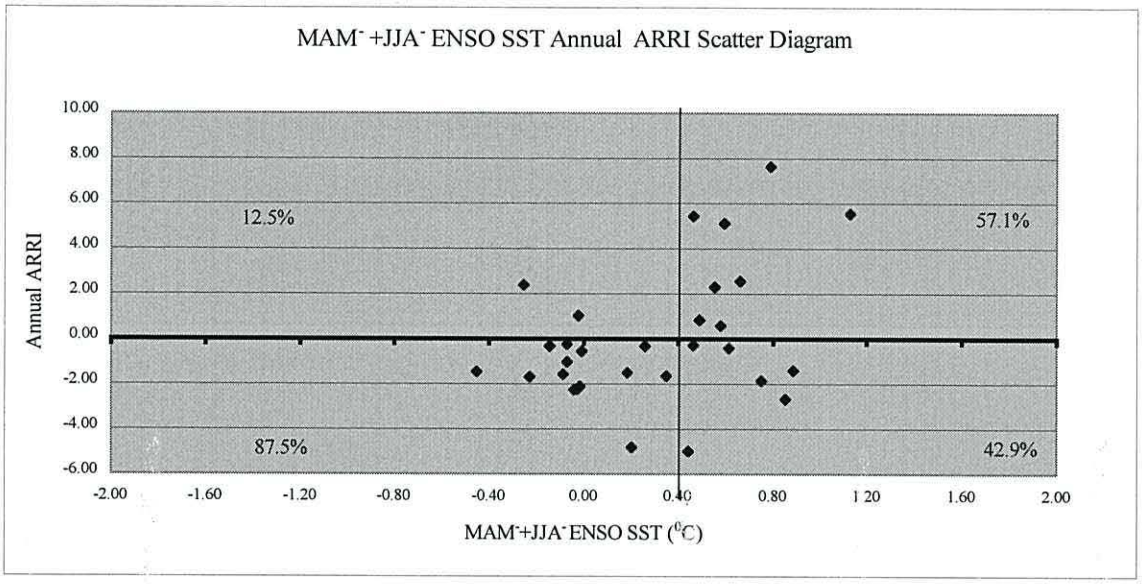


Figure 7.10: Scatter plot of the data showing the Jordanian Annual ARRI and MAM^{-} +JJA^{-} ENSO SST index, for the years 1960-1989. The coefficient of correlation is 0.377

To test if the combined indices affect the results, seasonal JJA^{-} and MAM^{-} ENSO SST indices were combined and the result correlated linearly with the annual ARRI. A correlation coefficient C_c of 0.377 was obtained that is significant at 95% significance level. Then the scatter diagram for the combined JJA^{-} and MAM^{-} ENSO SST indices and the annual ARRI was plotted as shown in Figure 7.10. The scatter diagram's regions or windows were identified based on that for ARRI values >0, the year has to be wet, while for ARRI<0 the year is dry. For the JJA^{-} and MAM^{-} ENSO SST indices if the combined ENSO SST>0.4 the condition is considered as a warm condition, while for the combined ENSO SST<0.4 the opposite occurs, i.e. the phase will be a cold phase. Using this scenario the rainfall probability model was developed. The probability of having a warm and a wet year is 57.1 percent, while the chance of having a warm and a dry year is going to be 42.9 percent. For the low positive and high negative values of the combined ENSO SST, it is highly possible that it will be dry most of the time. This is due to that the probability of having a cold and a dry is year is 87.5 percent compared with only 12.5 percent chance of having a cold and a wet year. Table 7.9 summarises the results of this approach.

Table 7.9: Probabilistic Model for Jordanian Annual Rainfall using JJA⁻+MAM⁻ seasonal ENSO SST

JJA⁻+MAM⁻ SST category	**Probability of Rainfall year Category**	
	Dry	Wet
Cold	87.5	12.5
Warm	42.9	57.1

These results shown above were verified and tested as done before for JJA⁻ and MMA⁻ ENSO SST separately. The model's efficiency has improved as it has predicted four dry and two wet years. Since the verification period has three dry and three wet years, the prediction met the actual values in five years out of six, i.e. the efficiency is 83.3 percent this time compared with 66.7 percent when dealt with JJA⁻ and MAM⁻ ENSO SST separately. This indicates that the individual and combined indices could be used as rainfall predictors. The combined ENSO SST verification Table is shown below in Table 7.10.

Table 7.10: Verification of the Probabilistic Model using JJA⁻+MAM⁻ ENSO SST

Year	MAM⁻ ENSO SST	Predicted ARRI	(Observed ARRI) class	Evaluation
1990	-0.24	Dry	(-0.43) dry	T
1991	0.02	Dry	(1.07) wet	F
1992	0.44	Wet	(2.00) wet	T
1993	0.39	Dry	(-0.59) dry	T
1994	0.60	Wet	(0.91) wet	T
1995	0.01	Dry	(-0.9) dry	T

Previously the JJA⁻ and MAM⁻ were combined, then the same was done for the rest of the indices and correlated them linearly with the annual ARRI, the resulted Cc(s) are listed in Table 7.11.

Table 7.11: Linear Correlation results for combined ENSO seasonal indices and annual ARRI

Combined Seasonal ENSO SST index	C_c
SON⁻+DJF⁻	0.306*
SON⁻+DJF-+MAM⁻	0.331*
SON⁻+DJF-+MAM-+JJA⁻	0.361*
DJF⁻+MAM⁻	0.336*
DJF⁻+MAM⁻+JJA⁻	0.376*
MAM⁻+JJA⁻	0.377*

Starting with SON$^-$+DJF$^-$ combined ENSO SST index, it appears that this is significantly correlated with the Jordanian annual ARRI. However, after plotting the scatter diagram and building the rainfall probability model it seems that this combined index is not helpful, since the same thing that happened with the individual DJF$^-$ ENSO SST index happened here. Looking at the scatter diagram (Figure F.2 in the Appendix F), it is clearly seen that after identifying the ENSO SST limit at >0.5, the prediction came out that there is 50-50 percent chance to have a wet-dry year which is not a significant prediction. Even the model gave an efficiency of 66.7 percent after verification but its use is still unreliable.

Row 3 in the Table 7.11 above shows the combined seasonal ENSO SST index for all the indices together, SON$^-$+DJF$^-$+MAM$^-$+JJA$^-$. After plotting the scatter diagram for the combined indices and the annual ARRI, the ENSO SST limit was set at >0.5 and <0.5. For the index value of >0.5 it is highly possible to have a dry year with a chance of 52.9 percent. The same applies for the index values that are <0.5, since it is possible with a probability of 84.6 percent to have a dry year as well, as most annual values are somewhat below the average.

The combination of DJF$^-$+MAM$^-$ gave 50 percent efficiency for rainfall prediction. The scatter diagram a boundary of 0.375 was taken for the DJF$^-$+MAM$^-$ ENSO SST index. A dry year is highly possible if the index value is >0.375,while the opposite (wet year) occurs if the index is <0.375. The same applies to the index of combining the three seasons of DJF$^-$+MAM$^-$ +JJA-, as it gave the same efficiency. But this time the ENSO SST limit was >0.7 and <0.7. Values > 0.7 indicate a dry year, while >0.7 indicate a wet year. The scatter diagrams and the probability models are shown in the Appendix F.

From the above analysis it can be concluded that the ENSO SST index could be used as a rainfall predictor for Jordan. The most reliable results came from the previous season (quarter), i.e. JJA$^-$ and the previous two quarters MAM$^-$ either individually or combined. This result alone is a very important one, as it will be very helpful if the rainfall could be predicted 6 or 3 months in advance. But to be sure enough it is

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* Significant at 90% or higher level of significance

preferable to also test other indices like SOI, NAOI and Indian Ocean SST anomalies, if they have the same sort of relation with the Jordanian rainfall and to check if they could be used as predictors.

7.13 SOI-ARRI

The Southern Oscillation Index SOI is another index that has been used to measure the strength of the El- Niño events. The ENSO SST index and the SOI are inversely proportional, the higher the SOI the lower the ENSO SST, therefore it indicates a cold phase or La- Niña conditions. While, the lower the SOI the higher will be the ENSO SST index, i.e. it is a sign of a warm phase, or El- Niño.

The annual SOI and ARRI time series between 1960 and 2000 is shown in Figure 7.3 indicates that during this period there was 10 La-Niña years (positive values of SOI) and 9 El- Niño years (negative SOI values). During La- Niña events eight out of ten years were dry in Jordan, as the ARRI values were below the average. The same dry conditions were experienced during El- Niño conditions, as five out of nine years were dry. But, it is noticed that during some of the El- Niño years the drought conditions were severe as the ARRI were very low, as in 1972/73 and 1976/77 where the drought extended for five years.

To check the effect of the SOI on the Jordanian rainfall in more detail, the SOI and the ARRI were cross and linearly correlated. But the cross correlation results were unreliable as mentioned before, only the linear correlation results are considered in the coming paragraphs. As shown in Table 7.3 the previous, current seasonal and annual SOI values were correlated with the annual ARRI. The significant correlation were only between the Annual ARRI and the SON$^-$, MAM$^-$ and (-1) year annual SOI.

The SON$^-$ (i.e. four quarters before) index is correlated with the Jordanian annual ARRI. The correlation was built using 1960-1989 data sets, bearing in mind that SON$^-$ SOI starts the years before i.e. 1959. Then, the scatter diagram was plotted in order to identify the regions. Actually identifying the SOI and ARRI limits is a subjective matter, as there are many alternatives to choose, (Eltahir, 1996). For the SON$^-$ SOI and annual ARRI scatter diagram the SOI limit was taken as 0. For SOI values >0, this means it is a cold or a La- Niña phase, while for <0 values it indicates a warm or El-Niño conditions. The annual ARRI limits were taken as well above and below 0. Positive values represent wet year (i.e. more than average rainfall), while negative ARRI assigns a dry year, (i.e. below average rainfall). The scatter diagram is shown in Figure 7.11, was used to build the rainfall probability model, using the limits mentioned. Results showed that for positive SON$^-$ SOI it is always predicted that the year will be a dry year. While for negative values there is a 55.6 percent possibility to have a wet year, and 44.4 percent chance to get a dry year. The rainfall probability model is listed in Table 7.12.

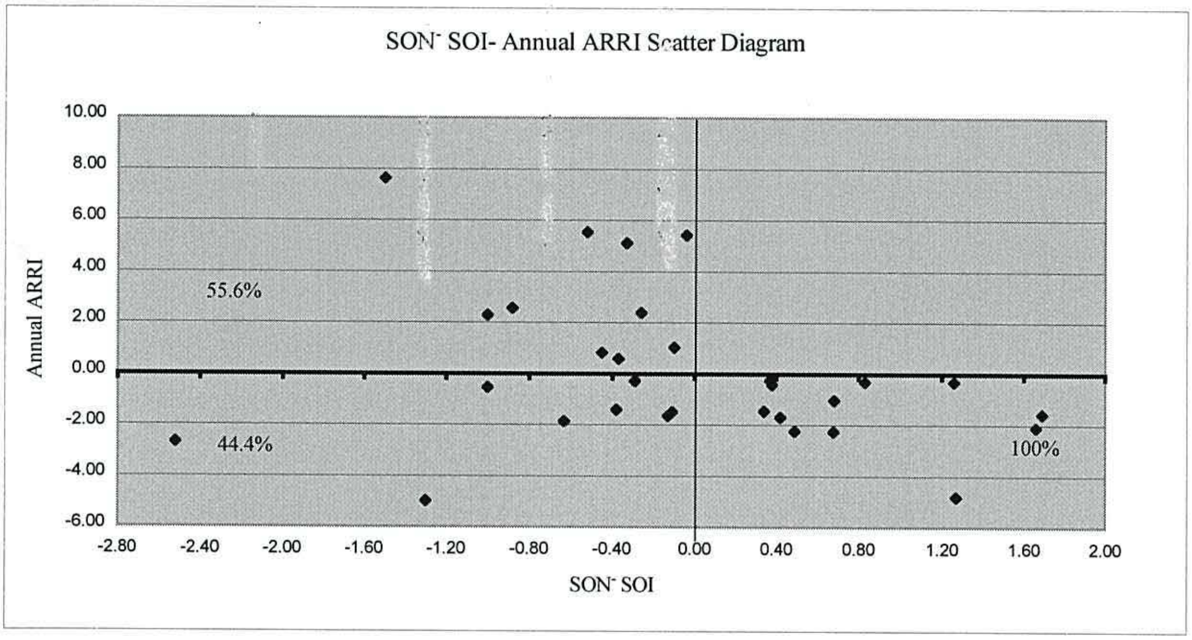


Figure 7.11: Scatter plot of the data showing the Jordanian Annual ARRI and SON$^-$ SOI, for the years 1960-1989. The coefficient of correlation is –0.296

Table 7.12: Probabilistic Model for Jordanian Annual Rainfall using SON$^-$ SOI

SON$^-$ SOI category	Probability of Rainfall year Category	
	Dry	Wet
Cold	100	0
Warm	44.4	55.6

The model was verified using recent SON$^-$ SOI and annual ARRI data from 1990 to 2000. As shown in Table 7.13 below the model has predicted four dry and seven wet years, while the actual figures were the opposite, i.e. four wet and seven dry years. This means that the model only gave a performance level of 54.5 percent only.

Table 7.13: verification of the Probabilistic Model using SON⁻ SOI

Year	SON⁻ SOI	Predicted ARRI	(Observed ARRI) class	Evaluation
1990	-1.73	Dry	(-0.43) dry	T
1991	0.25	Dry	(1.07) wet	F
1992	-0.54	Wet	(2.00) wet	T
1993	-1.34	Wet	(-0.59) dry	F
1994	-0.94	Wet	(0.91) wet	T
1995	-0.83	Wet	(-0.9) dry	F
1996	-1.36	Wet	(-0.18) dry	F
1997	-0.03	Wet	(0.6) wet	T
1998	0.24	Dry	(-0.53) dry	T
1999	-1.52	Wet	(-1.20) dry	F
2000	1.02	Dry	(-0.76) dry	T

The seasonal MAM⁻ SOI has a higher correlation with the annual ARRI (C_c=-0.362). Consequently, it gave a better performance for rainfall prediction. The MAM⁻ SOI annual ARRI scatter diagram was created from plotting the MAM⁻ SOI vs. the annual ARRI. The diagram is illustrated in Figure 7.12, was divided into six regions instead of four. The regions were identified based on identifying our SOI limits. The limits that have been taken are, >0.17 to indicate a cold phase, <-0.8 to refer to a warm phase and a normal phase in between these two limits (i.e. –0.8<MAM⁻ SOI<0.17). . The diagram indicates that during strong El-Ni o phases (SOI<-0.8), and during strong La-Ni a phases (SOI>0.17), it is highly possible to have a dry year. This explainsthe high percentage of dry years that is shown in Figure 7.3 before.

The rainfall probability model for Jordan based on this scenario denotes that there is 100 percent probability to have a dry year if the MAM⁻ SOI is in its cold phase, (>0.17), or with 60 percent probability if the index is in its warm phase (<-0.8). While, it will be possible with 57 percent chance to have a wet year if the index falls in its normal phase. The results of the probabilistic model are shown in Table 7.14 below.

Table 7.14: Probabilistic Model for Jordanian Annual Rainfall using MAM⁻ SOI

MAM⁻ SOI category	**Probability of Rainfall year Category**	
	Dry	Wet
Cold	100	0
Normal	42.9	57.1
Warm	60	40

The verified model gave a fairly high efficiency compared with the previous one. The efficiency of using MAM⁻ SOI as rainfall predictor is 81.8 percent. It has predicted nine years out of total eleven to be dry, while the actual number of dry years was seven out of eleven. This has raised the performance to that level. Verified rainfall probability model is as shown in Table 7.15.

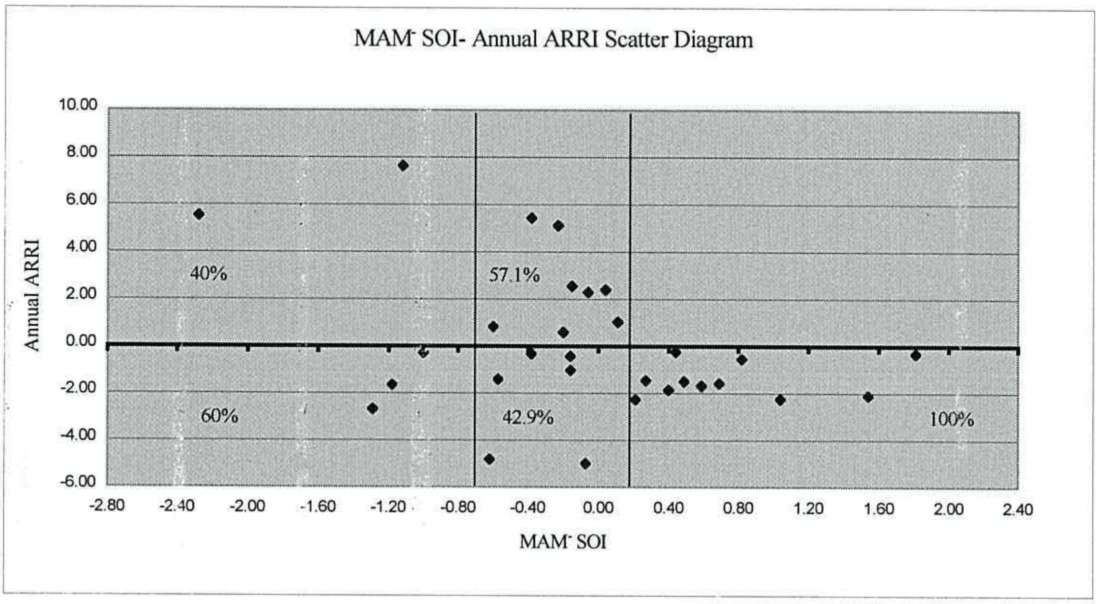


Figure 7.12: Scatter plot of the data showing the Jordanian Annual ARRI and SON⁻ SOI, for the years 1960-1989. The coefficient of correlation is –0.362

Table 7.15: verification of the Probabilistic Model using MAM⁻ SOI

Year	MAM⁻ SOI	Predicted ARRI	(Observed ARRI) class	Evaluation
1990	1.41	Dry	(-0.43) dry	T
1991	0.10	Wet	(1.07) wet	T
1992	-1.55	Dry	(2.00) wet	F
1993	-1.62	Dry	(-0.59) dry	T
1994	-1.34	Dry	(0.91) wet	F
1995	-1.75	Dry	(-0.9) dry	T
1996	-0.80	Dry	(-0.18) dry	T
1997	0.63	Wet	(0.6) wet	T
1998	-1.68	Dry	(-0.53) dry	T
1999	-1.98	Dry	(-1.20) dry	T
2000	1.11	Dry	(-0.76) dry	T

The (-1) annual SOI could not be used as a rainfall predictor, as there are some weak points in the model. After checking the correlation between the (-1) annual SOI and annual ARRI, they were found correlated with a significance level as we have seen in Table 7.3. Then the rainfall probability model was developed by selecting the SOI limits this time above and below 0. The values >0 always gave an indication of a dry year, as the probability was high (85.7 percent). The problem was with the <0 values, as the chance is 50-50 of having a wet-dry year, which is not useful for the management aspect. This leads to say that this model and any others that have the same characteristics will be discarded because of the unreliability. Figure 7.13 illustrates the scatter diagram for (-1) year SOI and annual ARRI. It is shown here just to give a brief description about its unreliability.

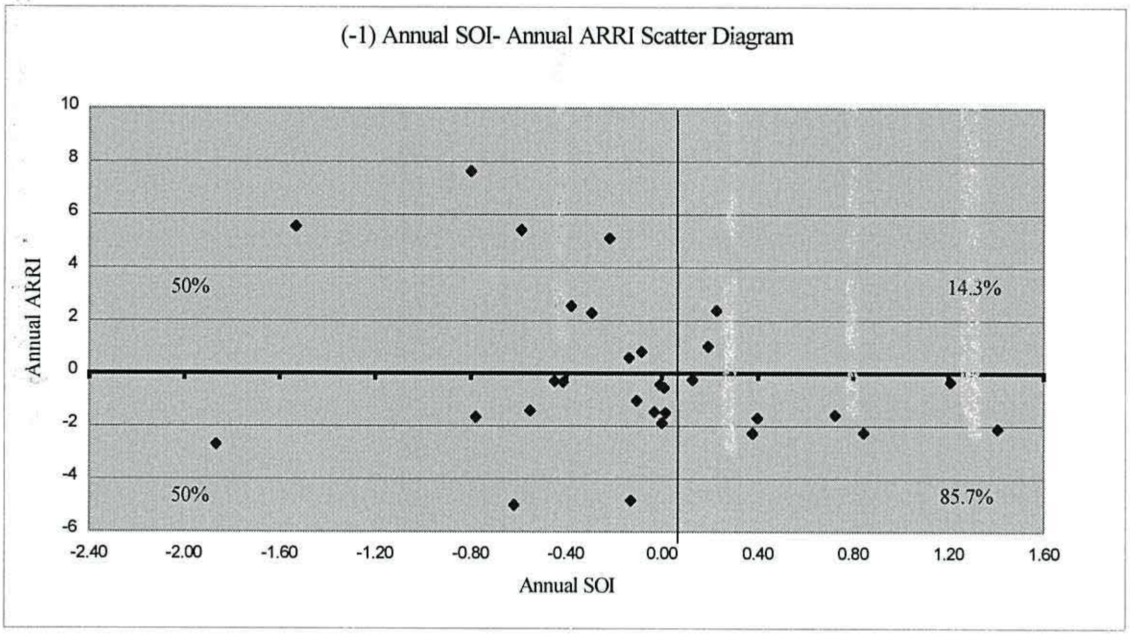


Figure 7.13: Scatter plot of the data showing the Jordanian Annual ARRI and (-1) year SOI, for the years 1960-1989. The coefficient of correlation is –0.286

From the modelling results it looks like that the most reliable predictor is MAM⁻ as it gave high performance level with both ENSO SST index and SOI, (66.7 and 81.8 percent respectively).

7.14 NAOI-ARRI

The third index to be tested if it has an effect on the Jordanian rainfall or not is the North Atlantic Oscillation Index (NAOI). The flip-flop pattern is shown in Figure 7.14 for the annual ANOI time series between 1821 and 2000. As mentioned before it is the pressure difference between the low pressure over Iceland and the high pressure over the Azores, Lisbon or Gibraltar. The NAOI was correlated with the Jordanian annual ARRI. The highly correlated seasons were MAM⁻ and JJA⁻.

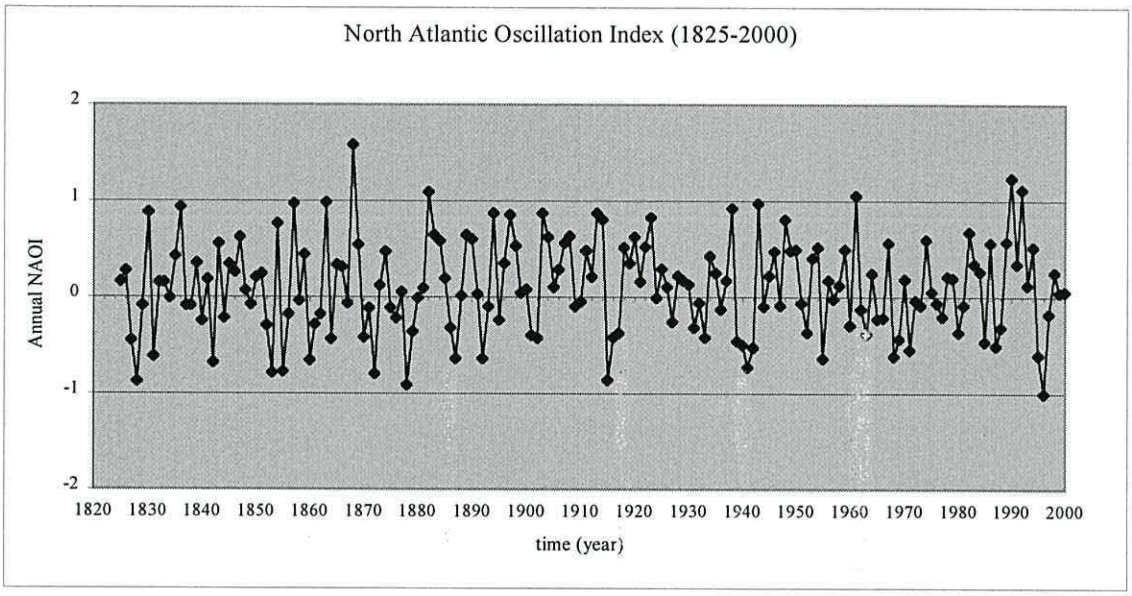


Figure 7.14: Annual NAOI Time Series between 1854-2000.

From the scatter diagrams of both MAM⁻ and JJA⁻ vs. the annual ARRI it is clearly seen that there is a lot of scatter, which made it very difficult to identify the limits reasonably. In the literature wherever NAOI is mentioned, we just only find that there are two phases for it, as we have seen before positive and negative. Both of these phases have different effect on the climate and the weather systems. But in the Jordanian example, it looks different. The reason for that is when we tested our MAM⁻ and JJA⁻ vs. annual ARRI scatter diagrams, they both gave the same peculiar result that is, whatever the NAOI is, the condition always tends to be a dry year. This does not make sense in terms of that there should be at least two opposite conditions, i.e. wet or dry (matches null, but means indicator is not successful). This means that this approach is not successful to be tried with the NAOI, i.e. the rainfall probability model for Jordan does not work with the NAOI. Figure 7.15 below is the scatter diagram for JJA⁻ NAOI vs. annual ARRI, just to show an example for one of them. In Figure 7.15 a limit of NAOI > -0.3 and <-0.3 was selected. For NAOI > -0.3 it is 75% possible to get a dry year, while if NAOI<-0.3 it is 50-50 percent chance to get a wet-dry year. MAM⁻+JJA⁻ were combined and correlated with the annual ARRI as another attempt. The result was a very low correlation coefficient of 0.031.

The final trial was done by linear regression. The annual ARRI was assumed to be the dependent variable (Y) and MAM^- and JJA^- NAOI as the independent variable (X). The regression equations are:

$$Annual\ ARRI = 1.004(MAM^{-}NAOI) - 0.0116$$

To have a wet year MAM^- NAOI has to be 0.012. The actual MAM^- NAOI values were applied to the equation to obtain the annual ARRI. Results showed that the efficiency of the model was 45.6 percent, which is not significant.

$$Annual\ ARRI = -1.1022(JJA^{-}NAOI) + 0.0122$$

The above equation indicates a wet year if JJA^- NAOI value is 0.011. Again, the equation was tested against actual JJA^- NAOI values between 1990 and 2000. It gave 45.6 percent efficiency as well. The summary of JJA^- NAOI probability model is given in Tables 7.16. Figure 7.16 shows the scatter diagram with the best-fit line of using JJA^- NAOI and annual ARRI.

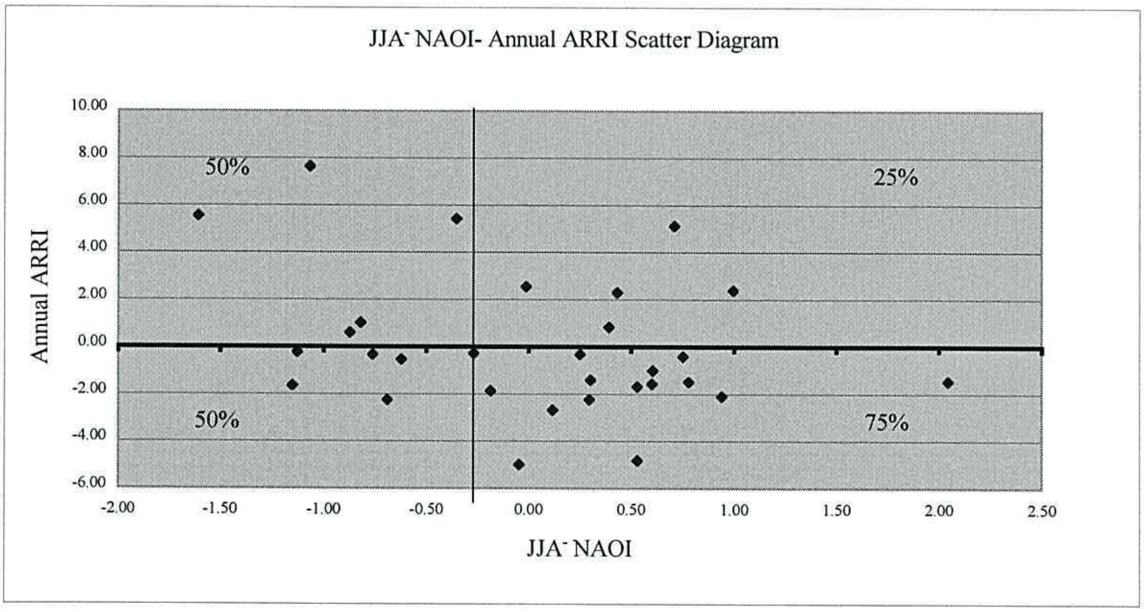


Figure 7.15: Scatter plot of the data showing the Jordanian Annual ARRI and JJA^- NAOI, for the years 1960-1989. The coefficient of correlation is 0.307

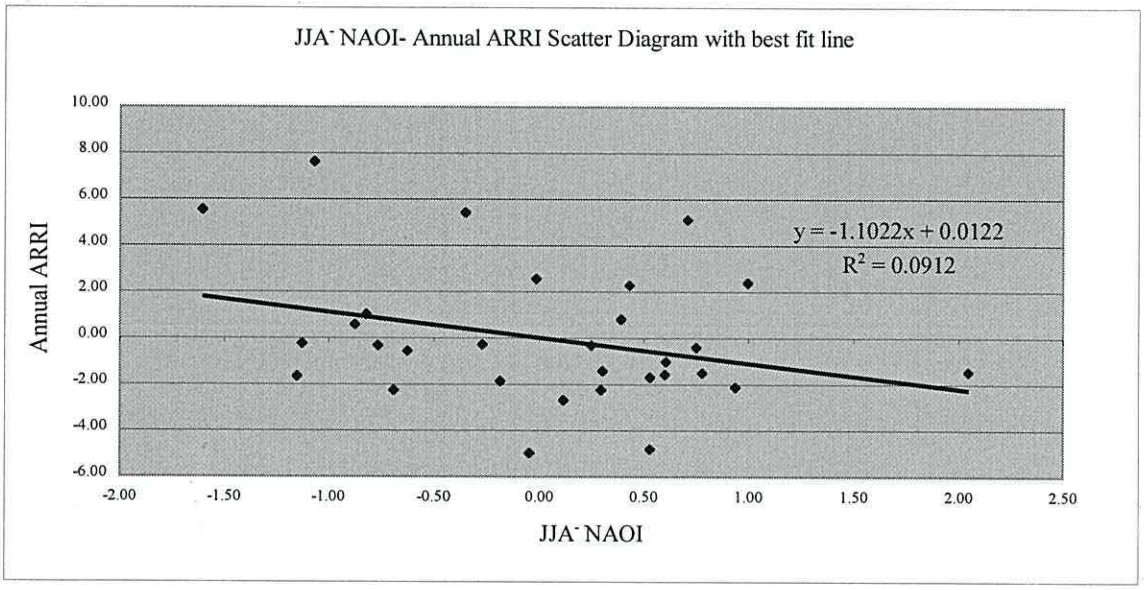


Figure 7.16: Scatter plot of the data showing the Jordanian Annual ARRI and JJA⁻ NAOI, with the best-fit line for the years 1960-1989. The coefficient of correlation is 0.302

Table 7.16: Verification of the Probabilistic Model using JJA⁻NAOI

Year	JJA⁻ NAOI	Predicted ARRI	(Observed ARRI) class	Evaluation
1990	0.60	Dry	(-0.43) dry	T
1991	1.72	Dry	(1.07) wet	F
1992	0.71	Dry	(2.00) wet	F
1993	1.09	Dry	(-0.59) dry	T
1994	0.52	Dry	(0.91) wet	F
1995	0.44	Dry	(-0.9) dry	T
1996	-1.88	Wet	(-0.18) dry	F
1997	0.90	Dry	(0.6) wet	F
1998	-0.36	Dry	(-0.53) dry	T
1999	0.13	Dry	(-1.20) dry	T
2000	-1.38	Wet	(-0.76) dry	F

From the above analysis between the annual ARRI and the seasonal NAOI, it is clearly seen that the NAOI could not be used as a predictor for the Jordanian rainfall, this could be due to some reasons. According to a report that was published by McCartney, (1998), in the New Scientist, no weather forecast could predict the exact evolution of the NAOI over more than a few weeks. The problem is that the atmosphere over the North Atlantic Ocean is chaotic. Though forecasts could work properly in the short run, but in the long run they diverge hopelessly. This is what experienced in the Jordanian situation as NAOI values were taken for the previous

MAM$^-$ and JJA$^-$, i.e. 6 and 9 months in advance before the rainy season, which is quite long time to predict the connection between the NAOI and the Jordanian rainfall.

Comparing NAOI with the ENSO SST index, the latter is mostly affected by the ocean itself, while, the NAOI is an atmospheric phenomenon, and subject to short-term variability. It is possible that the main influences from the North Atlantic on the Jordanian rainfall are on the strength, persistence, extent and location of high pressure over Balkans and East Europe, in late summer and early autumn. As these could control or modify the development and path of autumnal cold fronts, mainly Southeast from the Mediterranean.

Looking at the NAOI time series in Figure 7.14, it is seen that the NAOI has the seesaw pattern. The chart shows over a century of these long-term ups and downs that happened randomly. These long-term changes indicate that there is more than the ocean's chaos is going on. Atmospheric effects tend not to persist all that long unless there is something pushing them, (McCartney, 1998). Many scientists believe that the long-term memories that shape the NAOI are held beneath the waves, in the currents inside the North Atlantic.

McCartney admits that the natural shifts in the NAOI may be responsible for a proportion of the warming that is previously attached to the greenhouse gases. But he believes that the greenhouse effect may be changing the way that the NAO and other natural climate variations actually vary. This means that the changes in the stratosphere's structures could reflect changes in the NAO's behaviour, and the high index values in the early 1990s may be an example of that. One aspect of this may be that global warming reduces North Atlantic conveyer and this in turn weakens the Gulf Stream.

As mentioned before that the NAO has two phases, positive and negative and these have different effects on the world's climate. During its positive phase in autumn 2000, the NAO was to blame for the severe floods in many parts of the United Kingdom, (Matthews, 2000). This created an argument between the government officials and the climatologists, as the government officials related the flooding to climate change, while it was actually due to the NAO, as the scientists believed.

But, for Jordan it seems to be different story, as NAOI does not have large effect on the climate, based on the findings of this study. There could be other factors that have bigger effect such as ENSO. Even though this study is the first to be done about the teleconnection between these climatic indices and the Jordanian rainfall, the results look promising for the management aspect. It is very important to be pro-active (i.e. be able to act in advance), rather being reactive (i.e. wait until things have already happened and then take an action).

7.15 INDIAN OCEAN SST ANOMALIES (IO SST)-ARRI

The last index that was tested is the Indian Ocean Sea Surface Temperature Anomalies (IO SST). The findings from testing this index were not that optimistic. As shown in Table 7.3, the Indian Ocean SST did not have correlation with the Jordanian annual ARRI most of the time. The only high correlation was found between the current SON SST and the annual ARRI, with Cc=0.23, after testing for its significant it was found significant at 85%.

Based on this correlation coefficient the scatter diagram for the Indian Ocean SST vs. the annual ARRI was plotted, as represented in Figure 7.17. The diagram shows a lot of scatter, which caused a controversy in defining the limits for the Indian Ocean SST, and the annual ARRI. Then it was decide to take Indian Ocean SST limit of 0.2, and for the annual ARRI of 0. Based on these boundaries, four regions now have been identified with four possibilities as shown in Table 7.18 below.

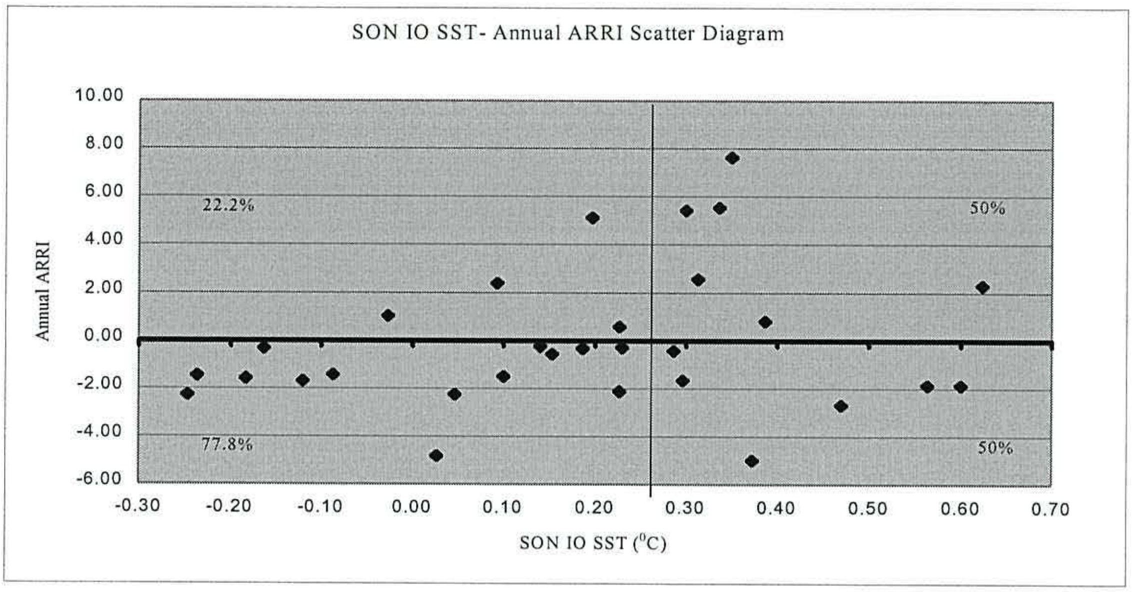


Figure 7.17: Scatter plot of the data showing the Jordanian Annual ARRI and SON IO SST, for the years 1960-1989. The coefficient of correlation is 0.23

Table 7.17: Probabilistic Model for Jordanian Annual Rainfall using SON IO SST

SON IO SST category	**Probability of Rainfall year Category**	
	Dry	Wet
Cold	77.8	22.2
Warm	50	50

From Table 7.17 it can be concluded that the IO SST is not helpful for rainfall prediction in Jordan, as a dry year is predicted no matter what the IO SST values are. If the IO SST above or below the chosen limit (0.2), a high possibility of having a dry year is always there. This kind of prediction is unreliable. One more thing is that, the SON IO SST is not a reasonable index to use because, as it will be too late as the rainy season has already started.

7.16 DISCUSSION

From the analyses that have been carried out between the four climatic indices and the annual ARRI in Jordan, it was found that only two indices provide any clear indications that affect the Jordanian rainfall. These are the ENSO SST index and the Southern Oscillation index, while, the other two, North Atlantic Oscillation index and the Indian Ocean SST do not display any clear correlation with the Jordanian rainfall. Reasons for that could be due to the nature of the indices themselves, as ENSO does have an influence on different parts of the world.

7.16.1 Correlation with Rainfall

A number of studies have been done and have linked the ENSO with different regions. Here it will be enough just to mention a few examples.

- Osman et al., (2001) did a study about the effect of ENSO on the variability of rainfall in Sudan. Their conclusion was that ENSO does affect the Sudanese rainfall.
- Other studies like Beltrando and Camberlin, (1993) who tested the relationship between rainfall variability in the Eastern Horn of Africa and the SOI and IO SST and pressure surface fields. Found that rainfall is correlated with both indices, with dry years mainly associated with La- Niña.
- Others studies about the connection between the SOI and autumn rainfall in Iran, (Nezamosadat and Cordery, 2000; Nezamosadat, 1999), suggested that Iranian rainfall was several times more than usual during ENSO (i.e. El- Niño and La- Niña) episodes.
- Between 1934 and 1999 there were sixteen La- Niña events, In Argentina the rainfall during nine of them was significantly below the average, which indicates that the La- Niña causes drought 56 percent of the time in Argentina, (de Rojas, 2000).

Summaries taken from different studies about the effects of El- Niño and La- Niña on the rainfall of countries near Jordan are shown in Tables 7.18 and 7.19. Table 7.18 shows the values of ARRI for Jordan, Syria, Iran, Eastern Horn of Africa and Sudan (both Savannah and Equatorial regions) during El- Niño and La- Niña years. From the Table it can be seen that the effect of El- Niño and La- Niña on the rainfall of these countries is variable, as in some years drought is associated with El- Niño, while in others La- Niña is responsible for the drought. The different effects of El- Niño and La- Niña years are summarised in Table 7.19.

Table 7.18: ARRI during El- Niño and La- Niña years for Jordan, Syria, Iran, E. Horn of Africa and Sudan.

year	Category	Jordan	Syria	Iran	E. Africa	Sudan (Sav.)	Sudan (Eq.)
1964/1965	La-Niña	-0.56	0.4	0.72	-1.00	1.33	0.00
1965/1966	El-Niño	-0.34	0.03	1.50	1.50	0.50	-0.55
1969/1970	El-Niño	-1.42	-0.74	0.78	-0.12	-0.22	0.00
1970/1971	La-Niña	2.54	0.48	0.76	-0.25	-0.11	0.17
1971/1972	La-Niña	-0.34	-0.28	-0.50	-0.13	-0.67	-0.22
1972/1973	El-Niño	-4.82	-0.98	1.35	0.75	-0.83	-0.55
1973/1974	La-Niña	2.28	1.08	0.65	-0.15	-0.44	-0.55
1975/1976	La-Niña	-2.26	0.06	0.10	-0.5	0.00	-1.33
1976/1977	El-Niño	-1.59	-0.25	0.00	2.23	-0.78	-2.22
1982/1983	El-Niño	5.41	-0.07	-1.75	1.75	-1.34	-0.78
1984/1985	La-Niña	-0.43	-0.70	0.2	-0.88	-2.77	-1.42
1986/1987	El-Niño	0.57	0.27	-1.25		-2.19	-0.88
1988/1989	La-Niña	-1.88	-0.98	0.80			
1991/1992	El-Niño	2.00					
1994/1995	El-Niño	-0.90					
1995/1996	La-Niña	-0.18					
1997/1998	El-Niño	-0.53					
1998/1999	La-Niña	-1.20					
1999/2000	La-Niña	-0.76					

Table 7.19: Number of Wet, Average and Dry years associated with El- Niño and La-Niña for Jordan, Syria, Iran, E. Horn of Africa and Sudan.

	Jordan	Syria	Iran	E. Africa	Sudan (Sav.)	Sudan (Eq.)
No. of El-Niño events	**9**	**6**	**6**	**5**	**6**	**6**
Wet	3	4	3	4	1	
Avg.			1			1
Dry	6	2	2	1	5	5
No. of La-Niña events	**10**	**7**	**7**	**6**	**6**	**6**
Wet	2	4	6		1	1
Avg.					1	1
Dry	8	3	1	6	4	4

A degree of variability is clearly seen from the Tables above, i.e. dry/wet years are not always associated with El- Niño or La- Niña years. Thus, a generalisation can not be made here, as the predictive capability of the rainfall is associated with the values of the climatic indices themselves (ENSO SST and SOI), not with the status of the year as an El- Niño or La- Niña year.

7.16.2 Correlation with River Flow

Other studies related the flow in rivers to the ENSO. An example, is the study by Wang and Eltahir, (1999) of the correlation between the ENSO and Nile floods, which led to the forecast of the flood based on the conditions of the ENSO. Amerasekera et al., (1997) studied the variability of the flow of tropical rivers (Amazon, Congo, Parana and Nile Rivers) in association with the ENSO. It was found that the Amazon and Congo rivers were weakly correlated with ENSO SST anomalies. The flow of the Parana River has found to be better correlated, while the best correlation was between the ENSO SST anomalies and the River Nile.

In this study it was found that the Jordanian rainfall is correlated with ENSO SST index and SOI. The ENSO SST correlation was noted between the seasonal climatic indices for the previous first and second quarters (i. e. JJA$^-$ and MAM$^-$) and the previous annual (-1) year ENSO SST indices. The correlation coefficients were 0.352, 0.331 and 0.361 for JJA$^-$, MAM$^-$ and (-1) year respectively. Positive correlation means that as ENSO SST increases, ARRI increases. The scatter diagrams display this, as do the rainfall probability model results, as the three models for the three indices indicated that wet years are associated with high positive values for ENSO SST. The (-1) year model gave a good performance at a 50 percent efficiency; the previous JJA$^-$ and MAM$^-$ individually gave 66.7 percent efficiencies, while the best performance of 83.3 percent came from the combination of JJA$^-$ and MAM$^-$ data.

SOI is a mirror image of ENSO SST index, i.e. if one is high the other should be low, so obviously the correlation coefficient with the Jordanian rainfall was negative. The ARRI was correlated with the previous fourth quarter of SOI (SON$^-$) with a correlation coefficient of –0.296. It was also correlated with the previous second quarter (MAM$^-$), at a maximum correlation coefficient of (-0.362). The previous year's annual SOI was correlated as well with the annual ARRI with a coefficient of –0.286. The developed rainfall probability models using the mentioned indices show that the previous annual SOI index will not be useful for rainfall predicting in Jordan. As during its positive phase (>0) it predicts a dry year most of the time, while during its negative phase it is quite confusing as it predicts 50-50 percent to have a wet-dry year, which in unreliable for prediction purposes.

SON$^-$ ENSO SST model gave 54.5 percent efficiency, as six out of eleven years were precisely predicted. But, the model that has been developed using MAM$^-$ SOI gave the best prediction, for nine out of eleven years the predicted values were the same as the actual, with a performance level of almost 82 percent. This means that the rainfall in Jordan could be predicted 6 months in advance based on the SOI conditions. This index most of the time was able to detect the dry years rather than the wet ones, which is an important issue especially in a country like Jordan, where more than 80% of the country is considered dry, as it receives an annual rainfall of less than 200mm. So, it is a major finding to be able to detect dry years more than the wet ones as the risk management issue here is very crucial. This aspect will be considered in detail in the next Chapter.

The other two indices NAOI and IO SST anomalies did not appear to have an effect on the Jordanian rainfall, as mentioned before. This could because the way that the indices were taken (seasonally and annually averaged) was not the perfect way to deal with them. Or even it could be due to the fact that the ARRI was taken for the whole country, which might affect the correlation. As it has been said before the rainfall is variable in Jordan temporally and spatially, so including all the stations in an overall index has an important impact in the correlation.

The rainfall data quality affects the analysis. For example, the data were obtained from two different sources, the University of Manchester and the Ministry of Water Resources in Jordan. The rain gauges mainly were the type that is normally checked on a daily basis. The records are taken at 8 o'clock every morning. Also, thirty years of data is relatively short and not enough to build the rainfall probability model, but this was the only set of data available for all the considered stations. Moreover, more data from Syrian, Lebanese and Palestinian stations would have been desirable.

7.17 CONCLUSIONS

It is concluded that the Jordanian rainfall is highly affected by the previous second quarter (MAM') SOI and ENSO SST indices. This means that they can be used as predictors for the Jordanian rainfall. The developed rainfall prediction models will be used in Chapter Eight to develop the decision making tree for barley cultivation in *Marab* Hassan.

It appears that La- Niña is associated with drought in Jordan, between 1960 and 2000 there were ten La- Niña episodes, eight out them resulted in dry conditions. While during the same period there were nine El- Niño events, five out nine were associated with below average rainfall. This concludes that the effect of El- Niño and La- Niña events is variable from year to year, and the rainfall prediction (wet, average or dry year) is associated with indices values, rather than the status of the year (El- Niño or La- Niña year).

Regarding NAOI it could be interesting to also examine the correlation using NAO Sea Surface Temperature (NAO SST) instead of the pressure difference. A study done by Saunders et al., (2000) suggested that the predicted DJF rainfall in the United Kingdom in winter 2000/01 would be 70% above the average, which was accurate.

The new procedures that have been introduced for the rainfall prediction are very helpful, as without them the best practical prediction will be just to predict the average rainfall. The analysis presented here suggests that the proposed procedures improve on this prediction. Such an improvement in the Jordanian annual rainfall should have a positive impact on the water resources management in Jordan, as well as the neighbouring countries if the study extends to include the neighbouring countries as Lebanon, Syria, Palestine, Iraq and Saudi Arabia.

Further research is needed to focus on adding other variables like the stream flow from the major rivers in Jordan, like River Jordan and Yarmouk River.

Once it is understood how the global systems influence the climate, here will be a better chance to develop long-term prediction tools. The climate change aspect is beyond the scope of this study, but it is an area where research is extremely important, in terms of the optimum allocation of resources in the new century.

CHAPTER EIGHT

WATER RESOURCES MANAGEMENT IN *MARAB* HASSAN AND OTHER *MARABS* IN THE BADIA AREA

8.1 INTRODUCTION

As discussed in Chapter Two (Sections 2.2 and 2.3) there are many *Marabs* in the Badia area. This chapter will emphasise on *Marab* Hassan in particular as a pilot study. A discussion about water harvesting will be followed by consideration of seasonal rainfall prediction and its use, particularly for agricultural activities in the *Marabs*. This discussion leads to review the possibilities of water resources management in *Marab* Hassan, using an important example with emphasis on the traditional approaches of cultivation and testing these approaches against the historical records and the prediction that can be made using climatic indices like El-Niño Southern Oscillation Index (SOI). Finally an outlined estimation of the cultivation cost, as well as the construction cost of the proposed water harvesting schemes in the *Marab* area will be given.

8.2 *MARAB* HASSAN

There are many *Marabs* in the Badia area that could be used for barley cultivation, but before introducing this practice, feasibility studies should be done, taking into account the *Marab*'s size, soil type, soil depth, water availability, catchment size that feeds it and accessibility. This chapter will focus on *Marab* Hassan as an example, because it is an important part of the study area, and because its characteristics can be used as an index against which other *Marabs* can be judged.

Marab Hassan is located 35-km southwest of Safawi, and almost 10-km from Azraq. From aerial photographs of 1:25,000 scale, (shown in Figure 8.1), 1:50,000 geological maps and ground truth inspections, it can seen that *Marab* Hassan shown in Figure 8.2 has formed as a result of the existence of natural structural systems (faults) in the area. Two major faults have played an important role in its formation; these are the Fuluk fault that is oriented NW-SE direction, as well as Zumal Al-Hashad Al-Asfar fault, which is oriented N-S direction. The *Marab* takes almost a pear shape, with an area of 3.5 km^2 and a catchment area of 357 km^2. It has two inlets and two outlets, one major outlet and one minor that only functions in cases of high floods. These are consequences of the geological and geographic history of the area in recent geological time. Table 8.1 summarises *Marab* Hassan characteristics.

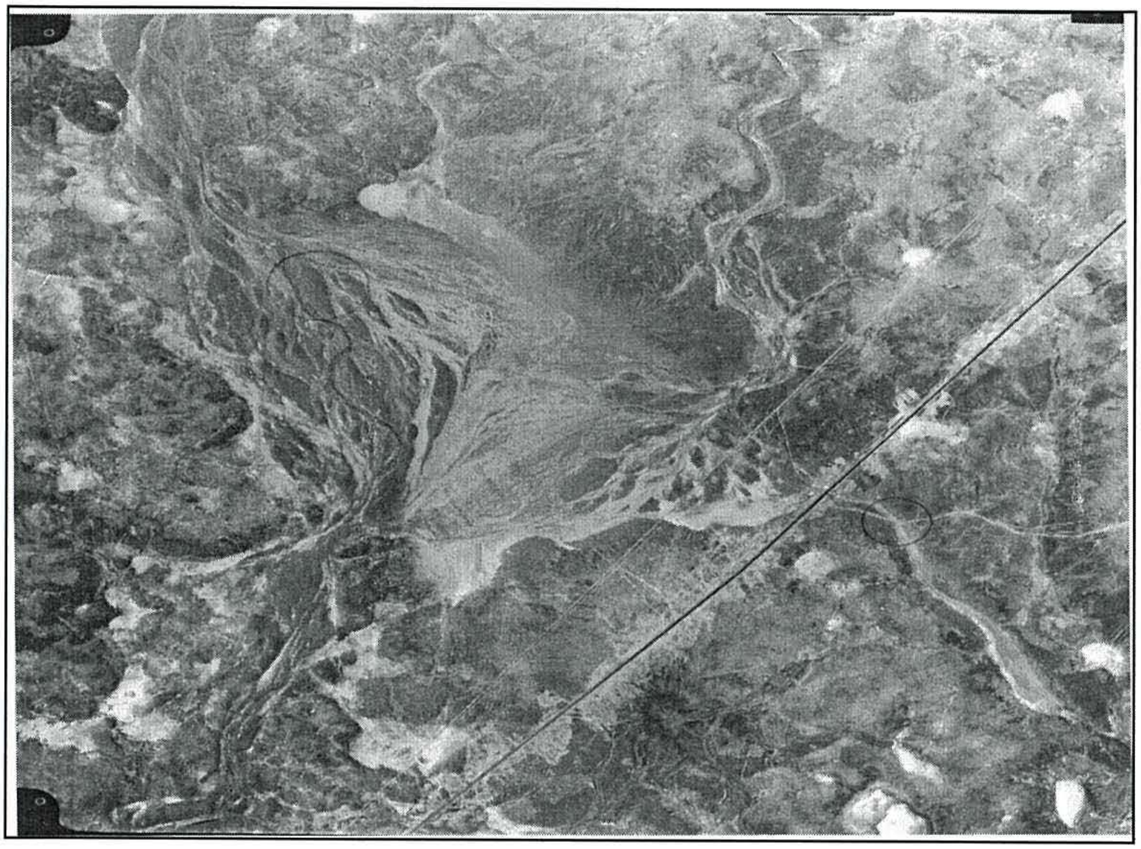


Figure 8.1: Original aerial photograph of *Marab* Hassan (scale 1:25,000).

Table 8.1: *Marab* Hassan characteristics.

Size (km^2)	3.5
Catchment area (km^2)	357
Mean annual rainfall (mm)	93.1
Median Length of wet season (month)	4
Median number of runoff events	6
Soil Type	NAT (loamy texture)
Depth of soil profile (cm)	100 – 200
Flow pattern across the *Marab*	Channel from the eastern Wadi and Sheet (overland) flow from the western Wadi

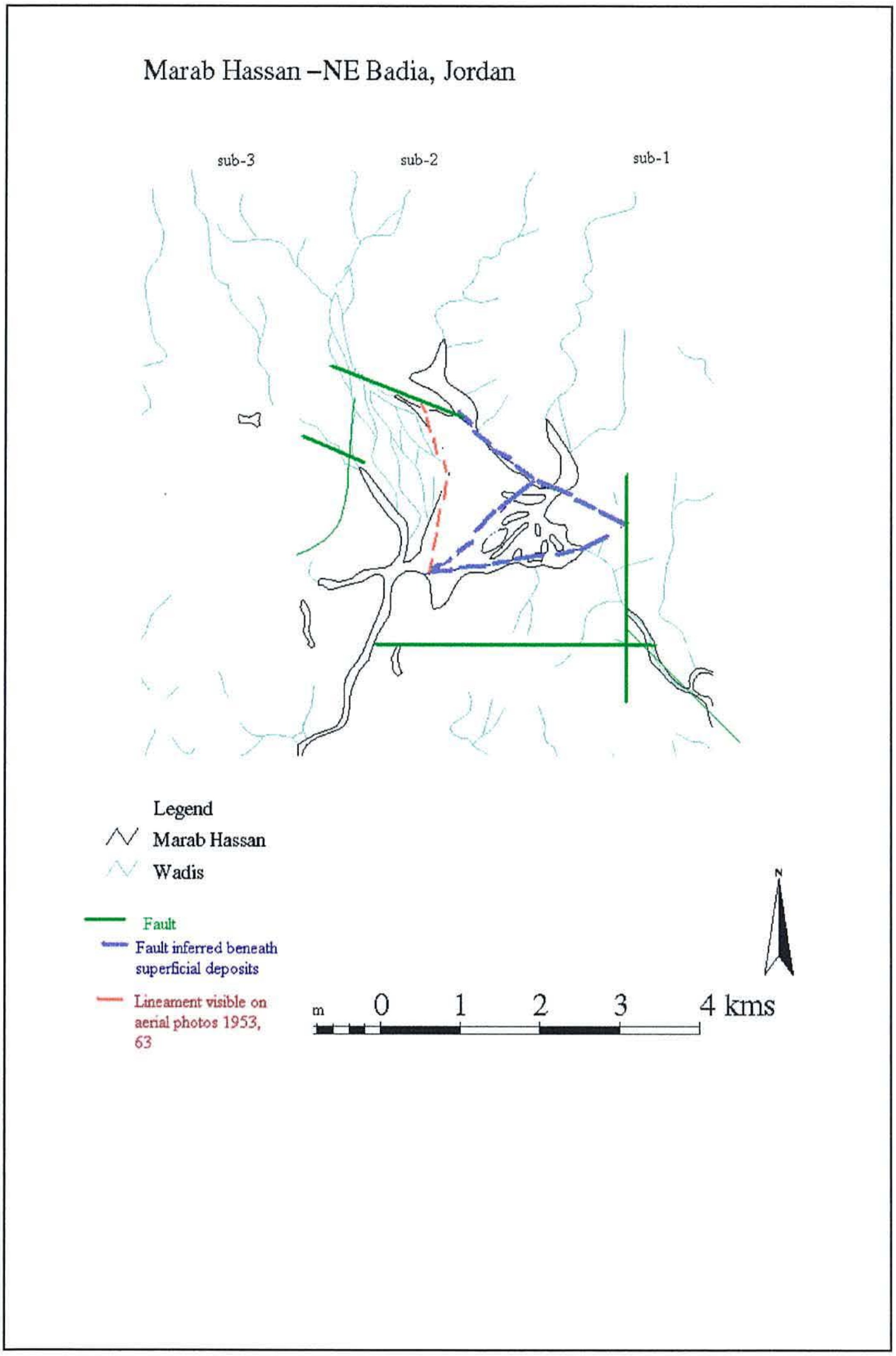


Figure 8.2: Faulting systems that have formed *Marab* Hassan.

Water feeds into the *Marab* from Wadi Hassan from the east and from the western main Wadi that comes from Syria. The flow enters the *Marab* in two different patterns. From Wadi Hassan it enters mainly as a defined channel flow that continues as an incised channel flow till it reaches the discharge point. From the aerial photos and the *Marab* flow pattern map that was developed using *CARTLINEX* software, it appears that there are a number of small channels that are connected to the main channel. These channels have a depth of up to 30-cm and a variable width between 10-100 cm as was seen during the field visit in November 2000.

The main wadi flow behaves in a different way, as it enters the *Marab* as a channel flow then rapidly starts to spread in a sheet flow (overland flow) of a depth between 40-50 cm, causing more ground flooding in the north-western part of the *Marab*. Figure 8.3 shows the flow pattern of the *Marab*. This Figure was developed based on using the aerial photograph that was traced, scanned and then digitised using the *CARTLINEX* software.

The aerial photograph (shown in Figure 8.1) has been used to develop a contour map (in association with Infoterra Ltd in the UK) of 2 metre contour interval for the *Marab* area as shown in Figure 8.4, which was used to analyse *Marab* flow to identify zones where channel flow predominated and also to look for the threshold for discharge into southeastern channel. The aerial photos were used to create a three dimensional view of it as shown in Figure 8.6. These aerial photos were taken in 1978, which means that some features of the *Marab* have changed since that time in regard to the development of agriculture. In the aerial photos it appears that the main wadi flows into two parts, one enters the *Marab* as a set of braided channels, which afterwards spread over it as a sheet flow. The second part of the flow keeps flowing just outside the *Marab* (adjacent to it) in a major incised channel. So, to make use of most of the flow for the cultivation purposes that take place in *Marab* Hassan, in summer 1997 the Badia programme built a diversion dam inside the wadi to interrupt the flow and divert most of it (almost half of it) inside the *Marab*. Soil was used to build the dam, of about 4-5 metres height and 300-metre length, (these measurement were estimated from the ground truth), as shown in Figure 8.5. The construction diverts 50 percent of the flow inside the *Marab*, (Al-Ayyash, 2000; Shahbaz, 2000). This affects the flow that is to be recorded at the gauge downstream at the *Marab* outlet. People who gave the Figure were senior personnel who have been involved in planning and implementation, however the rigorous hydrologic and hydraulic, as well as the cost analyses for the dam to substantiate these judgements do not exist, (i.e. no data before and after the construction of the dam are exist).

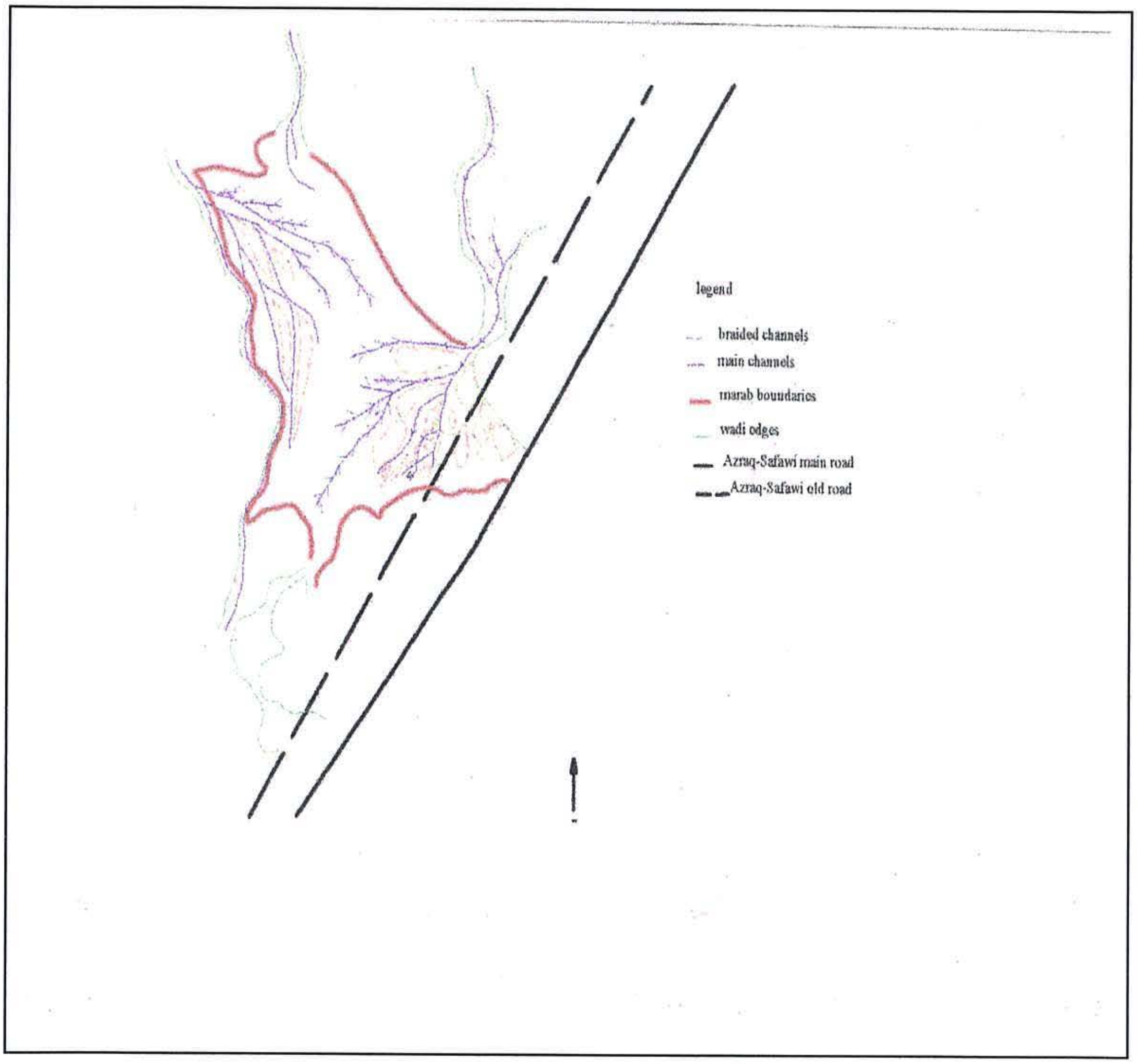
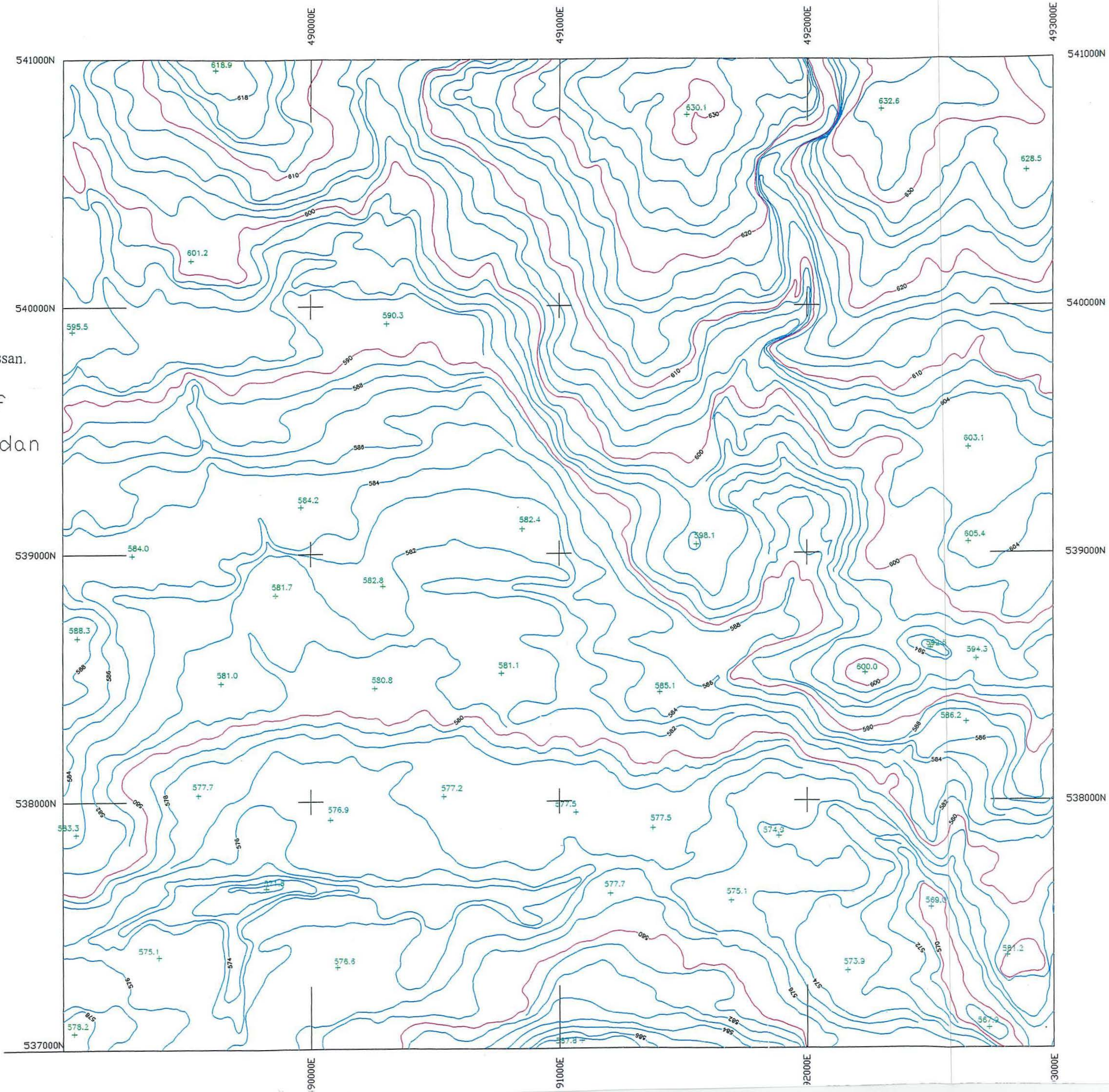


Figure 8.3: Flow pattern in *Marab* Hassan.

Figure 8.4: Contour map of Marab Hassan.

Contour Plot of

Marab Hassan, Jordan



Scale: 1:15000

Source: 1:25000 Photography
1:50000 Mapping

Date: 19 April 2001

Produced by: Infoterra Ltd,
Arthur Street,
Barwell,
Leicestershire,
LE9 8GZ

Figure 8.5: The diversion dam at *Marab* Hassan.

The *Marab*'s soil is NAT mapping unit, which has a loamy texture with 42.9% sand, 21.8% clay and 35.4% silt. As the flow enters and leaves the *Marab*, it washes the soil with it and washes out any accumulated salt that might build up due to the accumulation of the sediments, which makes it suitable for cultivation. The *Marab* floods between four and five times in a good year (i.e. a wet year), with water standing for about a week in each case.

Figure 8.6: Three-dimensional view of *Marab* Hassan, (where the red lines are the overlaid contours)

8.3 WATER HARVESTING

Water harvesting systems can be divided according to the source into two categories: rainwater harvesting (local source) and floodwater harvesting (channel source). The rainwater harvesting is also divided into sub-categories, which are rooftop harvesting and runoff harvesting (Thomas, 1997). This review will only deal with runoff water harvesting, as other divisions are not in the scope of this review.

In literature so many definitions of water harvesting are found, some of them are mentioned below:

- Water harvesting is an ancient technique used to provide water for small agricultural operations, stock or domestic needs (Medina, ~1976).
- A comprehensive term covers different means of the collection of surface and sub-surface water for productive use, Finkel & Segerros, (1995).
- It is an umbrella term describing a whole range of methods of collecting and concentrating various forms of runoff (rooftop runoff, dew, etc.) and for various purposes (agricultural, livestock, domestic and other uses), (Reij et al., 1988).

These definitions show that water harvesting encompasses methods to induce, collect and store runoff from various sources for various purposes. They also demonstrate that surface runoff is the key factor in water harvesting. Other important elements are the source of runoff, the form of runoff and the harvesting technique itself (Bores & Ben-Asher, 1982). Water harvesting techniques are common in high and low rainfall areas and they seem to work successfully. The harvested water may be used for domestic uses, livestock as well as supplementary irrigation as will be discussed later.

8.4 Factors Affect Water Harvesting

Important factors that affect water harvesting are climate, geomorphology and topography, as well as agricultural experience, (Jamous, 1992). Climatic factors include the rainfall depth, intensity, duration, and frequency, maximum and minimum temperature and wind speed that affect evaporation. In order to have sustainable water harvesting scheme these factors have to be taken into account. For example, rainfall intensity affects the percentage of runoff, as soon as rainfall intensity is greater than the infiltration rate runoff starts to generate. High intensity rainfall mostly generates runoff that is feasible for water harvesting schemes, while low intensity rainfall infiltrates and contributes to ground water recharge.

Geomorphologic and topographical factors that should be considered before establishing water-harvesting schemes are; the soil morphological characteristics like;

- The soil texture.
- How much water could be stored in the soil?
- Infiltration rate.

- The soil depth.
- Presence of rocks and stones on the soil surface.
- Slope and aspect.

The ratio between the catchment area and the cultivated area is another important factor that has to be considered when designing and water harvesting scheme. The ratio has to be within a certain range, which means that there should be enough amount of water harvested in order to keep the scheme running for long term (i.e. sustainable and feasible). Farmers should have an agricultural experience that gives them the capabilities to preserve the scheme's sustainability as maximum as possible

8.5 ANCIENT WATER HARVESTING TECHNIQUES

One of the techniques that have been used is floodwater farming or runoff farming. It provides sufficient water, which can be concentrated into the root zone in areas, which would otherwise be classified as being unsuitable for dry-land agriculture (Pacey and Collis, 1986). Runoff farming is the use of precipitation *in situ* with the addition of compensation water provided either naturally or by construction of a simple water control structures (Richards, 1989). These techniques are used on both micro and macro scales. Micro scale includes the micro-catchment system, which is defined by Oron et al. (1983) as an area up to few hundred square meters, which is used as a water-harvesting element for a single tree. The micro-catchment procedure may be used in complex terrain where other water harvesting techniques may be difficult to apply (Medina, ~1976). While, at the macro scale, floodwater from wadis or rivers can be channelled into fields at the wadi sides.

These techniques were in use and in some areas are still in use throughout North Africa and the Middle East, including Morocco, Libya, Egypt, Sudan, Eritrea, Ethiopia, Yemen, Oman and Iran (National Academy of Science, 1974). There is evidence to prove that rainwater harvesting has been practised in the most inhospitable environments. Traces of agricultural production systems from the Nabatean civilisation in the Sinai and Negev deserts were reported and have been intensively studied since 1950s (Evanari et al. 1971). Similarly, in the pre-desert of Libya evidence of Romano-Libyan agriculture was reported. In both of these environments annual rainfall is low and very variable and there is some evidence to suggest that the climates of these areas today are similar to these of two thousand years ago (Richards, 1989).

In Egypt evidence was found related to the rain-fed agriculture practised by Roman people. In northwestern Egypt over 2000 Roman storage cisterns are still in use (FAO, 1971). These cisterns consist of underground water storage chambers associated with catchment areas on very shallow slopes; low stonewalls are used at the edge of the catchment to channel runoff into the chambers.

Another ancient structure that thought to be of a Roman origin is what is known as the 'Karm'. Karms are formed in rectangular or horseshoe shape and have both central and external fields, and consist of banks of earth up to 5m high. The Karms were used to store runoff, and to provide water to central and surrounding fields to produce crops in most years (Richards, 1989).

An individual terraced Wadi is also an ancient technique that was practised in the Negev desert long time ago. This is the simplest method, which is still used by the Bedouins today (Bores & Ben-Asher, 1982). According to Evanari et al. (1982), they state that these individual terraces are ancient erosion and flood control structures. The terrace is a wall of stones built at a right angle to the wadi, with a 60-80 centimetre height measured from the lower terrace, and about 10-30 centimetres above the surface of the higher terrace. The terraces are built of five to seven layers of stones. The spacing between the terrace walls is usually 12-15 meters and their length across the terraces varies from 6 to 20 meters and depends on the slope of the Wadi bed.

The terraces are still in use by *Bedouins* in the Negev, and have also been used throughout the ages by all civilisations in the Negev. They were, and are still, used for agricultural purposes; this type of agriculture is called runoff farming because rainfall is harvested in the field for crop production (National Academy of Science, 1974). As floodwater cascades gently down from terrace to terrace, some water sinks directly into the terrace soil and some is ponded behind walls and the latter penetrates into the ground.

Two thousands years ago the Nabatean inhabitants of the Negev desert used another technique for water harvesting. It is described by building a channel across the hillside to harvest rainwater runoff. The channel leads water to a cistern excavated in the ground (National Academy of Science, 1974). Another ancient method that is also found in the Negev is the stone clearing technique. It was noticed that the gravel that covered the slopes had been moved to the sides, this is to increase the runoff amount. For example, runoff amount had been increased by 20-40% during the storm of 22 March 1965 (Evanari et al. 1971; Yair, 1983). This is due to the crust formation on the soil surface, which enables in increase of runoff amount as mentioned before.

Finally, one of the ancient systems that found in literature is the *Mahafir*[1]. *Mahafir* are excavations of various shapes and sizes found in the mud flats (*Qa*'as) of the Eastern Jordan Desert (Badia), and are believed that they had been used for water collection. *Mahfur* is an excavated depression, partially surrounded by low earth wall with possibly an opening pointing up slope to collect runoff for livestock and crops. It is also believed that *Mahafir* are water-harvesting systems, mostly old, some ancient and a few are recent (Agnew et al. 1995). Barrow (1987) describes *Mahafir* as shallow excavations 20 to 100 meters in diameter surrounded on three sides by earthen bunds, 1 to 4 meters high.

8.6 WATER HARVESTING FOR AGRICULTURAL USE

There are several techniques practised in different parts of the world for using the harvested runoff for agricultural purposes, two main methods will be discussed in the coming section. They are micro-catchments and macro-catchments.

Before discussing the two methods in detail, it is necessary to define some terms related to water harvesting. Runoff coefficient is the ratio of the amount of runoff that leaves the catchment area to the total amount of rainfall. This factor is important to be known as it gives an idea of how much water is available for the crops. The second important factor is the catchment target ratio, which is the ratio of the catchment area

[1] Mahafir plural, single is Mahfur

to the cultivated area. This ratio is determined to ensure a sufficient amount of runoff to satisfy crop water requirements, (Oweis, 1994). The target area is the agricultural land that receives the runoff. The catchment area can be as small as few square meters or as large as several square kilometres, it can be also adjacent to or far from the target area.

Micro-catchments are usually on-farm systems where both the catchment and target areas are close to each other and have small to moderate sizes. In these techniques water is harvested from a relatively short slopes and runoff is stored in the soil profile or sometimes in small reservoirs before it is used to supply the crops with the required moisture. The catchment area to the target area ratio ranges from 1:1 to over 15:1. Following are some techniques under the micro-catchment method.

One of the methods is a contour earth ridge for crops or trees, in this technique the ridges are constructed on the contour by digging a furrow and throwing the soil to the lower side. Ridges follow the contour and runoff is collected from the uncultivated strip between ridges and stored in a furrow just above the ridges. Crops are planted on both sides of the furrow. The yield of runoff from the very short catchment lengths is extremely efficient and when designed and constructed correctly there should be no loss of runoff out of the system. Another advantage is an even crop growth due to the fact that each plant has approximately the same the contributing catchment area. This method is good for plant production, where cereal crops such as sorghum or bulrush millet can be planted on both sides of the furrow, and the area between the ridges is kept bare as shown in Figure 8.7, (Thomas, 1997; Riej et al. 1988).

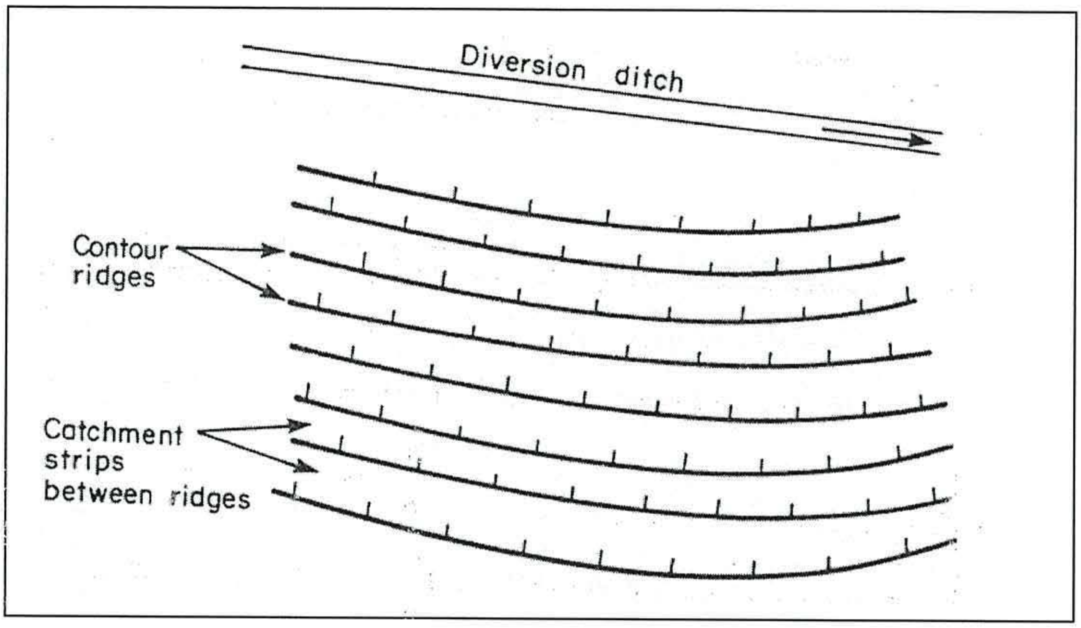


Figure 8.7: Contour ridges layout, (Source: Critchley and Siegert, 1991).

Another method is contour runoff strips (strip farming) that is similar to contour ridge method. In this technique terraces are established along the contour, with the area between them prepared to serve as a precipitation collection area. Runoff occurring between the terraces irrigates the crop or forage planted just upslope from the terrace, as shown in Figure 8.8, (Medina, ~1976).

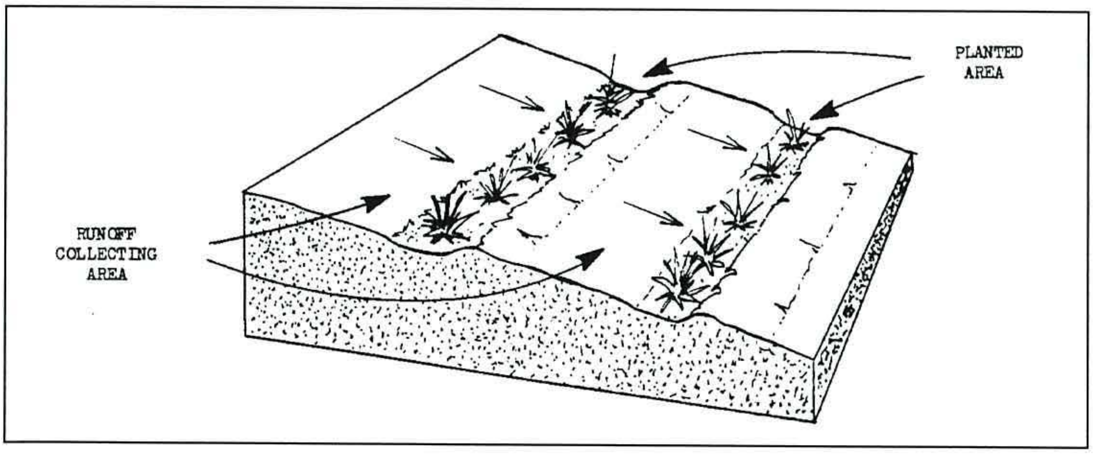


Figure 8.8: Desert strip farming makes use of water by employing a series of terraces: (Source: Medina, ~1976).

Small basin micro-catchments include two ways of harvesting the runoff. The first type is the "negarim" micro-catchment that consists of a closed grid of basins of diamond, square or rectangular shape, formed by small earth levees or gently sloping land with an infiltration area at the lowest corner where the crop is grown. Part of the area is used as a catchment and the second part, which is a tree most of the times, is considered as the target area. The area of a negarim ranges from 20 to 100 m^2. This technique is usually used to support trees, bushes and some times grasses or field in arid regions (Oweis & Taimeh, 1996). This technique is illustrated in Figure 8.9.

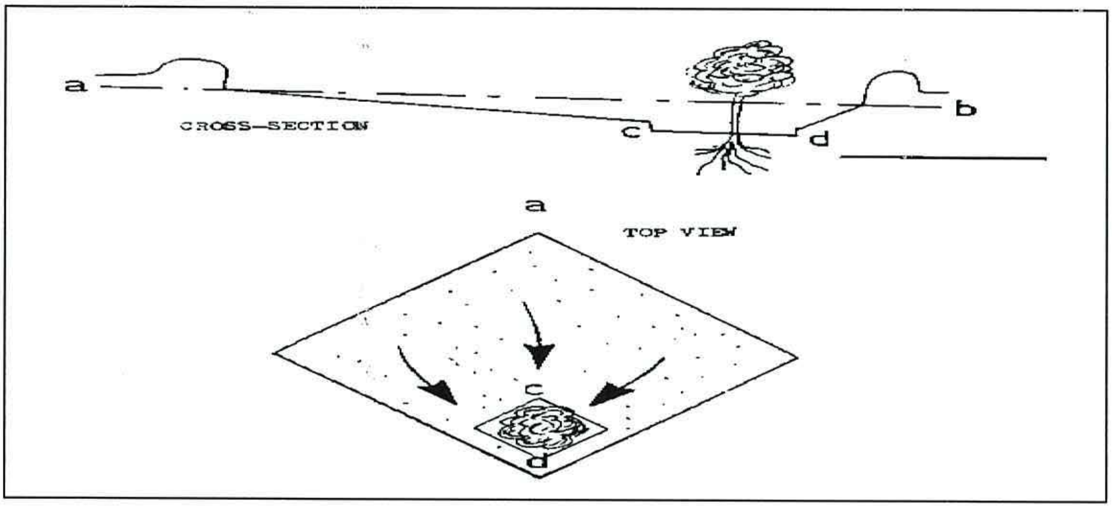


Figure 8.9: Sketch of a plan and cross-sectional views of a micro-catchment, (Source: Medina, ~1976).

The second type in micro-catchment system is called bunds. They are about 1 m high and laid out on the contour. The ends are turned uphill up to a vertical distance of 30cm. The recommended interval between the bunds is 60cm. The bunds are equipped with overland channel, anticipating runoff to pass a long the bunds. Bunds have different shapes like trapezoidal and semi-circular (Reij et al. 1988), as illustrated in Figure 8.10.

There are many other types of micro-catchments but all are modifications of the above types. Special topography and other field conditions may require amendments in the shape and the size of the basin to fit the farm. Generally micro-catchment techniques are on farm systems, easy to construct and maintain, help conserve the soil, and very effective in improving soil moisture within the plant root zone.

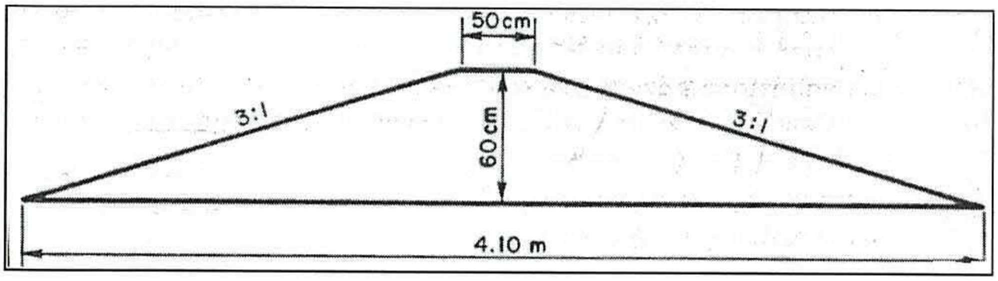


Figure 8.10: A trapezoidal bund, (Source: Critchley and Siegert, 1991)

8.7 MACRO-CATCHMENTS

8.7.1 Farm runoff systems

A farm runoff system is one of the techniques within the macro-catchments system. In this type harvested runoff travels along relatively long slopes, and usually catchments and target areas are not as close to each other as in the micro-catchment method. The catchment area is large and may range from few hundred square metres to several square kilometres. Some of the techniques within this category are trapezoidal bunds, contour stone and earth bunds and water spreading bunds.

8.7.2 Flood water runoff systems

This method involves concentrating runoff water flowing in the stream bed by blocking, it either completely or partially. Techniques utilised in this method include small dams and checks, water spreading drop structures and water diversion structures. Small dams and checks usually store water to be used directly or to be pumped or diverted to nearby fields. This technique is costly and needs proper engineering design, which are major constraints. Also, evaporation, silting and seepage reduce the harvested water amount and the water availability.

Water-spreading drop structures are constructed across a stream bed to raise the flow elevation to enable it to flow to the cultivated areas on one or both sides of the stream. This type is suiTable for rain fed agriculture as it provides crops with water whenever it is needed. Water diversion structures are quite similar to the spreading structures as they divert water to the cultivated lands but by building dams and diversion canals. This technique requires organised farming systems and good engineering knowledge.

8.8 Storage Systems

Harvested water can be stored in different ways according to the purpose for which it is harvested. For agricultural purposes various methods can be used, such as infiltration storage. While, for livestock and domestic use there are other method, such as: tanks, underground tanks, caves, open reservoirs and subsurface reservoirs (Thomas, 1997).

According to Medina (~1976), a complete runoff harvesting system includes a means to store the collected water. There are three basic storage systems:

(i) The excavated pits or ponds

(ii) Bags made of rubber or plastic

(iii) Tanks of steel or concrete.

The most appropriate system for a particular site depends up on the conditions of soils, site accessibility, available materials, cost of labour and material and life infrequent.

The success or failure of rainwater harvesting depends on the quantity of water that can be harvested from one area under given climatic conditions (Bores & Ben-Asher, 1982). Depending on climatic and catchment characteristics like: soil type, vegetation cover, the physiography (i.e. slope and aspect) of the catchment, crust formation as well as the rainfall characteristics of the catchment, like intensity and duration, all affect the water harvesting technique to be used. It can be seen that factors affect water harvesting are the same that affect runoff amount, so it can be can said that water harvesting is dependent on runoff volume.

Due to high variability of precipitation in arid areas, water harvesting cannot always provide a completely reliable supply of water. For this reason, if harvested water is to be used for agriculture, drought resistance plants should be planted and generally an alternate source of water should be available to ensure a minimum supply during the dry periods. Also, the emphasis is on seasonal and annual crops, but not perennial trees, so the consequence of supply failure is not long lasting.

Ancient water harvesting techniques were very practical so that they have been used for a long time and some of them are still in use. So, at some sites they again may be helpful in providing water for arid zones inhabitants, because they are proven and have low to intermediate technology requirements.

8.9 JORDANIAN EXPERIENCE IN WATER HARVESTING

Water harvesting has been practised in Jordan as well as other neighbouring countries like, Syria, Egypt, Palestine and many other countries in the Middle East and elsewhere in the world, (National Academy of Science, 1974). In Jordan the technique goes back for a very long time. The Nabatean people who inhabited Petra in the south of the country between 332 BC till 640 AD used to harvest water via channels that run through the city. Some of these channels still remain and can be seen while walking through the "Sique" that leads to the city. Archaeological studies also showed that the ancient civilisation cleared the stones from the foot of the mountains to increase the runoff, and they built terraces for harvesting water and they dug canals to convey water to the lowlands, (Jamous, 1992a).

A well-known ancient technique for storing the harvested water that has been practised in Jordan and other neighbouring countries is the cisterns system. In Jordan cisterns were found in the northeastern Badia near Jawa in the black lava desert, before 3000 BC; this type of cisterns also has been found at different parts of the country in the northwestern part as well as the middle and southern parts. The old cisterns also were found in Palestine also belong the period before 3000 BC.

The built cisterns varied in shape, size and capacity. Some of them took a bell shaped with a narrow opening at the top and symmetrically widening below. Others were bottle or pear shaped. The mechanism was to collect the rainwater from the roof of the house and to keep it in these cisterns. This indicates that the cisterns were traditionally used for household and domestic uses, including the watering of the flocks but not for irrigation. This technique has proved its success long time ago as it was used in the 1970s and even before that in the Jordanian rural and Badia areas and some of them are still in use today. One informant stated that even today in Amman it is legally required to include a cistern in any new house, but that some people fill them with piped water instead of rainwater, (Wåhlen, 1997).

Another ancient technique as described previously is *Mahafir*, which have been used in the Jordanian Badia. Another system that also continues to exist in the Badia is the ancient ponds, which are located in the northwest area of the Badia programme at Deir Al-Kahf, Mathnat Rajil and many other villages as shown in Figure 8.11. Some of these sites have been visited in summer 1999, it was noted that some of these schemes have been restored and are still used today for watering the flocks of sheep.

In the second half of the twentieth century water harvesting has developed and become more recognised because of the water shortage problem in Jordan. Runoff farming is one of the ancient techniques that has been used before and people have started using it again in the highland area in Jordan since 1960s. The runoff farming system works on a basis of harvesting the water from the high slope areas, then distributing it for trees and crops irrigation. The harvested water is mainly used for irrigating fruit-bearing and olive trees

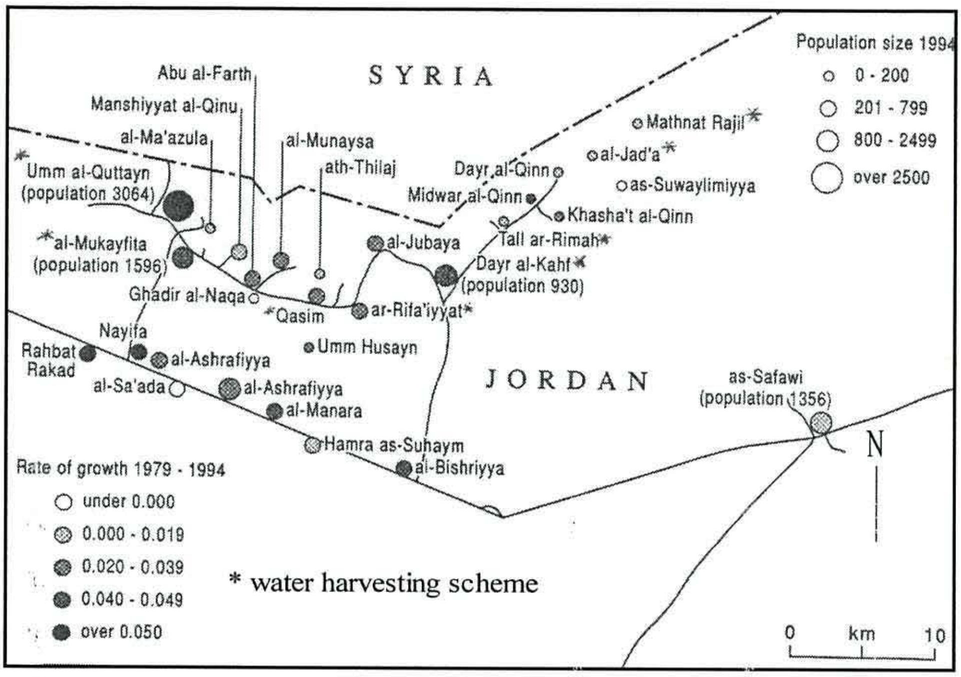


Figure 8.11: Water harvesting schemes in the NW part of the Badia area, (Source: Maani et. al., 1998).

Since early 1970s, other approaches have been introduced in the rural and Badia areas of Jordan, some of these techniques are ponds, cisterns, earth dams and micro catchments. The earth dams and micro catchments are used for agricultural purposes, while the ponds and cisterns are used for livestock watering, as shown in Figure 8.12. In the late 1980s the Zarqa basin development project started, which aimed to the optimum and best use of the land, according to its productivity. The project also developed land and water conservation methods. The earth dams and ponds techniques were also applied in the North-eastern Badia area in Al-Hammad basin development project. They are used for the sheep watering as this kind of schemes save the local people a lot of time and effort.

The micro-catchment system was constructed in Wadi Dhulail near Zarqa between 1985-1987, as part of a collaboration project between the Jordanian Ministry of Agriculture and the Arab Centre for Semi Arid Zones and Dry Lands (ACSAD). This technique is helpful as it keeps the trees soil moisture, controls the runoff movement and decreases soil erosion, (Jamous, 1992a). Micro-catchments are have also been installed at Jordan University research site at Al-Muwaqqer village, 50-km southeast of Amman.

Figure 8.12: Sheep watering using Deir Al-Kahf dam in NW part of the Badia.

In the early 1990s after the start of the Badia project, a proposal was made to focus on water harvesting in the Badia area. This is because of water harvesting is very important for the local nomadic *Bedouin* who need to travel hundreds of kilometres every few days to bring water for their livestock. Three ponds were dug at different sites within the Badia programme area and they seem to be successful. Another twelve have been proposed for other locations, which would raise the number to fifteen ponds. These ponds are mainly used for watering the livestock. These are in addition to the ponds that already exist at the northwestern part of the Badia programme area in Deir Al-Kahf, Mathnat Rajil, etc. A number of the ancient and new water harvesting schemes within the Badia programme area have been visited. It was noticed that most of the schemes were built in northwestern part of the programme area, this is because this zone is characterised by higher amounts of rainfall. The total number of schemes is twenty-three, most of them are cisterns in different shapes and capacities. The purpose of building them was for watering the sheep and goats.

Ancient schemes such as cisterns and dams built by the old nations were used for watering people and domestic uses until they had piped water supply, so the local people in Tall Rimah, and Deir Al-kahf villages said. Table 8.2 gives a brief description about the water harvesting schemes within the Badia programme area. It is necessary to investigate has it been wetter period in the last 10-20 years? Are the modern water harvesting approaches in the Badia, applicable to *Marabs* and their catchments?

Table: 8.2: A description of water harvesting schemes in Badia programme area, (Source: Al-Sallaq and Farah, 1993).

Location	No. of sch.	Type	Shape	Capacity (m^3)	O-N	Uses
Mathnat Rajil *	1	Cistern	square	6,600	N	Watering
Al-Jada'a	1	Cistern	circular	8,060	N	Watering
Dayr Al-Qinn	1	Cistern	rectangular	8,750	N	Watering
	1	Cistern	circular	2,500	N	Watering
Tyall Rimah *	1	Cistern	circular	7,200	N	Watering
	1	Cistern	rectangular		O	Watering
Dayr Al-kahf *	1	Cistern	rectangular	2,500	N	Watering
	1	Cistern	circular	3,500	O	Watering
	1	Dam		80,000	O	Watering
Jubaya	1	Cistern	hexagonal	1,500	O	Watering
Irnebat Al-Noimat	1	Cistern	square	2,600	N	Watering
Ar-rifayyat	1	Cistern	circular	5,000	N	Watering
	1	Cistern	circular	10,800	N	Watering
Qasim	1	Cistern	rectangular	1,500	N	Watering
At-Thulaj	1	Cistern	circular	1,800	N	Watering
Al-Munaysa	1	Cistern	rectangular	3,300	N	Watering
Manshyyat Al-Qinnu	1	Cistern	hexagonal	3,250	N	Watering
Abu Al-farath	1	Cistern	circular	12,000	N	Watering
Al-Mkayfita	1	Cistern	circular	14,000	N	Watering
Um Al-Qyttayn	1	Cistern	rectangular	23,000	O	Watering
	1	Cistern	square	7,500	N	Watering
Jawa*	1	Cistern			O	
	1	Dam			O	

* Means the scheme had been visited, (O is old, N is New)

8.10 Participatory Rural Appraisal

Participatory rural appraisal (PRA) refers to the involvement and the co-operation of the local people in a wide range of exercises leading to improvement in the understanding of existing conditions in rural communities. The technique involves creating knowledge and appreciation of the purpose of an intervention and enlisting the full participation of the people affected by the process. The approach was used in this study by conducting a number of semi-structured interviews with the local people who have been living in the catchment area, as well as *Marab* Hassan and other two *Marabs* in the Badia area. The following sections describe in detail how the interviews were conducted and what were the major findings.

8.10.1 The Catchment Area

There are a number of *Marabs* in the Badia area; some of them appear to be suitable for agriculture especially of the rain fed type. During a field survey in 2001 some interviews were carried out with the local people who have used and still cultivate some of the *Marabs* in the Badia. The questionnaire was completed by conducting interviews (both individual and group interviews) with the people who have been living in the catchment area, as well as those who are cultivating *Marab* Hassan and other two *Marabs* (Suawaied 30 km Northeast of Safawi and Al-BeQawyya that is 30 km southeast to Safawi).

One of the purposes of interviewing people who live in the villages of the catchment area was to develop a better understanding about the rainfall and flood events in the past ten to twenty years. The survey sample was the age groups of people above forty years old, as these age groups of people have been living in the area for quite a long time and they have "indigenous knowledge" about the weather systems and the floods in the area. All together twenty interviews carried out including the individual and group (four to five people) interviews. They were made in the northern part of the catchment at Deir Al-Kahf village and at the middle part near Al-Bishryya and Al-Hashmyya Al-Sharqya, as discussed in Section 3.5. Some of the villages that have been visited are shown in Figure 8.11. The interviews were arranged throughout the local councils, as a guide from each local council in the villages that have been visited helped to identify the people who could be interviewed.

The type of questions asked in the interviews with those who have been living in the catchment area for long time (more than 20 years), was mainly about the number of flood events, frequency, when the events have happened and the rainfall duration. An example of individual interviews is as shown in Table 8.3 below. The other nineteen interviews are listed in Appendix E. Table 8.4 summarises the questionnaire results.

Table 8.3: Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year, excluding 1998-2000.
What was the maximum depth?	Almost 1.5 m.
When did the major events happen?	1997/98, 2000/2001
Frequency of the floods?	2-3 times a year
After the flood happens how long does it take for the water level to reach zero?	24-36 hours.
Any ideas about the rainfall duration?	20-30 minutes either at night or during late afternoon. It is thunder type of rain

Table 8.4: Summary of the Participatory Rural Appraisal Questionnaire

Serial No.	No. of flood events	maximum flood depth (m)
1	almost annually, exclude 1998-2000	1.5
2	almost annually, exclude 1998-2000	> 2
3	annually except the last 3 years (1998-2000)	>1.5
4	every year apart from 1998-2000	>1
5*	before 1990s it was wetter, from 1990-95 it flooded annually, 1995-2000 it flooded 3 times	60-70 cm, in some places reached 1m
6	every year	1m, in some parts 50-60 cm
7	every year	>2.5
8	annually except the last 3 years	1-1.5
9	annually	1-2.5
10	almost annually, in the last 3 years it was dry	1.5-3
11	annually excluding 1998-2000	1-2 m
12*	before 10 years it used to flood annually, but lately it did not flow each year	1.5-2.5
13*	almost every year	1-2.5
14*	annually excluding 1998-2000	1-2 m
15	almost every year	>2
16	annually	1-2 m, in open parts 60-70 cm
17	annually apart from 1998-2000 when it did not	1-1.5
18	every year	2
19	almost every year	1.5-2.5
20*	annually excluding 1998-2000	1.5-2

Table 8.4 : Continued

dates of major events	frequency of floods	flood to reach zero (hr)	Rainfall duration (min)
1997/98, 2000/01	2-3 times	24-36	20-30 (thunder)
1993/94or 1994/95, 1996/97, 1997/98, 2000/01	2-3 times	24	10-15, max. 30 thunder
1994/95, 1996/97, 2000/01	before 1997 the no. was 2-3 times	24	10-15, max. 30 thunder
1986/87, 1991/92, 1994/95, 1996/97, 2000/01	2-3 times	24	15, but Max 30-45 thunder
1991/92, 1994/95, 1996/97, 1997/98, 2000/01	4-5 times	24	10-25, max. 30-45
1991/92, 1994/95, 1996/97, 1997/98, 2000/01	2-3 times	24	10-20, max. 30
1980/81, 1981/82, 1983/84, 1984/85, 1991/92, 1994/95, 1996/97, 1997/98, 2000/01	2-3 times	24	10-30 thunders in afternoon
1991/92, 1994/95, 1996/97, 1997/98, 2000/01	3-5 times	one day	20-50 (thunders in afternoon)
1944/45, 1948/49, 1968/69, 1983/84, 1991/92, 1994/95, 1996/97, 1997/98, 2000/01	2-3 times	one day	14-45 in afternoon and night
1991/92, 1994/95, 1996/97, 1997/98, 2000/01	2-3 times	24-36	30 thunder
1991/92, 1994/95, 1996/97, 1997/98, 2000/01	3-4 times	24	20-30, heavy thunder in afternoon
1991/92, 1993/94, 1996/97, 1997/98, 2000/01	3-4 times	24	30-45 thunders in afternoon or night
1981/82, 1983/84, 1991/92, 1994/95, 1996/97, 2000/01	3-4 times	24	20-40 in afternoon and at night
1981/82, 1983/84, 1984/85, 1991/92, 1994/95, 1996/97, 1997/98, 2000/01	3-4 times in wet years	24-36	15-30, thunders at night or afternoon
1981/82, 1984/85, 1991/92, 1994/95, 1996/97, 1997/98, 2000/01	2-3 times	24	20-30, occur as thunders at night or afternoon
1991/92, 1994/95, 1996/97, 1997/98, 2000/01	2-3 times	24	20-30, in afternoon or night
1986/87, 1991/92, 1994/95, 1996/97, 2000/01	3-4 times	24	20 and max. 30-45 at night
1993/94, 1996/97, 1997/98, 2000/01	2-3 times	24-36	10-15 and max. 30
1991/92, 1994/95, 1996/97, 1997/98, 2000/01	3-4 times	24	20-30 thunder in afternoon and night
1991/92, 1994/95, 1996/97, 1997/98, 2000/01	2-4 times	24	30-40, thunder

* Indicates a group interview

The major findings from these interviews are the following:

- Early rainfall at the beginning of the season (October and November) is locally known as "*Hareef*".
- Late rainfall at the end of the season (March, April and May) is known as "*KHareef*".
- Mid season rainfall is termed as "*Daim*" that occurs between December and February. "*Daim*" is particularly frontal type that affects the area for more than 3-4 days. While, if the front lasts for up to three days the rainfall is called "*Naou*"
- "*Hareef*" and "*KHareef*" both occur in a kind of thunderstorm type of rainfall that lasts for a short period of time, between 10 to 45 minutes. This type is the one responsible for floods in the wadis in the catchment area as elsewhere in the Badia.
- The wadis in the catchment area flow almost every year, but the thing that varies is the frequency of the floods. Most of the people recalled floods to occur twice or three times or sometimes four times in a wet year.

8.10.2 Marabs

Recently there have been some moves by individual(s) to establish arable farming on *Marabs*. This has potential economic benefits, however, the *Marabs* throughout the Badia need to be reviewed in terms of size, origin, soil type, soil depth, drainage, water availability, catchment size and accessibility. Three interviews were carried out with three *Marab* owners (or users). They are *Marab* Hassan and *Marab* Suwaeid that are owned by two different families (according to the concept of land tenure as mentioned in Section 2.3), as well as *Qa* Al-Beqawyya that is owned by a tribe, but one family is running the cultivation business.

8.10.2.1 Marab Hassan

The *Marab* is 3500 donums[2], but only 2000 donums are under cultivation. The eastern wadi (Wadi Hassan) feeds almost 1000 donum with water, and the other Wadi contributes to the other 1000. Before 1997 the main Wadi's flow was not used efficiently as it was just passing by the edge of the *Marab*, but after building of the

[2] 1 donum=1000 m^2 (0.001 km^2, 0.1 ha.)

earth diversion dam almost half of the flow was diverted into the *Marab*, (Shahbaz, 2000; Al-Ayyash, 2000).

The first interview was with *Marab* Hassan farmer who has been cultivating it since 1994. As shown in Table 8.5 below the *Marab* is mainly used for cereal cultivation (wheat and barley). Other crops, like lentils and chickpeas, were tried in the *Marab*, but the trials did not succeed as the type of soil is not suiTable and these kind of crop do not tolerate the dry conditions, (Al-Ryati, 2001). According to the interviews there are different scenarios for cultivation depending on the start of rainy season (i.e. early or late start) or the availability of the "local seeds".

Why is cultivation of *Marab* Hassan generally successful? How could it be made more successful? Physical improvements to the *Marab* to make the optimum use of the floodwater, by introducing water distribution system to the *Marab* that will help for spreading the water throughout the *Marab* properly to reach all parts. This would help to enhance the soil moisture and makes more water available to the crop most of the time. A better understanding of the winter rainfall is key to the potential exploitation of the *Marab's* potential for cultivation

The *Marab* floods three to four times in a wet year, when the flow takes a shape of sheet (overland flow) with a depth of 30-40 cm. This floodwater is important for cultivation as the *Marab* users use the "*Afeer*" type of cultivation, where they prepare the land by ploughing the soil and sowing the seeds between late August and late September, then they wait for the floodwater to arrive. Here the barley "local seeds" are used, as they are preferred for the animals compared with the imported seeds. Also the local seeds tolerate the drought, the seed size is bigger, and the rooting system is strong enough to reduce uprooting of the crop by flowing water. But the disadvantages of using them are that in the good water years the stems are flattened, (Al-Amri, 2001). If the water arrives in October or November this will be a good sign for a good crop yield, as in 1994/95, 1996/97 and 1997/98 rainy seasons. According to Al-Ryati (2001), it needs three days for the flow of the main Wadi that is coming from Syria to reach *Marab* Hassan, this kind of flow is locally known as "*Sail Darou*"(i.e. it is coming from a far distance), *Sail* is the Arabic word for flow. The productivity of barley (grain yield) in the Badia area is low (290 kg/ha, (Abu-Zanat, 2002), compared with elsewhere in Jordan. For example, in 1996/97 and 1997/98 in the transitional zone of Jordan (rainfall 250-300 mm/year) the productivity of barley (grain yield) was 2000 kg/ha., compared with wheat that had 700 and 1000 kg/ha. in 1996/97 and 1997/98 respectively, (Al-Amri et. al., 2001).

Table 8.5: *Marab* Hassan farmer interview results

For how long have you been cultivating the *Marab/Qa*?	I have been cultivating the *Marab* since 1994, before that it was not cultivated.
Normally how many flood events there are in the *Marab*, in both wet and dry years?	In good (wet years) there are 3-4 flood events, while in dry years there is almost no flood just a low flow that covers parts of the *Marab* only.
When was the major event(s)?	1994/95, 1996/97, 1997/98 & 2000/2001
What is the water depth in case of high and low flooding?	High flood: 5-10 cm at the *Marab* edges and 30-40 cm at the centre as a sheet flow. Low flood: 5-10 cm that covers the edges of the *Marab*, as most of the flow stays in the Wadis.
Could you describe the flow pattern in both high and low flood cases?	High flood: most of the *Marab* is covered with overland (sheet) flow. Low flood: well defined channels inside the *Marab*
What types of crops have you grown in the *Marab* area?	Wheat and Barley, but Barley most of the time.
What is the effect of flood on the crop yield?	The rain that falls directly on the crop is better than the flood as the flood causes erosion and damage of the crop sometimes.
In case of low flood seasons, do you have any other alternatives for irrigation? Or you just rely on rainfall (rain fed agriculture)?	Just rain fed agriculture.
Do you still cultivate the *Marab* if there is an indication that the year will be dry, or just keep the land bare?	Yes, as we use "*Afeer*" type, i.e. we sow the seeds, if it is a good year the crop will be harvested if not it will be left in place for grazing.
From dealing with the *Marab* for number of years, I think you now have a good experience, i.e. you know when it will be good season and when it will not, what is your comment on that?	If it rains as early as October, it is quite possible to have a good crop yield, but it is not guaranteed, as the crop needs the last rainfall in February, but if it does not occur it will affect the yield and the maturity of the crop.

Table 8.5: (Continued).

Were there any years when you had good crops grown at the beginning of the season, then the rain stopped and caused the death of the crop?	Yes there was but I cannot remember when that happened exactly.
What about water distribution through the *Marab*, how do you distribute it? Do you do anything about it or you just leave it flows naturally?	At the moment the water flows naturally without any distribution.

8.10.2.2 Marab Suwaeid

Marab Suwaeid is one of the largest *Marabs* in the Badia area, it is located almost 35 km to the Northeast of Safawi (32 17 N, 37 27 E). The *Marab* comprises of two parts, north and south of the main Amman-Baghdad highway. The northern part is 1,160 donum, with a catchment area of 25,600 donum, and the southern is 1,340 donum, with a catchment area of 20,000 donum. The Badia Programme dug a pond (locally known as Hafira), at the end of the *Marab* to store water and supply the local people who use or pass by the *Marab* with water for domestic and livestock uses.

During the field survey in January 2001, an interview was held with the *Marab* owner who has been farming there for more than forty years. The concept of "*Afeer*" cultivation is still valid in *Marab* Suwaeid as well, but it depends on the early flood. This means that if the "local seeds" are available, they sow them before the early rain, while if they are not available they wait till the *Marab* receives the first flood and afterwards they sow the seeds. Actually they cultivate every year, but the cultivated part is either 2/3 or 1/3 of the *Marab*. In some years they fallow the *Marab* and mostly this is in the dry years, especially when the *Marab* does not receive an early flood by October or November.

Marab Suwaeid Wadis drain a smaller area than *Marab* Hassan. This means that it does not receive that much flow from its tributaries, i.e. it does not receive "*Sail Darou*". This leads to conclude that the *Marab* does not flood unless it rains on the *Marab* or close by. The flow pattern in the *Marab* takes a form of channel flow at the *Marab* inlets and outlet, while inside the *Marab* it takes a sheet (overland) flow format. Table 8.6 summarises the interview results with *Marab* Suwaeid farmer.

Table 8.6: *Marab* Suwaeid Participatory Rural Appraisal results

For how long you have been cultivating the *Marab/Qa*?	I have been cultivating the *Marab* since 1960s.
Normally how many flood events there are in the *Marab*, in both wet and dry years?	In good (wet years) there are 1-4 flood events, while in dry years it does not flood. Even its tributaries are close to it, if it does not receive flow from them it will not flood, also if it does not rain in the *Marab* area it will not have flood.
When was the major event(s)?	1981/82, 1984/85, 1986/87, 1994/95
What is the water depth in case of high and low flooding?	High flood: 30-40 cm. Low flood: very few centimetres.
Could you describe the flow pattern in both high and low flood cases?	High flood: *Marab* inlets and outlet the flow takes a channel type, in the centre it is overland (sheet) flow. Low flood: channel flow of few centimetres depth.
What types of crops have you grown in the *Marab* area?	Wheat and Barley, but mainly Barley.
What is the effect of flood on the crop yield?	The rain that falls directly on the crop is better than the flood as the flood causes erosion.
In case of low flood seasons, do you have any other alternatives for irrigation? Or you just rely on rainfall (rain fed agriculture)?	Just rain fed agriculture.
Do you still cultivate the *Marab* if there is an indication that the year will be dry, or just keep the land bare?	Yes, as we use "*Afeer*" type, i.e. we planted the seeds, if it is a good year the crop will be harvested if not will be left in place for grazing.
From dealing with the *Marab* for number of years, I think you now have a good experience, i.e. you know when it will be good season and when it will not, what is your comment on that?	If it rains as early as October, it is quite possible to have a good crop yield, but if it rains late after November it is an indication for a bad season. For example, in 1987/88 when we cultivated the *Marab* late and the crop did not reach maturity because the seeds were sown late in December.
Were there any years when you had good crops at the beginning of the season, then the rain stopped and caused the death of the crop?	Yes in 1987/88, as we did not have rain in February, which caused the crop immaturity.
What about water distribution through the *Marab*, how do you distribute it? Do you do anything about it or you just leave it flows naturally?	There are stone terraces that have been built at the *Marab* inlet where the water enters the *Marab*. They have been built to retain water and keep it in the soil profile. But I believe they are not working properly as they are built at the entrance, which prevents water from reaching the other parts.

8.10.2.3 Qa Al-BeQawyya

Qa Al-BeQawyya is located 30 km south of Safawi (32 03 N, 37 08 E). The *Qa* is one of the biggest *Qas* in the Badia area as it has an area of 17.5 km^2 (17500 donum). The number of Wadis that contribute to the *Qa* flow is thirty-six, however in good years the *Qa* floods one to four times. As discussed before, the *Qa* receives the water, where it ponds and evaporates. Early season (*Hareef*) floodwater stays in the *Qa* for fifteen days, while the flood that occurs later in the season stays for a longer period that might stay for two months. This is because of that at the beginning of the season the soil moisture level is very low, which causes the infiltration of almost all the water quickly into the soil profile. Later in the rainy season the moisture level in the soil is enhanced, so that causes the water to stay for longer time in the *Qa*. Actually the water ponds mostly at the edges of the *Qa*, which makes this part not suiTable for agriculture because of the accumulation of salts. In the northern part of the *Qa* there is a pond "*Hafera*" used to store water for livestock use. Near the "*Hafera*" there is Pistachio atlantica tree that is believed to be there for hundreds of years, and it is has a holy value. The tree takes water from the *Hafera* through a canal that was dug to convey water from the *Hafera* to the tree.

The *Qa* is quite big, but not all the area is cultivated, only 1600 donums are used for barley cultivation and another 1200 (10% of the total area) planted with Olive tress. However, there are still other parts suitable for agriculture, but they are unused. This is due to financial reasons as the cultivation in the *Qas* and *Marabs* is more like a family business that is financially dependent on the families or individuals' capability. Moreover, there are 4000 donums that are considered unsuiTable for agriculture as water ponds there, which causes soil salinity problem.

Barley cultivation always takes place before the "*Hareef*" season. For example, in the rainy season 1999/2000 the people who cultivate the *Qa* have tried to sow the seeds before the *Hareef*, but it was not a successful trial that year, as the crop was grown up and was harvested in the next year in 2000/2001. The Olive trees use rain-fed and irrigated types of agriculture, the trees are only irrigated in summer months (once every twenty days using the "*Hafera*" water for irrigation), while in winter they rely on the rain and floodwater. The Participatory Rural Appraisal (PRA) results for *Qa* Al-BeQawyya are listed in Table 8.7 below.

Table 8.7:*Qa* Al-BeQawyya farmer questionnaire results

For how long you have been cultivating the *Marab*/*Qa*?	I have been cultivating the *Qa* since 1960s.
Normally how many flood events there are in the *Marab*, in both wet and dry years?	In good (wet years) there are 1-4 flood events, while in dry years it does not flood. Even its tributaries are close to it, if it does not receive flow from them it will not flood, also if it does not rain in the *Marab* area it will not have flood.
When was the major event(s)?	Between 1980-1995 they were mostly good years afterwards it became drier.
What is the water depth in case of high and low flooding?	High flood: 50-70cm. Low flood: 20-25 cm.
Could you describe the flow pattern in both high and low flood cases?	Overland (sheet) flow all the times.
What types of crops have you grown in the *Marab* area?	Wheat and Barley and part of the *Qa* are planted with Olive trees.
What is the effect of flood on the crop yield?	As the cultivation depends on the flood of the *Qa*, so if it does not flooded the crop will not be successful.
In case of low flood seasons, do you have any other alternatives for irrigation? Or you just rely on rainfall (rain fed agriculture)?	Rain fed agriculture for the cereals and irrigated for the Olive trees, using the water they buy especially in summer when the *Hafera* dries out of water.
Do you still cultivate the *Marab* if there is an indication that the year will be dry, or just keep the land bare?	No, because we wait till the early rain "*Hareef*", so if it rains and the *Qa* floods we do cultivate otherwise we leave it bare.
From dealing with the *Marab*/*Qa* for number of years, I think you now have a good experience, i.e. you know when it will be good season and when it will not, what is your comment on that?	If it rains as early as October, it is quite possible to have a good crop yield, also if the cultivation takes places after the "*Hareef*" the crop yield will be good.
Were there any years when you had good crops at the beginning of the season, then the rain stopped and caused the death of the crop?	As we wait till "*Hareef*" the *Qa* has to be flooded before we cultivate, so if does not flood no cultivation will take place. Even though the last rain is important for the crop maturity. It happened in some of the years when the crop did not reach maturity because of the lack of the last rain.

Table 8.7: (Continued).

What about water distribution through the *Marab*, how do you distribute it? Do you do anything about it or you just leave it flows naturally?	As the *Qa* is quite big (25 km^2) it needs time, money and effort to distribute the water properly. But at the western part of the *Qa* at *Marab* Ratha'an there is an earth dam was built which caused the retention of the flood water and preventing it from reaching the *Qa*. But in other parts the water flows naturally without any distribution techniques.

8.11 *MARAB* SELECTION CRITERIA

As discussed in the previous sections *Marab* Hassan has an area of 3.5 km^2, that is located 35-km Southwest of Safawi, and almost 10-km from Azraq. The *Marab* has a loamy soil texture that was found out after the soil texture analysis (discussed in Chapter Three), with a depth of 150 m (UNDP, 1994). Also soil moisture content vs. depth was developed as shown in Appendix A.

The second important factor to be considered is the available water capacity (AWC) of the soil; as for barley there should a certain amount of water hold in the soil to keep the crop alive. *Marab* Hassan AWC was measured using the moisture release characteristics curve and the bulk density. Both of them were measured as discussed before. The *Marab*'s soil AWC is 150mm/m.

The suitability of *Marabs* in the Badia area for agriculture is to be considered by checking different variables including;

- *Marab-Catchment characteristics*

- The soil profile
- The size of the *Marab*
- The drainage (catchment) area to the *Marab* area ratio
- The *Marab* location (i.e. how far south and east).

- *Climate characteristics*

- The average rainfall the area receives, as well as the rainfall intensity
- The length of the rainy season

The catchment area that feeds the *Marab* is 357 km^2, and the *Marab* is 3.5 km^2, so the ratio is 102:1. As will be seen later in the chapter, the rainfall is a very important factor that affects the design of any water harvesting scheme as well as any rain or flood fed agriculture that takes place in the *Marab*.

All the mentioned criteria for *Marab* selection allow for pre-screening to check the *Marabs* that do not qualify (i.e. those that are not suiTable for agriculture). Also, pre-screening allows identifying sites for inspection. Actually, there will be three criteria for phase review for *Marab* selection. The first criterion is pre-screening (or initial appraisal) using maps and desk study. This includes checking the *Marab*'s size and the size of the catchment area, also the amount of rainfall the *Marab* receives and the wet season median length, as well as the number of runoff events and the percentage of successful seasons. Moreover, the flow patterns across the *Marab* can be judged from maps and aerial photographs, as well as the geology and the remoteness of the *Marab* to towns or highways. The second phase of *Marab* selection is site inspection using soil types, evidence of ponding and evaporation and flow patterns from ground inspection. The third phase is to conduct geophysical and soil physical properties tests, as well as monitoring the flow the *Marab* receives. Establishing a generalised set of criteria would allow to quick screening of the *Marabs* and their classification as potentially suiTable, possibly suiTable and unsuiTable for development.

8.12 Crop Selection and Water Requirement

Barley cultivation on the *Marabs* is the main crop, but it seems that it is possible to optimise the use of floodwater to improve productivity. Improving the productivity of such areas is possible, if proper management plans are formulated. Moreover, as discussed earlier, the local people practice traditional farming. Thus, the challenge lies in the formulation of integrated packages that ensure sustainable farming systems, especially for such an area being allocated in the arid system where rainfall is erratic and unpredicTable.

The kind of crop to be grown in the *Marabs* depends on a number of major factors that all have to be considered. These factors are the length of the rainy season and the number and intensity of rainfall events that cause floods as well the amount of the floodwater that is available for crop use. This last factor is very significant for the crop, as it has to have a certain amount of water in the soil profile that is essential for it to reach maturity. Also it is important to have a good quality output, which is accepted in the market or even for animal use if the product is barley.

A further issue is cultivation demands, like the regulation of water supply (i.e. when and how much water needs to be given to the crop for its growth). Does the cultivation of certain crops require farmers to have specific skills, for example the knowledge of fertiliser and pesticide use. These factors need to be carefully thought out before selecting any kind of crop. Furthermore, there is need to account for possibility that some crop production may require machinery, (i.e. ploughing, seeding and harvesting).

The mentioned factors make barley the most popular crop to be cultivated in the *Marabs*. The optimum time to sow the barley seeds is in the last week of September to middle October. Rainfall has the highest contribution to grain yield during December and January, (Oosterom, 1993). Depending on variety and seasonal growing conditions, barley normally requires 90 to 120 days to reach maturity, however, local landraces in the Badia area would seem to require a longer period. Late seeding will increase the risk of lower yield. But, as mentioned before what controls the seeding time is the availability of the "local seeds" and/or the flood of the *Marab*. The most important factor that affects the barley is to have pre-sowing flood or irrigation water in case of irrigated type of cultivation, as soil needs adequate moisture content. Whatever amount of water the crop receives afterwards is not as essential as the pre-sowing amount. But, normally one or two floods later in the season around December and January are very helpful, especially for the grain yield. This requirement coincides with the traditional method of cultivation that is also called "*Afeer*", when people wait to sow the seeds after the *Marab* receives the floodwater.

The seasonal water requirement of the barley depends on variety, target yield and crop management. In Jordan, barley cultivation is very successful in the transition zone where rainfall is between 250 to 300 mm per year. In the Badia area where rainfall is variable from year to year, the productivity varies as well. But, even if it is not a good year, the barley is still usable as fodder; this is considered one of the major advantages of cultivating barley. Three outcomes are possible:

- A complete failure where there is no success at all.
- An immature crop that could be used as *in situ* fodder.
- A mature crop that gives grain and straw, which is used as well for feed.

In the Badia area barley's productivity is not that high, as the grain yield is 290 kg/ha. but the straw yield is 430 kg/ha, (Abu-Zanat, 2002). This indicates the importance of barley for fodder.

Barley needs a medium soil texture with medium clay content, so the water requirement is low to medium. The barley's tolerance to drought is medium to high, also its tolerance to salinity is high; these factors make it more favourable in arid environments. Barley needs a rooting depth of 100 to 150 cm, as it has a dense rooting system. The dense rooting system makes it more tolerant of drought.

Since barley is an early maturing crop with some drought tolerance, it has a relatively low water requirement. To achieve optimum yield, soil moisture levels should remain above 50 percent of available moisture in the active root zone from seeding to soft dough stage. With the rain-fed cultivation, the early October rain as well as the mid season rain between December and February are both essential to keep the moisture level in the optimum range. Rainfall that occurs in the end of season between March and May is quite important for the crop to reach maturity as long as it does not cause any damage to the ears. But most of the times the *Marabs* receive floods that cause harm to the crop, so water distribution systems that distribute the water evenly and effectively with minimising the effect of the damage level are very important. This aspect will be discussed in detail later in this chapter.

8.13 Indigenous Approaches in Barley Cultivation

As mentioned in the Participatory Rural Appraisal section, a survey about barley cultivation was done and results show that the cultivation has been practised there for quite a long time. This leads to the conclusion that people will not easily give up the barley cultivation, especially they mostly depend on as fodder for the livestock they have. However, new understanding of climate systems can help to improve the outcomes.

Different approaches of barley cultivation have to be tested against the available records. The procedure of testing them is discussed in details below.

- ***Rule of Thumb Approach***

It has been called "Rule of Thumb" as the farmers cultivate regardless how is the year going to be. In this approach, the *Marabs'* owners plant seeds every year, as they sow the seeds according to "*Afeer*" type with a rate of 80 kg/ha., (Abu-Zanat), without waiting for October rainfall. This approach involves risk in terms of cost and failure of the crop, as they will be planting (i.e. buying seeds, ploughing and sowing) without being sure that the amount of rainfall will be enough for the plant. As shown in Figure 8.13, most years (about 60%) have below average rainfall. Many of these will have so little rain; therefore partial or total failure of the crop will occur. This agrees with the probability density function for the dry years as shown in Figure 8.13. Probability density function is a curve that shows the probability of a random variable x, the probability of that x is less than y specific values a is the area under the curve up to the point y, (Montgomery and Runger, 1994). From the plot it is clearly seen that the Median (i.e. the middle or *((n+1)/2)*th observation if the n is odd, and halfway between the two middle observations if n is even) that is the dotted line in the Figure, is higher than the Mean which means that there is almost 60 percent chance to get below average rainfall (i.e. dry year). Figure 8.13 emphasises that this approach is not very successful. Based on the interview with the people, who cultivate *Marab* Hassan, the results were that four out of ten years were successful, i.e. most years were unsuccessful.

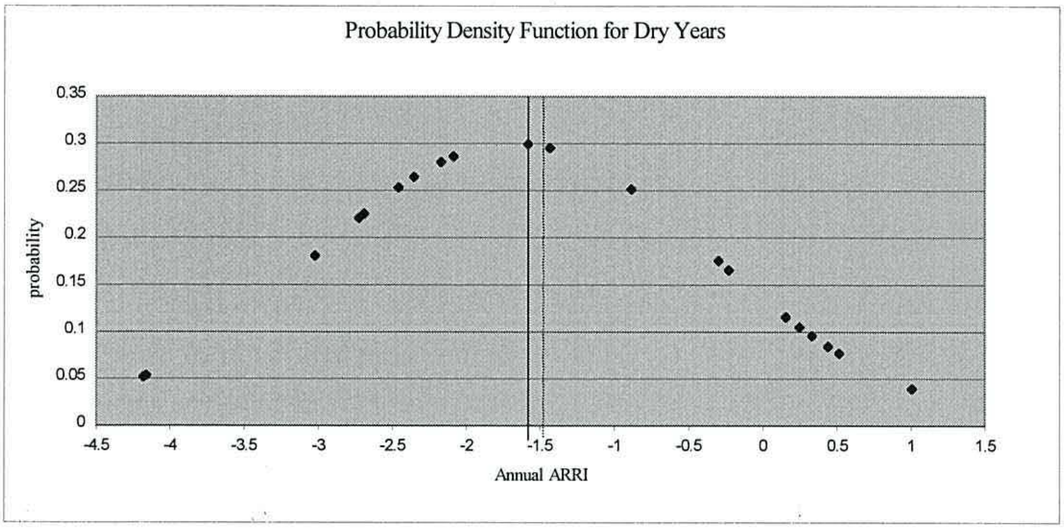


Figure 8.13: Probability density function for dry years.

- ***Traditional Approach***

This approach basically depends on the first significant rainfall in October or maximum by middle of November. This traditional approach depends on the availability of the local seeds, i.e. if the seeds are available they sow before October rainfall (using a rate of 110-120 kg/ha), otherwise they wait until the *Marab* floods, afterwards they sow the seeds. To evaluate this approach the onset and end of the rainy season have to be checked. Four stations were used to check this approach, Um Al-Quttein lies outside the catchment area to the Northwest. Two stations inside the catchment area, which are Deir Al-Kahf in the Northern part and Al-Aryyatein in the middle. Finally Azraq that is located 10 km outside the catchment to the South.

For the selected stations it was found that the total annual rainfall is related to the first significant rainfall (the rainfall that is greater than 5mm and occurs between beginning of October and middle of November). The 5-mm limit was defined according to the runoff plot experiments that have been established at different parts of the catchment area as discussed earlier. As shown in Figure 3.12 runoff started to generate with rainfall values of higher than 5-mm. The earlier the rain starts the wetter and the longer the season will be. After comparing the records with the interviews regarding the good and bad crop seasons, it was indicated that the good crop seasons are associated with the early start of the rainfall, in most cases not later than 20th of November. Figures 8.14 and 8.15 show the first and last significant rainfall vs. the total annual rainfall for Um Al-Quttein station. Figure 8.14 shows a gentle trend that indicates the later the first significant rainfall the less the annual rainfall. The longer the rainy season lasts the higher the annual total rainfall is expected to be, as shown in Figure 8.14 for Um Al-Quttein station. The Figure shows a well-defined trend of the annual total rainfall as a function of the end of the rainy season. Al-Aryyatein, Deir Al-Kahf and Azraq Figures are shown in Appendix G.

Taking the onset of the rainfall as the 10th of November as shown in the solid line in Figure 8.14, if rainfall starts before 10th of November virtually there is no chance of rainfall total to be below 100mm. If rainfall starts after the 10th of November there is a significant possibility of a very dry year. Eight out of twenty-six years have total rainfall less than or equal 100mm, where two of them have total rainfall of about 50mm.

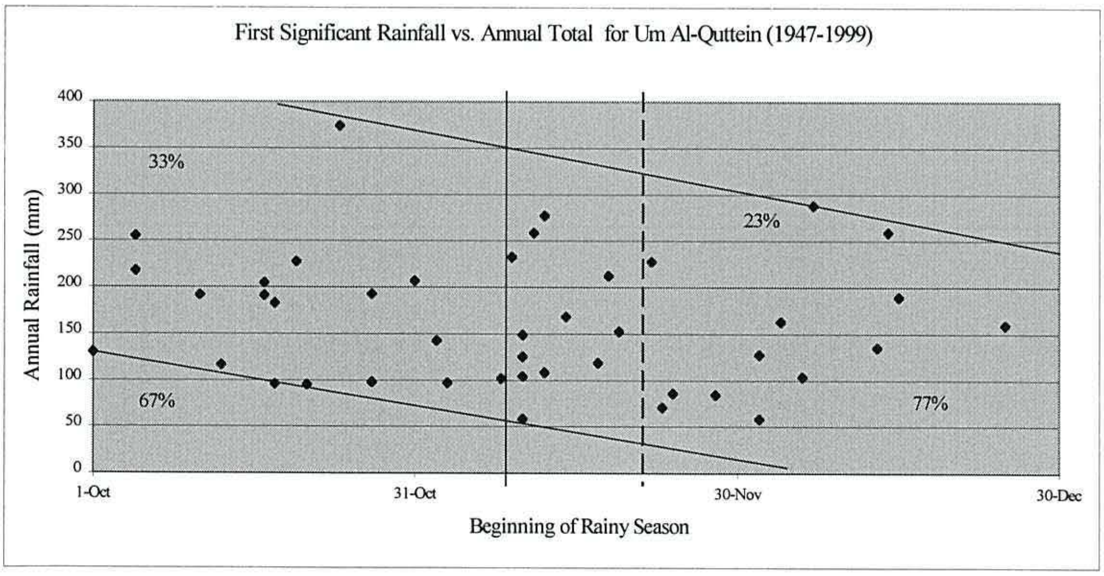


Figure 8.14: First significant rainfall for Um Al-Quttein station

If the onset of the rainy season is taken as 20th of November, (the dashed line in Figure 8.14), and taking the rainfall limit of 200mm. If the rainfall starts before the 20th of November there is 33% chance of having total rainfall over 200mm and 67% chance for the rainfall to be less than 200mm. But, if the rainfall starts after 20th of November, the possibility for the rainfall to be above 200mm is 23% compared with 67% chance of having rainfall less than 200mm.

Another test that has been carried out was to check the effect of the number of the rainy days, the number of the rainy days of rainfall higher than 5 mm and the length of the rainy season on the annual total rainfall for the same stations. The major finding was that the annual total rainfall is a function of the number of the rainy days as well as the number of the rainy days with rainfall > 5mm. The trend was very clear for all the stations, examples are shown in Figures 8.16 and 8.17 for Um Al-Quttein station. Obviously, the longer the rainy season the higher the annual total rainfall, as illustrated in Figure 8.18 for Um Al-Quttein station. Other stations' Figures are shown in Appendix G.

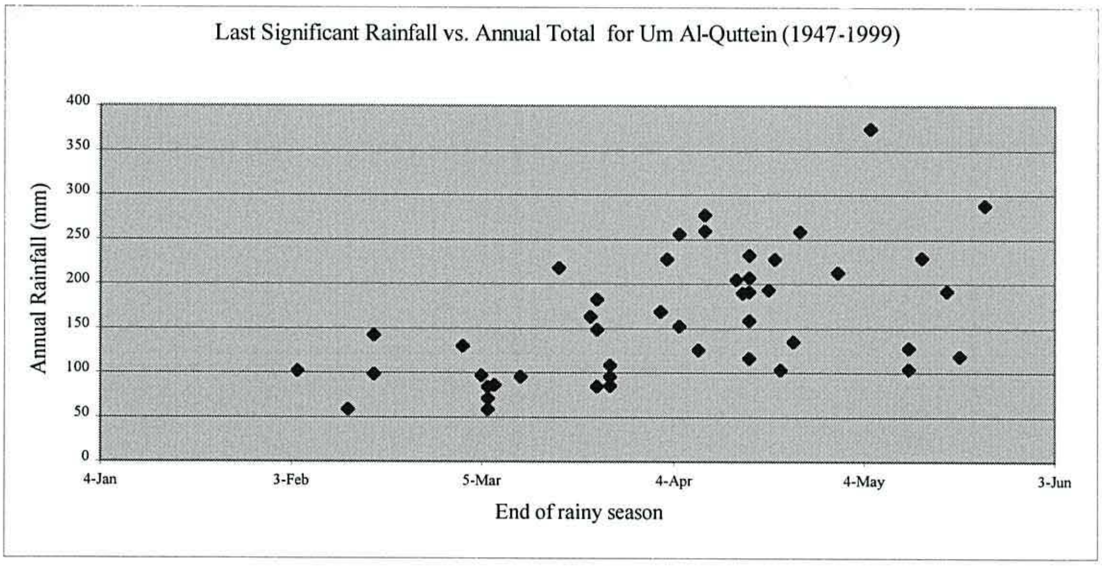


Figure 8.15: Last significant rainfall for Um Al-Quttein station between 1947-1999..

Due to limitations in data availability about the crop yield in *Marab* Hassan, as the current farmer has been cultivating it for almost ten years now, at the time the interview with him was done he indicated that since 1994 to 2000 they had three good and three bad years. The onset and end of season was checked for the mentioned years and the results shown in Table 8.8 below.

Table 8.8: Summary of Um Al-Quttein rainy seasons (1990-1999)

Year	Rain starts	rain ends	No. of rainy days	days>5mm	length of season (month)
1990	14-Nov	3-Apr	37	15	5
1991	10-Nov	13-May	25	11	6
1992	4-Dec	16-Apr	29	15	4
1993	12-Oct	5-Apr	34	10	6
1994	14-Nov	24-Apr	24	5	5
1995*	3-Nov	9-Apr	33	9	5
1996	23-Nov	9-Apr	15	5	4.5
1997*	8-Nov	23-May	23	6	6
1998*	17-Oct	5-May	29	10	7
1999	2-Jan	7-Feb	6	1	1

From the Table above it is clearly seen that for the good years (the ones with*) the rainfall has started early as the latest was 8th of November, and has ended late in April and May. The length of the rainy season in these years is between five to seven months which is quite good, also the number of rainy days in the season is considered high, from which almost 30 percent received rainfall more than 5 mm, that related in runoff. In these years the *Marab* has received floods and the crop yield was good compared with 1994, 1996 and 1999, according to the farmer. Actually, the records support what people have said, as with the barley the pre-sowing flood is essential, so for the *Marab* to receive flood within November is important to establish the soil moisture content that is very important for barley cultivation.

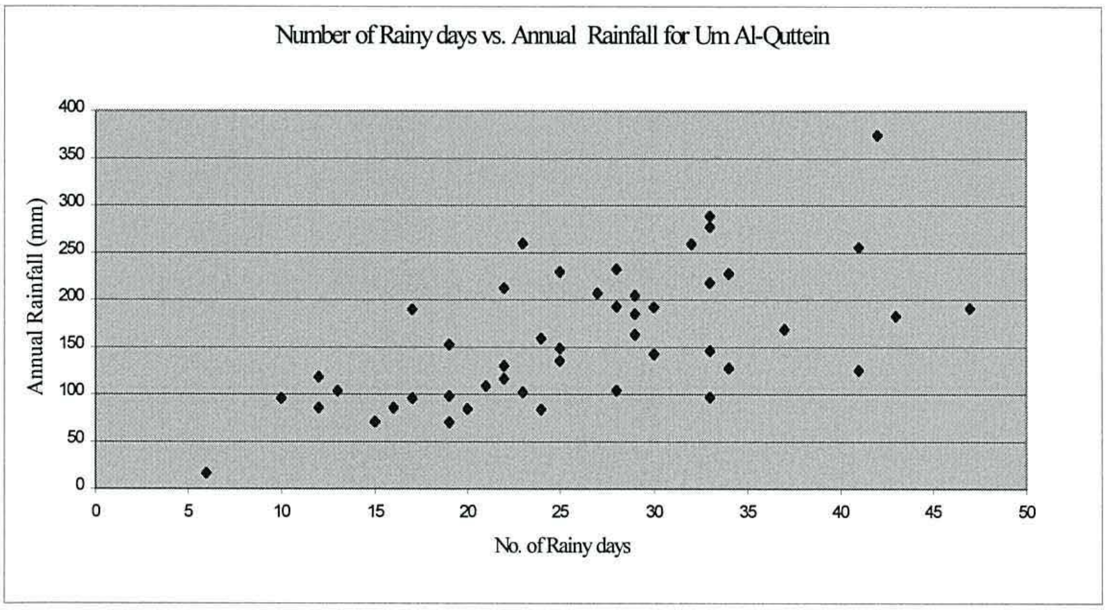


Figure 8.16: Number of rainy days vs. annual rainfall for Um Al-Quttein station

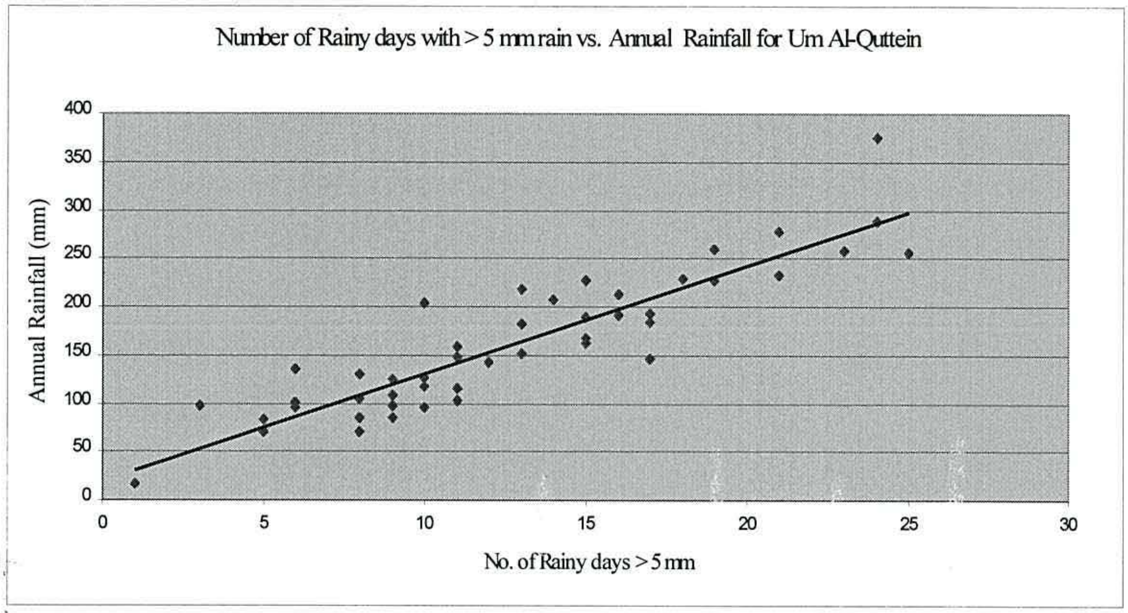


Figure 8.17: Number of rainy days of rainfall >5mm for Um Al-Quttein station.

Table 8.9 below gives a summary about Al-Aryyatein station. It can be clearly seen that for two out of three good years rainfall has started early somehow, as in 1995 and 1998 and it has lasted for a reasonably long season of four and six months respectively. In 1997 rainfall has started later in early December and lasted for four months, but at the same time the number of the rainy days during the season was the maximum (35 days), from which 22 days had 5mm or more of rainfall.

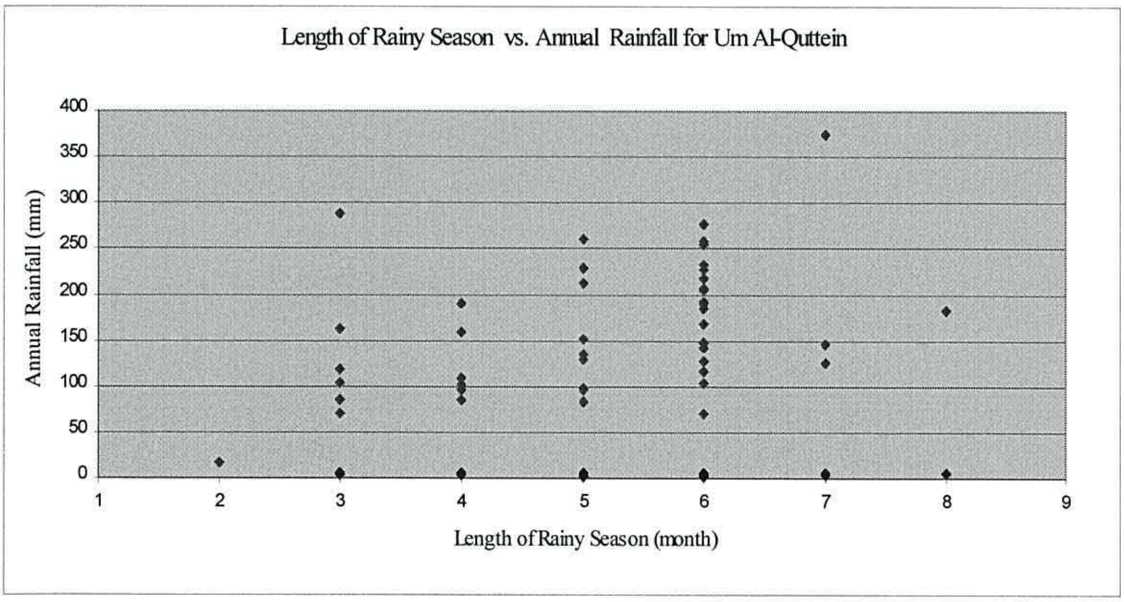


Figure 8.18: Length of rainy season for Um Al-Quttein station

Table 8.9: Summary of Al-Aryyatein rainy seasons (1990-1999)

Year	rain starts	rain ends	No. of rainy days	days>5mm	Length of season (month)
1990	14-Nov	1-Apr	17	8	4.5
1991	20-Oct	21-Mar	14	11	5
1992	17-Oct	1-Mar	11	6	3
1993	10-Nov	15-Mar	8	5	4.5
1994	4-Nov	8-Mar	15	7	4
1995*	14-Nov	3-Apr	8	3	4.5
1996*	2-Jan	27-Mar	18	6	2.5
1997	3-Dec	8-Mar	35	22	3
1998*	17-Oct	25-Apr	30	5	6
1999	25-Dec	7-Feb	3	2	1.5

8.14 FLOOD IRRIGATION REQUIREMENTS IN *MARAB* HASSAN

It is very crucial for the *Marab* to receive flow that gives surface inundation (excess rainfall), as this flood determines whether or not to proceed with the "Traditional Approach" of cultivation. Based on the onset of first significant rainfall (i.e. >5 mm) for some of the stations (Um Al-Quttein, Al-Aryyatein and Azraq), it is seen that flows occur at intervals throughout the growing season. Table 8.10 shows that in 1995 and 1997 the first significant rainfall has occurred in November, and for 1998 the first significant rainfall has started in October. In November 1995 four out of ten rainy days received rainfall higher than 5 mm (values in brackets), then rainfall occurred in December, February and March with almost two out of five rainy days receiving rainfall greater than 5mm. The 5mm concept as discussed in Chapter Three is based on the runoff plots, rainfall of this value or greater indicates surface flow initiation, thus there is a likelihood of having a flood in the *Marab*. For barley cultivation receiving a series of flows during the rainy season starting from October (pre-sowing) till April or May, when the crop reaches maturity, is very important. This means that the distribution, the timing and the number of the rainfall and flood events are more important for the crop yield than the amounts.

Table 8.10: Um Al-Quttein monthly rainy days (>5 mm) (1990-1999)

year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
1990	1 (0)	2 (2)	7 (2)	10 (4)	9 (4)	6 (2)	2 (1)	
1991		2 (1)	3 (1)	7 (4)	7 (3)	4 (2)	2 (0)	
1992	1 (0)		7 (5)	8 (6)	12 (3)	1 (1)		
1993	3 (1)		10 (0)	5 (3)	6 (0)	6 (2)		4 (2)
1994		2 (1)	2 (0)	9 (2)	4 (2)	7 (0)		

Table 8.10: (Continued)

1995	8 (0)	10 (4)	5 (1)		5 (2)	5 (2)	
1996		2 (1)	2 (0)	10 (4)	1 (0)		
1997	1 (0)	3 (1)	4 (2)	8 (0)	6 (3)		1 (0)
1998	4 (3)	4 (1)	5 (2)	10 (2)	3 (1)		3 (1)
1999				2 (1)	4 (0)		

October rains imply winter rain movement NW-SE is already established; therefore it is likelihood of wet winter. Tables 8.11 and 8.12 below also imply the fact that the earlier the rain starts the longer the season is likely to be. In relation to the monthly double mass curves for these two stations plus Um Al-Quttein, it can be concluded that the rainfall is more consistent during the winter months (December to February), and the localised effect is clearer in the beginning and the end of the rainy season.

Table 8.11: Al-Aryyatein monthly rainy days (>5 mm) (1990-1999)

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
1990		2 (1)	1 (0)	2 (2)	7 (3)	5 (2)	
1991	2 (2)			4 (4)	2 (1)	6 (4)	
1992	2 (1)		4 (3)	1 (0)	3 (2)	1 (0)	
1993		2 (1)	1 (1)	2 (1)	1 (1)	2 (1)	
1994	1 (0)	2 (1)	2 (1)	7 (4)	1 (0)	2 (1)	
1995		1 (1)	3 (0)		3 (2)		1 (0)
1996	2 (0)	1 (0)	3 (0)	8 (5)		4 (1)	
1997	4 (2)	1 (0)	2 (1)	11 (4)	13 (12)	4 (3)	
1998		4 (0)	5 (2)	10 (2)	3 (1)	5 (0)	3 (0)
1999		1 (1)		1 (0)	1 (1)		

Table 8.12: Azraq monthly rainy days (>5 mm) (1990-1999)

year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
1990		3 (1)	1 (0)	3 (1)	5 (2)	3 (2)	2 (1)	
1991	2 (1)		1 (0)	8 (3)	2 (0)	4 (1)		
1992	2 (1)	1 (0)	3 (1)	2 (1)	4 (1)	1 (0)		
1993		3 (0)		4 (0)	4 (2)			2 (0)
1994			2 (0)	4 (1)	1 (0)	2 (1)		
1995	1 (0)	6 (2)	4 (1)		5 (2)			1 (0)
1996		1 (0)	2 (0)	4 (0)	2 (0)	1 (0)		
1997		2 (1)	2 (1)	3 (1)	3 (1)	1 (0)		
1998		1 (1)	13 (3)	8 (0)	3 (0)	2 (1)	2 (0)	1 (0)
1999			1 (0)	6 (0)	1 (1)			

8.15 *Marab* Hassan Strategic Management and Decision Making in Barley Cultivation

8.15.1 MAM⁻ SOI – Annual ARI Correlation (Um Al-Quttein)

As described in Chapter Seven, the correlation between the El-Niño Southern Oscillation Index (SOI) and the annual rainfall for Um Al-Quttein, Al-Aryyatein and Deir Al-Kahf has been established. For each station the Average Rainfall Index (ARI) was calculated as in equation below, then the ARI values were linearly correlated with the seasonal SOI. Four seasons were chosen to develop the correlation; they are the previous autumn (SON^-), the previous winter (DJF^-), the previous spring (MAM^-) and the previous summer (JJA^-). Table 8.13 summarises the correlation results between the Average Rainfall Index for individual stations (ARI) and the SOI.

$$ARI = \frac{R - \bar{R}}{\sigma_R} \qquad [8.16.1]$$

ARI is the average rainfall index for individual stations

R is the annual rainfall of the station.

$\bar{R}$ is the average annual rainfall for the same station.

σ_R is the standard deviation of the annual rainfall values.

Table 8.13: Linear Correlation results between ARI and seasonal SOI

SOI	ARI Um Al-Quttein	Al-Aryyatein	Deir Al-Kahf
SON^-	-0.11	-0.06	0.12
DJF^-	0.03	-0.20	-0.03
MAM^-	0.21	0.01	0.13
JJA^-	0.27	0.29	-0.01

For Um Al-Quttein rainfall data is available between 1952 and 2000, the period between 1953 and 1989 was used to build the correlation (rainfall probability model) and the last 11 years (1990-2000) were used to verify it and check its efficiency. From Table 8.13 it is clearly seen that the maximum correlation is between the ARI and MAM^- and JJA^- SOI. The scatter diagram between annual ARI and MAM^- SOI for Um Al-Quttein is shown in Figure 8.19 below. The diagram is a result of plotting MAM^- SOI vs. annual ARI and then dividing the plot into windows according to the selected MAM⁻ SOI and ARI limits. The limits that have been used in this diagram are 0 for annual ARI, as for ARI> 0it is considered a wet phase while ARI< 0 is a dry phase. For MAM⁻ SOI three limits have been selected, they are cold phase for MAM⁻ SOI>0.8, warm phase for MAM⁻ SOI>-0.4 and normal phase for –0.4<MAM⁻ SOI<0.8.

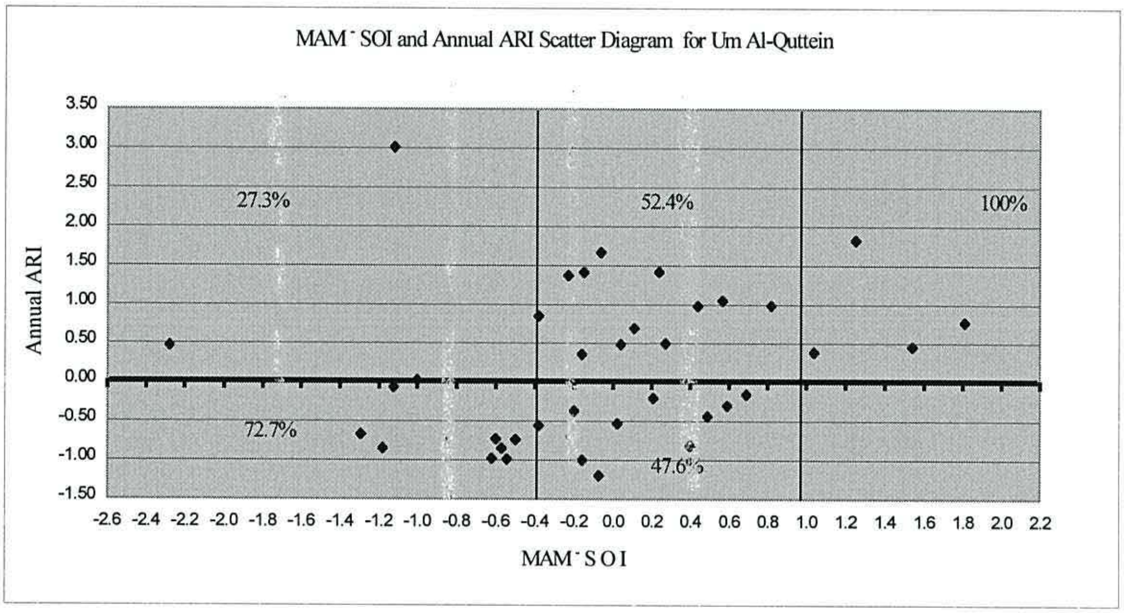


Figure 8.19: Scatter plot of the data showing the Um Al-Quttein Annual ARI and MAM⁻ SOI, for the years 1953-1989. The coefficient of correlation is 0.21

Table 8.14: Rainfall Probabilistic Model for Um Al-Quttein station using MAM⁻ SOI

MAM⁻ SOI category	Probability of Rainfall year Category	
	Dry	*Wet*
Cold	0.00	100
Normal	47.6	52.4
Warm	72.7	27.3

The rainfall probability model has been verified using the annual ARI data for Um Al-Quttein station between 1990 and 2000. It has given 82 percent efficiency, as the model has predicted eight years to be dry and three to be wet, while in reality the number of dry years is six and the wet years are five, Table 8.15 below explains more about the model verification.

Table 8.15: Verification of the Probabilistic Model using MAM⁻ SOI

Year	MAM⁻ SOI	Predicted ARRI	(Observed ARRI) class	Evaluation
1990	1.41	Wet	(0.85) Wet	T
1991	0.10	Wet	(1.09) Wet	T
1992	-1.55	Dry	(0.49) Wet	F
1993	-1.62	Dry	(-0.24) Dry	T
1994	-1.34	Dry	(-0.02) Dry	T
1995	-1.75	Dry	(-0.46) Dry	T
1996	-0.80	Dry	(0.07) Wet	F
1997	0.63	Wet	(1.80) Wet	T
1998	-1.68	Dry	(-1.38) Dry	T
1999	-1.98	Dry	(-0.96) Dry	T
2000	-1.11	Dry	(-1.24) Dry	T

8.15.2 JJA⁻ SOI – Annual ARI Correlation (Um Al-Quttein)

Table 8.13 above shows that the maximum linear correlation coefficient (C_c=0.27) for Um Al-Quttein station is found between the annual and the previous summer JJA⁻ SOI. This Cc is statistically significant as discussed before in Chapter Seven. The scatter diagram between the annual ARI and JJA⁻ SOI has been developed as shown in Figure 8.19. This diagram is based on choosing one limit for ARI that is 0. Positive ARI value indicates a wet year, while a negative value represents a dry year. JJA⁻ SOI limit is –0.2, with values > -0.2 indicates a cold phase and values < -0.2 point a warm phase. The rainfall probability model is summarised in Table 8.16.

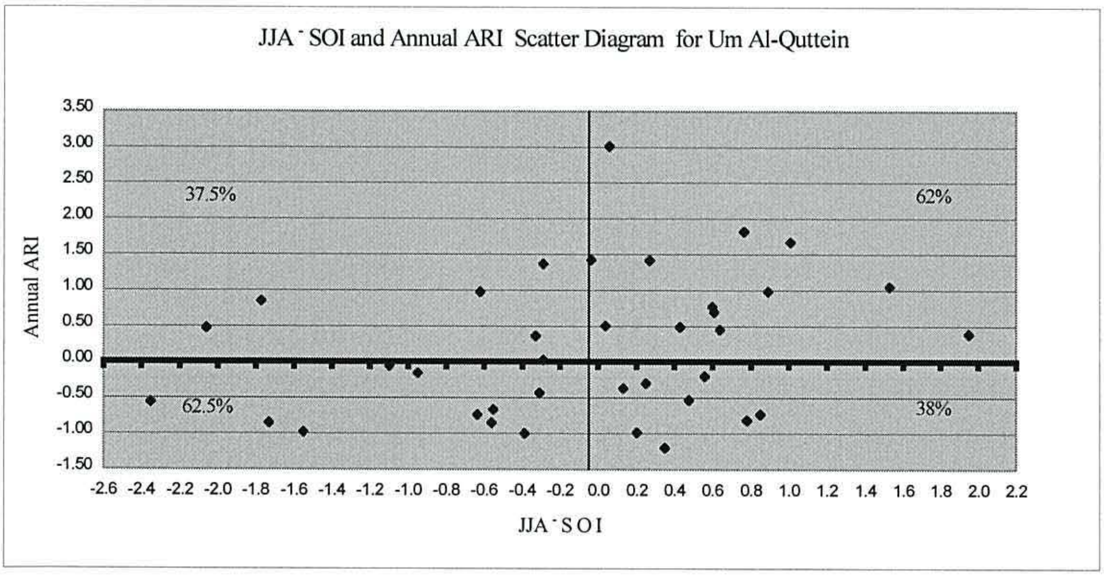


Figure 8.20: Scatter plot of the data showing the Um Al-Quttein Annual ARI and JJA⁻ SOI, for the years 1953-1989. The coefficient of correlation is 0.29

Table 8.16: Rainfall Probabilistic Model for Um Al-Quttein station using JJA^{-} SOI

MAM^{-} SOI category	**Probability of Rainfall year Category**	
	Dry	*Wet*
Cold	38.0	62.0
Warm	62.5	37.5

Table 8.16 is based on Figure 8.20, as each of them explains that the probability of having a wet or a dry year depends on the value of JJA^{-} SOI. The model is built using 1953 to 1989 data, and it is verified using the recent data from 1990 to 2000. The model has anticipated six wet and five dry years, but the actual Figures show that there is four wet and seven dry years, i.e. the model's efficiency is 73 percent. The detailed analysis of the model's efficiency is shown in Table 8.17.

Table 8.17: verification of the Probabilistic Model using JJA^{-} SOI

Year	**JJA^{-} SOI**	**Predicted ARRI**	**(Observed ARRI) class**	**Evaluation**
1990	0.31	Wet	(0.85) Wet	T
1991	-0.07	Wet	(1.09) Wet	T
1992	-0.64	Dry	(0.49) Wet	F
1993	-0.82	Dry	(-0.24) Dry	T
1994	-1.66	Dry	(-0.02) Dry	T
1995	-1.73	Dry	(-0.46) Dry	T
1996	0.01	Wet	(0.07) Wet	T
1997	0.88	Wet	(1.80) Wet	T
1998	-2.08	Dry	(-1.38) Dry	T
1999	1.12	Wet	(-0.96) Dry	F
2000	0.16	Wet	(-1.24) Dry	F

8.15.3 ARI- SOI Correlation vs. Traditional Approach

Using El-Niño Southern Oscillation Index (SOI) as a rainfall predictor is very good and reliable approach, especially in such a fragile and harsh environment as the Jordanian Badia. A combination of testing the "Traditional Approach" and the global phenomena will be very important for the strategic management aspect in the area. So in this section, the prediction of rainfall using SOI is to be tested against the onset of the rainy season. This will be done to enable the *Marabs*' farmer to build a decision tree in order to give them some kind of help to be able to act knowing in advance how the season is likely to be (i.e. to be pro-active). Table 8.18 shows the combination of using MAM^{-} SOI and JJA^{-} SOI with the onset of the rainy season (onset that has been used here is the first significant rainfall that is > 5mm).

Table 8.18: MAM^{-} and JJA^{-} rainfall predictors and onset of rainy season for Um Al-Quttein station (1990-2000).

Year	MAM^{-} SOI prediction	JJA^{-} SOI prediction	Onset of rainy season
1990	T	T	T (Nov)
1991	T	T	T (Nov)
1992	F	F	F (Dec)
1993	T	T	T (Oct)
1994	T	T	T (Nov)
1995	T	T	T (Nov)
1996	F	T	T (Nov)
1997	T	T	T (Nov)
1998	T	T	T (Oct)
1999	T	F	F (Jan)
2000	T	F	F (Dec)

The true results in the Table for MAM^{-} SOI and JJA^{-} SOI predictions mean that the predicted annual ARI matches with the actual Figures as shown before in Tables 8.15 and 8.17. Moreover, for the onset of the rainy season T stands for that if the season has started in October or by the end of November at the latest this is considered as a true (T) result, otherwise it is false (F).

Table 8.18 can be used in another way to develop a decision tree that gives the farmer who cultivates the *Marab* sometime in advance to take a decision either to sow the seeds or not. The decision tree for barley cultivation in *Marab* Hassan is shown in Figure 8.22. From the Figure it is clearly seen that the first step is to check the correlation between MAM^{-} SOI and annual ARI, then between JJA^{-} SOI and annual ARI. If both MAM^{-} SOI and JJA^{-} SOI give dry prediction then this is the end and the tree stops here (i.e. no action and fallow the land). But if both MAM^{-} SOI and JJA^{-} SOI give wet prediction, then an action of preparing the land for cultivation. If any of them gives a dry prediction and the other gives a wet prediction the next to be checked is the start (onset) of the first significant rainfall. If the rainfall is predicted to start early this means that farmers have to decide to prepare their land and to sow their seeds, as the prediction is having 73 percent probability to occur. But, if the rainfall is to start late then the decision is to fallow the land. If both MAM^{-} and JJA^{-} SOI predict a wet year then this means the early occurrence of significant rainfall and a 100% confidence of success, so the preparation for cultivation can be started. Figure 8.22 is a combination of two Figures, 8.21(a) and 8.21(b). The first Figure was developed based on the correlation results of the Southern Oscillation Index (SOI) and the annual rainfall. While, Figure 8.21(b) is a result of the traditional approaches of cultivation in the *Marab*

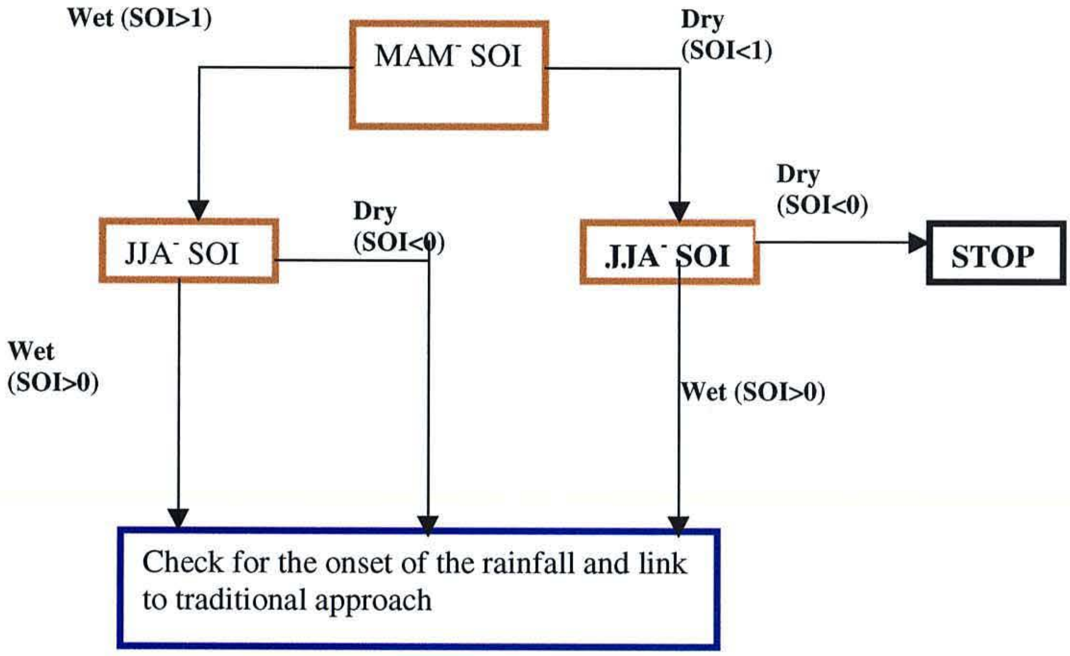


Figure 8.21(a): First part of decision tree of barley cultivation in *Marab* Hassan (based on correlation with SOI)

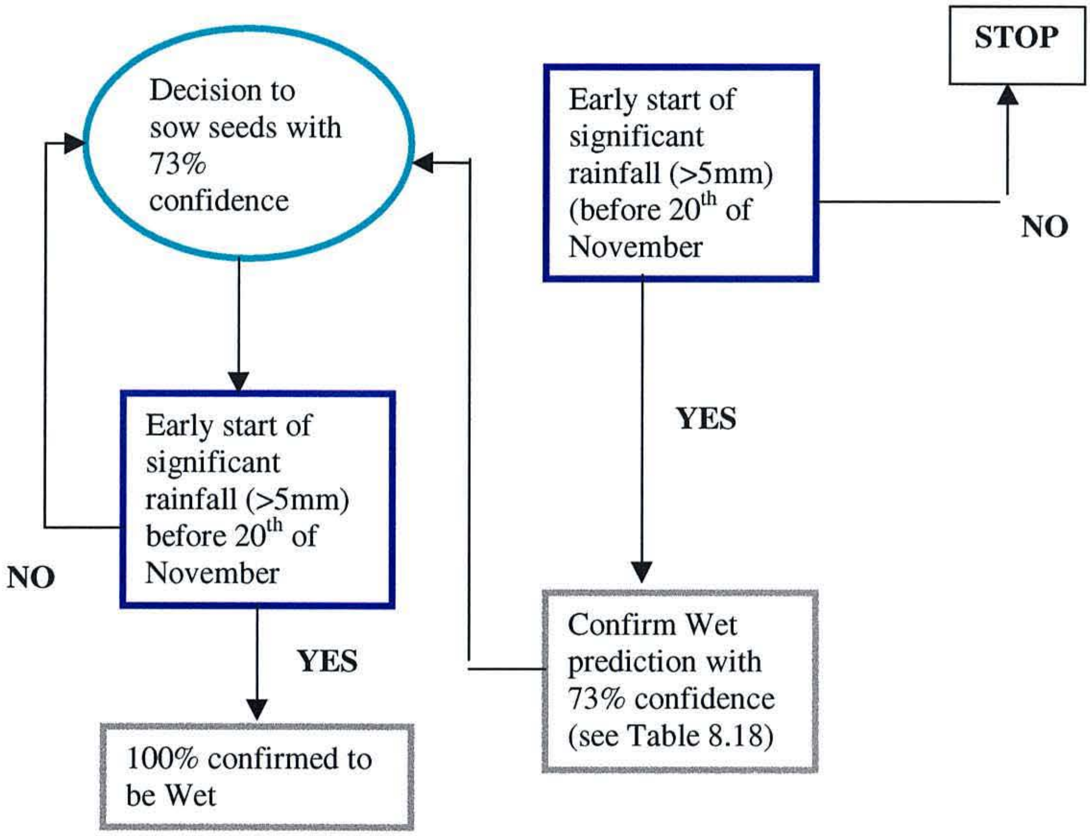


Figure 8.21 (b): Second part of decision tree of barley cultivation in *Marab* Hassan (based on the traditional approach)

Decision Tree for Barley Cultivation in *Marab* Hassan

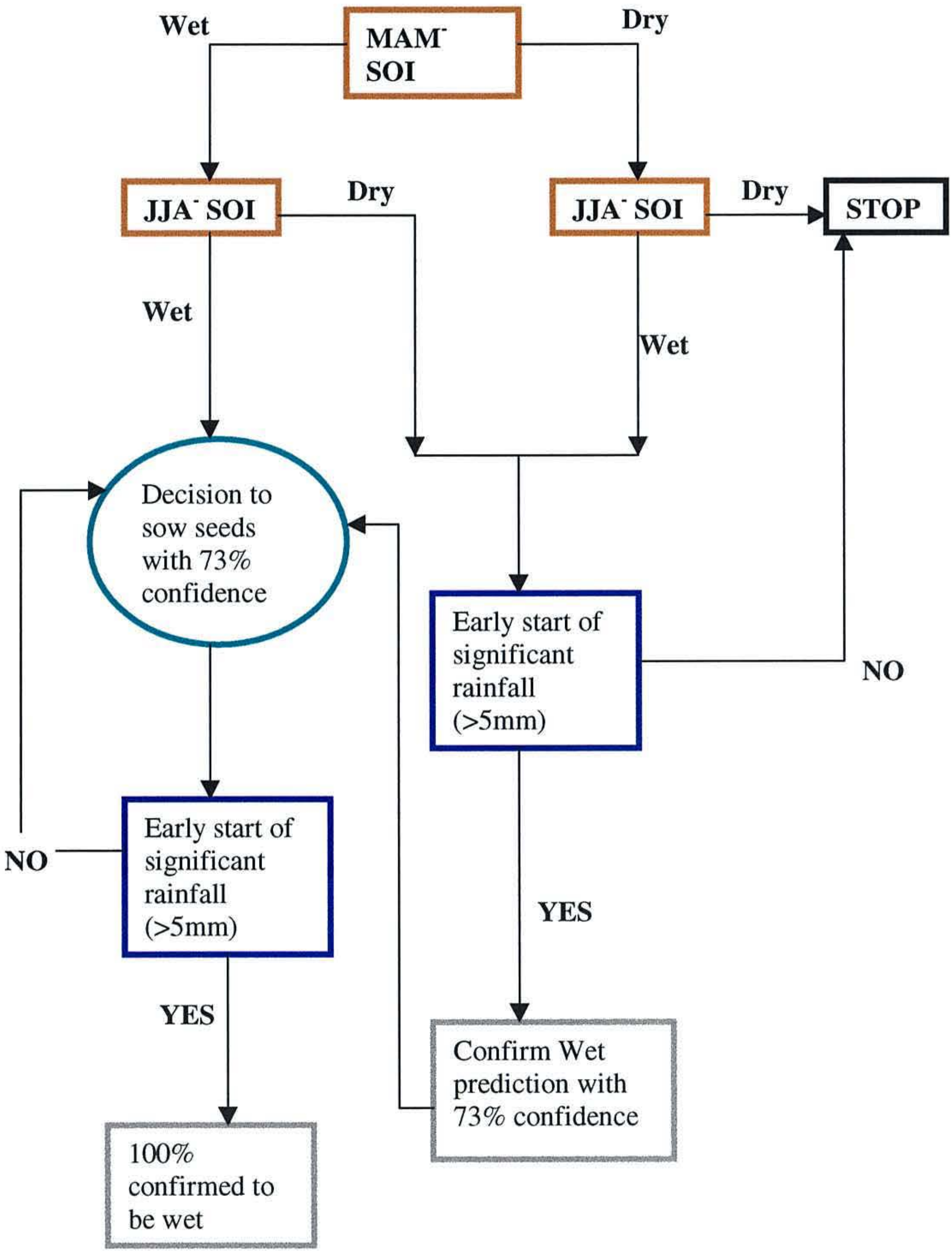


Figure 8.22: Decision tree for barley cultivation.

8.16 Potential for Improved Water Resources Management in the *Marab* Area

Marab Hassan receives water from the catchment that feeds to it. The amount of water received depends on the water years, i.e. wet, dry or average. A rainfall probability analysis was done for the wettest station in the Northwest (Um Al-Quttein), as for design purposes any structure will depend on the maximum rainfall that is received. Taking the annual rainfall for the mentioned station and calculating the probability of occurrence after ranking the data in a descending order did the probability analysis. Weibull's plotting position or the probability for each point has been used, which is ($P=m/n+1$), where m is the rank and n is the total number of data points. Figure 8.23 shows the rainfall probability distribution for Um Al-Quttein station that gives an idea about how much it is possible to have a certain value of rainfall, also it shows that the high rainfall values is less probable to occur. The probability of having above average rainfall (average is 158.8 mm) is just over 40%, while most of the occurrences are below average and have high probability to occur (i.e. just under 60% of the years have a below average total rainfall). The occurrences with high probability are more likely to reoccur after a short period of time, as the return period is the reverse of the probability ($T=1/P$). The return period diagram for Um Al-Quttein station is also shown in Figure (8.23).

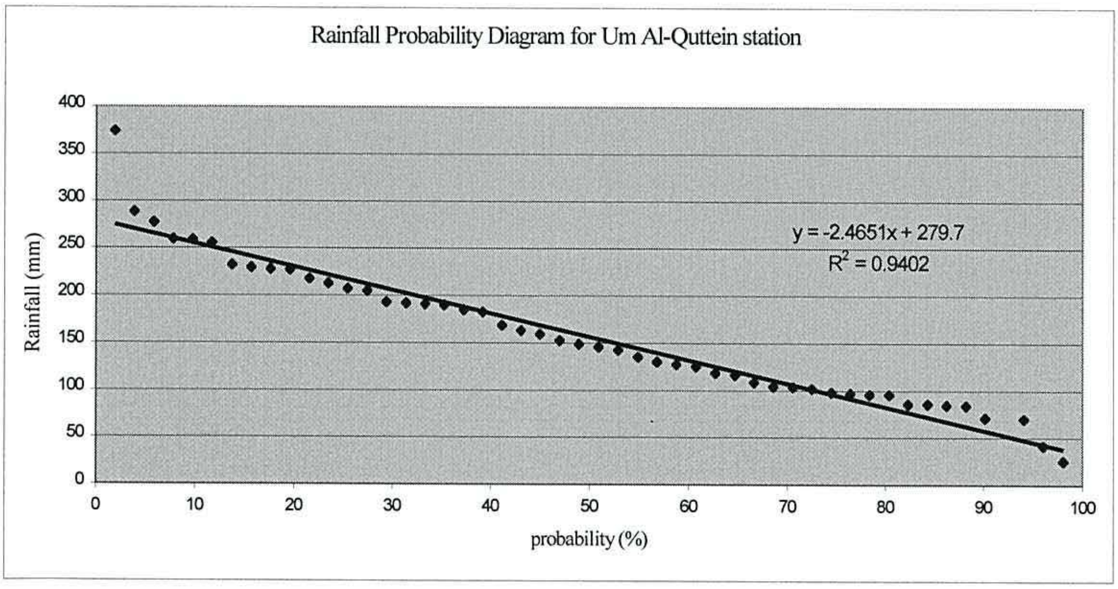


Figure 8.23: Rainfall probability diagram for Um Al-Quttein station

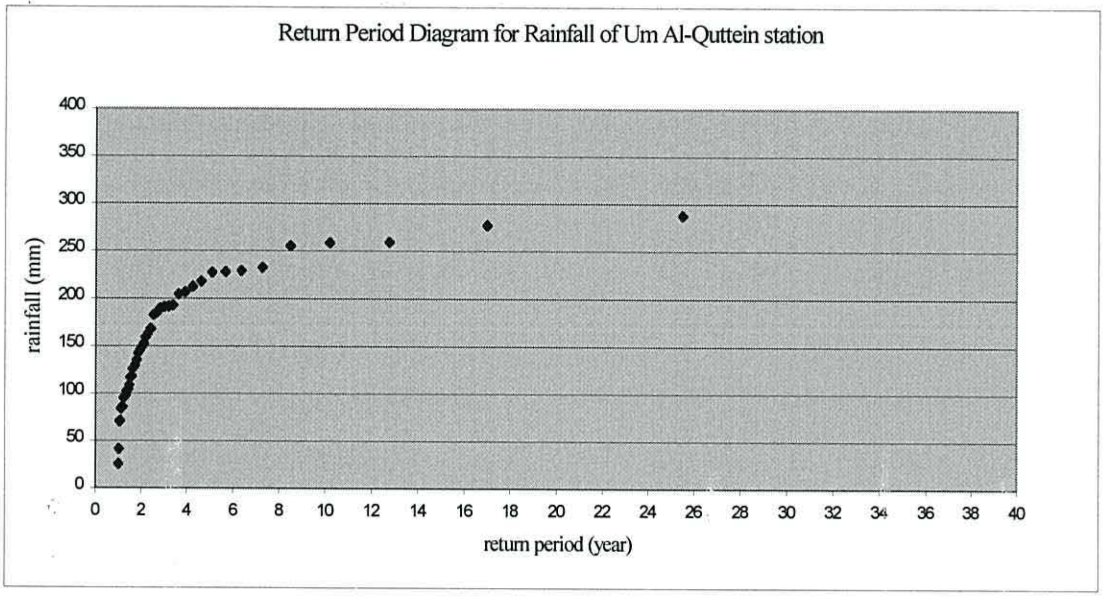


Figure 8.24: Return period diagram for Um Al-Quttein station

There are different possibilities of using the water once it reaches the *Marab*.

- *Ad-hoc Grazing*

This means to leave the land bare without cultivation and just to be used for animal grazing depending on the natural vegetation for grazing. It is good in a way it saves people's time, effort and money, as buying feed for their livestock does cost them a lot of money especially after the removal of the subsidies in 1996. Also, it is advantageous as it saves people's time and stops them from travelling every now and then looking for feed for their sheep and goats. The disadvantage of this way is that it leaves the land unused properly especially when it is a dry year, as the natural vegetation will not grow that much. Another disadvantage of this alternative is that it leads to land degradation because of the continuous use for grazing, as some vegetation species might not re-establish, so as a major consequence of overgrazing will be desertification. In a wet year the natural vegetation may not be adequate to allow additional grazing production.

- *Rain/Flood Fed Agriculture*

This alternative is basically to use the water that comes from the catchment area, once it reaches the *Marab,* it can be used for agriculture, i.e. rain or flood fed type of agriculture. This method is beneficial as it utilises the floodwater for agriculture especially in the *Marab* area, where it is mainly has been used for barley cultivation. Runoff (flood) fed agriculture seems to be effective as it directly stores available moisture in the root zone and most of the rainfall is used effectively for plant growth. The barley outcome could be in three shapes, a complete failure, immature crop where could be used for fodder (i.e. in situ grazing) or the crop might reach maturity. Once the crop reaches maturity this will give the maximum benefit as the straw will be used for fodder and the grains will be used as well. This technique has a fairly good economic outcome for the farmers, but on the long term it is not considered a good investment as using the cultivated barley for animal production is not that profitable. In other words the rate of conversion of barley to meat is low and takes long time. This is one of the disadvantages of using this approach, another one is that it causes land degradation of using the land every year, as the extensive cultivation threatens the biodiversity and the sustainability of the *Marabs*. Moreover, relying on rainwater for agriculture in this fragile, harsh environment does not look reliable enough as the risk of failure is always there.

- *Impoundment / Diversion of Water in the Marab*

Using such techniques for impounding water and then spreading it in a proper way ensures the soil saturation to get the maximum use of the water is essential for the rain or flood fed agriculture in the *Marabs* in the Badia area.

Permeable Rock Dams

There are benefits in starting to control and manage the wadi flow before it reaches the *Marab*, as the wadi flow has a quite high velocity and once it reaches the *Marab* it causes erosion and damage to the crops. So, to reduce this effect, one of the solutions is to build permeable rock dams in the wadi bed to reduce the flow velocity. The preamble rock dams are considered as a form of terraced wadis. The terraces are to be built at the *Marab* inlets (at Wadi Hassan and the main wadi).

A permeable rock dam is a long, low structure that is built a cross the wadi floor and built from loose material (normally gabion baskets), (Critchley and Siegert, 1991), as shown in Figure 8.25. Permeable rock dams can be used under the following conditions.

- Rainfall has to be between 200 and 700 mm per year.
- Soil is agricultural soil.
- Slope is best to be below 2 percent if the most effective water spreading is desired.
- Topography is recommended to be wide and shallow Wadi beds.

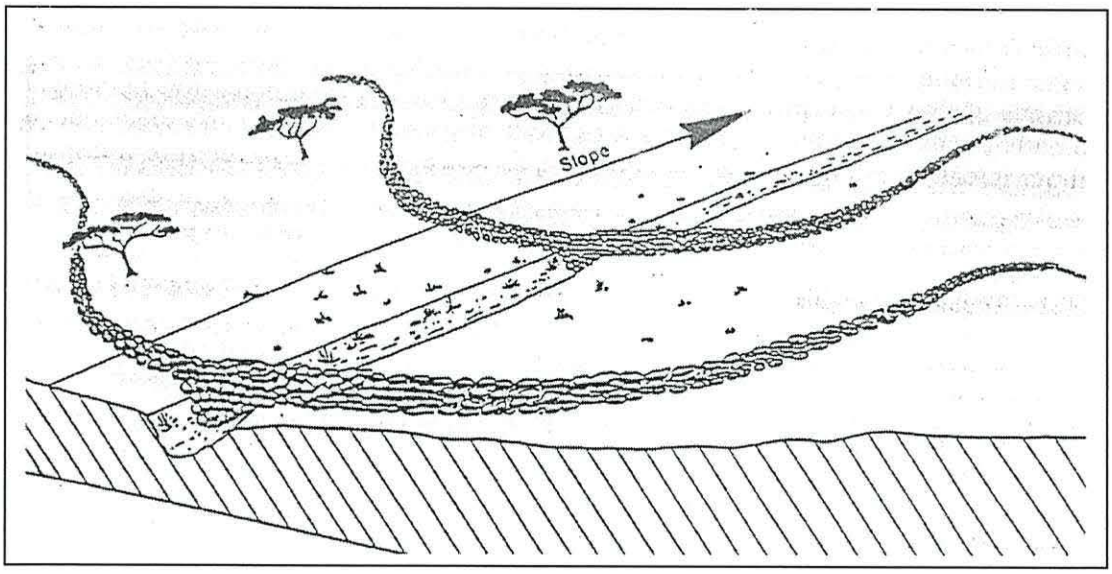


Figure 8.25: A permeable rock dam, source (Critchley and Siegert, 1991)

The integrated management plan after building the rock dams could be as follows:

1. In winter months (October to April) the rough part of the *Marab* that is mostly vulnerable to the floodwater is to be planted with forage shrubs to re-introduce them to the area and to increase the biodiversity in the *Marab*.
2. The flat part is to be cultivated with barley but making sure that the terraces evenly distribute water.

3. During summer (April to October) some kinds of summer crops can be grown in the area like grass, as it has been tested in similar areas with optimistic results of high productivity.

The proposed dams are to be built at the inlets of *Marab* Hassan (cross sections are shown in appendix C). Following is the design details of the dams.

1. Eastern inlet

- Cross-sectional area is 14.78 m^2.
- Depth is 1.40 m.
- Slope 0.0204 m/m.
- Velocity of the flow is 5m/s.
- Number of dams is 14.
- Building material is stone available locally.

2. Western inlet

- Cross-sectional area is 10.13 m^2.
- Depth is 1.3 m.
- Slope is 0.045 m/m.
- Velocity of the flow is 5m/s.
- Number of dams is 35.
- Building material is stone available locally.

The given design should not require any significant maintenance work. It will tolerate some overlapping in heavy floods. Nevertheless, there may be some stones washed off, which will require replacement. In general, no structure in any water harvesting system is entirely maintenance free, and all damage, even small should be repaired as soon as possible to prevent rapid deterioration.

By applying such a management plan different aims will be achieved at the same time. This means that the land will be used effectively almost all year through for different types of production, that are mainly for animal use (feed). In terms of the local economy, this helps the local people a lot as it saves them a lot of money for buying feed for their livestock. The estimated cost of building the dam is given in Section

8.17. However, the application of such a plan is subjective and controversial as the low water amounts and the infrequent flood events that the *Marab* receives may make it unreliable for commercial production. An alternative could be to keep the natural vegetation cover, though preserving it for organised grazing and introducing new productive plants and shrubs that can endure the Badia harsh meteorological and hydrological conditions.

There are socio-economic impacts of building such a structure, as the dams are characterised by needing large quantity of stones. This means that could bring the whole community together to help in doing the job, which leads to the co-operation of farmers with each other. However, outside help from governmental or non-governmental organisations is essential to facilitate the job and providing some basic necessities like transporting the stones.

Water Spreading Bunds

The second suggested management plan is water-spreading bunds, which are used to spread floodwater that has either been diverted from a watercourse or has naturally spilled onto the floodplain. The water spreading bunds intend to spread water rather than impounding it. They are made of earth and specially designed to slow the floodwater and spread it over the land to be cultivated, therefore it allows infiltration, which will enhance the soil moisture content across the *Marab*.

The water spreading bunds are designed according to certain criteria that have to be met, which are listed below.

- Rainfall has to be between 100 to 300 mm per year (i.e. arid to hyper arid areas).
- Soil like alluvial fans or floodplains with deep fertile profile is recommended.
- Slope of 1 percent or below is most suiTable for them.
- Even topography is required.
-

***Marab* Hassan criteria**

- Area is 350 ha.
- Cross-sectional area of one bund is 1.38 m^2.

- Length is 100m/bund.
- Number of bunds per ha. is 3.
- Total number of bunds across *Marab* Hassan is 1050.
- Annual rainfall in the catchment area is 100 to 300 mm.
- The *Marab*'s soil profile is quite deep (100-150 cm), with an even topography.
- Slope between 0.5 to1 percent

The design of the bunds depends on the slope, as for the areas with slope up to 0.5 percent straight bunds are used, while for slopes between 0.5 and 1 percent graded bunds are more appropriate. Graded bunds are bunds with constant cross section that are graded along the ground slope, each successive bund in the series downslope is graded from different end, (Critchley and Siegert, 1991). Figure 8.26 shows an example of flow diversion system with water spreading bunds.

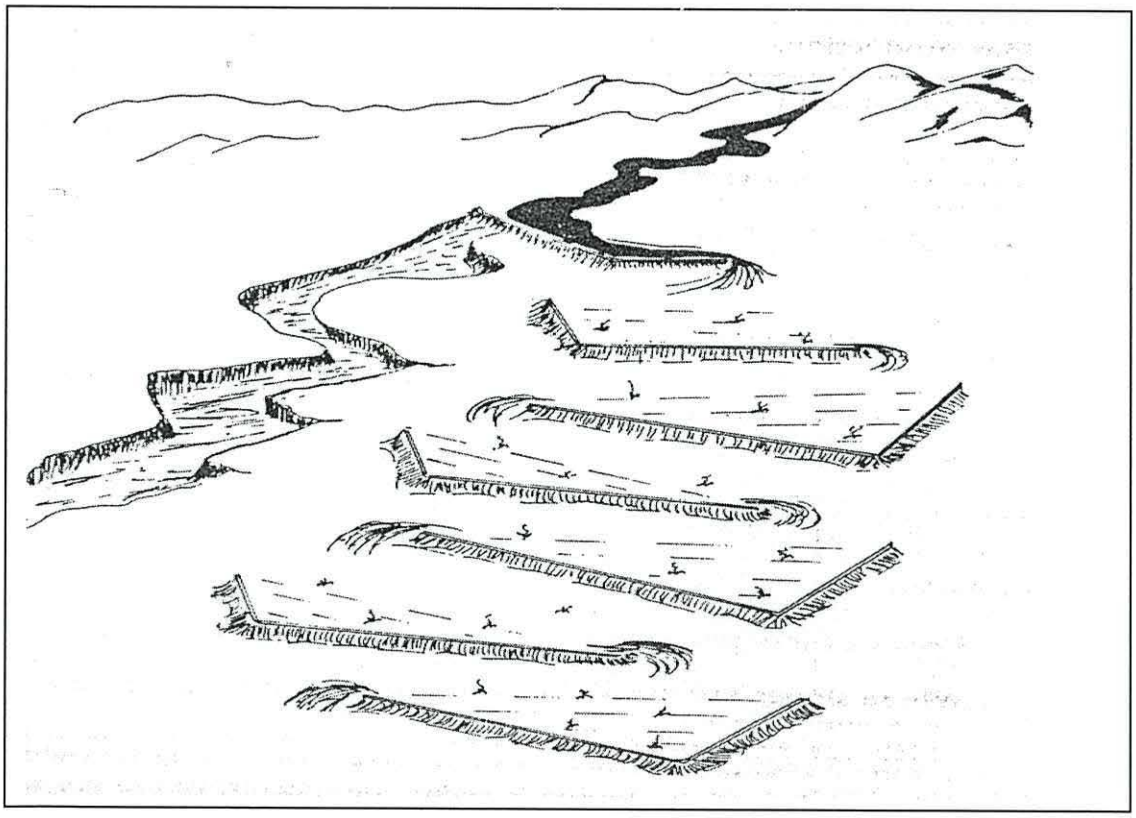


Figure 8.26: Graded water-spreading bunds for crop production, source (Critchley and Siegert, 1991)

Water spreading bunds are normally used for crops and particularly for cereals. One particular feature of this system when used in arid areas with erratic rainfall is that sowing of the crop should be undertaken in response to flooding. The direct contribution of the rainfall to the crop growth is very little. Seeds should be sown into residual moisture after a flood, which gives assurance of germination and early establishment. Further floods in the rainy season will bring the crop to maturity.

The implementation of water spreading bunds is relatively large exercise, which needs to be organised by special organisations that can be interested in offering help to the local community. Also, the government could subsidise the cost either totally or partially, as cost wise (as will be discussed later), these kinds of structures involve high construction cost.

- *No Action*

No action means to leave the water passing through the *Marab* leaving it freely till it reaches Azraq *Qa* (mud pan). Actually this alternative is presently occurring in the *Marab*. The major consequence of this is that the water has not been used efficiently for crop production, as some of it infiltrates into the soil profile and the majority leaves and disappears into the ground. In one way or the other this is good for ground water recharge, especially Azraq groundwater basin is one of the major basins in the country, as the aquifers in it supply the major three cities in the kingdom, which are the capital Amman, Irbid in the north and Mafraq 100 km northwest of Safawi. Therefore, building any sort of water conservation system on the up stream of Wadi Hassan before it reaches Azraq will help in groundwater recharge.

During the field survey that was carried out about the catchment and *Marab* areas in 2001, a number of farms (five of them) in Azraq area have been visited. The farms are all private ones that use the groundwater for irrigated agriculture, where the farms' owners grow different kinds of crops like olive trees, fruit trees, etc. these farms have affected the groundwater resources in the Azraq basin as the amounts of pumped water have increased due to the increase on water demand for irrigation. This is because of that the size of the irrigated area has expanded from 2500 donum (250 ha.) in the early 1970s to more than 30000 donum (3000 ha.) now, (Ganghar, 1996). Pesticides and

fertilisers are used in these farms that affect both the surface and groundwater resources in the area.
Also, this water can be used in salt production in the salt refineries that exist in the area, as Azraq is considered a main salt supply for the whole of Jordan. Actually, due to the depletion of the groundwater level because of the continuous pumping, the groundwater has been mobilised and salt started to accumulate in the *Qa* and most of it became salty. Overall the hydrological and ecological situations of the *Qa* area has been getting worse since early 1980s, because of social and economical growth of the area that has demanded a lot of facilities and services of which the use of water is considered as major need.

The decision of whether to leave the floodwater flowing freely until it reaches *Qa* Azraq or retain it at the *Marab*, seems to be quite a controversial decision and many issues need to be analysed before making the decision. Once the water reaches the *Qa* it accumulates and remains there until it evaporates, thus making no use of this water. But, if an integrated management plan is considered the outcome will be much better for the benefit of the people, or may be for industry or even tourism. The *Qa* area is well known as a natural reserve where different kind of migrating birds stop there on their way south during winter. Also, there are a number of palaces and castles in the area that attract tourists from different parts of the world, this means that they need to have restaurants, hotels, services… etc., which increase the demand of water supplies.

8.17 Estimation of the Cost of Barley Cultivation in *Marab* Hassan

Barley production cost

The estimation of the cost for the barley cultivation process, as well as the proposed water impounding/spreading structures in the *Marab* area is essential. According to Abu-Zanat, (2002) the outline cost of the barley cultivation in *Marab* Hassan (area is 350 ha.) is listed below.

- Sowing rate = 80kg/ha. (local variety).
- Cost of seeds = £110/ton-£120/ton (avg. £115/ton)= £9.2/ha.
- Cost of manual broadcasting = £1-2/sack (1 sack = 50 kg.), (use avgerage of £1.5/sack)= £2.4/ha.

- Cost of ploughing = £10/ha.
- Harvesting cost = £10/ha.
- There is no use of fertilisers.

The productivity rate of grain yield is 290kg/ha. and straw yield is 430 kg/ha. According to Al-Amri, (2001) the selling rate is £100/ton for grain and £7.5/43kg (£174/ton) for the straw.

Based on the above outline cost, the total cost of barley production in *Marab* Hassan is **£11,060** per year. The earning from selling the grain and straw is **£36,400** per year. The net revenue after deducting the cultivation cost is **£25,340** per year. Table 8.19 summarises the cost and befits of barley cultivation in *Marab* Hassn, providing that all the 350 ha. are used.

Table 8.19: Estimated cost and benefit of barley cultivation in *Marab* Hassan.

Total production cost (for 350 ha.)	£11,060
Earning from grain (101.5 ton/350 ha.)	£10,150
Earning from selling straw (150.5 ton/350 ha.)	£26,250
Total earning from grain and straw	£36,400
Net Revenue	£25,340

Construction cost of water harvesting schemes

The two water harvesting schemes have been proposed for *Marab* Hassan include permeable rock dams (PRD) and water spreading bunds (WSB). The capital cost of construction for the schemes has been estimated based on the design criteria that have been given in Section 8.16. Table 8.20 gives a summary of the estimated cost for hand built and mechanised construction, excluding the maintenance cost, as it was not possible to obtain information about the maintenance cost. This construction cost is capital cost that will be paid once when establishing the schemes. The building material is locally available, as it is stones for the permeable rock dams and earth for water spreading bunds. For the permeable rock dams £1000/dam was added to the sub-total to compensate for transporting the stones within the site.

The labour cost is £5/person/day, providing that for permeable dams the construction rate is 0.5 m^3/person/day. For water spreading bunds the rate is 1.5 m^3/person/day with the same cost of £5/person/day. The machinery (bulldozer) production cost is £2/m^3.

Table 8.20: Summary of construction cost of water harvesting schemes in *Marab* Hassan.

Manual construction cost of PRD (Eastern inlet)	£16,940
Manual construction cost of PRD (Western inlet)	£39,550
Total construction cost for both PRD(s)	£56,490
Manual construction cost of WSB	£483,000
Machinery (bulldozer) construction cost of WSB	£289,000
Total cost for manual construction (PRD and WSB)	£539,490
Total cost for machinery construction (PRD and WSB)	£345,490

Comparing the machinery construction cost of the water harvesting schemes in the *Marab* area (£345,490), which is almost 14 times the net revenue of the barley cultivation (£25,340). This indicates that the scheme will economically feasible after fourteen years of the construction. Therefore, on the individual level the farmer will be financially capable to pay for the construction cost, i.e. he has to have aid from either governmental or non-governmental organisations.

This issue has different perspectives. Firstly, the government may help in subsidising the cost totally or partially, as this kind of project aims to the sustainable development of the local people, which will not be achieved without governmental support. The second contribution from the government could be by giving the farmer interest free loan with flexibility to pay it back. This supports the idea of that the government aims to "welfare maximisation" and not making profit. This means helping in the sustainable development issue of the local communities rather than making profit

Another alternative is that the local community could help in the construction, which will reduce the labour cost. Also, this encourages the local communities to take a role in the development aspect, as they will be more involved in the whole issue. This increases their sense of awareness and could help in their better understanding of such schemes. This may help in facilitating their involvement in the safety issue of the gauges and other future activities, reducing interference and vandalism. Local councils could help in organising meetings and workshops for getting people together, they will also play a role in the development process, as they will be the link between the farmers, the local people and the government.

Finally, as the last option, water spreading bunds could be constructed for free, using the machinery (bulldozers) of the governmental authorities like ministries, armed forces or local council. This issue needs an agreement to be reached between the farmers and the authorities in charge.

8.18 CONCLUSIONS

To recommend optimum water resources development options in the *Marabs* throughout the Badia area, the *Marabs* themselves have to be screened against specific criteria. Specifically, size, drainage area: *Marab* area ratio, how far the *Marab* is south or east, how much water does it receive and how frequent through the growing season?

The current situation of most of the *Marabs* in the Badia area is quite similar, as they have been used for barley cultivation for a long time. This practice has to be thought about many times and from different perspectives. The main reason that keeps this practice going is the need of the barley for fodder, as most of the people in the Badia still keep livestock, which are an important symbol of their background and will not give up keeping them, but keeping the livestock does not seem a profiTable business on the long run.

Once *Marabs*, which have potential, have been identified, climate and PRA results form structural measures of screening of the *Marabs*. In order to achieve optimum development, some factors have to be evaluated like selecting appropriate water spreading techniques, as well as water storage and use efficiency if the water is to be stored. Then the hydrological characteristics of the *Marab* catchment area have to be studied carefully. Finally water-harvesting techniques for different purposes (agricultural or animal use) have to be introduced.

The traditional approaches for barley cultivation in the *Marabs* offer a very useful guidance, especially in an environment where lack of data is a serious problem. This shows that indigenous knowledge will always will be a good reference for arid zone management plans, as the most important factor is the people's interest and agreement. This is because of that the *Marabs* are based on the concept of land tenure where if some people have taken a piece of land and kept for a long time, then at the end of the day it is their land and no one could argue with them. So, asking them and discussing the management plans with them will save a lot of time and effort and will help them a lot.

Reviewing the *Marabs* in northeastern Badia of Jordan and, using *Marab* Hassan as a guide, seems appropriate to use the three-phase process. This process includes screening, inspection and testing, cost estimation (as described in Section 8.17) and finally monitoring and engineering work. This could lead to;

- The identification of other *Marabs* that are possible for development.
- The confirmation of suitability of these *Marabs* for development.
- The identification of counter indications (harmful flows).
- The planning of site-specific works to maximise the effective utilisation of the *Marab* and its presently transient water resources, as this is one of the main outcomes of the study.

Using the global climatic indices offers great potential in predicting the rainfall three or six months ahead, thus it gives a lead time for the farmers to prepare themselves, either to plant or not. If they are going to plant they will have sometime to prepare the land and the seeds and then to sow them. Also, having an idea in advance about the rainy season how it is going to be is very advantageous in terms of that it helps for the implementation of water harvesting techniques. These approaches will save farmers a lot of time, effort and money. As discussed earlier the barley cultivation and the construction of water harvesting schemes in the *Marab* area are costly, therefore, accurae cost benefit analysis needs to be conducted with each scheme.

Better understanding of the climate, together with statistically reliable forward predictions of the characteristics of the next rainy season offer real opportunities to improve the utilisation of water and land resources to achieve real economic benefits.

The use of ENSO and other measures allow a 20 to 30% improvement compared in anticipating wet winter season and with significant lead time, which allows ground preparation, seed sowing, etc. stronger economic and water management benefit of SOI type of correlations used as predictor.

Finally, the implementation of water harvesting schemes helps in getting the local communities together. With the aid of a third party (the extension unit in the Badia programme or the Ministry of Agriculture), the message about the importance of these schemes as well as the predictive approaches of rainfall could be conveyed to the local people. This third party will establish the link between the scientists and the farmers, by introducing both the predictive and traditional approaches in barley cultivation and the benefits of linking these approaches together. This could be done by organising meetings and workshops including the three stakeholders; the farmers, the scientists and the extension department personnel.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

The aims and general objectives of this study as outlined in section 1.5 of the introduction of this thesis were to evaluate the surface water resources of Marab Hassan catchment area in the northeast Badia of Jordan. The evaluation was carried out using different approaches.

9.1.1 Hydrograph Development

Developing a rainfall-runoff model for Marab Hassan catchment area was one of the major aims of this study. Unfortunately due to the lack of runoff records this aim was not analysed completely. Therefore, synthetic approaches of modelling the catchment runoff like Snyder, Soil Conservation Services (SCS) and Geomorphologic Instantaneous Unit Hydrograph (GIUH) were used.

The Geomorphologic Instantaneous Unit Hydrograph (GIUH) based on the use of Horton's laws was developed using the catchment characteristics (i.e. stream lengths, areas and stream orders). The developed GIUH for Marab Hassan catchment as discussed in Section 6.4 resembled the "standard arid zone hydrograph". This concludes that this approach was reliable to some extent as it considered all the streams compared with Snyder's and SCS that only had taken the main stream in the catchment. The GIUH has a good potential to estimate the design flood (the peak flow) for Marab Hassan that would be useful for any water resources management scheme to take place in the Marab.

Another synthetic approach that was used in this study was the Snyder synthetic unit hydrograph. From the shape and the characteristics of the developed hydrograph (i.e. peak flow Q_p, time to peak t_p and time base T) as was described in Section 5.11.1, it was concluded that this method is not applicable to Marab Hassan catchment area. This was because Snyder (1938) originally developed his method for the Appalachian highlands in the United States (a temperate climate), and hence the constant values he used were not applicable to Marab Hassan catchment area where the environment is different, and hence this caused the discrepancy in the results.

The third approach to develop the catchment's unit hydrograph was using the United States Soil Conservation Services (SCS) unit hydrograph method as described in Section 5.11.2. The hydrograph that was shown in section 5.11.2 was not the suggested shape of "the standard arid zone hydrograph". However as shown in Figure 6.13, SCS and Geomorphologic Instantaneous Unit Hydrographs are comparable.

From the three used approaches it can be concluded that Snyder approach would not be applicable to Jordan without calibration of the regional coefficients. The SCS and GIUH seemed to be more reliable than Snyder as they gave better hydrograph shape. However, the GIUH needed more data and time compared with the SCS, which involved less work and data.

9.1.2 Winter Rainfall Characteristics

As rainfall is the major source of runoff and due to its importance in the study area, a review of the rainfall records of the catchment area (both monthly and annually) was done. From the review it was concluded that the rainfall over the study area is variable both in space (spatially) and time (temporally). Rainfall decreases from the Northwest to the Southeast, also rainfall values differ from one season to another in the catchment area. According to the quantitative and qualitative (Participatory Rural Appraisal) analysis there were three types of the rainfall in the study area, as described in Chapter Four (Section 4.5).

The double mass curve technique was used as a quantitative measure to check the reliability of the rain gauges in the catchment area. It also indicated that the rainfall pattern for the Syrian stations is more consistent when compared with the Jordanian ones. Also the double mass curves enforced the fact of the decrease of the rainfall from northwest to noutheast, as the reliable wet season is shorter towards the Southeast with less annual total rainfall and fewer events of > 5mm rainfall.

9.1.3 Global Influences on Regional Rainfall

A new scope of analysis was introduced to the area by considering the effects of the global climate cycles (El-Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Indian Ocean Sea Surface Temperature). The correlation between the Annual Regional Rainfall Index (ARRI) and the seasonal climatic indices showed that there was a significant correlation, which could be used for developing the rainfall probability model for the region.

Different rainfall probability models were developed between the variable indices and ARRI. The most efficient model was the one that predicted the Jordanian rainfall by using MAM⁻ (the previous spring, i.e. March, April and May) SOI (Southern Oscillation Index) and MAM⁻ ENSO SST (El- Niño Southern Oscillation Sea Surface Temperature) (described in Chapter Seven) as rainfall predictors. Similar studies had been done in different parts of the world, one of which was the study by Osman et. al., (2001) about the Sudanese rainfall in the Savannah and Equatorial regions. Their major findings were that the rainfall in the Savannah region had the maximum correlation with MAM (the current spring) ENSO SST and the rainfall of the Equatorial region was mostly correlated with SON (the current autumn) ENSO SST. This concludes that the global climate cycles of ENSO have impacted different parts of the world (e.g. Africa, Australia, North and South America and Asia) as was reported in (Nezamosadat and Cordery, 2000; Nezamosadat, 1999; de Rojas, 2000; Wang and Eltahir, 1999), that means the effect of these cycles will always be there. Moreover, these cycles have to be considered in any issue related to water resources management and planning.

The other two indices that were studied North Atlantic Oscillation (NAO) and Indian Ocean Sea Surface Temperature (SST) did not show any significant correlation with the Jordanian rainfall. However, Turkish winter rainfall showed a high correlation with the North Atlantic Oscillation Sea Surface Temperature (NAO SST) index between 1930-1994 of r =-0.70 and exceeded 99.9 confidence interval. Another study was done by Saunders et al., (2000) which showed that the predicted (December, January and February) DJF rainfall in the United Kingdom in winter 2000/01 was 70% above the average due to the effect of NAO.

9.1.4 Forward Prediction

Once it was understood how the global systems influence the Jordanian climate this gave a better understanding of how these cycles work, and this led to a full image of long-term prediction of the Jordanian rainfall. The better understanding of the climate helped in giving a statistically reliable forward prediction of the character of the next rainy season, which offered useful opportunities to improve the utilisation of water and land resources sustainability for good economic return. Thus it could help in the decision-making aspect regarding the barley cultivation in Marab Hassan.

9.1.5 Other Marabs

Reviewing of other Marabs in the northeastern Badia of Jordan and using Marab Hassan as a guide was useful and lead to the identification of other Marabs that could be possible for development. It also gave an indication about the sustainability and the planning of water harvesting technique that could be used to maximise the effective utilisation of the Marab and its presently transient water resources.

9.2 Recommendations

DEM work anticipated runoff data being available, but that was not the case. Nevertheless, rainfall-runoff modelling with adequate data to calibrate the model will be essential in the future. Also more quantitative approaches are required for better water management.

Runoff plots were part of an "initial" attempt to supplement estimation of losses for rainfall-runoff modelling. However, limitations of time, equipment and logistic support, curtailed the number of runoff plot experiments. The data collected from the runoff plots are useful indices of loss rate, but need confirmation and calibration for the catchment scale to support reliable runoff and rainfall-runoff modelling.

Given the variability of rainfall in the area and the daily records available for stations, thirty years of rainfall data was not adequate for developing the rainfall probability model. Rainfall data that have been used in the analyses were a mixture of daily and monthly records; however, four new continuous rain gauges were installed in different parts of the catchment area in 2000/2001 rainy season. But, the rainfall records from these gauges are not enough to develop the hydrograph from the unit hydrograph, as the unit hydrograph itself is still susceptible.

The scarcity of runoff data means the sources of rainfall data have been invaluable The work that has been done is semi quantitative, from reports of the local people about the number of events per year in each wet and dry years, as well as the pattern of the inundation. Future work should include development of water balance, either seasonally or event basis. Work should also focus on determining the losses by implementing more runoff plot experiments to cover the whole scale of the catchment area. The use of floodwater for irrigation has to be emphasised by calculating the quantities of available water and how much of this amount the crop needs. Moreover, further research is needed to derive regional parameters for Snyder's approach.

The rainfall prediction model has been developed and verified using forty years of annual rainfall for some Jordanian stations (they were selected to represent the whole country). However, additional rainfall data from neighbouring countries like Syria in the north, Iraq in the east and Saudi Arabia in the south will be beneficial in terms of extending the prediction, as well as detecting if they have the same pattern and the same prediction ability.

NAOI and ARRI correlation was established using the NAOI pressure difference between Iceland and Lisbon, which did not give promising results. The correlation may be re-established between the annual ARRI and the Sea Surface Temperature

(NAOI SST). This attempt has already tested by Saunders et al., (2000) who predicted the DJF rainfall in the United Kingdom in winter 2000/01 would be 70% above the average when using the NAOI SST.

Seasonal ENSO and SOI indices were correlated with the annual rainfall for the Jordanian stations and the results were extremely promising. However, more work is needed, possibly by correlating the ENSO and SOI indices on a monthly basis with the annual rainfall; as one particular month may have more effect on the correlation rather than taking the average of three months together (seasonal). Also, more work on sunspot activity and its effect on the climatic indices needs to be taken into account. There seem reasons to expect some useful additional results.

Further work on establishing the correlation between ENSO SST or SOI and the annual ARRI by using the backward annual ENSO and SOI (i.e. by going back of the ENSO and SOI indices 7 years) is recommended to check if the correlation matches with the El-Niño cycle.

Most years have below average rainfall, and the rain only occurs during the wet season, therefore, it seems inappropriate to consider the use of perennial crops or trees due to their high water requirement, their high establishment cost, their low financial returns and their risk of failure. Water harvesting needs to be utilised for production that is short term, does not cost much money in terms of land preparation and buying the seeds and does not need much labour or machinery.

These considerations dictate that the crop should not be for fodder because livestock keeping is a long-term commitment. In addition quality sensitive crops (e.g. high quality vegetables to export where quality and timing are crucial) should not be considered.

Marab Hassan has potential for future agricultural development as the traditional approach of cultivation can be improved by the correlation with the climatic indices. However, extra work concerning the soil profile is needed. There is potential to introduce similar development to other *Marabs* in the Badia area. However, further investigations of the characteristics of each *Marab* are needed.

The role of the local people in such studies in very important, as they are the ones who will be affected by the positive and the negative impacts of the study. Thus, any future work should include more emphasis on the participation of the local communities in the development and planning aspects of the Marabs of the Badia area. Because these people have been involved in the cultivation process for many years, it is difficult to convince them to change their way of utilising the Marabs. Also the involvement of the local communities in the implementation of the water harvesting schemes like water spreading bunds and permeable rock dams, as well as the safety of the gauging sites should be considered. As the local people's role in protecting the gauges should be more addressed and they have to be more aware of that any study takes place in the Badia area is mainly for the development of the area and its inhabitants.

Future work is needed to establish the link between the traditional and the predictive approaches of barley cultivation. This can be achieved by seeking further guidance and advice about the implementation of these approaches in the field from the extension department at the Jordanian Ministry of Agriculture. This department could help in conveying the right message about these approaches to the local people, by organising workshops and meetings in different parts of the Badia area. Also, this department could play the role of the link between the scientists and the local people.

Detailed cost benefit analysis is recommended for further future work, as this type of analysis enables to predict the feasibility of the proposed management plans. Also, if possible to compare this study with other studies in the Badia area or even elsewhere in the Middle East, as at present I am not a ware of any study that tackles this issue in detail.

This study is a first study of its type carried out on this catchment area. In particular it was the first to deal with the correlation between the Jordanian rainfall and the global climatic indices. Inevitably it identifies the shortage and inadequacy of data, questioning the soil maps, topography, geology, etc., also focusing on development issues that are very important in a country like Jordan that suffers from severe water shortage.

Important approaches that offer significant improvement in the reliability of decision making for rain-fed wet season irrigation have already been developed in this study. There are reasons to expect that improved understanding of climatic processes and cycles, plus improved data collection (rainfall and runoff) in the Badia area, will contribute to offer new opportunities to improve the predictive capability of water availability forecasting allowing pro-active agricultural management with significantly improved economic returns.

This study may be applied not only on the national level of Jordan, but also on the international level of the neighbouring countries. In the southern part of Syria and the northwestern part of Saudi Arabia as both of them with the Jordanian Badia form one major basalt plateau, which is called "Harrat Ash- Sham Basalt plateau". This plateau has an area of 45,000 km^2 where 11,000 km^2 lies in the Jordanian northeast Badia and the rest in Syria and Saudi Arabia. This means that the characteristics of the three areas are the same and the implementation of the same agricultural procedures is feasible.

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APPENDIX A

MEASUREMENT OF SOIL MOISTURE CONTENT IN MARAB HASSAN CATCHMENT

Table A.1: Soil Samples from Marab Hassan taken on Mon. 14/12/1998

POINT	DEPTH (CM)	WT. OF CAN (GM)	WT. OF WET SOIL (GM)	WT. OF DRY SOIL +CAN (GM)	WT. OF DRY SOIL (GM)	WT. OF WET – DRY (GM)	S.M.C %
1	10.00	21.30	35.80	54.70	33.40	2.40	7.19
	20.00	21.50	27.30	47.40	25.90	1.40	5.41
	30.00	21.50	11.70	32.20	10.70	1.00	9.35
2	10.00	21.40	18.60	39.20	17.80	0.80	4.49
	20.00	21.60	16.10	36.70	15.10	1.00	6.62
3	10.00	21.10	23.00	43.50	22.40	0.60	2.68
	20.00	20.70	19.50	36.90	16.20	3.30	20.37
	30.00	21.80	19.20	36.00	14.20	5.00	35.21
	40.00	22.00	10.30	32.00	10.00	0.30	3.00
4	10.00	21.40	23.50	43.40	22.00	1.50	6.82
	20.00	22.50	15.90	36.90	14.40	1.50	10.42
	30.00	21.50	14.70	34.00	12.50	2.20	17.60
	40.00	21.00	11.00	30.20	9.20	1.80	19.82
5	10.00	20.30	30.60	49.40	29.10	1.50	5.15
	20.00	22.90	16.70	38.30	15.40	1.30	8.44
	30.00	20.00	17.10	35.60	15.60	1.50	9.62
	40.00	21.70	16.30	36.40	14.70	1.60	10.88
6	10.00	20.00	24.70	43.80	23.80	0.90	3.78
	20.00	23.10	14.10	36.40	13.30	0.80	6.02
	30.00	20.70	18.40	37.90	17.20	1.20	6.98
	45.00	21.00	14.50	34.50	13.50	1.00	7.41
7	10.00	19.10	29.40	47.10	28.00	1.40	5.00
	20.00	19.30	21.00	38.90	19.60	1.40	7.14
	30.00	20.50	20.00	38.80	18.30	1.70	9.29
	40.00	21.70	11.80	32.30	10.60	1.20	11.32
8	10.00	21.40	22.30	42.60	21.20	1.10	5.19
	20.00	20.90	15.50	35.60	14.70	0.80	5.44
	30.00	21.10	15.20	35.70	14.60	0.60	4.11
	40.00	21.50	10.80	31.70	10.20	0.60	5.88
9	10.00	21.70	33.00	53.00	31.30	1.70	5.43
	20.00	21.60	12.70	33.90	12.30	0.40	3.25
	30.00	21.50	12.70	33.50	12.00	0.70	5.83
	40.00	21.60	19.40	38.80	17.20	2.20	12.79
10	10.00	1.40	19.40	19.90	18.50	0.90	4.86
	20.00	1.40	12.70	13.40	12.00	0.70	5.83
	30.00	1.40	12.20	12.90	11.50	0.70	6.09
	40.00	1.60	11.30	12.00	10.40	0.90	8.65
11	10.00	1.50	21.90	22.90	21.40	0.50	2.34
	20.00	1.30	11.80	12.70	11.40	0.40	3.51
	30.00	1.30	12.30	12.90	11.60	0.70	6.03
	40.00	1.40	10.20	10.30	8.90	1.30	14.61
12	10.00	1.20	28.00	28.80	27.60	0.40	1.45
	20.00	1.50	12.70	13.60	12.10	0.60	4.96
	30.00	1.40	12.70	13.20	11.80	0.90	7.63
	40.00	1.20	15.30	14.90	13.70	1.60	11.68

Figure A.1: Soil Moisture Content vs. Depth for Marab Hassan (NAT soil on 14/12/1998)

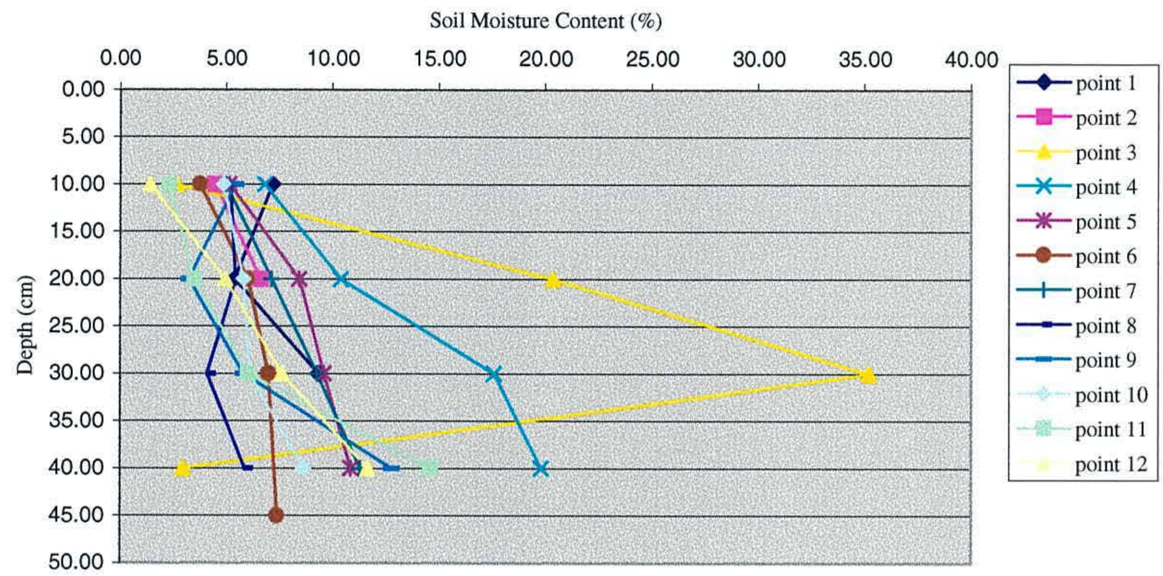
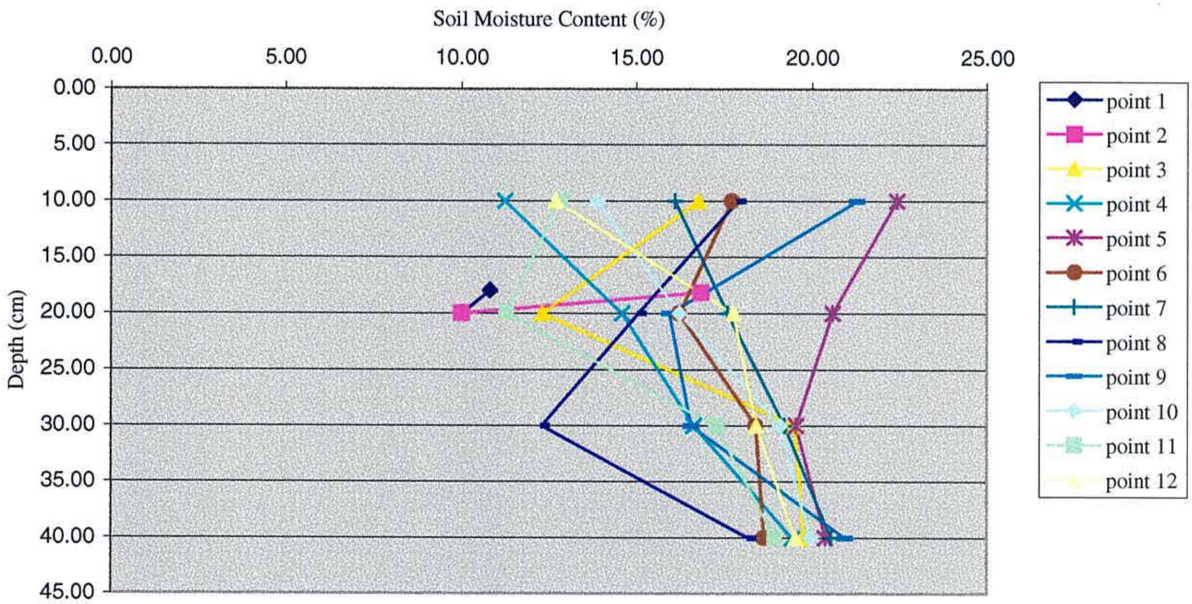


Table A.2: Soil Moisture Content analysis for soil samples taken from Marab Hassan on Sun. 21/2/1999

POINT	DEPTH (CM)	WT. OF CAN (GM)	WT. OF WET SOIL (GM)	WT. OF DRY SOIL+CAN (GM)	WT. OF DRY SOIL (GM)	WET-DRY WT. (GM)	S.M.C %
1	10.00	20.00	43.00	58.80	38.80	4.20	10.82
	20.00	22.10	46.70	61.70	39.60	7.10	17.93
2	10.00	21.40	48.60	63.00	41.60	7.00	16.83
	20.00	21.00	44.30	58.50	37.50	6.80	18.13
3	10.00	1.50	46.00	40.90	39.40	6.60	16.75
	20.00	1.30	45.60	41.90	40.60	5.00	12.32
	30.00	1.20	42.90	37.10	35.90	7.00	19.50
	40.00	1.10	40.60	35.00	33.90	6.70	19.76
4	10.00	21.40	43.50	60.50	39.10	4.40	11.25
	20.00	21.00	42.40	58.00	37.00	5.40	14.59
	30.00	21.70	47.00	62.00	40.30	6.70	16.63
	40.00	20.90	41.80	55.90	35.00	6.80	19.43
5	10.00	20.30	54.60	64.90	44.60	10.00	22.42
	20.00	22.90	58.60	71.50	48.60	10.00	20.58
	30.00	20.00	62.40	72.20	52.20	10.20	19.54
	40.00	21.70	57.90	69.80	48.10	9.80	20.37
6	10.00	20.10	60.50	71.50	51.40	9.10	17.70
	20.00	23.20	64.50	78.70	55.50	9.00	16.22
	30.00	20.90	58.60	70.40	49.50	9.10	18.38
	40.00	21.10	66.90	77.50	56.40	10.50	18.62
7	10.00	19.10	64.20	74.40	55.30	8.90	16.09

	20.00	19.30	59.50	69.90	50.60	8.90	17.59
	30.00	20.60	60.20	71.10	50.50	9.70	19.21
	40.00	21.70	57.50	69.40	47.70	9.80	20.55
8	10.00	21.40	45.50	60.00	38.60	6.90	17.88
	20.00	21.00	40.50	56.20	35.20	5.30	15.06
	30.00	21.90	44.70	61.70	39.80	4.90	12.31
	40.00	21.50	44.20	58.90	37.40	6.80	18.18
9	10.00	21.90	47.30	60.90	39.00	8.30	21.28
	20.00	21.60	48.00	63.00	41.40	6.60	15.94
	30.00	21.60	49.30	63.90	42.30	7.00	16.55
	40.00	21.60	43.90	57.90	36.30	7.60	20.94
10	10.00	1.40	37.70	34.50	33.10	4.60	13.90
	20.00	1.50	35.80	32.30	30.80	5.00	16.22
	30.00	1.40	33.70	29.70	28.30	5.40	19.08
	40.00	1.60	37.10	32.70	31.10	6.00	19.94
11	10.00	1.50	39.60	36.60	35.10	4.50	12.82
	20.00	1.30	36.50	34.10	32.80	3.70	11.28
	30.00	1.20	38.70	34.20	33.00	5.70	17.27
	40.00	1.40	39.60	34.70	33.30	6.30	18.92
12	10.00	1.20	35.50	32.70	31.50	4.00	12.70
	20.00	1.50	34.50	30.80	29.30	5.20	17.75
	30.00	1.30	36.70	32.30	31.00	5.70	18.39
	40.00	1.30	34.90	30.50	29.20	5.70	19.52

Figure A.2: Soil Moisture Content vs. Depth for Marab Hassan (NAT soil on 21/12/1998)



APPENDIX B

MONTHLY AND ANNUAL RAINFALL AND DOUBLE MASS CURVES FOR JORDANIAN AND SYRIAN STATIONS

Jordanian Stations:

- Al-Aryyatein
- Azraq
- Um El-Quttein
- Deir Al Kahf
- Safawi
- Mafraq
- Amman Airport
- Aqaba Airport
- Deiralla
- Errabah
- Ruwaished
- Irbid
- Jordan University
- Maan

Syrian Stations:

- Imtan
- Kirbet Awwad
- Salkhad

Monthly and Annual Rainfall for Al-Aryyatein

YEAR	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	TOTAL
1963	0	0	0	0	0	0	17.2	41	58.2
1964	1.5	0	20	18.5	27.5	15	0	0	82.5
1965	0	7.5	25.5	80.5	0	2.5	4	0	120
1966	36.5	4	14	10.5	24.5	17.5	0	0	107
1967	4.5	38.5	26.5	0	9.5	33	0	24.5	136.5
1968	10.1	0	1	6.5	5	53.1	0	0	75.7
1969	0	5	22.5	35	10	34.5	7	5	119
1970	13.5	1.5	0	15	4	20.5	0	0	54.5
1971	0	6	12.4	29.6	10.6	8.4	48	1	116
1972	0	6	10.4	19.5	28.5	13.5	27	0	104.9
1973	0	21	0	24	14.7	1	0	0	60.7
1974	0	23	11.5	49.5	47.5	22	0	0	153.5
1975	0	25.3	3.5	6.5	67.2	6.6	0.4	0	109.5
1976	0	1	16.6	5.7	25.5	45.1	10	0	103.9
1977	13	7	0	32	9	6	4	0	71
1978	0	1	8.7	21	7.5	27	0	0	65.2
1979	0	0	2.5	9.7	10.1	3.6	1.3	4.4	31.6
1980	0	42	26	25	29	43	1	0	157
1981	0	9	63	15.5	2	6	5	0	100.5
1982	0	10.5	0	14	13.2	0	21	26.1	84.8
1983	2	12.4	6	17	13	3.3	0	0	53.7
1984	0	6.3	10.8	19.3	10	9.4	0	0	55.8
1985	4.6	22	10.8	2.7	18.3	20.3	1.6	1.6	81.9
1986	0.1	12.1	23.7	2	6	0	25.9	1.5	71.3
1987	4	55	8	5	5.2	13.6	0	0	90.8
1988	19	0	31.1	35.4	17.4	28.4	16	0	147.3
1989	5	0	77	31.5	2.5	2	0	0	118
1990	0	6.5	0.5	13	49.5	34	8.5	0	112
1991	21	0	0	41.5	11	63	0	0	136.5
1992	10	0	32	4	20	2	0	0	68
1993	0	16	11	18.5	12	12.5	0	1	71
1994	4	7	9	54	3	23.9	0	0	100.9
1995	0	20	6	0	18	0	2	0	46
1996	0	0.5	3.5	30.5	0	11	0	0	45.5
1997	3	3	16	46	84	27	0	0	179
1998	20.8	6.3	21.7	25.5	9	12.8	6.1	0	102.2
1999	0	7	0	3	6	0	0	0	16

Monthly and Annual Rainfall for Azraq

YEAR	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	TOTAL
1969	0	0	8.2	12.2	5.3	11.7	12.2	7	56.6
1970	17.5	2.1	0	3.9	2	6.6	3.9	0	36
1971	0	10.3	3	25.2	4.3	2.9	32.6	0	78.3
1972	0	0.1	45.9	1.6	19.5	40.1	20	0	127.2
1973	0.3	34.3	1	9.5	2.2	1.6	0.8	0	49.7
1974	0.2	1.6	4	35.6	17.9	33.8	0.7	0	93.8
1975	0	22.8	6.9	8.6	50.2	2.8	0.3	0	91.6
1976	0	0.7	7.1	2.4	8.6	34.5	7	0	60.3
1977	0.2	1	0	5.2	2.1	1.3	0.3	0	10.1
1978	0	1.2	17.5	15.1	2.9	4.5	0	0	41.2
1979	2	0.8	0.8	10.5	9	0.2	1	5.5	29.8
1980	0	11.5	24.2	14.8	15.4	10.9	0	0	76.8
1981	2.8	15.8	38.9	1.9	6.5	5.5	6.5	0	77.9
1982	0	3.2	0	11.1	7	7.1	15	17	60.4
1983	16.8	19.3	5.6	7	6.8	0.5	1	17	74
1984	0	0.7	2.5	5.8	1.3	10.2	0	0	20.5
1985	1.5	3.9	9.2	2.2	6.7	28.5	0	3.3	55.3
1986	1.3	10.8	17.6	5	2.1	0	3.1	0	39.9
1987	0	22.6	0.8	4.5	5.4	9.5	0	0	42.8
1988	4.6	0	27.6	24.7	4.9	12.5	11.7	1.3	87.3
1989	65.7	0	54.6	22.3	11.7	4	0	0	158.3
1990	0	10.5	2.5	12.2	19	32.5	15.5	0	92.2
1991	3	0	8.5	40.3	1.5	29	0	0	82.3
1992	1.5	5	18	11	6.3	0.5	0	0	42.3
1993	0	8.3	0	6.5	20	0	0	4.5	39.3
1994	0	0	1.5	18	0.5	1.5	0	0	21.5
1995	7	40.3	13.5	0	27.6	0	0	3	91.4
1996	0	1	4	4.6	2.5	1	0	0	13.1
1997	0	4.5	13	11	22.5	1	0	0	52
1998	0	2	37.8	21.2	3.7	4	18.1	0.2	87
1999	0	0	1.2	11.8	0.5	0	0	0	13.5

Monthly and Annual Rainfall for Um El-Quttein

YEAR	OCT.	NOV	DEC.	JAN.	FEB.	MAR.	APR.	MAY	TOTAL
1948	0	5	0	8	30	15	0	0	58
1949	0	0	0	32	26	0	0	0	58
1952	0	0	81	50	46	21	16	15	229
1953	0	0	22	39	55	106	37	0	259
1954	0	20	29	12	69	0	22	0	152
1955	0	13	55	0	14	26	3	7	118
1956	0	68	56	36	14	47	11	0	232
1957	0	2	33	73	43	80	35	22	288
1958	0	13	16	58	8	0	8	0	103
1959	0	0	0	19	45	18	3	0	85
1960	0	6	11	32	1	33	1	0	84
1961	0	20	13	42	46	14	7	0	142

1962	15	15	67	42.5	34	1	18	0	192.5
1963	1	0	10	6.5	77.5	22	14.7	3	134.7
1964	9	7	46.5	52	58.5	42	12	0	227
1965	0	33	48	88	18	12.5	28	0	227.5
1966	33	14.5	11.5	24	32	102.5	0	0	217.5
1967	25.5	36	83.5	73	35	89	0	32	374
1968	29	40	21.5	40	20	7	9	25	191.5
1969	7.5	13.5	47.5	37.5	13	76	11.5	0	206.5
1970	13	9.5	0	13.5	13	46	0	0	95
1971	0	16	67.5	52	43	22	58	0	258.5
1972	0	11	60	14	34	53	40	0	212
1973	0	12.5	0	37	6.5	26	3.5	0	85.5
1974	0	25	13.5	109.5	93	25	11	0	277
1975	0	0	11	26	99.3	48	5	0	189.3
1976	0	4.6	41.6	16.4	44.5	61.7	15.6	0	184.4
1977	18.4	12.1	1.7	43.2	17.2	27	25.7	0	145.3
1978	4	1.5	10.1	25	14	40.5	0	0	95.1
1979	0	0	17.1	19.2	13.8	14.4	4.7	0.7	69.9
1980	8.5	50	48	38	65.7	35.5	9.5	0	255.2
1981	3	0	82.7	13.9	38	17	4	0	158.6
1982	0	14	3.5	24.5	21	20.5	11.1	9.2	103.8
1983	8	14	11	32	28	23	0	0	116
1984	0	12.3	5.7	40.6	9	39.2	1.2	0	108
1985	15.5	26.5	24	20	52.5	38.8	3	2	182.3
1986	2	7	39	15.6	40.4	1	10.5	9.4	124.9
1987	15.8	64	9.5	17.8	9	13.5	0	0	129.6
1988	14.4	3.6	60.4	37.5	20	45.1	9	0.6	190.6
1989	0	4	61.1	19	5.5	8	0	0	97.6
1990	0	0	9	14	35	42	45.5	2.5	148
1991	0	1	0	58	44.5	54	5	0	162.5
1992	0	0	10	30	30	11	13	0	33
1993	0	0	2	5	34	24	18.5	0	83.5
1994	0	10.5	39	18	0	24	5	0	096.5
1995	0	0	7	2	30	3.5	28	0	70.5
1996	0	1	13	21	22.1	31	13	0.5	101.6
1997	0	40.5	11.6	44.3	50.8	18.1	26.5	12.6	0204.4
1998	0	0	0	0	9	5	1	1	16
1999	0	0	0	2	15	20	3	1	41
2000	0	0	0	0	12	10	2	1	25

Monthly and Annual Rainfall Deir Al-Kahf

YEAR	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	TOTAL
1964	4	0	37.5	33	43	22	9	0	148.5
1965	0	19.5	23.5	89.5	19.5	15.5	22	0	189.5
1966	7	0	0	15	28	52.5	0	0	102.5
1967	24.5	44	55	37	18.5	67	0	42	288
1968	9	15	0	23	10	0	0	0	57
1969	0	4	40	42.5	47.5	0	0	0	134
1970	33.5	0	0	29.5	9.3	60	0	0	132.3

1971	0	16	15.5	26	19	18	71	0	165.5
1972	0	6	64.5	3	33	23.5	55	0	185
1973	0	20	5	14	0	19	0	0	58
1974	0	29	18	68.5	71.1	12	0	0	198.6
1975	0	8	0	3.5	93	17	0	0	121.5
1976	0	2	38	11	39	62	11.9	0	163.9
1977	14	11	2	24	18.5	22	13	0	104.5
1978	0	1	8.8	23	10	34	0	0	76.8
1979	0.4	0	8.3	10.6	10.5	7.2	3.3	1.6	41.9
1980	12	70	62	29	58.8	53.5	6	0	291.3
1981	4	11	93.5	23.7	24	15	34	0	205.2
1982	0	11	3.5	16	28	17	16.5	38	130
1983	0	0	12.9	44	9	0	0	0	65.9
1984	0	5	4.5	16.5	10	27.7	1	0	64.7
1985	9	6	12.3	3.5	12	17	0	1	60.8
1986	0.6	15	24	1.5	36.4	1.2	15.7	8.5	102.9
1987	13	62.4	7.8	23.5	6	28	0	0	140.7
1988	4.5	1.2	41.5	45.5	28	39	7.5	0.5	167.7
1989	9	0	48	16.5	0.5	0	0	0	74
1990	0	6	5	52	46.5	27.5	3	0	140
1991	0	0	0	36	13	39	0	0	88
1992	0	0	0	35.5	40	0	0	0	75.5
1993	0	9	9	17	17.5	18	0	3	73.5
1994	0	0	0.5	22	8	0	0	0	30.5
1995	2	31.5	43.5	0	8	9.5	0	0	94.5
1996	0	2	6	49.5	10	6.5	0	0	74
1997	1	12	8	13	29	4.5	0.5	0	68
1998	31	9	34	39.2	13.9	19.8	9.1	0	156
1999	0	0	0	4.5	8.5	0	0.5	0	13.5

Monthly and Annual Rainfall for Safawi

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1943	4	10.3	24	4.2	6.9	31.4	4.7	0.4	85.9
1944	2.3	0	16.6	42.3	2.4	15.4	0.5	21.9	101.4
1945	0	43.2	62.9	35.5	11.8	12.1	2.5	25.7	193.7
1946	0	16.2	18.2	1.5	36.3	1.5	0	8.3	82
1947	0	10.4	0.6	4	14.9	4.5	0	0	34.4
1948	0	0	0	0	2	0.5	15.4	0	17.9
1949	0	0	10.4	2.2	32.3	3	2	0	49.9
1950	0	0	44.4	7.6	10.1	12	9.8	12.5	96.4
1951	0	2.6	8.2	0.7	3.6	0	0.7	0	15.8
1952	0	0	44.1	5.3	20.6	3.6	0	0	73.6
1953	1.5	0.2	8.9	6.7	20.1	27	10.7	0	75.1
1954	0	8	3	1.7	18.1	7.2	11.3	0	49.3
1955	2.8	17.3	32.8	0	2	4.6	0.6	0	60.1
1956	0	13.2	10.2	1.5	1.5	11.4	0	0	37.8
1957	0	0	12.1	7.6	22.1	23.9	5	10.1	80.8
1958	0	0	7	4	2.5	0	0	0	13.5
1959	0	0	1	2.5	3.8	24.2	2.2	0	33.7

1960	0	8.4	9.5	3	2.5	0	0	0	26.4
1961	0	11	6	6.9	24.3	1.5	0	0	49.7
1962	5	37	37.5	17	11	0	12	3	122.5
1963	8	0	3.5	8	53	4.5	18	18	113
1964	1	0	20	11.5	19	2	0	0	53.5
1965	0	2.5	24.5	44	2.5	5.4	4	0	82.9
1966	12	11	2	11	18.2	14.2	0.2	0	68.6
1967	16.7	27.5	26.5	22.8	12.5	15.9	0	16.2	138.1
1968	39	3	0	30	10	0	0	0	82
1969	3.3	4.7	14.9	19	2.5	28.1	3.3	2	77.8
1970	12.2	0	3.7	13.5	13.5	8.8	0.5	0	52.2
1971	0	0	4.4	23.7	8.3	5.4	31.2	2.2	75.2
1972	0	0.4	34.3	0.9	15.2	15.7	31.6	1.7	99.8
1973	0	25.5	0	18.2	1.7	2.2	0.4	0	48
1974	0.9	17.4	14.5	35.3	73.4	29.2	4.2	0	174.9
1975	0	26.8	0.1	2.9	42.1	2.1	0.5	0	74.5
1976	0	0.4	7.8	3.9	25.5	27.5	7.9	0	73
1977	4.7	1	0.6	13.2	2.5	4.4	1.2	0	27.6
1978	0	1.2	14	4	2	4.4	0	0	25.6
1979	0	0	0	4	6.7	3.7	0	2.8	17.2
1980	0	49	12.4	1.2	17.6	10.3	0	0	90.5
1981	3.1	0	48.4	11.7	10.3	6.7	9.2	0	89.4
1982	0	5.4	0	21.5	7.5	1.9	23.1	8.4	67.8
1983	3	6.4	10.7	11	9.2	4.5	1.2	3	49
1984	0	7	6.8	9.8	3	10.3	0.8	0	37.7
1985	4.1	8.6	8.1	1.3	7.8	27.2	0	0	57.1
1986	0	30	30.5	0.2	5.4	0	39.3	0	105.4
1987	0.2	30.3	1.2	1.4	2.3	0	31.5	0	66.9
1988	4.9	0	15.3	40.1	10.9	28.7	5.4	0	105.3
1989	32.8	60.8	56.7	25.8	1.5	11.1	0	0	188.7
1990	0	25.1	0	0.5	35.5	2.8	51.6	1	0
1991	0	0	5.8	14.9	5	16.2	1.8	0	3
1992	0	0	9.3	6.2	6.9	18.7	6.4	0.5	2.1
1993	0	3.2	1.4	10.1	30	3.3	4.6	0	0
1994	0	0.6	34.3	12.7	0	42.4	3	3.2	0
1995	0	0	0	7.8	19.5	4.7	12.5	0	0
1996	0	0	46.5	14.8	18	13.1	6.5	0.3	0
1997	0	16.3	4.7	17.9	20.5	7.3	10.8	4.7	0
1998	0	0	0.4	0.7	11	21.5	1.2	0	0
1999	0	0	2	2	7	14	4	2	0
2000	0	0	0	0	5	12	3	1.1	0

Monthly and Annual Rainfall for Mafraq

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	0	7	17	28.4	17	5.1	20.8	2	0	97.3
1961	0	0.8	35.3	16.9	42.4	32.2	18.5	7.1	2.6	155.8
1962	0	2	8	44.1	17.9	25.3	1	1.8	0	100.1
1963	0	2.1	0	9.4	6.1	39	6.1	5.7	10.3	78.7
1964	0	7	5.4	31.6	31.9	46.5	35.7	3.5	0	161.6
1965	0	0	15.5	50.5	85.7	9.7	6.6	18.5	0	186.5
1966	0	23.4	2.9	8.8	21.6	17.8	67.8	0.5	0.8	143.6
1967	0	15	15.9	75.1	53.7	23.2	59.7	0	18.3	260.9
1968	0	28.7	26.7	11.3	38.1	15.2	18.7	15.9	4.3	158.9
1969	0	1.4	7.7	32.2	46.7	10.6	51	10.8	3.8	164.2
1970	0.3	14.9	15.3	4.4	28.5	18.9	33.9	7.5	0	123.7
1971	0	2.9	8.2	20	36	21.7	21.7	52.6	0	163.1
1972	0	0.1	16.9	51.8	18.1	45.4	29.3	14.4	1.2	177.2
1973	0	0.5	24.7	2.4	32.5	3.2	19.4	5.7	0.5	88.9
1974	0	0.6	24.6	9.2	99.3	57.5	22.2	12.7	0	226.1
1975	0	0	11.4	22.5	8.6	76.2	21.4	20.5	0	160.6
1976	1	0.2	11.2	22.1	13.2	32.8	56.1	5	10	151.6
1977	0	4.3	4.5	2.2	35.6	8.3	18.5	15.1	0.2	88.7
1978	0	9.1	2	38.9	21.2	13.7	19.5	4.5	0	108.9
1979	0	4.2	1.1	21.9	17	19	10.6	0.5	0	74.3
1980	0	24.4	71.1	59.6	37.9	44	52.9	11.5	0	301.4
1981	0	2.6	2.6	97.1	14.5	26.1	27	6.1	0	176
1982	0.7	0	19.5	3.6	41.9	25.4	11.7	28.8	20.8	152.4
1983	3.4	8.4	35.5	11.8	30.6	51.5	36.4	1.5	2	181.1
1984	0	0	1.6	3.9	34.2	9.7	50.6	2.1	0	102.1
1985	0	20	16.1	26.8	16.3	76.1	28.9	5.8	2.1	192.1
1986	0	1.6	2.5	18.2	11.6	39.1	4.4	3.3	1.9	82.6
1987	0	7.6	97.8	17.9	27.7	17.9	35.4	0	0	204.3
1988	0	22.7	6.1	37.2	82.6	70.6	42.2	11.7	0	273.1
1989	0	4.7	9	68.4	33.4	9.2	15.4	0	0	140.1
1990	0	3	17.7	13	20	10	14	2	0	79.7
1991	0	10.7	25.3	79.9	46.6	28.1	34.4	0.6	0	225.6
1992	0	5	16.2	49.6	195	102	14.2	0.2	3.2	385.4
1993	0	0.8	6.8	7.5	26.4	22.1	15.9	0	3.7	83.2
1994	0	7.2	96.8	47.6	52.5	21.5	31.7	0	0	257.3
1995	0	2.3	12.6	9.2	0.7	34.4	16	2.7	0	77.9
1996	0	8.7	20.7	17.9	59.2	8.6	53.5	4.6	0	173.2
1997	0	11.6	26.3	31.2	45	39	24.6	0.7	1.2	179.6
1998	0	0	12	32	33.2	7.5	57.1	5	0	146.8
1999	0	2	24	5.1	19	36.1	2.5	0.7	0	89.4
2000	0	0	0	0	81.2	8	15.8	3	0	108

Monthly and Annual Rainfall for Amman Airport

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	7	0	6	12	30.9	8	43	5	0	111.9
1961	0	0	41	18	86.9	80.2	10.5	8.4	4.3	249.3
1962	0	1.8	14.7	149.6	31.8	63.8	0.5	4.2	0	266.4
1963	0	4.8	0	20.3	6.8	58.9	30.2	13.2	23.3	157.5
1964	0	20.1	24.1	107.7	67.5	76.5	38.1	4.2	1.1	339.3
1965	0	0	39.3	30.4	98.5	34	25	44.8	0	272
1966	0	12.9	18.6	34.6	21.5	20.4	110.8	0.1	0	218.9
1967	0	16.9	31.2	121.8	106.3	26.1	156.2	0	0.3	458.8
1968	0	11.1	37.4	42.7	124.3	25.4	11.3	7	5.2	264.4
1969	0	1.6	13.6	55.8	73.5	17.4	144.3	16.9	1.6	324.7
1970	0	18.2	13.1	10.5	45.5	24.8	58	10.5	0	180.6
1971	0	1.5	5.2	37.4	17.9	36	53	151	0	302
1972	0	0	14	122	32	55	39	44	7	313
1973	0	0	31	6	105.9	19.9	29	1	0	192.8
1974	0	4	51	32	235	99.9	12	21	0	454.9
1975	0	0	36	25	17.9	126	33	5	0	242.9
1976	0	0	21	23	29	42.9	69	11	7	202.9
1977	0	1	11	1	43	25	52	58	2	193
1978	0	28	6	72	39.9	28	67	6	0	246.9
1979	0	2	1	43	42	11	35	3	1	138
1980	0	35	133	87	77	76	78	16	0	502
1981	0	2	7	173	48	37	21	111	0	399
1982	0	0	25	1	57.9	56	43	13	20	215.9
1983	1	10	34	19	118.9	129	99	31	1	442.9
1984	0	0	26	4	61.9	26	80	6	0	203.9
1985	0	7	16	31	24	151	42	2	2	275
1986	0	10	4	23	26.9	58.9	6	3	8	139.8
1987	0	27	106	32	46	16	39	0	0	266
1988	0	33	5	72	50	126	63	13	0	362
1989	0	8	15	121	44	26	32	0	0	246
1990	0	0	2	4	91	47	44	0	2	190
1991	0	4.7	35	166.4	90.9	47.2	43.5	6.2	2.1	396
1992	0	0	39.6	71.5	112.1	200	15.7	0	6	444.9
1993	0	0	22.1	16.8	67.5	49.5	17.1	0	11.6	184.6
1994	0	12.6	97.3	99.5	74.3	17.6	29	0.7	0	331
1995	0	0	1.8	0	1.7	36.2	27.3	4.2	0	71.2
1996	0	0.7	32.1	28.2	81.3	18.4	66.9	9.8	0	237.4
1997	0	16.5	10.7	59.4	66.1	82.4	54.8	3.6	0.8	294.3
1998	0	0.4	0.7	3.6	60.8	34	75	1.9	0.3	176.7
1999	0	0	0.5	3.3	29.2	57.7	11.7	3.9	0	106.3
2000	0	0	0	0	117.4	20.8	30.1	0	0	168.3

Monthly and Annual Rainfall for Aqaba Airport

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	0	1.2	3	7.6	1.8	0	0	0	0	13.6
1961	0	0	1.8	1.4	4.3	0	0	0	0	7.5
1962	0	5	0	21	5.8	0	0	0	0	31.8
1963	0	0	0	0.2	0.6	3.4	3	39.9	0.8	47.9
1964	0	1	0.6	8.8	7.3	0	0	2.2	0	19.9
1965	0	0	0	19.5	27	0	4.8	1.8	0	53.1
1966	0	0.2	1	0	36.8	12.1	3.5	0	0	53.6
1967	0	0	0.4	0.2	0.4	1.3	0	0.3	1	3.6
1968	0	8.9	1.5	0	0.8	5.5	4.2	6.1	10	37
1969	0	0	27.2	0.8	15.1	0	29	5.7	0	77.8
1970	0	0.7	3.4	0	1.3	0	0.2	0	0	5.6
1971	0	0	0.5	0	17.8	0.7	6.1	21.7	0	46.8
1972	0	0	2.6	20.9	5.6	0.1	8.4	1	0	38.6
1973	0	0	17.6	0	0	0	0	1.2	0	18.8
1974	0	0	12.8	0.3	9	6.4	5.5	0	0	34
1975	0	0	1.5	14.1	1	67.2	0.3	0.1	0	84.2
1976	0	0	0	17.3	0	0	6.3	0	3.4	27
1977	0	0.1	0	1.5	0.7	0	0.1	12	0	14.4
1978	0	0	0	13.5	7.6	15.4	0	0	0	36.5
1979	0	0	0	17.3	0	19.2	0	0	0	36.5
1980	0	0	1.3	1.8	1.2	2.2	3.7	0.2	0	10.4
1981	0	0	2	43.3	1.8	0	1.6	0.6	0	49.3
1982	0	8.3	0	0	9.7	12	4.6	6	7.3	47.9
1983	0	0	6.8	0	0	5	3.9	0	0	15.7
1984	0	0	0	1.2	2.8	0	5.1	0	0	9.1
1985	0	0	0	0	1.1	0.8	11.6	0.2	1.5	15.2
1986	0	0	0	22.2	0	2.2	3	11.5	14.1	53
1987	0	0	8.7	1	0	11.7	9	0	0	30.4
1988	0	21.8	0	17.5	20.6	3	6.1	0	0	69
1989	0	1.1	0.1	6.8	4.5	2.2	5	1	0	20.7
1990	0	0	15.2	0	6.1	5.6	4.1	3.7	1.2	35.9
1991	0	1.3	0	3.6	4.5	0	13.9	0	0	23.3
1992	0	0	10.6	0.5	6.4	2.1	0	0	0	19.6
1993	0	9.3	0	33.1	5.6	4.3	0	0	0	52.3
1994	0	0.2	5.4	0	37.3	1	4.7	0.2	0	48.8
1995	0	0	0	0	0	6.2	0	3.4	0	9.6
1996	0	0	0.2	0.4	0.8	0.5	0.2	0	0	2.1
1997	0	28	0	0.3	9	0.7	3.3	0	0	41.3
1998	0	0	0.3	0	0.8	0.3	1.3	0.3	0	3
1999	0	0	0	0	0.7	28.3	1.9	0	0	30.9
2000	0	0	0	0	2.4	0	0	0	0	2.4

Monthly and Annual Rainfall for Deiralla

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	0	0	8.8	12.6	50.4	1.4	34.4	5.1	1.9	114.6
1961	0	0	47.4	21.7	69.9	73.8	3.7	32.9	12.1	261.5
1962	0	3.2	12.9	118.4	57.2	39.8	0.5	21.7	19.2	272.9
1963	0	10.8	0	45.8	28	61.1	19.1	5.4	14.4	184.6
1964	0	14.8	27.1	87.8	34.8	99.4	65.7	1.8	0	331.4
1965	0	0	53.8	55.9	107.6	22.3	36	23.3	0	298.9
1966	0	22.4	14.5	44	26.3	44.5	60.1	0	0.2	212
1967	0	12	7.2	166.1	91.6	50	100	1.5	12.3	440.7
1968	0	37.5	34.2	21.1	77	14.5	14.5	40.8	3.4	243
1969	0	2.2	12.4	64.8	84.3	12.5	91	4.4	0.2	271.8
1970	2.6	9.2	24.2	9.6	81.5	11.5	86.6	10.4	0	235.6
1971	0	2.6	17	62.7	55.3	59.1	29.1	103.2	0	329
1972	0	0	35.1	77.8	50.1	68.1	78.3	32.7	0.7	342.8
1973	0	1.3	25.5	12.8	64.1	11.6	65.9	0	6	187.2
1974	0	0.5	74.2	13.7	225.6	101.6	51.9	37.7	0	505.2
1975	0	0	26.7	41.7	15.9	109.7	35.7	5.8	0	235.5
1976	0.5	0	18.4	30.3	30.3	52.1	53.2	14.9	2.2	201.9
1977	0	5.6	52.5	9.5	68.3	22.7	45	52.2	0.3	256.1
1978	0	28.8	0	87.4	32.8	20.9	37.3	8.9	0	216.1
1979	0	16.7	6.6	56.4	35.6	14	41.5	0.4	0.2	171.4
1980	0	32.9	87.8	121.8	52	76.5	79.6	6.2	0	456.8
1981	0	18	8.6	82.2	87.8	28.7	32.2	9.6	0.4	267.5
1982	0	0.2	42.9	7	53.9	87.6	55.8	7	1.6	256
1983	1.6	0.4	75.9	22.9	90	113.7	76.8	6.8	4.6	392.7
1984	0	0.8	41.8	2.4	53.7	20.9	74	36	0	229.6
1985	0	9.5	8.4	22.2	34.5	88.7	25.8	20.4	0.6	210.1
1986	0	8.4	21.5	40.4	45.5	86	10.8	8	18.8	239.4
1987	0	8	165.1	43.6	42.2	14.6	23.3	0	0.6	297.4
1988	0	26.1	4	82.5	68	132	25.4	8.8	0	346.8
1989	0	1.2	21.3	104.9	47.9	23.5	49.4	0	0	248.2
1990	0	0	9.1	46.4	84	56	46	0	0	241.5
1991	0	11.5	74.3	176.7	91.9	29.1	83.7	16.4	0	483.6
1992	0	0	21.4	150.5	114.8	183.4	32.8	1.2	4.9	509
1993	0	6.6	8	6.5	49.7	47.3	17.8	0	0.6	136.5
1994	0	28.2	202.6	75.5	87.4	37.7	22	0.8	0	454.2
1995	0	1	49.1	22	9.4	49.1	6.1	10.3	0	147
1996	0	14.1	7.7	48.2	90.7	11.4	87.6	4.8	0	264.5
1997	0	8.5	74.2	92.9	111.5	105.9	76.9	0.7	1	471.6
1998	0	0.4	0.3	1.6	75.1	18.8	75.4	5.6	1.8	179
1999	0	3.7	1.8	4.7	57.4	22	17.7	2.7	0	110
2000	0	0	0	0	148.9	54.3	47.4	0	0	250.6

Monthly and Annual Rainfall for Errabah

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	0	1	25	65.3	32	2.4	50.9	2.5	0	179.1
1961	0	0	18	18.9	91.5	152.2	23	10	5	318.6
1962	0	4.5	21	104.2	37.2	39	38	13	0	256.9
1963	0	0.6	0	10.6	8.4	112	10.2	6.8	3.8	152.4
1964	0	6	23.6	90.4	85.7	107.8	36.8	10.4	0	360.7
1965	0	0	52	65	357.9	18.7	58	3.5	0	555.1
1966	0	52.7	32.1	25.3	33.2	44.5	80.4	0	0	268.2
1967	0	10.5	1.7	141.4	54.6	32.9	111.9	0	12.4	365.4
1968	0	0	46.1	29.5	158	24.8	18.5	41.5	3.5	321.9
1969	0	8	36.9	94.8	61.4	2	112.8	14	0	329.9
1970	0	0	20.8	24.9	55.9	17	128.8	20	0	267.4
1971	0	0	2.5	47	64.5	16.6	27	238.5	0	396.1
1972	0	0	24.5	210.8	27.5	79	114.2	13	0	469
1973	0	3.6	53.4	30	93.3	14	18.9	0	0	213.2
1974	0	1.6	57.6	21.7	191.3	80.6	30	37.9	0	420.7
1975	0	0	24.9	73.3	18	145.2	52.2	0.5	0	314.1
1976	0	0.3	32.7	32.2	27.6	58.7	64	21.2	4.3	241
1977	0	5.3	15.2	11.9	109.5	22.1	13.7	98.5	11	287.2
1978	0	1.2	13	111.3	39	24.6	62.4	7	0	258.5
1979	0	0.3	3	47.5	110	26.3	83.5	1.8	13	285.4
1980	0	8.4	119.3	178.1	91.6	121.1	8	0.8	0	527.3
1981	0	7	1.2	176.6	33.6	69.9	64.7	11.2	0	364.2
1982	0	0	24.1	0	69.2	119.4	44.6	6.8	36.8	300.9
1983	0	0	69.7	44.3	189.9	105	85.2	4.3	0.2	498.6
1984	0	0	2.9	8.4	85.5	16.5	101.1	1.8	0	216.2
1985	0	27.1	17.1	40.3	6.2	192.6	40.8	58.4	5.8	388.3
1986	0	4.4	2.6	72.5	31.2	62.3	5.1	13.6	13.4	205.1
1987	0	1.8	137.9	32.1	26.1	35.6	92	0.5	0	326
1988	0	4.9	0.3	75.3	133.8	143.3	86.4	16.6	0	460.6
1989	0	3.6	1.7	122.2	72.6	151.6	62.8	0	0	414.5
1990	0	0.8	5.7	18.5	34	55	0	0	0	114
1991	0	13.7	27.7	151.7	118.3	42.4	245.2	0.7	0	599.7
1992	0	0	94.9	108.8	127.4	159.8	26.9	0	0	517.8
1993	0	0	46	45	58.7	65.3	18.6	0	0	233.6
1994	0	13.8	128.6	90.7	138.1	68.2	52	0	0	491.4
1995	0	0	18	14.3	0.7	69.7	3.6	0	0	106.3
1996	0	11.7	6.3	46.1	83.3	19.1	90.3	2.2	0	259
1997	0	4	1.5	73.5	101.6	102.5	57.8	4.9	0	345.8
1998	0	0	1.7	2.5	76.7	44.3	64.8	0	0	190
1999	0	0.6	0.2	5.1	32.5	79.3	6.2	18.3	0	142.2
2000	0	0	0	0	76.1	5.2	37.5	0	0	118.8

Monthly and Annual Rainfall for Ruwaished

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	0	0	9	11.1	7.5	0	9.9	0	0	37.5
1961	0	0	29	16.2	18.2	32.2	0	27.5	0.6	123.7
1962	0	17.5	24.2	9.1	20.5	0.6	0	8	3.3	83.2
1963	0	0.6	2.1	1.4	16	19.1	6.7	20.8	7.5	74.2
1964	0	9.5	8.3	6	7.8	30.2	3.8	22.6	1.1	89.3
1965	0	0	0	19.6	40.6	1.9	9.7	3.2	0	75
1966	0	6.8	4.2	0.2	21.4	10.3	6.7	0.2	2.3	52.1
1967	3.4	19.6	22.6	4	4.1	8.6	2.3	0	27.1	91.7
1968	0	16	10.5	0.9	9.7	6.9	0.7	7.9	25.6	78.2
1969	0	5.9	13.8	14.4	17.2	0	14.5	12.5	5.4	83.7
1970	0	24.5	1.4	8.8	11.9	9.3	3	4.9	0	63.8
1971	0	0.6	8.2	0.7	30	15	18	35	4	111.5
1972	0	0	1	26	5	8	44	13	0	97
1973	0	1	10	0	6	5	1	5	0	28
1974	0	0	15	1	22	42	12	3	0	95
1975	0	0	17	12	5	49	0	3	1	87
1976	0	0	4	40	0	23	36	8	6	117
1977	0	0	12	3	16	2	0	8	14	55
1978	0	5	44	9	1	8	1	0	0	68
1979	0	0	1	6	9	5	6	0	0	27
1980	0	2	5	12	9	11	9	1	0	49
1981	0	0	0	48	1	9	15	22	2	97
1982	0	0	3	0	45	12.2	15	81	9	165.2
1983	3	47	29	9	6	5	12	41	7	159
1984	0	0	3	7	5	3	13	1	0	32
1985	0	23	28	8	5	1	31	1	2	99
1986	0	2	19	12	1	6	0	24	4	68
1987	0	3	32	4	0	2	32	0	0	73
1988	0	54	0	13	37	10	20	28	28.2	190.2
1989	0	5	4	51	29	4	10	0	0.8	103.8
1990	0	0	5	1.1	8.6	26.2	33.8	3.7	0	78.4
1991	0	11.3	0	1.8	23.9	5.2	37.3	0	0	79.5
1992	0	4.7	1.3	0	10.9	29.4	0.2	2	0	48.5
1993	0	0	3.8	23.4	3.3	8.6	0	19.2	0	58.3
1994	0	23.7	4.3	2.5	27.3	5.8	15.5	0	0	79.1
1995	0	22.7	36.5	6	0	39.9	0.3	7.3	0	112.7
1996	0	0	0	22	9.7	14.4	19.7	0	0	65.8
1997	0	0.2	0	23.9	24.4	15.6	21.2	0.4	0	85.7
1998	0	3.8	25.5	0	25.2	17.2	8.1	0.8	0	80.6
1999	0	0	2	3	5	3	2.5	0.7	0	16.2
2000	0	0	1	2	7	4	15.8	0	0	29.8

Monthly and Annual Rainfall for Irbid

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	23.1	0.6	14.3	8.5	45.1	24.7	91.4	26	1	234.7
1961		13	39	68.3	74.2	89.4	33.9	15.8	2.6	336.2
1962	0	0	84.3	250.9	82.5	90.8	3.7	15.6	0	527.8
1963	0	3.4	23.2	73.5	52.5	135.6	73.5	26.7	23.8	412.2
1964	0	0.4	0	97.4	87	156	104.5	4.9	12.8	463

1965	0	37.5	22.7	55	145.8	67.9	43.6	44.2	0.4	417.1
1966	0	0	107.7	68.2	49.3	70.9	127.3	6.9	3.7	434
1967	0	52.1	20	191.2	183.1	74.7	215	5.5	8.7	750.3
1968	0	38.3	32.5	78.4	236.8	46.8	31.7	20.9	14.7	500.1
1969	0	13.3	76.2	162.4	162.2	34.8	143.2	14.6	0	606.7
1970	0	15.8	28.3	27.5	140.3	46.3	154.2	28.6	0.7	441.7
1971	5.6	29.8	44.3	87	74.9	146.3	70.4	192.6	1	651.9
1972	0	11.2	18.9	163.6	81.6	112.3	60	35.2	5	487.8
1973	0	0	26.4	16.5	156.1	32.9	96.4	4.4	7	339.7
1974	0	6.6	28.5	56.9	270.4	94.7	69.4	40.1	0	566.6
1975	0	9	88.2	49.4	38.4	154.5	78.7	6.1	0.1	424.4
1976	0	0	20.5	92.6	61.3	103.5	83.3	31.6	15.4	408.2
1977	2.8	1	54.1	28.7	103.3	26.1	102.7	75.7	3.3	397.7
1978	0	16.8	58.5	131.4	64	66.3	121.9	13.5	0.7	473.1
1979	0	17	11.9	46.5	64	21.7	73.5	6.9	0	241.5
1980	0	25.1	3.4	198.1	116.9	109.6	142.7	19.3	3.6	618.7
1981	0	40.6	111.8	147.1	111.4	71.6	47.2	18.8	0	548.5
1982	0	21.2	10	28	71.4	114.3	95.6	5.7	38.5	384.7
1983	0	0	55.3	47.9	148.6	219.1	109.9	20.5	5	606.3
1984	2.4	4.1	62.1	15.9	117.5	42.9	145.9	77.2	0	468
1985	0	2.4	44.7	73.9	48	245.9	22.5	11.2	0.6	449.2
1986	0	30.6	50.6	30.6	103.4	106.3	37.2	35.2	28.9	422.8
1987	0	18.9	35	103.4	89.7	42.9	114.4	1.8	0	406.1
1988	0	31	214.5	126.5	133.8	149.3	115.2	16.7	0	787
1989	0	15.5	8.2	106.9	30.3	47.6	59.1	0	0	267.6
1990	0	4.2	22.9	30.3	101.9	87.1	81.8	26.3	6.9	361.4
1991	0	0	62.3	233.3	165.7	48.4	116.5	43.6	2.7	672.5
1992	0	0	58.9	197.5	214.6	346	36.2	4.4	12.1	869.7
1993	0	17.3	17	20.8	73.4	62.8	34.4	0	33.2	258.9
1994	0	29	152.3	120	118.1	65.5	98.8	4	0.4	588.1
1995	0	5.5	67.3	19.2	17.8	63.3	54.3	23.7	0	251.1
1996	0	36.5	25.1	53	138	17	100.3	14.9	0	384.8
1997	0	17.6	43.4	95.1	54.3	192.4	92.4	21.6	2.6	519.4
1998	0	2	1.7	28.4	122.8	58.9	169.3	10.8	2.6	396.5
1999	0	0	8.1	21.2	69	66.3	35.3	7.6	0	207.5
2000	0	0	0	0	208.8	65.7	42.5	1.7	0	318.7

Monthly and Annual Rainfall for Jordan University

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	0	0	3	96	59.9	15.2	89.6	7.5	0	271.2
1961	0	0	0	32.4	123.8	137.7	20	28.1	6.2	348.2
1962	0	0	5.5	210.3	69.4	93.8	2.9	11	0.8	393.7
1963	0	0	2.6	38.4	55.6	144.1	60	14	54.7	369.4
1964	0	1.8	8.6	204.7	127.7	156	76.6	1.5	3	579.9
1965	0	0	0	55.2	171	50.1	57.6	59.1	0	393
1966	0	0	11.9	62.6	35.4	49.3	90.9	0.2	0	250.3
1967	0	0	25.8	224.9	165.8	46.3	202.1	2.4	0	667.3

1968	0	0	18.6	70.1	162.3	45.9	19.2	12.2	5.5	333.8
1969	0	0	22.9	136.5	153	37.1	234	21.6	0	605.1
1970	0	0	15	16.7	109.1	45.1	143.9	25.2	0	355
1971	0	0	0	86.3	45.3	92.1	76	268.3	0	568
1972	0	0	0	193.4	65.5	78.5	60.2	48.2	3.9	449.7
1973	0	0	1.8	2.9	158.1	29.5	79.1	2	0	273.4
1974	0	0	1.5	58.9	345.7	158.6	23.6	39.2	0	627.5
1975	0	0	0	49.7	23	206	69.2	12.8	0	360.7
1976	0	0.5	0.4	58.9	50.4	87	94.7	19.8	4.6	316.3
1977	0	0	4.8	7.2	119	49.6	114.7	101.3	0.2	396.8
1978	0	0	92	159.8	84.4	56.3	129.7	13	0	535.2
1979	0	0	10.7	93.2	83.4	14.6	79	3.5	0	284.4
1980	0	0	27.5	186	111.3	127.6	121.1	19.2	0.1	592.8
1981	0	0	2.2	261	113.4	79.6	43.3	16.3	0	515.8
1982	0	1	0	11.9	128.1	124	89.5	19.5	31	405
1983	0	5	8.6	44.8	188	201.6	143.2	10.4	2.8	604.4
1984	0	0	1.8	7.6	145.4	55	180.2	51.8	0	441.8
1985	0	0	15.5	32.8	45.4	285.1	38.9	11.5	1.2	430.4
1986	0	0	20.5	41.4	56.7	126	29.4	10.9	18.8	303.7
1987	0	0	50	73.2	101.8	42.2	76	1.5	0	344.7
1988	0	0	22.4	181.9	91.8	243	102.4	16.7	0.6	658.8
1989	0	0	11.8	232.7	95.4	48.6	115.1	0	0	503.6
1990	0	3.5	18.9	29.7	140.5	78.2	82.1	40	0	392.9
1991	0	5.5	83	3.7	199.3	89	120.4	14.2	0	515.1
1992	0	6.8	97.2	392.7	298.6	306.1	53.1	2.5	8	1165
1993	0	0	20.7	186.1	141.4	84	25	0	12.7	469.9
1994	0	16	196	25.9	179.5	44.6	82.6	5.8	0	550.4
1995	0	16	36.2	170	13.3	90.2	32	15.5	0	373.2
1996	0	0	14	28.9	182.3	21.8	135.7	9.5	0	392.2
1997	0	17.7	42.7	51.4	102.4	204	95.8	7	5	526
1998	0	11.2	0	91.2	110.2	60.5	121	1.8	1.2	397.1
1999	0	0.8	2	7.5	60.8	116.7	30	9.5	0	227.3
2000	0	0.7	28.2	14	201.3	52.5	74.2	0.8	0	371.7

Monthly and Annual Rainfall for Maan

YEAR	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1960	0	3.6	4.2	7.1	0	0	0	0	0	14.9
1961	0	8.6	5.6	0.3	2.2	2.6	0	3	1.4	23.7
1962	0	8.5	2.5	21.6	8.7	0	0	8.1	0	49.4
1963	0	0	0	2.2	0.5	9.4	1.3	15.8	0.2	29.4
1964	0	0.2	2	11.5	11.3	4.6	0	7.2	0	36.8
1965	0	0	0	4.4	33.7	0.6	7.6	3.7	0	50
1966	0	29.9	0.9	0.2	7.6	5.5	12.4	0	0.9	57.4
1967	0	4.1	10.9	1.9	3.3	4.3	9.3	0	25.4	59.2
1968	0	13.2	52.4	0.5	2.5	6.1	0	3.2	4.3	82.2
1969	0	0	13.8	1.2	9.8	0	15	1.1	2.2	43.1
1970	0	14.1	1.7	0	10.7	1.6	2.9	0	0	31
1971	0	0	2.1	4.4	14	0	2	20	1	43.5
1972	0	0	0	18	2	12	9	9	0	50
1973	0	0	14	1	3	0	0	0	0	18
1974	0	0	1	1	22	14	13	2	0	53
1975	0	0	7	8	2	46	0	4	0	67
1976	0	0	0	7	0	1	11	0	2	21
1977	0	1	0	0	8	1	0	13	0	23
1978	0	0	0	7	1	1	6	0	0	15
1979	0	3	0	8	4	13	1	0	8	37
1980	2	1	1	11	2	28	10	0	0	55
1981	0	0	0	41	1	0	0	3	0	45
1982	0	1	1	0	5	3.8	4	0	8	22.8
1983	5	18	6	6	8	9	10	0	0	62
1984	0	0	0	0	3	0	9	0	0	12
1985	0	0	1	2.9	0	3	9	2	5	22.9
1986	0	6	0	30	1	9	5	8	1	60
1987	0	0	10	2	0	1	16	0	3	32
1988	0	4	0	8	31	22	41	2.2	0	108.2
1989	0	0	0	21	8	19	4	0	0	52
1990	0	0	0	1	3.6	2.5	8.2	9.6	0	24.9
1991	0	0	0.2	0	27.3	0	28	0	0	55.5
1992	0	1.3	1.6	7	14.6	9.4	0.6	0	0	34.5
1993	0	0	0	3.3	3.3	0.4	3	0	0	10
1994	0	37.4	20.3	4.8	27	9.5	12	0	0	111
1995	0	27.4	0	3.7	0	3.5	12	7	0	53.6
1996	0	0	22.2	0.4	19.8	0	5.6	0.2	0	48.2
1997	0	0	29.4	0	15.7	1.4	0.6	0	0	47.1
1998	0	52.4	0	3.6	0	3.5	1.6	0	0	61.1
1999	0	0	0	0	3.8	18.6	0	0	0	22.4
2000	0	0	29.4	0	6.9	2	6.1	0	0	44.4

Monthly and Annual Rainfall for Imtan

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1964	10	13.7	53.4	72.8	82.8	53.4	16.1	0	302.2
1965	0	46.4	40.6	124.8	48	15.2	28.1	0	303.1
1966	14	3.1	15.4	29.2	54.5	103.5	0	1.1	220.8
1967	35.7	30.2	110.3	101.6	57	113.5	1	71.2	520.5
1968	12.5	36	12.6	71.5	15	11	0	4	162.6
1969	7	18	75.3	107.9	20.5	100.3	15.5	0	344.5
1970	11.8	8.7	2.9	49.8	16.4	90.4	4	0	184
1971	1.2	22.6	38.7	40.2	30.7	0	127.3	7	267.7
1972	0	9	80.1	30	52	39	18	0	228.1
1973	3	37.5	6.5	72	6	34	0	0	159
1974	0	53	34.5	98	78	20	11	0	294.5
1975	0	10	17	10	87.7	23	4	0	151.7
1976	0	2	56	15.5	49	67.5	14	0	204
1977	28	15	0	32	22	12	48	0	157
1978	4	2	45	45	19	47	3.3	0	165.3
1979	0	0	19	15.3	16	12.5	9.8	0	72.6
1980	8	97	57	34.2	79.2	51.5	5	0	331.9
1981	0	3	143.5	32	50	22.5	14	0	265
1982	0	16.9	0	53	39.5	25	8	19	161.4
1983	0	20	20	83.2	47	44.1	3.8	0	218.1
1984	0.5	13.8	7.7	79.3	19.7	30	5.6	0	156.6
1985	17.4	20	15.6	18.2	48.7	44.3	2.5	2.8	169.5
1986	1.8	0	43.8	20.8	25.8	4.7	30.9	9.6	137.4
1987	19.7	77.4	0	16	14.7	55.8	0	0	183.6
1988	13.2	2.4	73	20	39.9	27.5	14.4	0.6	191
1989	6.1	7.3	68.8	26.6	6.6	16.3	0.8	1.6	134.1

Monthly and Annual Rainfall for Kirbet Awwad

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1964	9	6	35	62.9	50.4	30	0	0	193.3
1965	0	37.5	40.7	164	18.5	13.5	32.4	0	306.6
1966	20.7	3	7.5	4.3	56	92	0	0	183.5
1967	24.9	18.5	135.9	115.8	36.6	107.4	0	23	462.1
1968	10	42.5	4.5	94	46	1	2	4	204
1969	6	10	40.5	89.5	15	98	15	4.5	278.5
1970	13.5	12	0	47	23.5	89	24	0	209
1971	0	0	21	46.5	39	14	101	0	221.5
1972	0	4	45	22	50	46.5	29	0	196.5
1973	2.5	37	7.5	47.5	3.5	29	0	0	127
1974	14.2	33.4	15.7	106.6	92.3	17.5	7.7	0	287.4
1975	0	12	13.4	11.6	70.7	32.8	7.6	0	148.1
1976	0	5.5	45.6	21.1	45.5	62.5	23.3	9	212.5

1977	21.2	11	0	58.2	18.7	28.5	32.6	0	170.2
1978	0	4.3	54.5	31.6	22.5	39	5	0	156.9
1979	2	0	23.8	26.8	18	13.6	7.3	0	91.5
1980	4.6	71.5	70	41.1	57.8	46.3	12	0	303.3
1981	0	4.5	93.5	13	41	11.6	13.8	0	177.4
1982	0	12.3	0	48	48	47.7	7.5	12	175.5
1983	3.2	24.4	14.7	99.9	38.9	37	2	2	222.1

Monthly and Annual Rainfall for Salkhad

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	TOTAL
1964	10.1	11.4	99.5	89.2	118.1	90.8	23.3	0	442.4
1965	0	85.6	43.2	189.2	74.8	41.3	37.7	0	471.8
1966	34.4	10.7	35.9	31.8	77.1	106.5	0.9	6	303.3
1967	33	19.3	54.4	125.5	68.8	153.4	6.2	78.6	539.2
1968	32	50.9	50.3	122.2	31.6	41.9	8	17.7	354.6
1969	8.4	12.4	81.1	115.5	24.9	107.4	30.2	5.4	385.3
1970	40.8	35.3	15	56.6	34.8	99.2	11	0	292.7
1971	1.6	33.7	47.6	70.1	72	22.2	165.7	0	412.9
1972	0	14	152.2	44.7	78.1	37	29	0	355
1973	4	41	9.4	83.1	9.8	79.9	7	0	234.2
1974	67.4	53.7	33.8	176.4	148.3	35.5	16.7	0	531.8
1975	0	12	23.8	14	114	29.9	6.4	0	200.1
1976	0	13.6	80.6	37.4	95.5	113	26.4	6	372.5
1977	41.4	27.4	5	106.6	26.4	60.7	70	0	337.5
1978	24.7	10.7	60.5	45.4	43.4	25.6	6.5	0	216.8
1979	1.4	0	44	46	27.6	47	8	0	174
1980	24	119.4	123.2	79	85.8	84.4	16.8	0	532.6
1981	6	10	183	41	63.8	38	23	0	364.8
1982	0	47.4	6.6	56.6	84.4	79.5	12.5	18	305
1983	10.8	51.4	32	62.1	154.8	75.1	5.5	0	391.7
1984	2	21.5	10	89	40.5	125.5	19	0	307.5
1985	19.9	21.2	46	28.5	150.3	64	4.8	5.5	340.2
1986	2	37	28	54	126.5	15	70.5	0	333
1987	24.5	135.5	52.5	69	29.5	139.5	0	0	450.5
1988	15.8	0	110.5	100.9	58	136.5	24	0	445.7
1989	2.6	23.3	137	33	16	54	3.5	7	276.4
1990	0	23.5	31	93.8	88	46.6	0	0	282.9

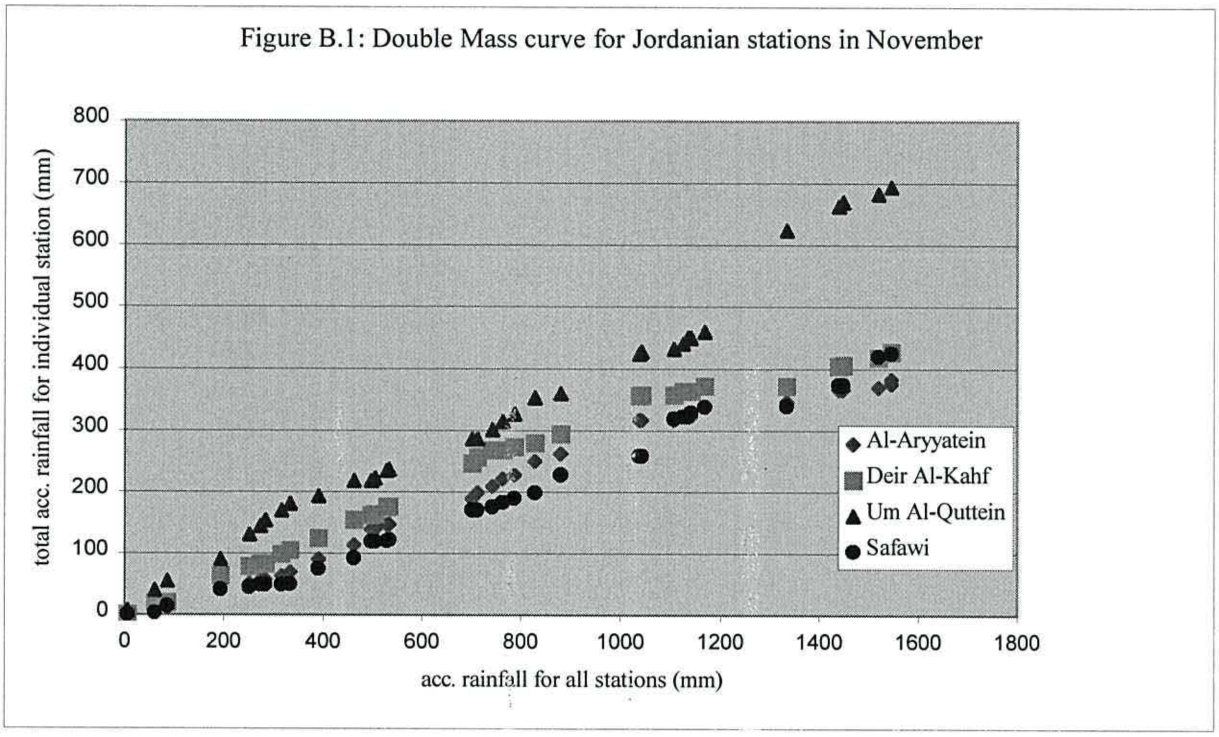


Figure B.1: Double Mass curve for Jordanian stations in November
total acc. rainfall for individual station (mm)
acc. rainfall for all stations (mm)
0
100
200
300
400
500
600
700
800
0
200
400
600
800
1000
1200
1400
1600
1800
Al-Aryyatein
Deir Al-Kahf
Um Al-Quttein
Safawi

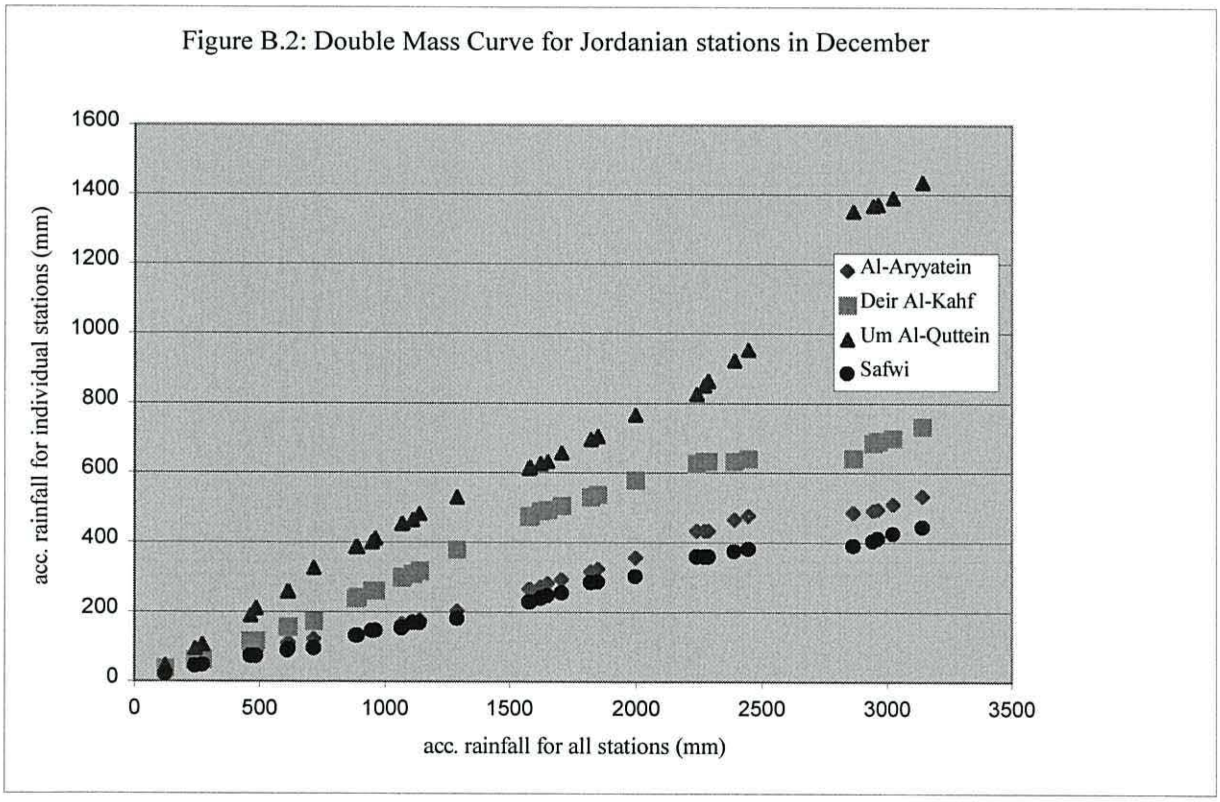
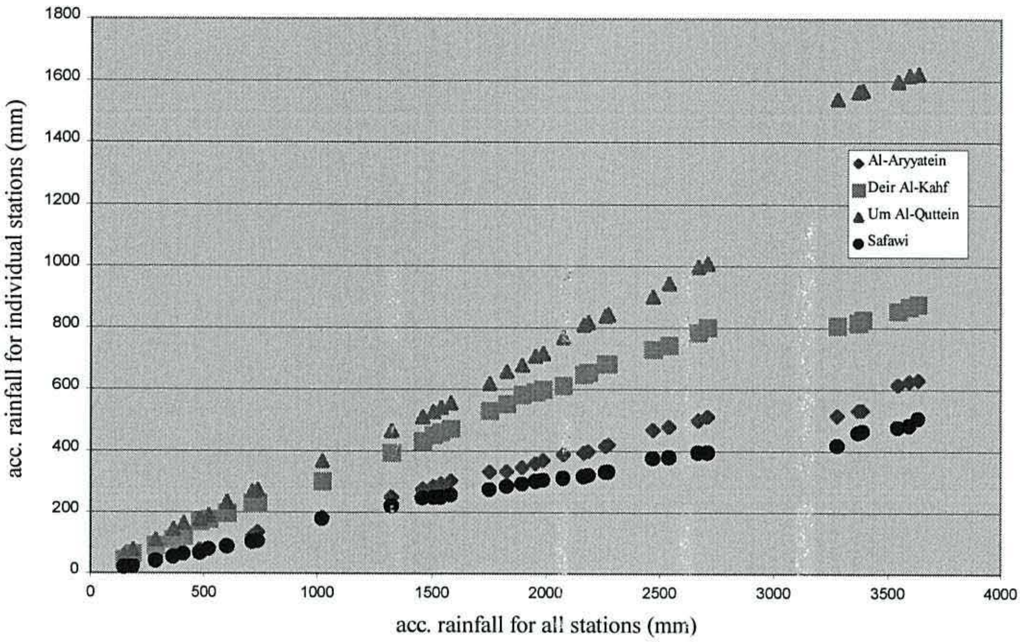


Figure B.2: Double Mass Curve for Jordanian stations in December
acc. rainfall for individual stations (mm)
acc. rainfall for all stations (mm)
0
200
400
600
800
1000
1200
1400
1600
0
500
1000
1500
2000
2500
3000
3500
Al-Aryyatein
Deir Al-Kahf
Um Al-Quttein
Safwi

Figure B.3: Double Mass Curve for Jordanian stations in February



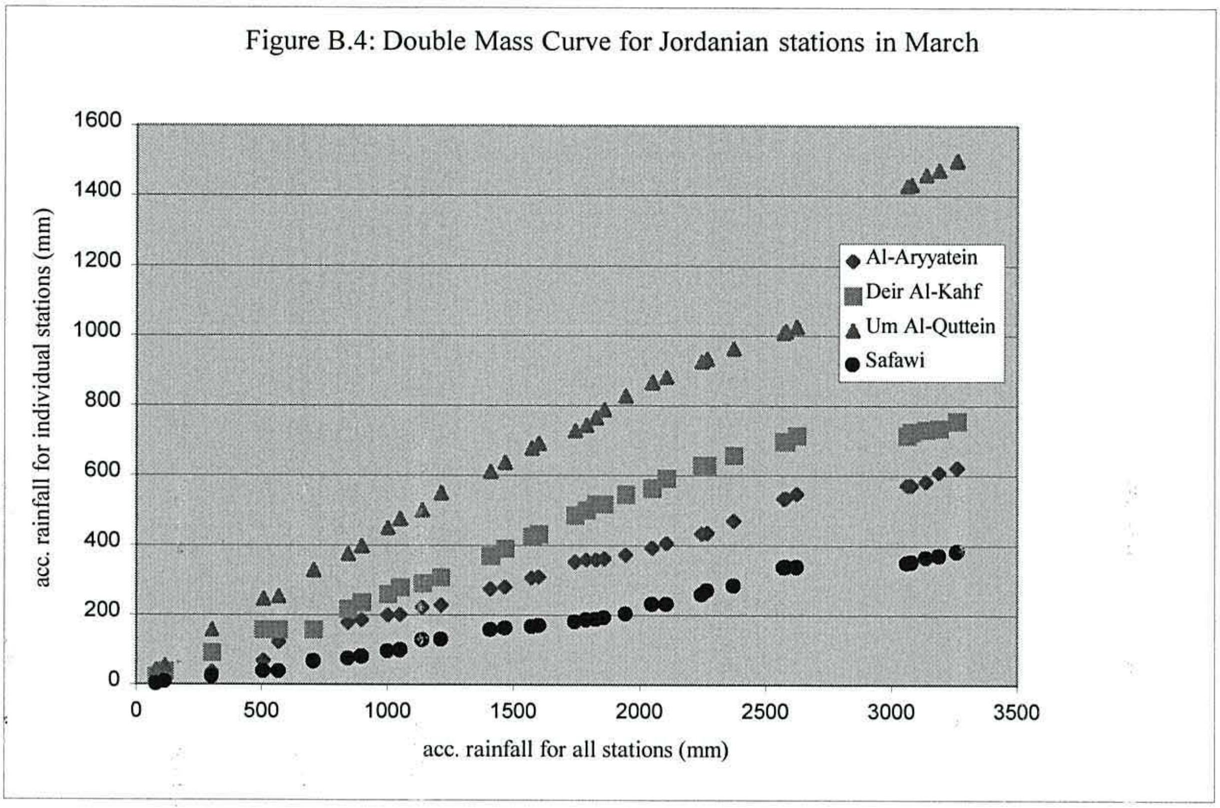


Figure B.4: Double Mass Curve for Jordanian stations in March
acc. rainfall for individual stations (mm)
acc. rainfall for all stations (mm)
Al-Aryyatein
Deir Al-Kahf
Um Al-Quttein
Safawi
0
200
400
600
800
1000
1200
1400
1600
0
500
1000
1500
2000
2500
3000
3500

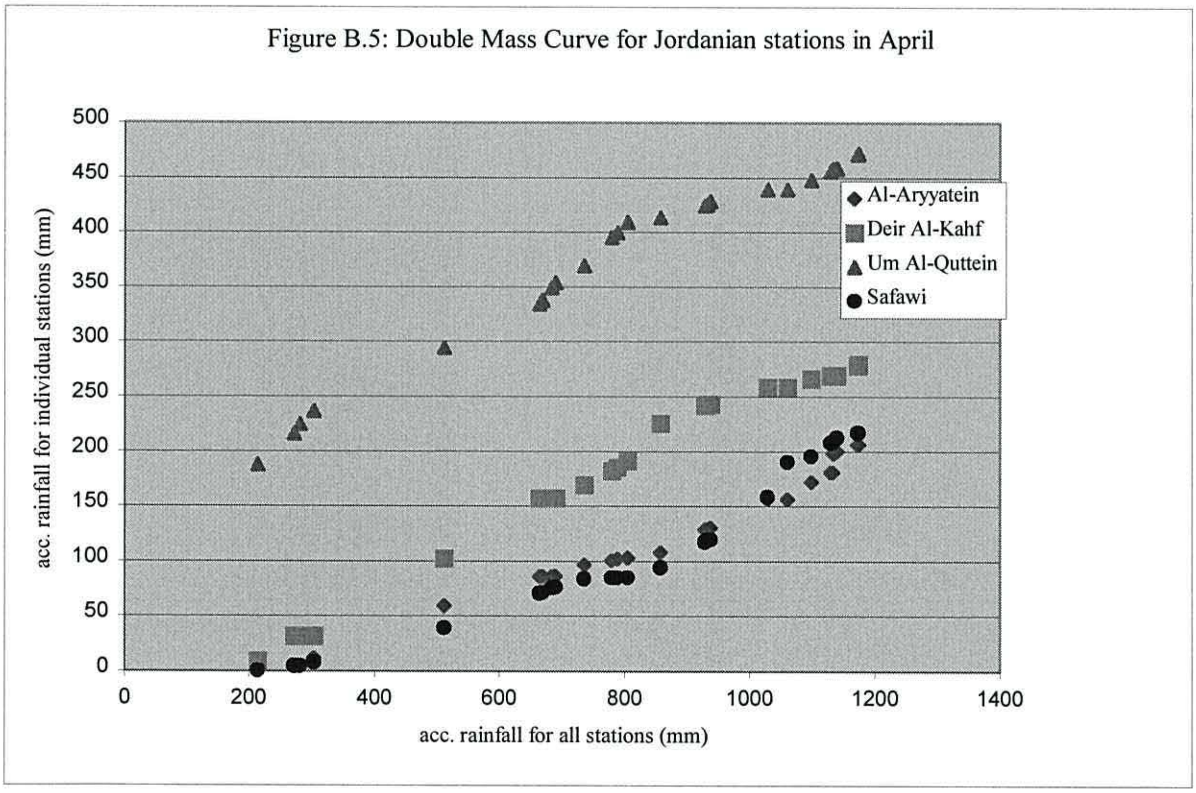


Figure B.5: Double Mass Curve for Jordanian stations in April
acc. rainfall for individual stations (mm)
acc. rainfall for all stations (mm)
Al-Aryyatein
Deir Al-Kahf
Um Al-Quttein
Safawi
0
50
100
150
200
250
300
350
400
450
500
0
200
400
600
800
1000
1200
1400

Figure B.6: Double Mass Curve for Syrian stations in November

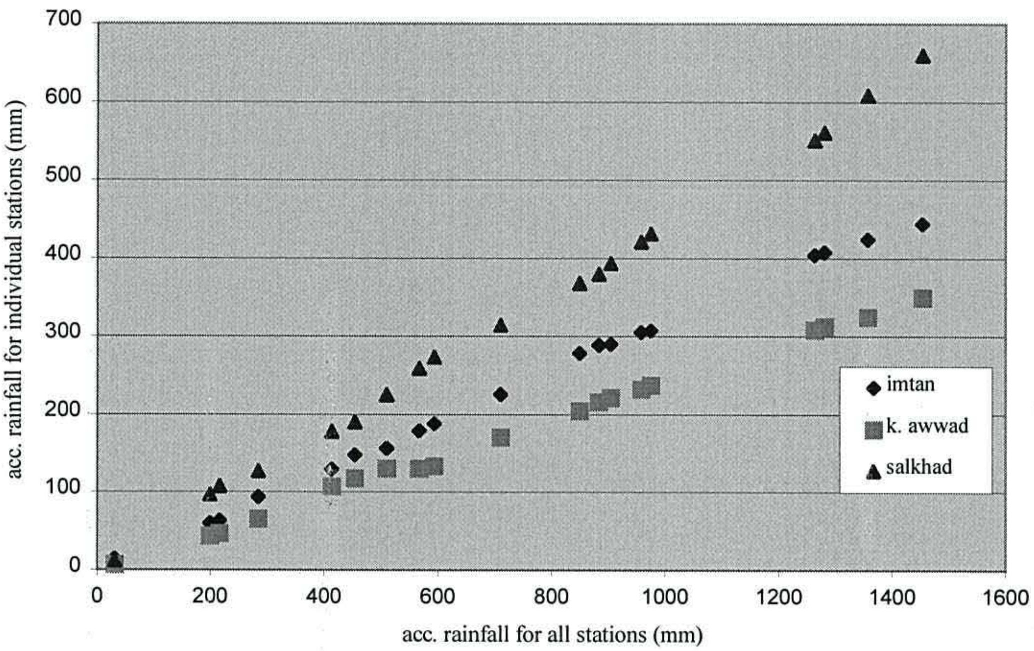
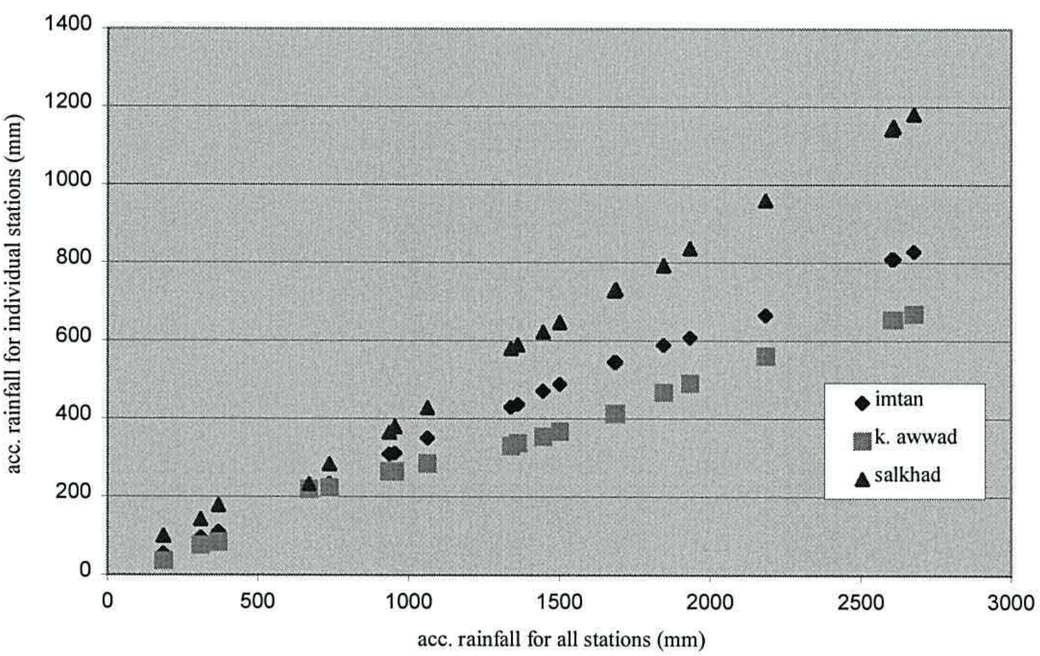


Figure B.7: Double Mass Curve for Syrian stations in December



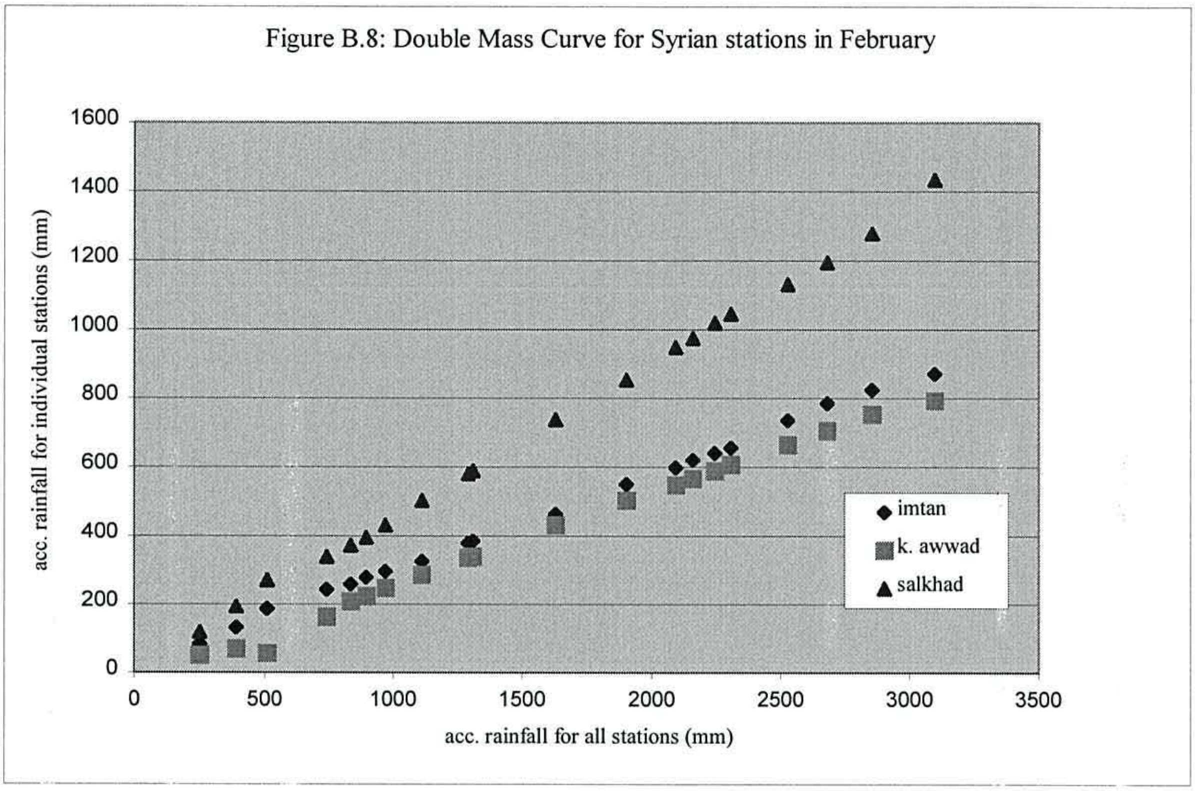


Figure B.8: Double Mass Curve for Syrian stations in February
acc. rainfall for individual stations (mm)
acc. rainfall for all stations (mm)
imtan
k. awwad
salkhad
0
200
400
600
800
1000
1200
1400
1600
500
1000
1500
2000
2500
3000
3500

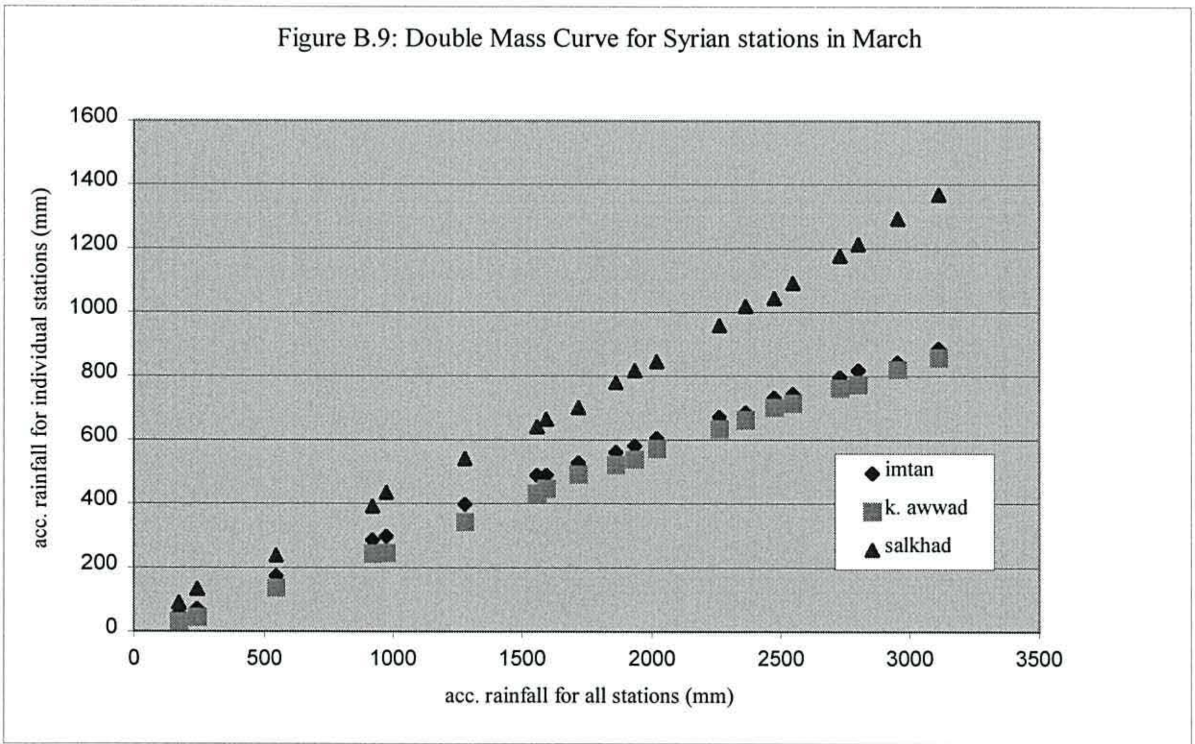
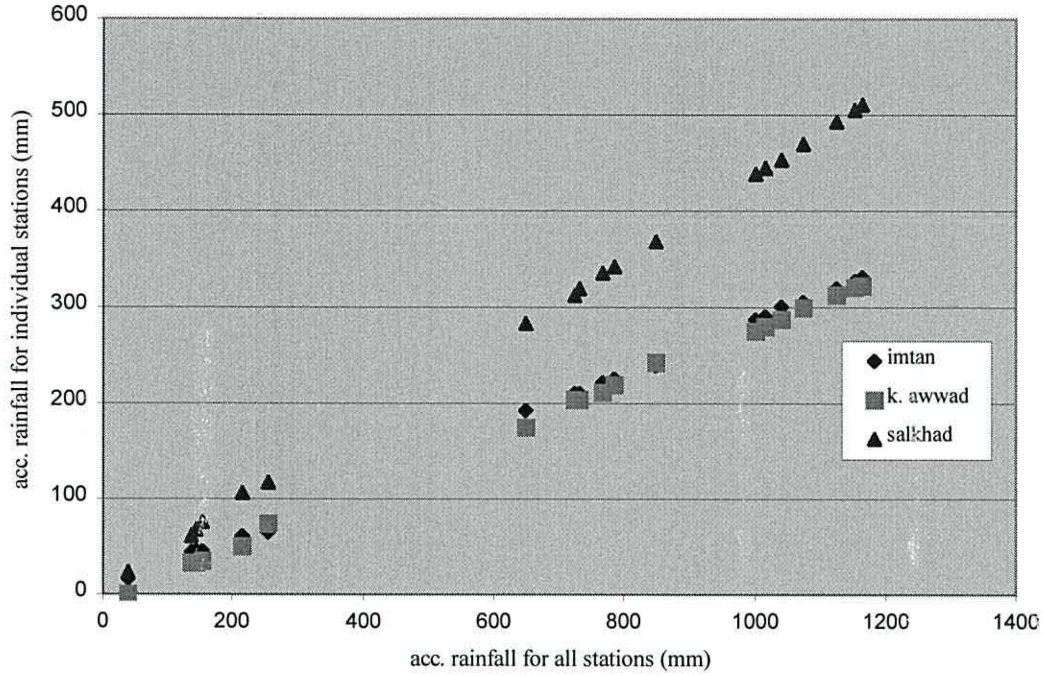


Figure B.9: Double Mass Curve for Syrian stations in March
acc. rainfall for individual stations (mm)
acc. rainfall for all stations (mm)
imtan
k. awwad
salkhad
0
200
400
600
800
1000
1200
1400
1600
500
1000
1500
2000
2500
3000
3500

Figure B.10: Double Mass Curve for Syrian stations in April



APPENDIX C

- CREST GAUGES DESIGN AND FLOW RATING CURVES FOR GAUGING STATIONS

Figure C.1: Crest Gauges Design (obtained from the USGS)

CREST-STAGE GAGE

The crest-stage gage is a device for obtaining the elevation of the flood crest of streams. The gage is widely used in the U.S.A. because it is simple, economical, reliable, and easily installed. Because of those attributes the crest-stage gage has become a basic instrument in regional studies of flood frequency. For such studies the network of standard gaging stations is augmented by a network of crest-stage gages, thereby providing flood-peak information at a great many sites in the region at reasonable cost.

A crest-stage gage is also a valuable adjunct to the nonrecording gage at nonrecording gaging stations. It provides a record of the peak stages of stream rises, and those stages can be used with the observer's routine readings when sketching the estimated continuous-stage graph through the plotted points of observed stage.

Many different types of crest-stage gages have been tested by the U.S. Geological Survey. (See, for example, Friday, 1965, and Carter and Gamble, 1963.) The one found most satisfactory is a vertical piece of 2-in (0.05 m) galvanized pipe containing a wood or aluminum staff held in a fixed position with relation to a datum reference. (See fig. 40.) The bottom cap has six intake holes located as shown in figure 40 to minimize nonhydrostatic drawdown or superelevation inside the pipe. Tests have shown this arrangement of intake holes to be effective with velocities up to 10 ft/s (3 m/s) and at angles up to 30 degrees with the direction of flow. The top cap contains one small vent hole.

The bottom cap, or a perforated tin cup or copper screening in cup shape attached to the lower end of the staff, contains regranulated cork. As the water rises inside the pipe the cork floats on the water surface. When the water reaches its peak and starts to recede the cork adheres to the staff inside the pipe, thereby retaining the crest stage of the flood. The gage height of a peak is obtained by measuring the interval on the staff between the reference point and the floodmark. Scaling can be simplified by graduating the staff. The cork should be cleaned from the staff before replacing the staff in the pipe to prevent confusion with high-water marks that will be left by subsequent peak discharges.

The datum of the gage should be checked by levels run from a reference mark to the top of the staff, the graduated staff being of

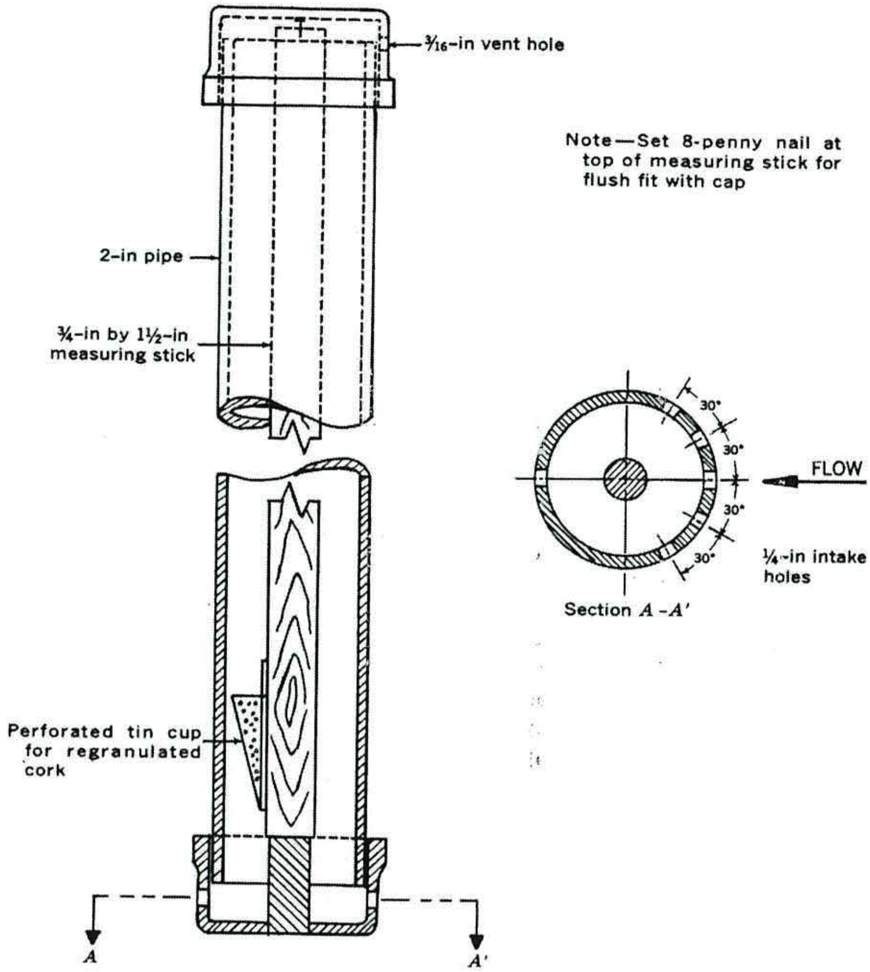


FIGURE 40.—Crest-stage gage.

known length. The gage itself should be serviced on a regular basis. However, the staff should not be removed from the pipe for any reason when the stage is high. If, after such removal, the staff is reinserted when water stands high in the pipe, the resulting surge of the water displaced by the staff will leave an artificial "high-water mark" on the staff.

Table C.1: Crest gauges reading for Marab Hassan catchment area

Date	Eastern Hassan	Western Hassan	Outlet
14/12/00	70	100	110
21/12/00	108	135	150
4/2/01	no flood in Hassan	75.5	109
27/2/01	64	37	75

Figure C.2: Sub-catchment 1 SCS, Snyder and GIUH (s) before routing through the Marab

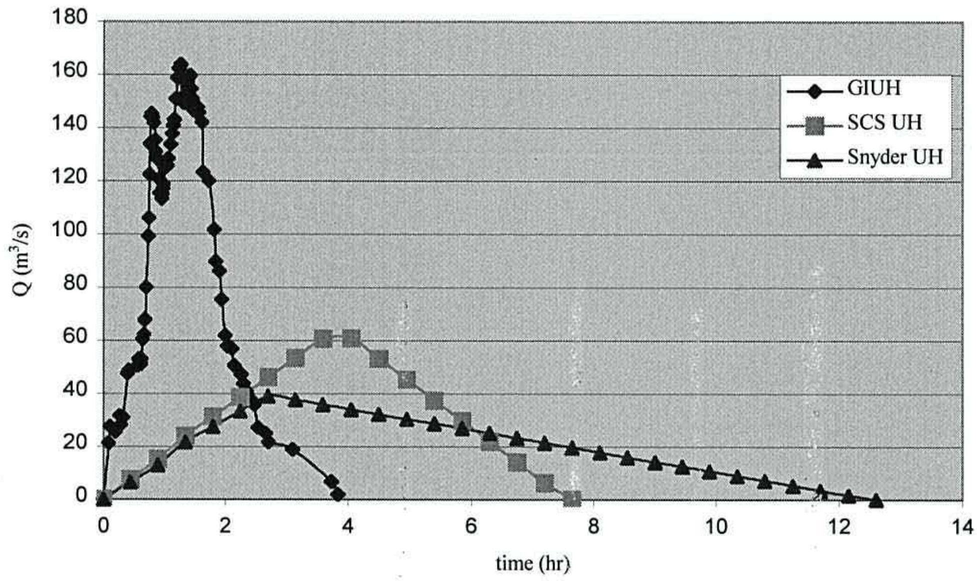


Figure C.3: Sub-catchment 2 SCS, Snyder and GIUH (s) before routing through the Marab

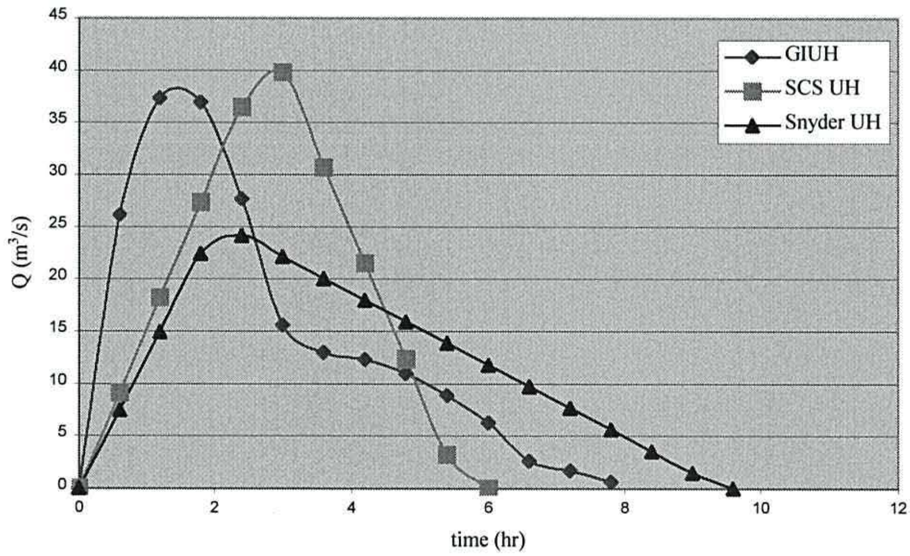


Figure C.4: Sub-catchment 3 SCS, Snyder and GIUH (s) before routing through the Marab

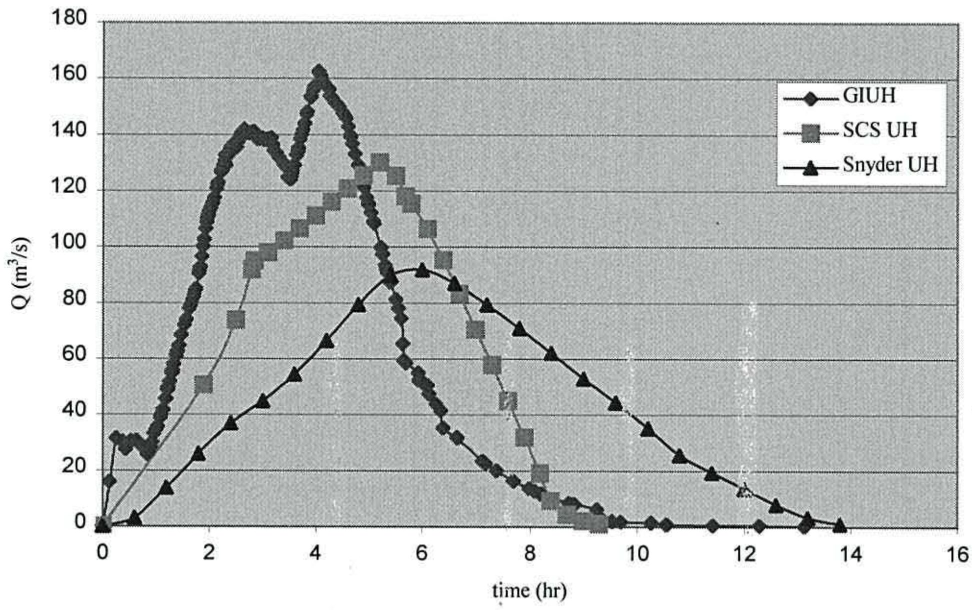


Figure C.5: Cross-section of the Eastern inlet of Marab Hassan

Project Description	
Project File	c:\fmw\hassan.fm2
Worksheet	East Hassan Area
Flow Element	Irregular Channel
Method	Manning's Formula
Solve For	Discharge

Section Data		
Wtd. Mannings Coefficient	0.028	
Channel Slope	0.014900	m/m
Water Surface Elevation	101.07	m
Discharge	61.30	m³/s

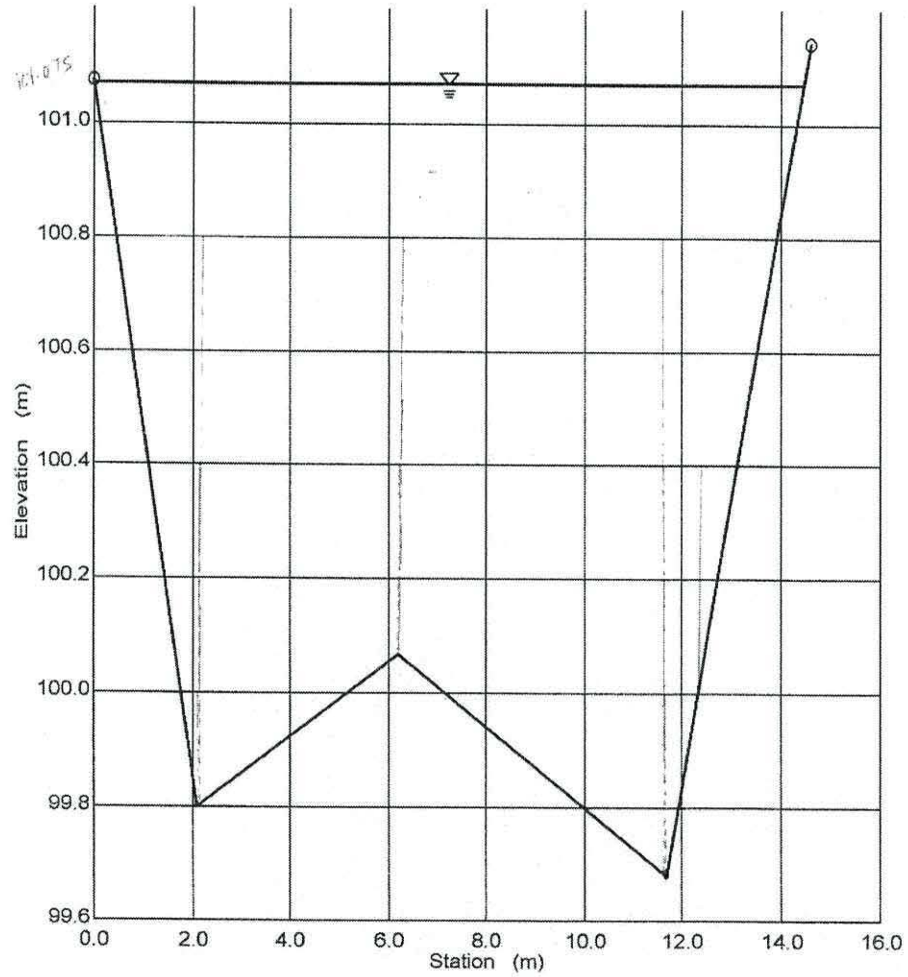


Figure C.6: Flow rating curve for the Eastern inlet of Marab Hassan

Project Description	
Project File	c:\fmw\hassan.fm2
Worksheet	East Hassan Area
Flow Element	Irregular Channel
Method	Manning's Formula
Solve For	Discharge

Constant Data	
Channel Slope	0.014900 m/m

Input Data	Minimum	Maximum	Increment
Water Surface Elevation	-0.39	1.08	0.01 m

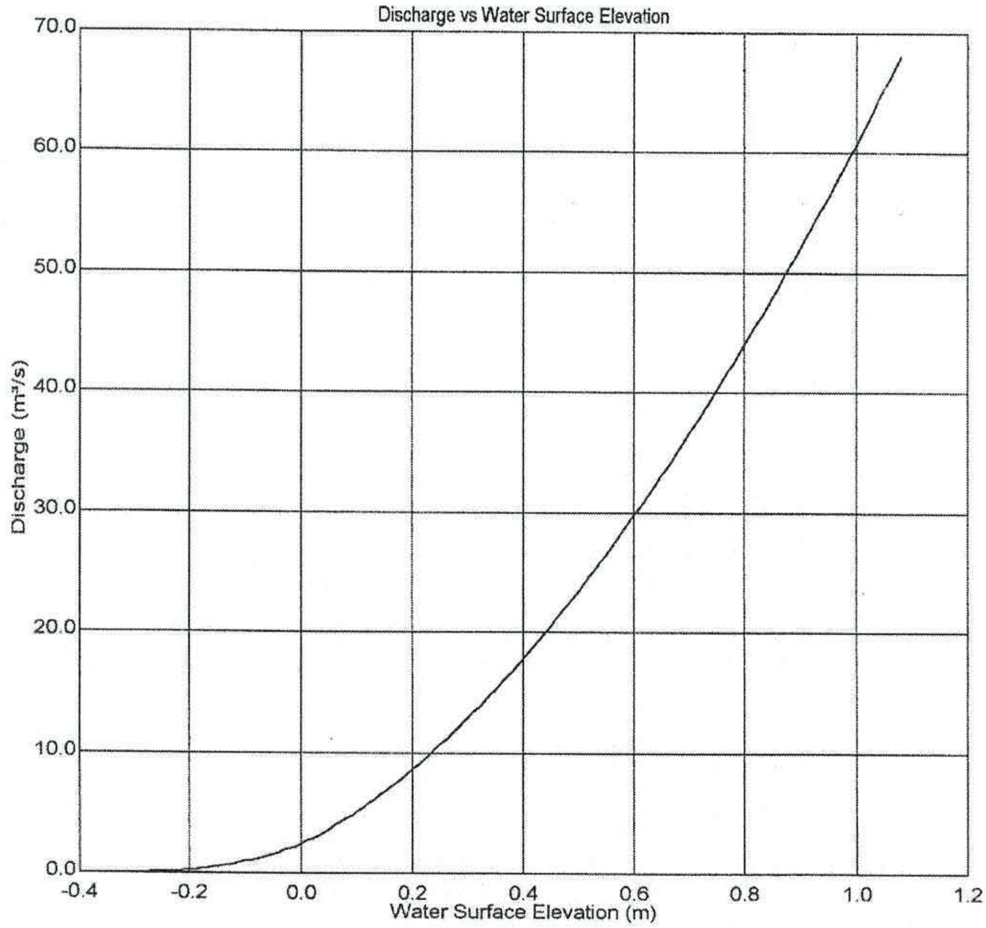


Figure C.7: Cross-section of the Western inlet of Marab Hassan

Project Description	
Project File	c:\fmw\project2.fm2
Worksheet	rug-hassan
Flow Element	Irregular Channel
Method	Manning's Formula
Solve For	Discharge

Section Data		
Wtd. Mannings Coefficient	0.035	
Channel Slope	0.016200	m/m
Water Surface Elevation	1.54	m
Discharge	52.59	m³/s

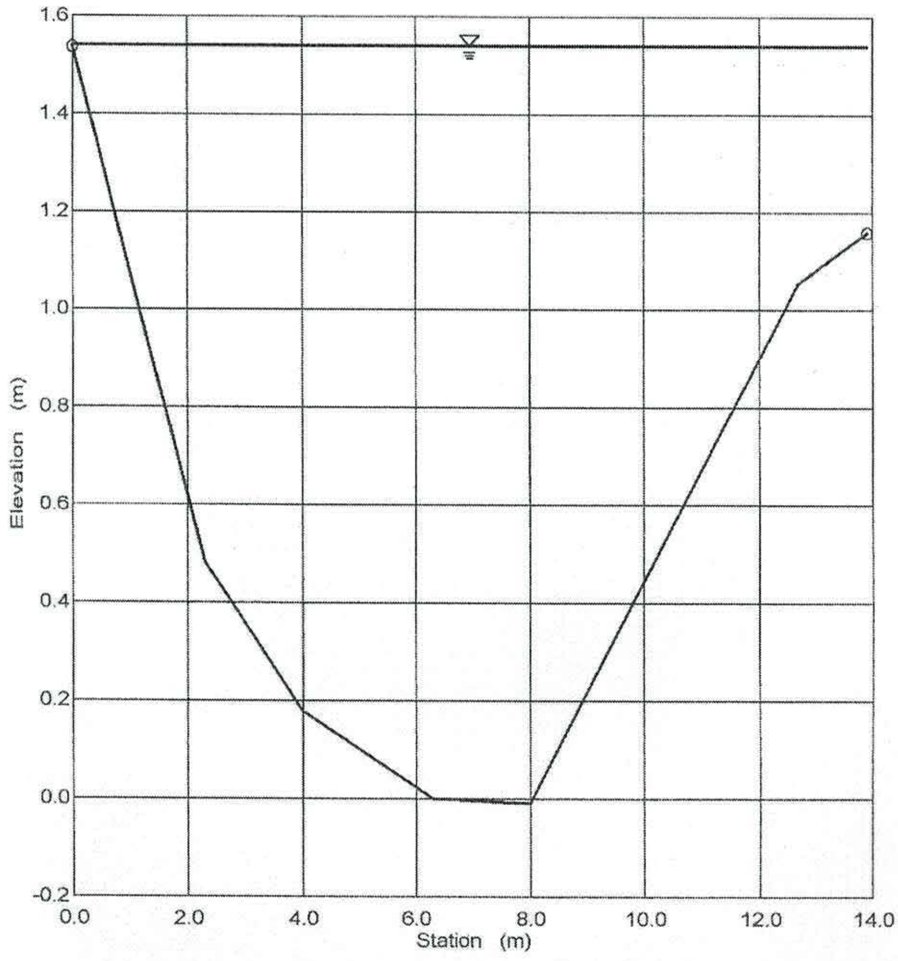
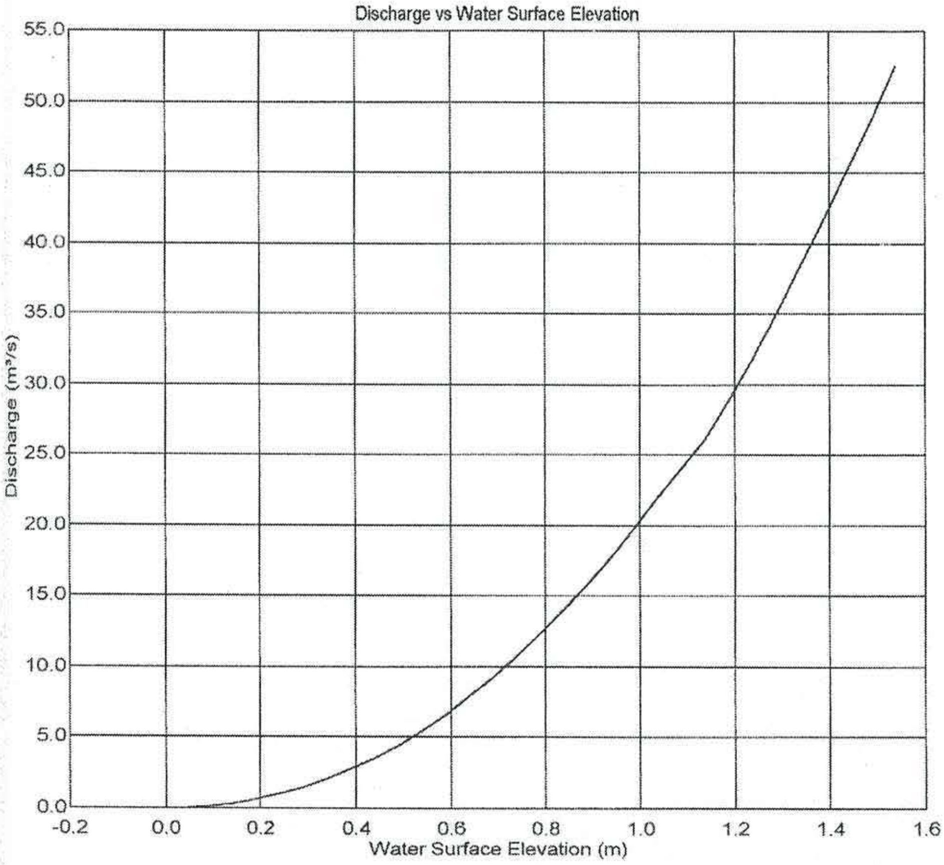


Figure C.8: Flow rating curve for the Western inlet of Marab Hassan

Project Description	
Project File	untitled
Worksheet	rug-hassan
Flow Element	Irregular Channel
Method	Manning's Formula
Solve For	Discharge

Constant Data	
Channel Slope	0.016200 m/m

Input Data	Minimum	Maximum	Increment
Water Surface Elevation	-0.01	1.54	0.05 m



APPENDIX D

GIS COMMANDS FOR EXTRACTING CATCHMENT CHARACTERISTICS

GIS Commands

1. DEM Generation for Marab Hassan Catchment area

Arc: Topogrid demall 30
Topogrid: datatype contour
Topogrid: contour data height
Topogrid: tolerance 2.5 1 0
Topogrid: end

2. Flow Direction

Grid: flow-dir= flowdirection (DEM)

3. Flow Accumulation

Grid: flow-acc= flowaccumulation (flow-dir)

4. Flow Length

Grid: Flowlenght=flowlength ({dir-grid}, {weight-grid}, {downstream|upstream})

5. Stream Network Derivation

Grid: streamnet = con (flow-acc > 100, 1)

In the above all cells with more than 100 cells flowing into them are given a value of 1, and all others are assigned as NODATA.

or

Grid: streamnet = setnull (flow-acc < 100, 1)

In the above all cell with less than 100 cells flowing into them are given a value of 1, and all others are assigned as NODATA.

6. Stream Order

Grid: usage streamorder
Usage: STREAMORDER (<net_grid>, <dir_grid>, {STRAHLER, SHREVE}

7. Watershed (Catchment) Delineation

Catchment = watershed(<dir-grid>, selectpoint(dem,))*

Points are selected manually from the screen from using the derived stream network as a guide.

SNAPPOUR (<| source_grid | point _file>, <acc_grid>, {snap_distance})*

Grid: watershed = watershed (flow-dir, pour-points)

Minimum stream length:

Grid: length=flowlength (flow-dir)

Grid: lenmin =zonalmin (watershed, length)

Individual stream length:

Grid: lenmax=zonalmax (watershed, length)

Grid: watershedlenght=lenmax-lenmin

To get the stream order, length and sub_ID for each sub-area:

Grid: watershedorder=(order+watershed) - watershed

Grid: orderlength=combine (watershedorder, length)

Grid: watershedlenght=combine (watershedlenght, watershedorder, watershed)

Then to download the data in tabular format, the Tables command is used:

Tables: select watershedlenght.dat

Tables: unload watershedlenght.dat watershed watershedorder watershedlength lenmin

8. Slope and Aspect

Grid: slope

Grid: slope = slope (dem, percentrise)

Grid: aspect

Grid: aspect = aspect (dem)

APPENDIX E

PARTICIPATING RURAL APPRAISAL QUESTIONAIRE

Participatory Rural Appraisal Questionnaire

The catchment area:

1. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year, excluding 1998-2000.
What was the maximum depth?	Almost 1.5 m.
When did the major events happen?	1997/98, 2000/2001
Frequency of the floods?	2-3 times a year
After the flood happens how long does it take for the water level to reach zero?	24-36 hours.
Any ideas about the rainfall duration?	20-30 minutes either at night or during late afternoon. It is thunder type of rain

2. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year except between 1998-2000 when it was dry.
What was the maximum depth?	> 2 m.
When did the major events happen?	1993/94 or 1994/95, 1996/97 or 1997/98 (not sure) and 2000/2001, but there was 3 major floods.
Frequency of the floods?	2-3 times a year
After the flood happens how long does it take for the water level to reach zero?	It takes 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last between 10-15 and maximum 30 minutes.

3. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year a part from the last three years (1998-2000) when it was completely dry.
What was the maximum depth?	> 1.5 m.
When did the major events happen?	1994/95, 1996/97, 2000/2001
Frequency of the floods?	Before 1997 Wadi was flowing 2-3 times a year
After the flood happens how long does it take for the water level to reach zero?	It takes 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last between 10-15 and maximum 30 minutes.

4. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year except the last three years (1998-2000) when it did not.
What was the maximum depth?	> 1m.
When did the major events happen?	1986/87, 1991/92, 1994/95, 1996/97, 2000/2001
Frequency of the floods?	Wadi flows 2-3 times a year
After the flood happens how long does it take for the water level to reach zero?	It takes 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last for 15 and maximum 30-45 minutes, in the afternoon or at night.

5. Group interview

How many flood events did you have in the past 15-20 years?	Before 1990s it was wetter with good pasture. Between 1990-95 the Wadi flowed annually, while between 1995-2001it only flowed three times.
What was the maximum depth?	60-70 cm and in some places it reached > 1 m.
When did the major events happen?	1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 4-5 times a year in good years, but in very dry years it does not flow at all.
After the flood happens how long does it take for the water level to reach zero?	It takes 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last for 10-25 and maximum 30-45 minutes, in the afternoon or at night.

6. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	1 m but in the open parts it reaches 50-60 cm.
When did the major events happen?	1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 2-3 times a year.
After the flood happens how long does it	It takes 24 hours for the flow to reach

take for the water level to reach zero?	zero.
Any ideas about the rainfall duration?	Thunder storms last for 10-20 and maximum 30 minutes, in the afternoon or at night. Thunder storms only cause floods.

7. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	> 2.5 m.
When did the major events happen?	1980/81, 1981/82, 1983/84, 1984/85, 1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 2-3 times a year.
After the flood happens how long does it take for the water level to reach zero?	It takes 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms last for 10-30 minutes, in the afternoon or at night. Thunder storms cause floods.

8. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	1-1.5 m.
When did the major events happen?	1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 3-5 times per year.
After the flood happens how long does it take for the water level to reach zero?	It needs one day for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms last for 20-50 minutes, in the afternoon or at night.

9. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	1-2.5 m.
When did the major events happen?	1944/45, 1948/49, 1968/69, 1983/84, 1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.

Frequency of the floods?	Wadi flows 2-3 times per year.
After the flood happens how long does it take for the water level to reach zero?	It needs one day for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms last for 15-45 minutes, in the afternoon or at night. Few of them that last for few days cause the flood.

10. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	1.5-3 m.
When did the major events happen?	1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 2-3 times per year.
After the flood happens how long does it take for the water level to reach zero?	It needs one day for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms last for 30 minutes, in the afternoon or at night.

11. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year, but it was dry between 1998-2000.
What was the maximum depth?	1-2 m.
When did the major events happen?	1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 3-4 times per year.
After the flood happens how long does it take for the water level to reach zero?	It needs 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms last for 20-30 minutes, in the afternoon or at night. Heavy thunderstorms cause flood.

12. Group Interview

How many flood events did you have in the past 15-20 years?	In the last 10 years the Wadi did not flow each year, while before that it used to flow yearly.
What was the maximum depth?	1.5-2.5 m
When did the major events happen?	1991/92, 1993/94, 1996/97, 1997/98, 2000/2001.

Frequency of the floods?	Wadi flows 3-4 times a year in good years, but in very dry years it does not flow at all like between 1998-2000.
After the flood happens how long does it take for the water level to reach zero?	It takes one day for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last for 30-45 minutes, in the afternoon or at night.

13. Group Interview

How many flood events did you have in the past 15-20 years?	If it is a good year the Wadi flows, if it is not it does not. Normally it flows almost every year.
What was the maximum depth?	1-2.5 m
When did the major events happen?	1981/82, 1983/84, 1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 3-4 times a year in good years, but in very dry years it does not flow at all.
After the flood happens how long does it take for the water level to reach zero?	It takes one day for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last for 20-40 minutes, in the afternoon or at night.

14. Group Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	1-2 m
When did the major events happen?	1981/82, 1983/84, 1984/85, 1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows on average of 3-4 times a year in good years, but in very dry years it might flood once or it might not at all.
After the flood happens how long does it take for the water level to reach zero?	It takes one to one and a half-day for the flow to reach zero.
Any ideas about the rainfall duration?	Thunderstorms that last for 15-30 minutes occur in the afternoon or at night.

15. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.

What was the maximum depth?	> 2 m.
When did the major events happen?	1981/82, 1984/85, 1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 2-3 times a year.
After the flood happens how long does it take for the water level to reach zero?	It takes 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms last for 20-30 minutes, occur in the afternoon or at night and cause floods.

16. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	1-2 m but in the open parts it reaches 60-70 cm.
When did the major events happen?	1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 2-3 times a year.
After the flood happens how long does it take for the water level to reach zero?	It takes 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunderstorms cause floods most of the time, and they last for 20-30 minutes. Most of the time they occur late afternoon or at night.

17. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year except the last three years (1998-2000) when it did not.
What was the maximum depth?	1-1.5 m.
When did the major events happen?	1986/87, 1991/92, 1994/95, 1996/97, 2000/2001
Frequency of the floods?	Wadi flows 3-4 times in a good year
After the flood happens how long does it take for the water level to reach zero?	It takes 24 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last for 20 and maximum 30-45 minutes, in the afternoon or at night.

18. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	2 m.
When did the major events happen?	1993/94, 1996/97, 1997/98 and 2000/2001.
Frequency of the floods?	2-3 times a year
After the flood happens how long does it take for the water level to reach zero?	It takes 24-36 hours for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last between 10-15 and maximum 30 minutes.

19. Individual Interview

How many flood events did you have in the past 15-20 years?	The Wadi flows almost every year.
What was the maximum depth?	1.5-2.5 m.
When did the major events happen?	1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 3-4 times per year.
After the flood happens how long does it take for the water level to reach zero?	It needs one day for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms type of rain that last for 20-30 minutes, in the afternoon or at night.

20. Group Interview

How many flood events did you have in the past 15-20 years?	Mostly the Wadi flows every year, except between 1998-2000 when it did not flow at all.
What was the maximum depth?	1.5-2 m
When did the major events happen?	1991/92, 1994/95, 1996/97, 1997/98, 2000/2001.
Frequency of the floods?	Wadi flows 2-4 times a year in good years, but in very dry years it does not flow.
After the flood happens how long does it take for the water level to reach zero?	It takes one day for the flow to reach zero.
Any ideas about the rainfall duration?	Thunder storms that last for 30-40 minutes.

APPENDIX F
GLOBAL CLIMATIC INDICES (ENSO SST, SOI, NAOI and Indian Ocean SST Anomalies)

Indices obtained from the following Web addresses

- ENSO SST (http//:www.jisao.washington.edu/date_sets/globalsstenso)
- SOI(www.cru.uae.as.uk/cru/data/soi.htm)
- NAOI (www.cru.uae.as.uk/cru/data/nao.htm)
- Indian Ocean SST Anomalies (http:/tao.atmos.washington.edu/data_sets/ind

Table F.1: North Atlantic Oscillation Index

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1959	-1.15	2.46	1.82	1.51	-2.22	1.51	0.29	0.02	-1.81	1.51	-0.04	1.98
1960	-0.7	-1	-0.87	1.93	0.07	-0.41	0.18	-1.84	0.24	-3.08	1.4	0.46
1961	1.46	4.06	2.08	0.71	-0.94	2.13	0.63	3.38	2.01	1	-2.15	-1.72
1962	2.44	0.77	-3.78	0.74	-0.1	1.41	-2.1	2.28	0.02	-0.34	-2.23	-0.66
1963	-4.09	-1.9	2.79	-0.46	1.91	-1.77	-0.65	-0.96	0.94	2.79	-0.15	-3.09
1964	0.93	-0.13	-0.77	0.95	2.51	-1.85	2.44	-2.46	0.5	0.63	1.33	-1.24
1965	0.01	-3.03	0.23	2.14	-0.08	0.87	-1.71	1.59	-1.01	-1.26	-1.78	1.24
1966	-1.01	-0.38	1.05	1.18	1.51	0.82	-1.99	-2.03	-0.47	-2.89	-0.07	1.68
1967	0.04	1.7	3	-0.76	-0.46	1.96	1.44	-0.41	0.32	1.34	-0.91	-0.53
1968	1.65	-1.53	0.34	-0.71	-1.5	0.95	-1.96	-1.45	0.5	0.03	-2	-1.73
1969	-1.64	-3.16	-1.81	1.11	-0.23	-1.17	3.7	-1.62	0.38	0.7	-1.28	-0.26
1970	-1.16	1.1	-1.78	2.52	1.87	-0.11	0.27	-0.2	0.47	0	0.76	-1.58
1971	-0.43	1.21	-1.76	-3.15	-0.62	-1.32	-1.04	0.07	-0.54	1.63	-1.46	0.76
1972	-0.52	-0.2	0.26	0.22	1.24	1.07	0.41	0.11	-4.11	-1.74	0.64	2.11
1973	1.37	1.22	1.04	-2.61	0.37	0.83	-1.85	2.32	-0.79	-1.03	-0.26	-1.65
1974	3.75	0.68	-0.81	-2.3	-0.01	-0.14	2.07	0.89	0.11	-1.44	1.27	3.06
1975	2.43	0.4	-1.26	-0.84	-2.42	0.18	0.63	0.08	1.75	0.39	0.86	-1.57
1976	0.75	1.29	1.87	-1.53	1.2	1.76	-0.57	0.62	-3.46	-0.64	1.5	-3.63
1977	-2.36	0.28	1.33	1.07	-1.62	-0.89	-1.14	-1.42	1.64	0.45	0.37	-0.25
1978	0.46	-1.99	3.1	-3.12	0.37	0.14	-0.33	0.05	1.96	0.02	3.91	-2.08
1979	-3.22	-0.62	0.54	-0.79	1	0.45	2.53	-0.85	1.12	-1.95	1.95	2.07
1980	-1.8	0.7	-0.68	0.03	-2.26	-0.2	-0.91	0.3	1.72	-0.87	-2.06	1.55
1981	1	1.04	0.01	-3.04	0.05	-1.57	1.74	1.01	0.27	-1.06	1.66	-2.2
1982	-0.72	2.25	1.66	-0.99	1.1	-1.86	-0.65	1.45	1.08	0.32	1.71	2.64
1983	4.82	-1.25	1.79	-1.01	-0.57	0.54	-0.75	0.56	-0.65	2.06	-2.28	0.83
1984	2.53	1.73	-2.12	0.33	-2.34	0.33	0.93	1	-1.31	1.66	-1.16	1.52
1985	-2.87	-0.24	0.07	0.34	-2.13	-1.08	1.09	2.33	0	0.14	-2.85	-0.43
1986	1.46	-4.02	2.86	-0.93	2.16	-1.29	0.88	-2.21	-1.34	2.27	3.41	3.42
1987	-2.12	-0.24	0.29	2.59	-0.81	-0.58	-1.24	-2.99	1.27	-0.8	-0.67	-0.81
1988	0.53	-0.11	0.78	-2.39	-1.24	-2.75	1.46	0.73	0.8	-2.02	-1.47	1.85
1989	3.53	3.61	2.45	-0.48	1.16	-0.53	0.58	1.76	-0.96	0.88	-2.97	-2.23
1990	3.5	5.11	3.11	1.77	-1.19	0.42	1.43	3.31	-0.99	-0.59	-1.48	0.34
1991	1.87	-0.02	-1.37	1.48	-0.04	-0.31	-0.28	2.71	-1.12	-1.77	1.68	1.24
1992	0.64	3.18	1.66	1.32	0.8	-1.74	1.04	3.97	0.99	-3.33	4.52	0.21
1993	3.91	0.11	1.47	0.83	-2.59	0.16	0.64	0.75	-2.6	-4.13	0.77	2.17
1994	1.28	0.07	3.68	1.38	-1.43	2.99	-0.09	-1.59	-2.85	-1.88	1.68	2.86
1995	2.7	3.13	1.06	-1.81	-0.36	-3.36	-0.96	-1.33	-1.55	1.22	-2.73	-3.33
1996	-3.27	-0.12	-2.57	-0.31	-1.5	1.43	1.47	-0.19	-2.23	-0.07	-0.05	-4.7
1997	-1.95	5.26	2.09	-0.97	-1.35	-4.05	1.18	1.78	-0.67	-2.26	-0.99	-0.2
1998	-0.28	2.44	1.24	-0.39	-1.26	-0.85	-0.57	1.8	-3.48	1.34	1.13	1.95
1999	0.9	1.8	-0.72	0.43	1.03	1.39	-1.85	-3.67	-0.51	-0.69	0.3	2.13
2000	0.35	4.37	0.54	-3.34	0.31	0.89	-2.99	0.78	-1.1	2.26	-0.024	-1.41

Table F.2: Southern Oscillation Index

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1959	-0.94	-1.5	0.77	0.35	0.14	-0.96	-0.47	-0.68	-0.01	0.34	0.9	0.81
1960	-0.05	-0.25	0.47	0.79	0.3	-0.47	0.5	0.53	0.65	-0.2	0.6	0.63
1961	-0.43	0.58	-2.47	1.15	0.18	-0.53	0.18	-0.16	0.11	-0.73	0.68	1.31
1962	1.72	-0.41	-0.32	0.3	1.1	0.37	-0.04	0.26	0.53	0.95	0.27	-0.1
1963	0.8	0.26	0.66	0.51	0.14	-1.3	-0.13	-0.43	-0.6	-1.46	-0.93	-1.35
1964	-0.53	-0.13	0.71	1.78	-0.02	0.72	0.62	1.32	1.29	1.26	-0.06	-0.49
1965	-0.52	0.01	0.24	-1.34	-0.03	-1.63	-2.32	-1.37	-1.41	-1.22	-1.86	0.02
1966	-1.36	-0.54	-1.75	-0.9	-0.71	0.14	-0.15	0.19	-0.24	-0.33	-0.2	-0.61
1967	1.52	1.2	0.65	-0.12	-0.41	0.67	0.18	0.44	0.44	-0.17	-0.57	-0.78
1968	0.47	0.77	-0.56	-0.31	1.21	1.27	0.77	-0.2	-0.36	-0.35	-0.44	0.13
1969	-1.36	-0.85	-0.03	-0.9	-0.78	-0.24	-0.73	-0.71	-1.1	-1.35	-0.18	0.24
1970	-1.26	-1.22	0.06	-0.56	0.04	1.02	-0.52	0.31	1.18	0.74	1.85	1.83
1971	0.23	1.44	1.98	2.58	0.88	0.21	0.17	1.42	1.51	1.75	0.55	0.15
1972	0.33	0.67	0.13	-0.46	-1.52	-1.68	-1.84	-1.12	-1.48	-1.13	-0.38	-1.47
1973	-0.43	-1.47	-0.06	-0.37	0.25	1.22	0.63	1.18	1.27	0.85	2.85	1.76
1974	2.16	1.49	2.1	1.27	1.24	0.14	1.23	0.56	1.16	0.72	-0.42	-0.14
1975	-0.62	0.46	1.14	1.48	0.51	1.69	2.13	2.03	2.15	1.67	1.25	2.05
1976	1.19	1.18	1.33	0.24	0.5	-0.16	-1.24	-1.46	-1.29	0.13	0.76	-0.48
1977	-0.39	0.65	-1.2	-1.17	-1.18	-2.33	-1.45	-1.42	-0.95	-1.39	-1.56	-1.23
1978	-0.48	-2.63	-0.82	-0.88	1.5	0.4	0.53	0.12	0.06	-0.76	-0.28	-0.21
1979	-0.45	0.61	-0.49	-0.65	0.46	0.58	-0.76	-0.69	0.11	-0.37	-0.61	-0.9
1980	0.28	-0.02	-1.06	-1.6	-0.35	-0.68	-0.14	-0.06	-0.54	-0.34	-0.47	-0.21
1981	0.27	-0.47	-2.01	-0.6	0.82	1.28	0.87	0.4	0.52	-0.71	0.07	0.41
1982	0.87	-0.03	0.05	-0.46	-0.74	-2.49	-1.89	-2.66	-2.12	-2.2	-3.25	-2.48
1983	-3.36	-3.46	-3.25	-1.41	0.79	-0.58	-0.7	-0.37	0.91	0.34	-0.12	-0.17
1984	-0.03	0.43	-0.85	0.39	-0.03	-1.22	0.12	0.1	0.17	-0.61	0.12	-0.24
1985	-0.55	0.79	0.2	1.42	-0.15	-1.39	-0.2	0.66	0	-0.76	-0.35	0.12
1986	0.82	-1.28	-0.09	0.11	-0.63	1.01	0.24	-0.85	-0.53	0.54	-1.57	-1.64
1987	-0.75	-1.41	-2.03	-2.69	-2.12	-2.69	-1.82	-1.67	-1.13	-0.69	-0.07	-0.66
1988	-0.31	-0.65	0.13	-0.03	1.09	-0.2	1.17	1.36	1.92	1.35	1.92	1.09
1989	1.31	0.8	0.59	2.18	1.45	0.81	0.95	-0.82	0.52	0.61	-0.38	-0.62
1990	-0.21	-1.79	-1.09	-0.01	1.41	-0.07	0.57	-0.71	-0.78	-0.17	-0.68	-0.38
1991	0.45	-0.06	-1.35	-1.55	-1.74	-0.79	-0.07	-1.07	-1.64	-1.55	-0.77	-2.02
1992	-2.85	-1.05	-2.85	-2.06	0.06	-1.82	-0.63	-0.01	0.06	-2.03	-0.84	-0.71
1993	-0.93	-0.96	-1.13	-2.29	-0.59	-2.18	-1.06	-1.73	-0.78	-1.57	-0.13	0.07
1994	-0.25	-0.06	-1.35	-2.63	-1.26	-1.46	-1.7	-2.03	-1.7	-1.58	-0.81	-1.41
1995	-0.51	-0.35	0.24	-1.72	-0.91	-0.31	0.44	-0.11	0.28	-0.34	-0.02	-0.72
1996	0.82	-0.02	0.53	0.91	0.46	1.6	0.7	0.33	0.66	0.26	-0.21	0.71
1997	0.29	1.21	-1.09	-1.55	-2.41	-3.02	-0.91	-2.31	-1.55	-1.69	-1.31	-1.12
1998	-2.53	-1.97	-3.31	-2.8	0.17	1.05	1.49	0.83	1.04	1.01	1.01	1.32
1999	1.58	0.58	0.78	2.1	0.44	0	0.52	-0.03	-0.07	0.95	1.22	1.37
2000	0.47	1.24	0.88	1.76	0.42	-0.87	-0.34	0.48	0.97	0.87	2.02	0.77

Table F.3: El-Ni o Southern Oscillation Sea Surface Temperature

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1959	-5	3	-4	1	-5	13	-7	-19	-28	-18	-15	-5
1960	4	4	21	6	3	-21	-13	-8	-18	-24	-11	5
1961	8	11	-7	-7	-17	-30	-41	-33	-34	-31	-26	-19
1962	-21	-43	-25	-20	-1	-4	-8	-10	-23	-14	-14	-23
1963	-22	-23	-21	-13	5	-11	2	17	15	14	29	30
1964	40	34	16	-2	-18	-13	8	7	0	2	-13	-28
1965	-31	-8	-2	14	19	8	13	26	40	28	38	39
1966	47	61	46	52	26	33	45	35	21	15	31	33
1967	8	-11	-23	-2	6	0	-13	-44	-26	-28	-34	-20
1968	-23	-23	-22	-31	-20	7	33	26	15	19	18	37
1969	45	38	60	50	58	55	27	16	20	39	36	33
1970	48	48	57	42	36	28	30	5	7	-1	-7	13
1971	16	5	-3	-7	-9	-7	-20	3	14	-17	-10	-20
1972	-5	7	-17	-8	10	22	15	39	43	76	69	46
1973	52	51	38	27	29	20	27	25	17	10	8	5
1974	-24	-21	-27	-21	-5	6	23	19	5	17	11	1
1975	-12	-12	-7	-1	-10	6	11	-7	-5	-2	-10	-9
1976	-11	-15	-20	-13	-10	-6	5	18	28	36	54	26
1977	32	12	1	8	16	31	20	29	11	21	19	15
1978	27	22	30	30	25	17	19	12	6	4	-2	-6
1979	18	25	32	31	37	32	30	16	25	15	13	12
1980	19	12	9	15	38	25	28	24	33	41	37	36
1981	30	25	33	27	28	14	30	15	30	52	38	37
1982	27	15	10	7	14	27	35	46	43	41	43	56
1983	42	53	47	37	30	53	47	42	38	36	24	29
1984	29	31	52	44	34	27	29	-2	27	29	22	12
1985	18	24	9	-4	-5	4	17	34	22	19	26	27
1986	4	24	12	28	21	30	49	34	41	38	45	26
1987	36	34	48	41	56	64	56	74	68	85	82	69
1988	50	57	59	42	38	26	28	32	49	28	29	10
1989	-1	-11	-25	-27	-20	-8	10	-3	4	24	24	21
1990	3	3	-5	-7	4	5	8	0	2	16	24	21
1991	21	19	17	6	30	25	30	24	19	32	39	38
1992	20	18	1	19	15	15	30	38	36	42	26	15
1993	5	4	20	26	24	40	43	27	38	52	55	53
1994	35	33	24	4	5	9	-23	-15	12	32	20	15

Table F.4: Indian Ocean Sea Surface Temp. Anomalies (Hundred Degrees)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1959	0	-12	-14	-1	13	6	-13	-16	-30	-21	-23	-16
1960	-18	0	-3	-7	-30	-12	-24	-18	-25	-18	-28	-4
1961	20	16	11	-17	1	-3	17	4	-8	-1	-27	-30
1962	-31	-21	-5	15	14	7	23	28	19	14	9	5
1963	2	-1	-9	13	5	-10	18	5	8	16	22	25
1964	11	20	17	22	-17	-2	-21	-14	-14	-7	-28	-26
1965	-10	4	-6	-14	-19	-5	21	18	42	33	30	19
1966	14	40	-5	-5	10	20	24	28	23	5	0	-14
1967	-15	-7	4	-6	12	24	4	-15	-15	3	4	4
1968	-11	-7	-5	-21	-19	-17	-10	-7	-3	-14	-9	-5
1969	16	21	51	44	38	8	4	10	10	42	42	41
1970	52	40	21	7	9	8	31	27	28	5	23	17
1971	25	-1	16	34	18	3	3	24	12	-13	9	20
1972	42	9	0	8	34	44	39	64	70	69	48	36
1973	26	30	22	33	19	9	30	11	15	34	19	6
1974	-7	-14	5	2	3	25	36	21	-2	7	9	14
1975	-6	-3	-25	-12	6	19	26	3	5	-31	-29	-13
1976	-10	22	5	6	23	35	44	24	21	31	37	26
1977	45	13	21	30	35	39	31	40	27	43	42	46
1978	44	33	29	39	16	-4	-3	16	16	25	18	6
1979	28	20	26	28	29	42	21	8	15	27	27	18
1980	16	12	4	25	51	26	17	16	23	39	54	45
1981	51	48	48	25	40	23	28	19	26	48	16	17
1982	21	27	1	9	51	48	67	64	59	50	32	26
1983	12	26	19	13	37	71	74	60	39	29	18	20
1984	1	-18	1	16	8	7	4	-13	-6	7	29	25
1985	42	26	30	40	46	15	15	25	34	11	23	14
1986	6	17	9	30	42	50	49	25	36	24	41	21
1987	24	43	44	30	63	37	58	72	72	52	45	44
1988	53	62	59	55	35	51	51	65	71	55	54	48
1989	-14	-7	-6	-25	-16	-28	-6	-5	18	26	35	32
1990	16	24	1	-7	21	3	15	-2	3	11	26	34
1991	40	30	13	11	31	-1	21	9	19	27	33	14
1992	-5	-11	-70	-35	13	17	39	28	26	14	34	9

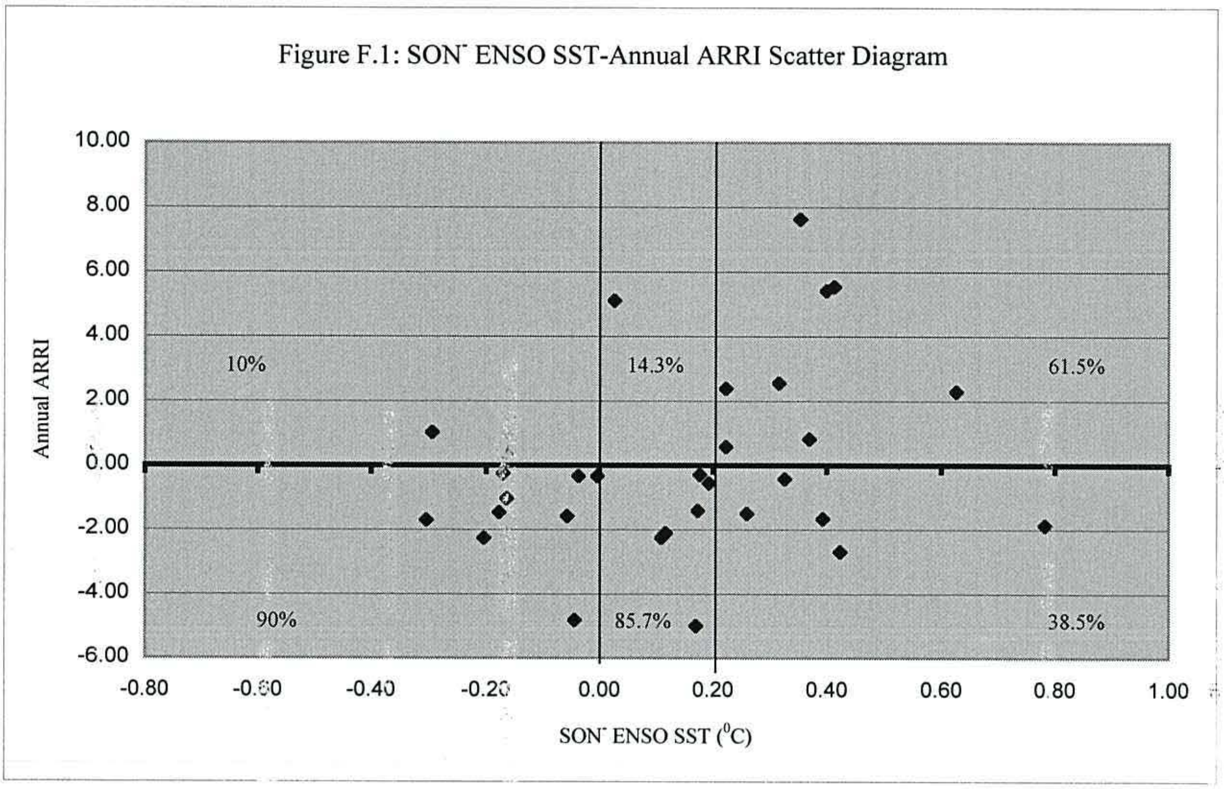


Table F.5: Probabilistic Model for Jordanian Annual Rainfall using SON⁻ Seasonal ENSO SST

SON⁻ SST CATEGORY	PROBABILITY OF RAINFALL YEAR CATEGORY	
	Dry	**Wet**
Cold	90	10
Normal	85.7	14.3
Warm	38.5	61.5

Table F.6: Verification of the probabilistic model using SON⁻ ENSO SST

YEAR	SON⁻ ENSO SST	PREDICTED ARRI	OBSERVED ARRI (CLASS)	EVALUATION
1990	0.35	Wet	(-0.43) dry	F
1991	0.17	Dry	(1.07) wet	F
1992	0.14	Dry	(2.00) wet	F
1993	0.3	Wet	(-0.59) dry	F
1994	0.35	Wet	(0.91) wet	T
1995	0.48	Wet	(-0.9) dry	F

Figure F.2: SON⁻+DJF⁻ ENSO SST-Annual ARRI scatter diagram

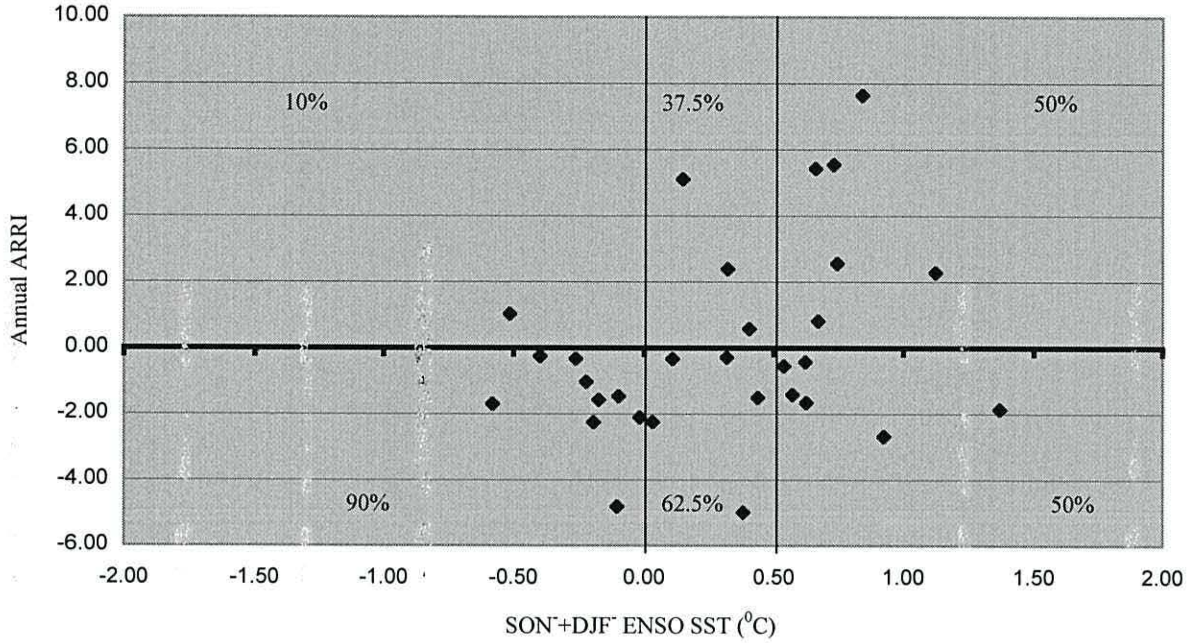


Table F.7: Probabilistic Model for Jordanian Annual Rainfall using SON⁻+DJF⁻ Seasonal ENSO SST

SON⁻ + DJF⁻ SST CATEGORY	PROBABILITY OF RAINFALL YEAR CATEGORY	
	Dry	**Wet**
Cold	90	10
Normal	62.5	37.5
Warm	50	50

Table F.7: Verification of the probabilistic model using SON⁻+DJF⁻ ENSO SST

YEAR	SON⁻+DJF⁻ ENSO SST	PREDICTED ARRI	OBSERVED ARRI (CLASS)	EVALUATION
1990	0.35	Dry	(-0.43) dry	T
1991	0.26	Dry	(1.07) wet	F
1992	0.34	Dry	(2.00) wet	F
1993	0.55	Dry/Wet	(-0.59) dry	T
1994	0.43	Dry/Wet	(0.91) wet	T
1995	0.89	Dry/Wet	(-0.9) dry	T

Figure F.3: DJF⁻ +MAM⁻ ENSO SST - Annual ARRI scatter diagram

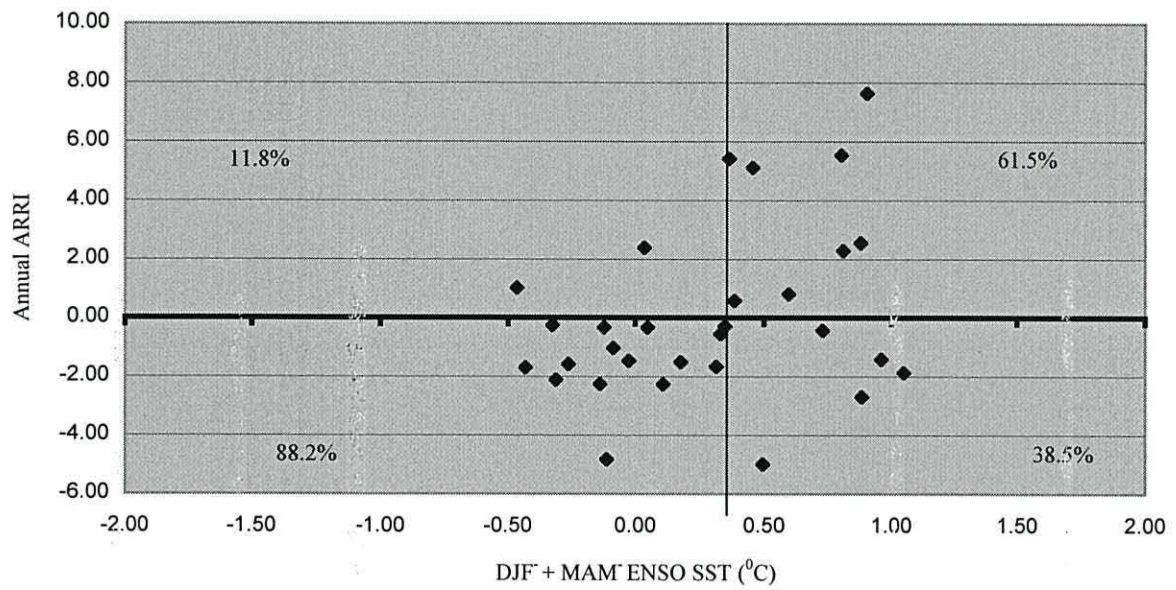


Table F.8: Probabilistic Model for Jordanian Annual Rainfall using DJF⁻+MAM⁻ Seasonal ENSO SST

SON⁻ SST CATEGORY	PROBABILITY OF RAINFALL YEAR CATEGORY	
	Dry	**Wet**
Cold	88.2	11.8
Warm	38.5	61.5

Table F.9: Verification of the probabilistic model using DJF⁻+MAM⁻ ENSO SST

YEAR	DJF⁻+MAM⁻ ENSO SST	PREDICTED ARRI	OBSERVED ARRI (CLASS)	EVALUATION
1990	-0.25	Dry	(-0.43) dry	T
1991	0.06	Dry	(1.07) wet	F
1992	0.38	Wet	(2.00) wet	T
1993	0.37	Dry	(-0.59) dry	T
1994	0.31	Dry	(0.91) wet	F
1995	0.51	Wet	(-0.9) dry	F

Figure F.4: DJF⁻ + MAM⁻ +JJA⁻ ENSO SST-Annual ARRI scatter diagram

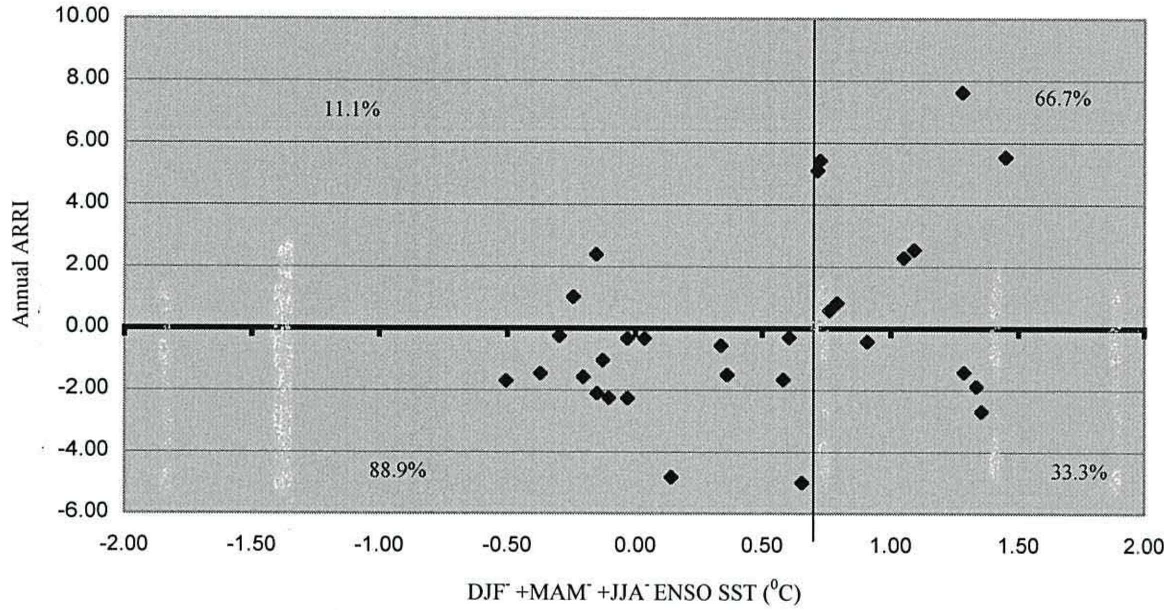


Table F.10: Probabilistic Model for Jordanian Annual Rainfall using DJF⁻+MAM⁻ +JJA⁻ Seasonal ENSO SST

SON⁻ SST CATEGORY	PROBABILITY OF RAINFALL YEAR CATEGORY	
	Dry	Wet
Cold	88.9	11.1
Warm	33.3	66.7

Table F.11: Verification of the probabilistic model using DJF⁻+MAM⁻+JJA⁻ ENSO SST

YEAR	DJF⁻+MAM⁻+JJA⁻ ENSO SST	PREDICTED ARRI	OBSERVED ARRI (CLASS)	EVALUATION
1990	-0.25	Dry	(-0.43) dry	T
1991	0.11	Dry	(1.07) wet	F
1992	0.64	Dry	(2.00) wet	F
1993	0.65	Dry	(-0.59) dry	T
1994	0.68	Dry	(0.91) wet	F
1995	0.42	Dry	(-0.9) dry	T

APPENDIX G

ONSET, END, NUMBER OF RAINY DAYS, NUMBER OF RAINY DAYS > SMM AND LENGTH OF RAINY SEASON FOR:

- Al-Aryyatein
- Azraq
- Deir Al-Kahf

Figure G.1: First Significant Rainfall vs. Annual Total for Al-Aryyatein (1968-1999)

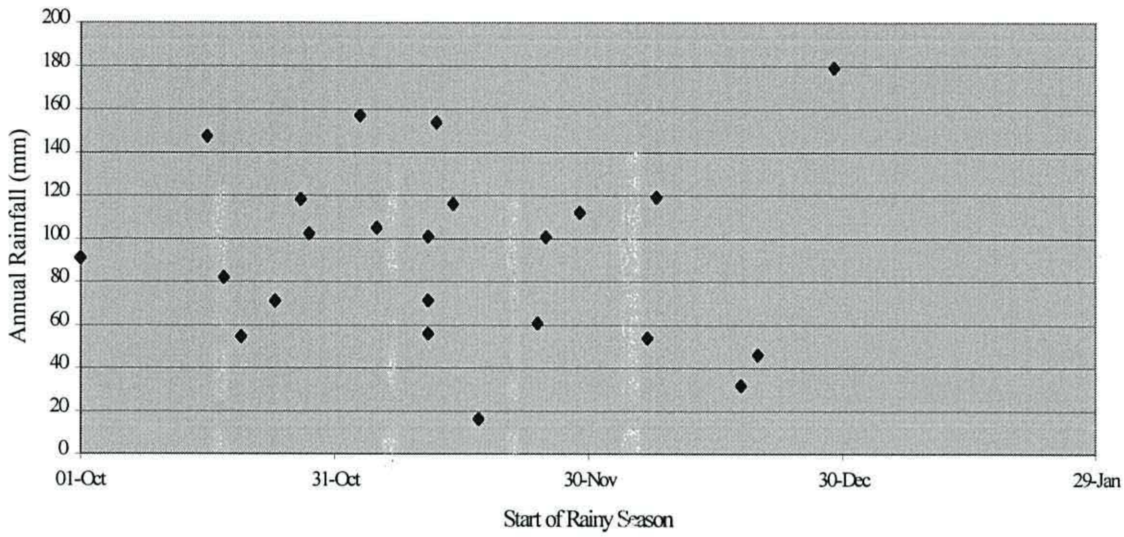
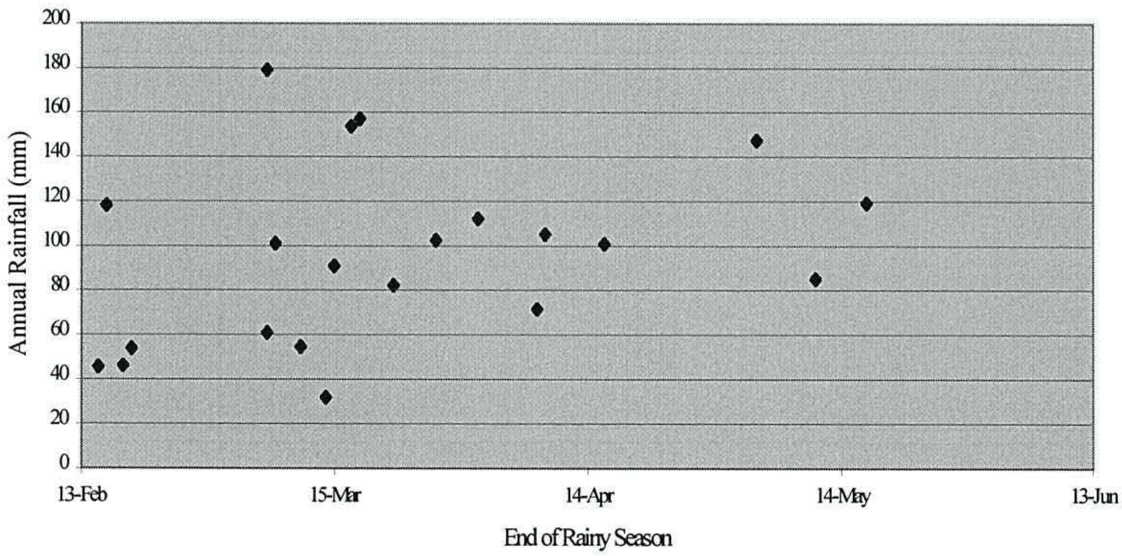


Figure G.2: Last Significant Rainfall vs. Annual Total for Al-Aryyatein (1968-1999)



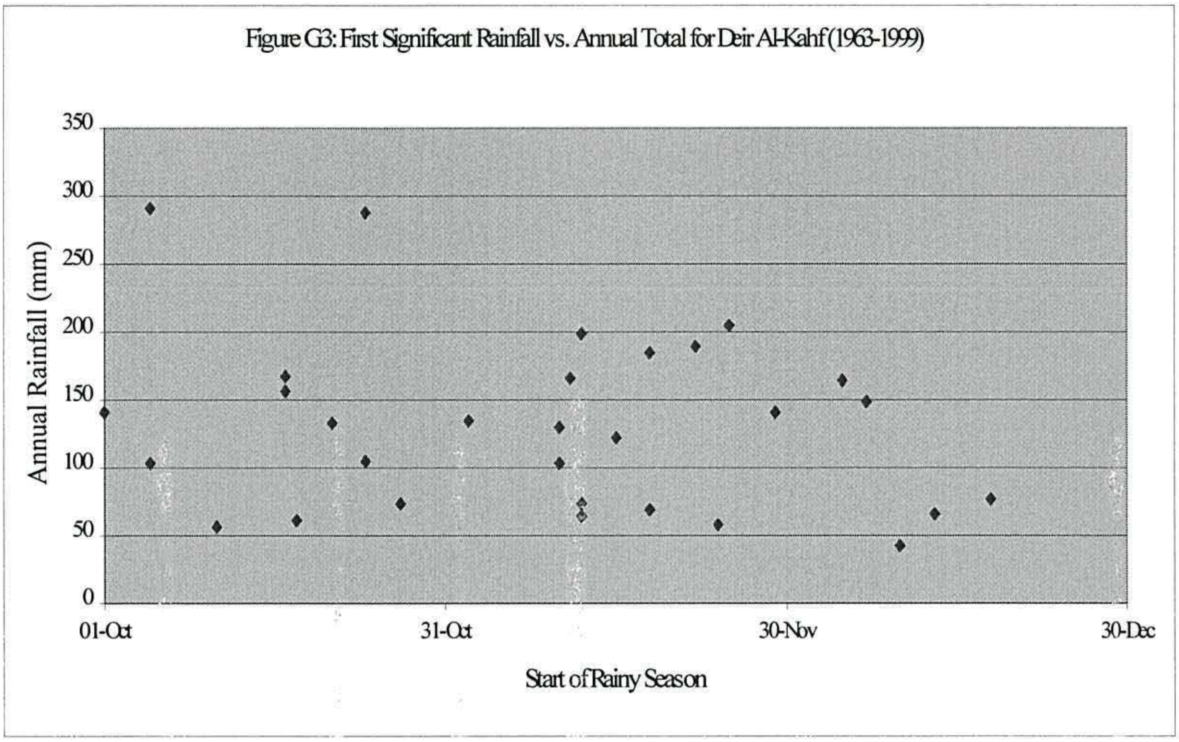


Figure G3: First Significant Rainfall vs. Annual Total for Deir Al-Kahf (1963-1999)
Annual Rainfall (mm)
350
300
250
200
150
100
50
0
01-Oct
31-Oct
30-Nov
30-Dec
Start of Rainy Season

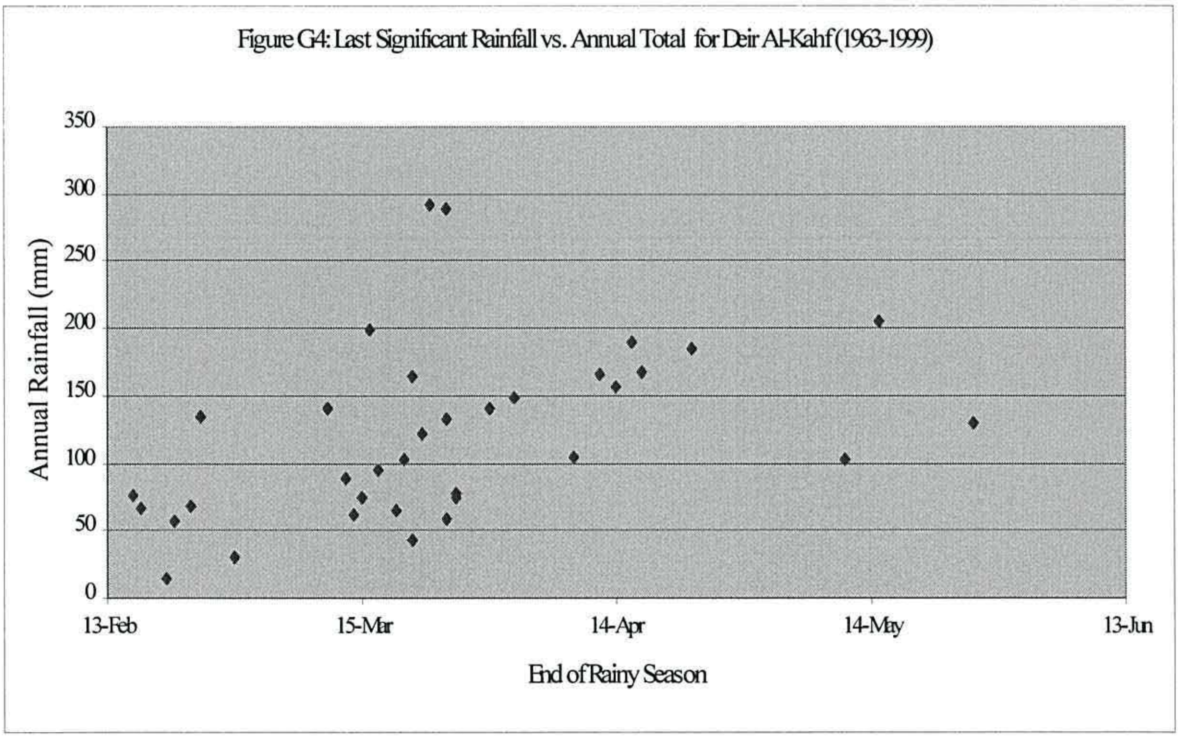


Figure G4: Last Significant Rainfall vs. Annual Total for Deir Al-Kahf (1963-1999)
Annual Rainfall (mm)
350
300
250
200
150
100
50
0
13-Feb
15-Mar
14-Apr
14-May
13-Jun
End of Rainy Season

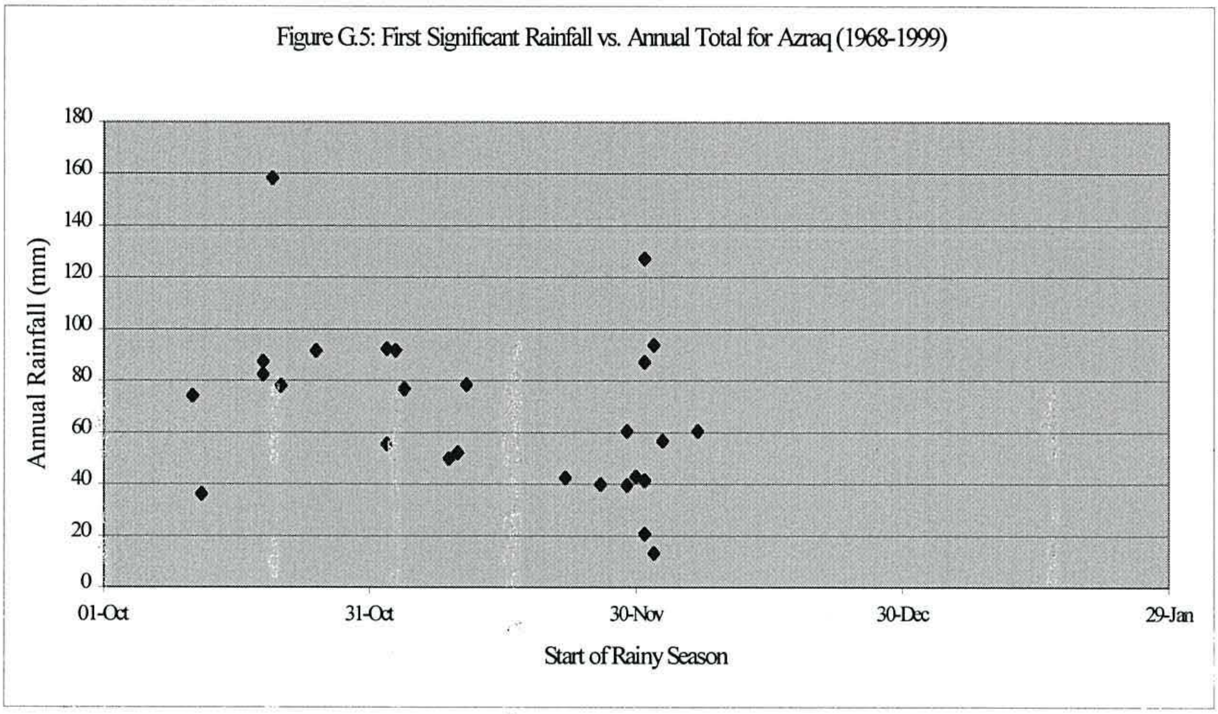


Figure G.5: First Significant Rainfall vs. Annual Total for Azraq (1968-1999)
Annual Rainfall (mm)
180
160
140
120
100
80
60
40
20
0
01-Oct
31-Oct
30-Nov
30-Dec
29-Jan
Start of Rainy Season

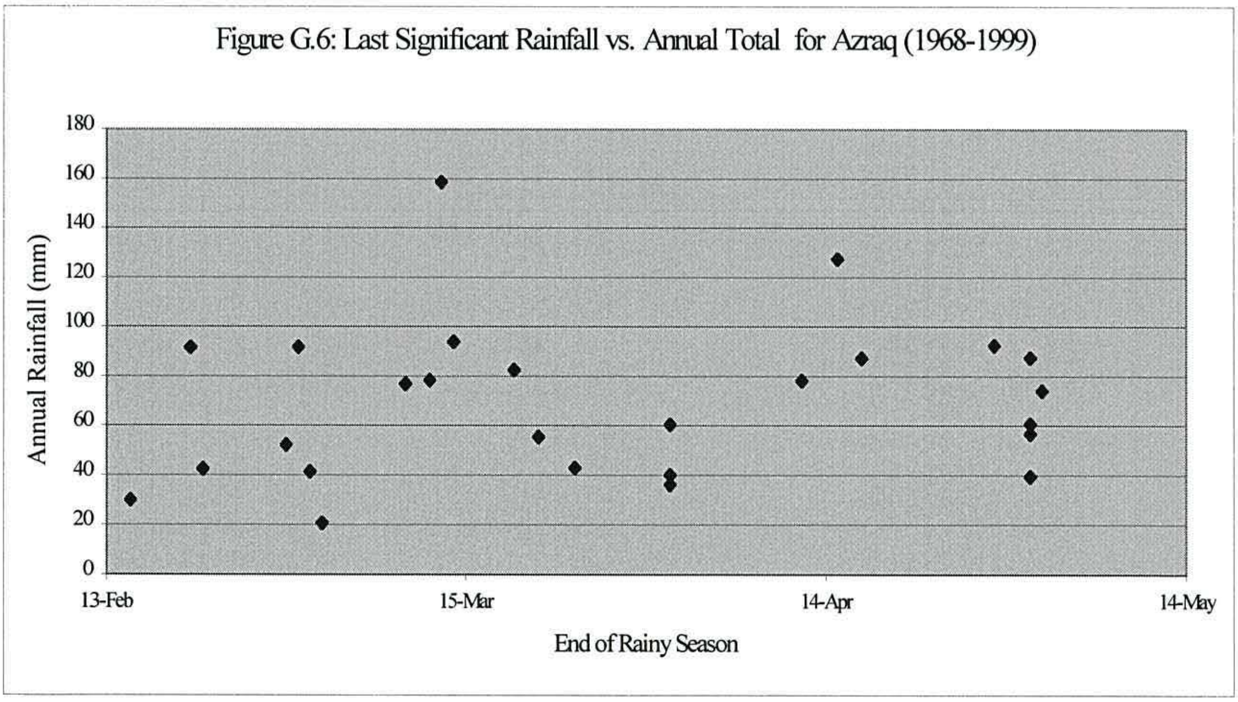


Figure G.6: Last Significant Rainfall vs. Annual Total for Azraq (1968-1999)
Annual Rainfall (mm)
180
160
140
120
100
80
60
40
20
0
13-Feb
15-Mar
14-Apr
14-May
End of Rainy Season

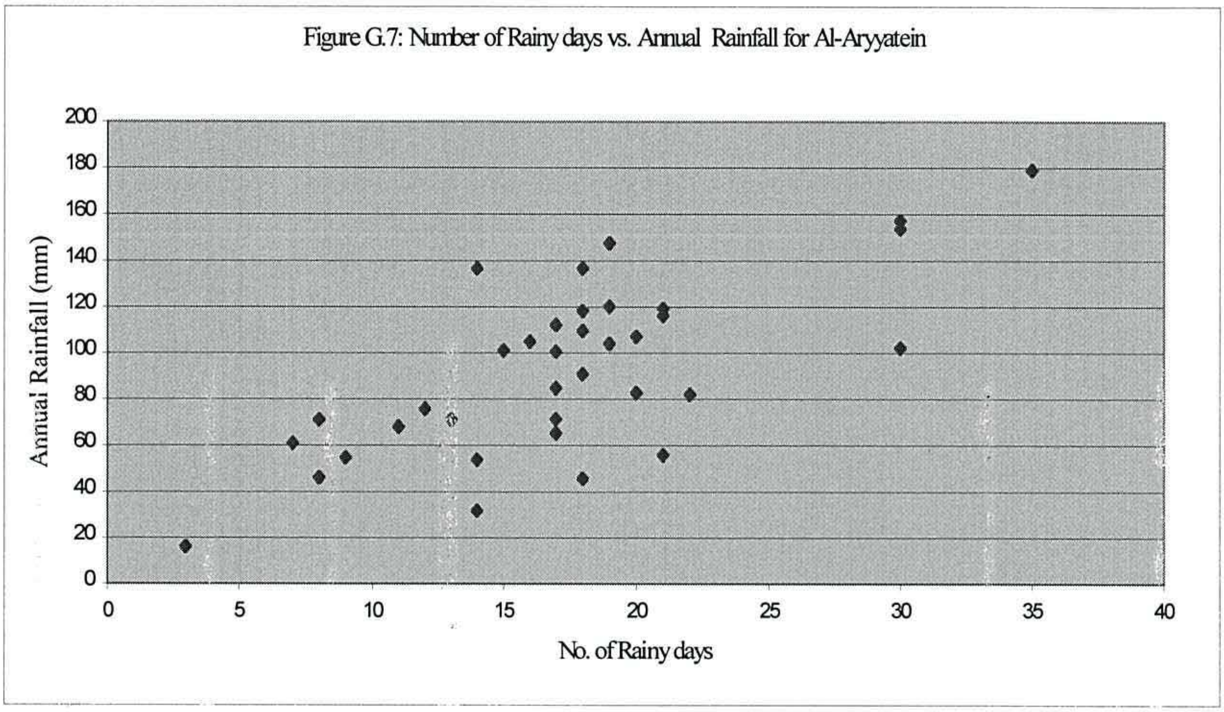


Figure G.7: Number of Rainy days vs. Annual Rainfall for Al-Aryyatein
Annual Rainfall (mm)
200
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
No. of Rainy days

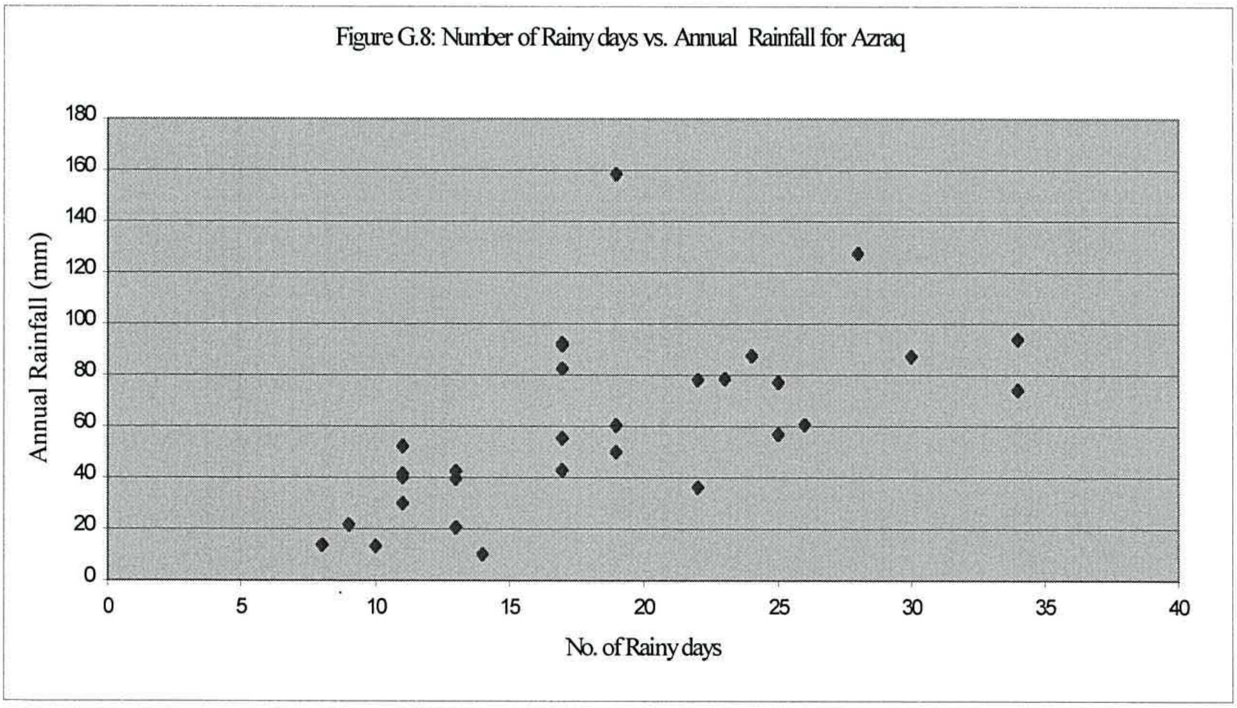


Figure G.8: Number of Rainy days vs. Annual Rainfall for Azraq
Annual Rainfall (mm)
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
No. of Rainy days

Figure G.9: Number of Rainy days with > 5 mm rain vs. Annual Rainfall for Al-Aryyatein

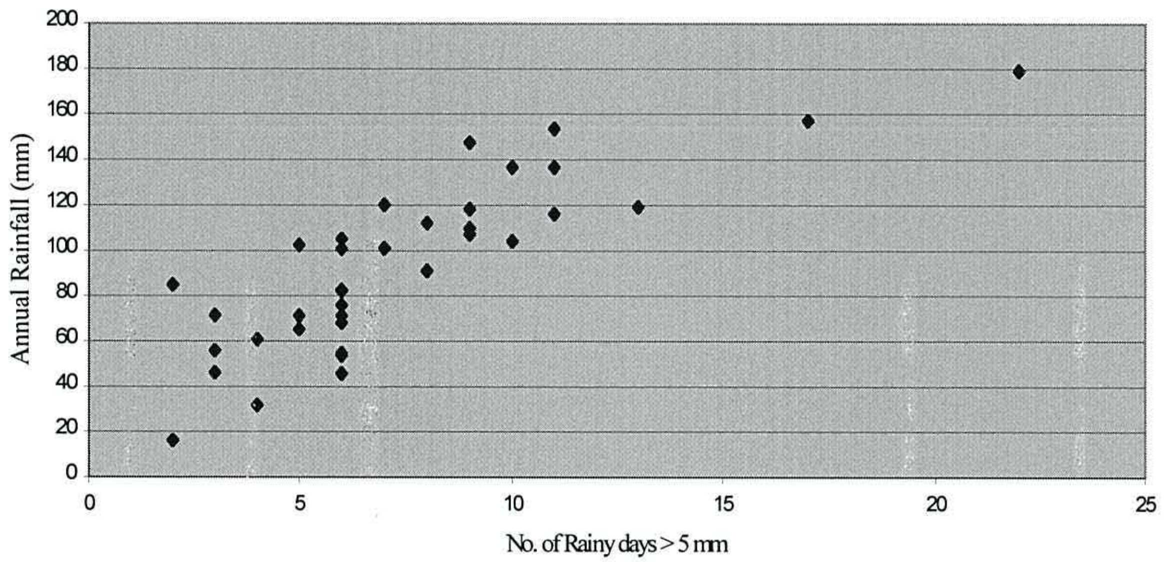


Figure G.10: Number of Rainy days with > 5 mm rain vs. Annual Rainfall for Azraq

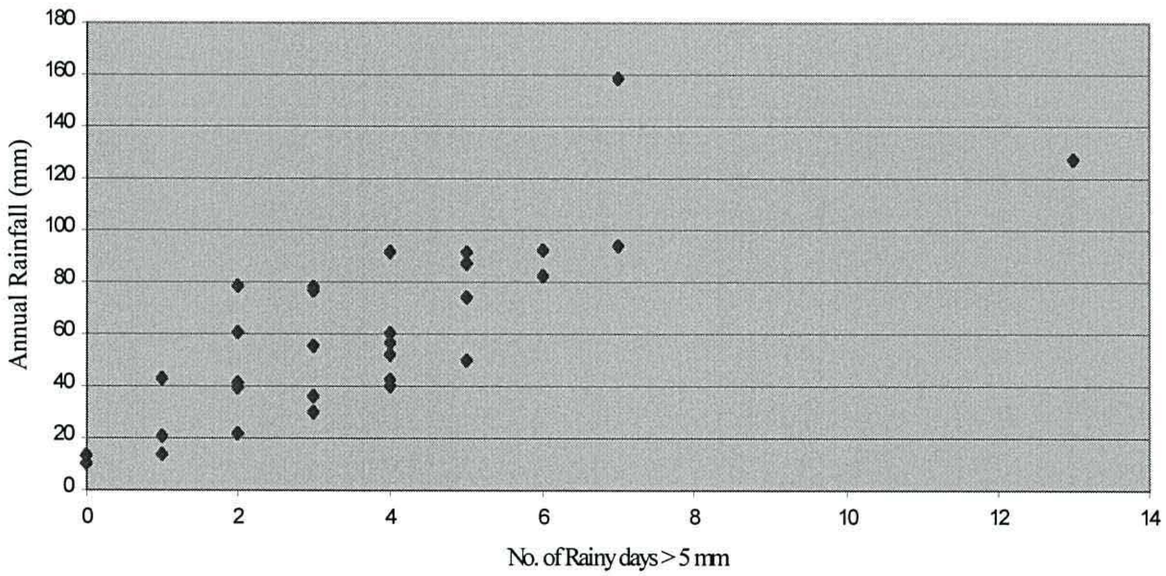


Figure G.11: Length of Rainy Season vs. Annual Rainfall for Al-Aryyatein

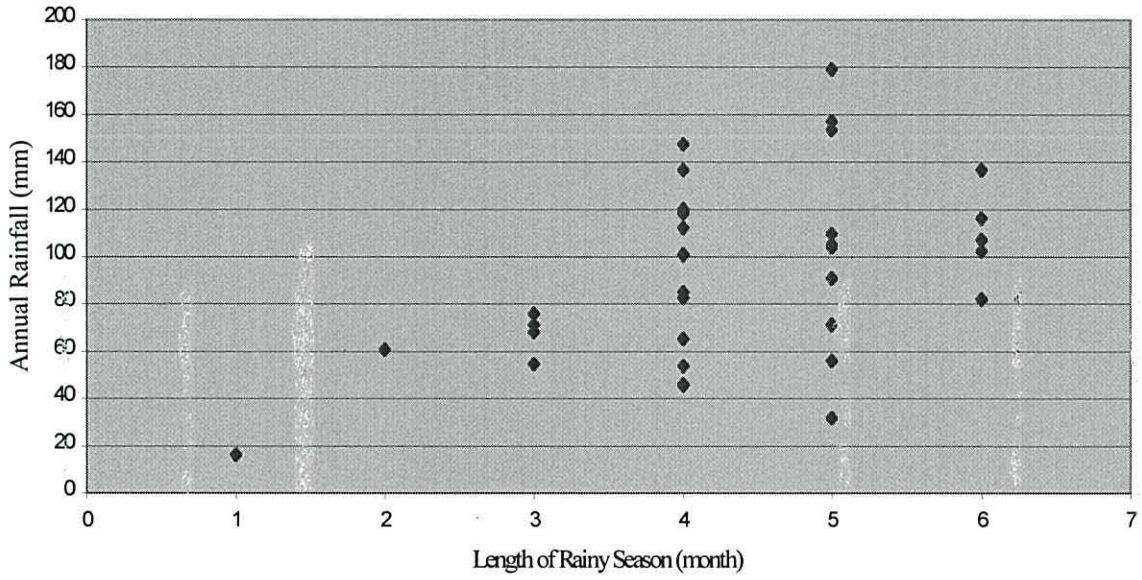


Figure G.12: Length of Rainy Season vs. Annual Rainfall for Azraq