GIS-Based Identification of Suitable Areas for Various Kinds of Water Harvesting in Syria

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Abstract

Main obstacle to development in the dry areas in Central Syria is the scarce and erratic rainfall. Water resources therefore run short in meeting the demand. Water harvesting has shown to be an appropriate means to garantee the sustainability of water resources designed for use in agricultural production and drinking water supply. Scope of the study is the determination of appropriate sites and techniques for water harvesting in Central Syria.

Different parameters, such as rainfall, topography, land use and cover, soil and vegetation cover are important to runoff generation in semi-arid areas. Rainfall characteristics were evaluated by modern interpolation techniques such as kriging according to daily records of stations within the research area. Vegetation cover within the rangeland of Central Syria is highly depleted due to overexploitation by grazing. Infrastructure and accessibility of the research area is low. Remote sensing is therefore an appropriate tool to determine land cover and land use for vast areas. Landsat TM 5 data were analyzed using scenes of four dates, two recorded within the rainy season and two during the dry period. The research was focussed on an area of about 19,200 km². Land use and cover were classified by analysis of the satellite data according to the concept of Maximum Likelihood Classifier using ERDASImagine. Soil moisture could be partly analyzed by Tasseled CAP transformation. A Digital Terrain Model was created according to the interpolation of digitized contour lines of maps of the scale 1:100 000. All the different data sets including soil data are analyzed within the geographical information system using ArcView GIS.

The runoff potential was analyzed by two methods: the US Soil Conservation Service (SCS) method and the indexing method. Since the indexing method allows to consider all the determinants this method has advantages compared to the SCS method.

The process to decide finally on suitable sites for a water harvesting technique involves the assessment of alternatives. The Analytical Hierarchical Process (AHP) is a decision support system which allows to rank and weight different alternatives. Different parameters influencing the choice of water harvesting systems include the runoff potential, slope, the proximity to roads, soilscape units, proximity to military, industrial sites and badland areas and the neighborhood to settlement areas. The weighing and ranking of these alternatives allowed to present two different maps showing the suitability to floodwater harvesting or micro- / macrocatchment systems. According to these results most part of the research site is more suitable to micro- / macrocatchment systems. The maps are basis to further planning and design for water harvesting structures in the research area.

Zusammenfassung

Die rasch wachsende Bevölkerung Syriens ist auf eine ausreichende Lebensmittelversorgung und Trinkwasserversorgung angewiesen. Der zentrale Bereich von Syrien, der die Trockenzone zwischen 100 bis 200 mm umfasst, wird vorwiegend zur Weidewirtschaft genutzt. Die schnell ansteigende Zahl von Weidetieren hat in den letzten Jahren zu einer starken Degradierung der Steppenvegetation geführt. Diese wird verstärkt durch die natürlichen Voraussetzungen. In diesem typisch semi-ariden Gebiet ist der Niederschlag nur sporadisch und begrenzt auf eine über die Wintermonate andauernde Regenzeit zwischen November und April. Die meisten Regenfälle zeichnen sich durch kurze intensive Schauer aus, wobei der Abfluss meist unkontrolliert versickert. Zur Nutzung dieser Resource des Abflusses bietet sich die Anwendung von Sturzwasserbewässerungs- bzw. Wasserkonzentrationstechniken (Water harvesting) an. Die jahrtausendalte Ablenkdammbewässerung bei Marib (Jemen) zeigt, dass diese Techniken schon früher von den Sabatäern erfolgreich angewendet wurden. Die Arbeit konzentriert sich im wesentlichen auf zwei Beispiele von Wasserkonzentrationstechniken: Micro- / Macrocatchment- und Flutwasserkonzentrationsanlagen. Beispiele für Microcatchment-Systeme sind Halbmonde und halbkreisförmige Mulden, die das Wasser für die Pflanzen auffangen. Beispiele für Macrocatchment-Systeme sind Steindämme entlang der Abflussrichtung am Hang, die das Wasser auf Felder am Hangfuß leiten. Flutwasserkonzentrationstechniken umfassen beispielsweise Ablenkdämme im Bereich von Trockentälern (Wadis), die das Wasser auf angrenzende Felder leiten.

Da es sich bei dem Untersuchungsgebiet um einen großen, zum Teil nur schlecht erschlossenen Bereich der Provinz *Homs* und *Tadmor* handelt, wurden ausgiebige Feldbegehungen zur Bewertung des Anwendungspotentials von Wasserkonzentrationstechniken ausgeschlossen. Moderne Techniken, die Datenerhebungen und –analyse für schwer zugängliche Gebiete ermöglichen, sind Fernerkundungsmethoden und die Anwendung von Geografischen Informationssystemen (GIS). Satellitenbilder des Landsat TM 5 waren zu Beginn des Projektes Mitte der 90er Jahre gängige und viel verwendete Arbeitsmittel in der Fernerkundung. Für das Untersuchungsgebiet wurden Landsat TM 5 Szenen aus vier Zeitpunkten ausgewählt, zwei aus der Trockenperiode (Oktober 1993 und Juli 1994) und zwei aus der Regenzeit (April 1994 und April 1995).

Für das Abflussgeschehen in semiariden Gebieten spielen verschiedene Faktoren eine Rolle. Der Oberflächenabfluss erfolgt hier zumeist nach dem Horton'schen Prinzip: Die stark intensiven Regenfälle führen bald zu Oberflächenabfluss, da die Infiltrationskapazität der häufig mit einer Kruste bedeckten Böden nicht ausreicht, die in kurzer Zeit dargebotene Wassermenge aufzunehmen. Zu den Parametern, die den Abfluss in semi-

ariden Gebieten bestimmen, gehören klimatische Faktoren wie z. B. Regenmenge und Regenfallintensität, topographische Faktoren wie Hangneigung, Landnutzung und Charakteristika der Böden wie Bodenfeuchte und Bodentextur.

Die meteorologischen Daten, die Regenfall und Temperaturdaten von mehreren Stationen im Untersuchungsgebiet betrafen, wurden ausgewertet und mithilfe von Interpolationstechniken wie Kriging-Verfahren regionalisiert. Jährliche Niederschlags-summen geben nur wenig Auskunft über das tatsächliche Wasserangebot in semi-ariden Gebieten, da Menge, Zeitdauer und Intensität eines Niederschlagsereignisses ausschlaggebend für das Abflussgeschehen sind. Es wurden tägliche Niederschlagswerte ausgewertet, wobei Niederschläge über 2 mm und über 5 mm täglich explizit betrachtet wurden, da diese nach Literaturangaben zu nennenswerten Abflussereignissen in semi-ariden Gebieten führen. Die Niederschläge wurden zudem über Extremwertverfahren analysiert, wobei 2-, 5- und 10-Jährlichkeiten von Extremniederschlägen ermittelt wurden. Informationen zur Temperatur ermöglichten die Ermittlung der potentiellen Verdunstung nach drei verschiedenen Verfahren, Penman-Monteith, Thornthwaite und Blaney-Criddle. Sie liegt im Bereich zwischen 1600 bis 2000 mm pro Jahr im Untersuchungsgebiet.

Die Topographie, die eine starke Rolle beim Abflussgeschehen und der Auswahl von Wasserkonzentrationstechniken spielt, wurde über ein regelmässig gerastertes digitales Geländemodell in einer Auflösung von 100 m erfasst, das aus der Interpolation von Höhenkonturlinien aus Karten im Maßstab 1 : 100 000 erstellt wurde. Die Verteilung der Hangneigungsklassen zeigt, dass es sich um ein relativ flaches Gelände handelt mit der dominanten Hangneigungsklasse von 0 bis 1%. Zudem wurden anhand des digitalen Geländemodells die bevorzugten Abflusswege und deren Länge ermittelt.

Bei den Böden im Untersuchungsgebiet handelt es sich vorwiegend um Aridisols (USDA Klassifizierung), die zum Teil stark zur Verkrustung neigen. Es wurde die Textur einiger typischer Böden und der Aggregatzustand des Oberbodens untersucht, die wichtige Parameter bezüglich der Infiltrationskapazität von Böden darstellen. Die Böden wurden aufgrund ihrer Eigenschaften, die Lithologie, Geologie, Landschaftsform, Hangneigung, Bodentiefe und Steinigkeit umfassen, in Bodeneinheiten unterteilt.

Vegetation und Landnutzung wurden über die Auswertung der Satellitenbilder erfasst. Das Gebiet zählt zu über 50% zur Steppe, welche zur Weidewirtschaft von Schafen genutzt wird. Nur 2% des Landes im Bereich des Untersuchungsgebietes wird nach der offiziellen Statitistik für bewässerte Landwirtschaft genutzt. Die Grenze zum Regenfeldbau verläuft am nordwestlichen Rand des Untersuchungsgebietes entlang der Isohyete von mehr als 250 mm jährlichem Regenfalls. Die stark ansteigende Zahl von Schafen hat in den letzten Jahren zu einer starken Degradierung der Steppenvegetation geführt. Der Degeneration der Steppenvegetation wird z.T. durch Pflanzungen bzw. gezieltem Aussäen von

Futterpflanzen begegnet. Die Auswertung der Satellitenbilder wurde auch zur Beschreibung der Vegetation benutzt. Hierbei wurden verschiedene Indices betrachtet, der NDVI (Normalized Difference Vegetation Index) und der PVI (Perpendicular Vegetation Index) -Ansatz. Der PVI-Ansatz beinhaltet, dass die Grauwerte des unbedeckten Bodens im Satellitenbild innerhalb des infraroten und roten Spektralbereichs eine lokalspezifische Linie bildet, die als sogenannte Bodenkennlinie bezeichnet wird. Diese wurde für die zwei Satellitenszenen aus April 1994 und April 1995 ermittelt. Es zeigte sich im Gegensatz zum NDVI-Ansatz, dass sich nur die mit dichter Vegetation bedeckten Bereiche in den Trockentälern (Wadis) bei der PVI-Analyse besser unterscheiden ließen. Somit wurden keine weiterführenden Kenntnisse über den Status der Vegetation über die rein visuelle Auswertung der Satellitenbilder hinaus gewonnen, so dass diese Auswertung nicht in die weiteren Betrachtungen miteinbezogen wurde.

Um die Bodenfeuchte zu erfassen, wurde der Tasseled Cap Ansatz verwendet. Dieser basiert auf einer Hauptkomponentenanalyse, wobei die digitalen Werte der einzelnen Spektralbänder des Satellitenbildes über eine festgelegte Matrix multipliziert werden. Die erste Hauptkomponente stellt die Bodenhelligkeit dar, die Achse diagonal zur Bodenlinie den Vegetationsindex und die dritte Komponente zeigt den Feuchtegrad. Es zeigte sich, dass die Szenen aus der Regenperiode (April 1994 und April 1995) deutlich höhere Feuchtegrade zeigen.

Die Landnutzungsklassen wurden über die Klassifizierung der Satellitenbilder ermittelt. Hierbei wurden während verschiedener Geländebegehungen Trainingsgebiete der unterschiedlichen Landbedeckungs- bzw. Landnutzungsklassen erfasst. Diese gingen ein in die Maximum-Likelihood-Analyse, die eine gängige Klassifizierungsmethode von Satellitenbildern bildet. Es wurden dreizehn Landnutzungsklassen unterschieden, wobei z.B. Klassen wie dichte Vegetation innerhalb der Trockentäler oder vegetationsfreie Böden unterschieden wurden.

Die meisten Unterschiede der untersuchten Szene von April 1994 und 1995 zeigte die Klasse der dichten Vegetation innerhalb der Wadis. Schwierigkeiten der Klassifikation bildeten vor allem die Unterscheidung von Strassen oder Besiedlungen, da diese meist bedeckt sind von dem Staub aus der Umgebung. Auch gab es häufig Überlappungen der Klassen dichter Vegetation innerhalb der Trockentäler und bewässerter Getreidefelder.

Die verschiedenen Daten wurden alle geometrisch kodiert und innerhalb des Geographischen Informationssystem (GIS) ausgewertet. Auch die Satellitenbilder wurden über Passpunkte, die im Gelände und auf dem Satellitenbild bestimmt wurden, in ein kartographische Koordinatennetz überführt, wobei das Universal Mercator System (UTM) gewählt wurde. Die Passpunkte im Gelände wurden über das GPS (Global Positioning System) bestimmt.

Die Analyse des Abflusspotentials wurde über zwei Ansätze ausgeführt: die US Soil Conservation Methode, kurz SCS Methode genannt, und die Indizierungsmethode. Bei der SCS Methode flossen die Klassifizierung der Landnutzungsdaten aus der Satellitenbildauswertung und die Einteilung der Bodeneinheiten in hydrologische Bodenklassen ein. Der Regenfall wurde über die Zwei-Jährlichkeiten-Verteilung von Extremereignissen im Untersuchungsgebiet erfasst.

Bei der Indizierungsmethode wurden verschiedenen Datenebenen Gewichtungen zugeteilt und ausgewertet. Die Datenebenen umfassten die Hangneigung, Bodentextur, Pflanzendecke, Steinigkeit der Bodenoberfläche, den Feuchteindex aus der Tasseled-Cap-Analyse und die Länge der Abflusswege. Der Einfluss der Pflanzendecke oder die Menge der Steine an der Bodenoberfläche in den einzelnen Landnutzungsklassen auf das Abflussgeschehen wurde anhand von Geländebegehungen und Erfahrungswerten aus der Literatur abgeschätzt. Es wurden zwei Szenarios berechnet, Szenario A die Länge der Abflusswege ausschließend, und Szenario B, jene einschließend. Es zeigte sich, dass die Indizierungsmethode das Abflusspotential schlüssiger im Gegensatz zur *SCS* Methode berechnet. Die *SCS* Methode gibt auch hinsichtlich der Menge des zu erwartenden Abflusses Aufschluss, allerdings muss hierbei beachtet werden, dass die Vorhersage von Niederschlagsereignissen in semi-ariden Gebieten mit vielen Schwierigkeiten behaftet ist.

Um letztendlich die Eignung des Gebietes für verschiedene Wasserkonzentrationstechniken zu ermitteln, wurde ein Modell der Entscheidungsfindung (Decision process) angewendet. Hierbei handelt es sich um den Analytischen Hierarchischen Prozess (Analytical Hierarchical Process: AHP), der eine Gewichtung hinsichtlich der Präferenz von Alternativen der einzelnen Kriterien, die in der Entscheidungsfindung wichtig sind, erlaubt. Der AHP wird innerhalb von fünf elementaren Schritten unternommen: Eine klare Unterscheidung der Ziele muss getroffen werden. Die Faktoren, die die Entscheidung beieinflussen, müssen in einer Entscheidungshierarchie strukturiert werden. Die Gewichtung jedes Faktors muss anhand der Eigenvektorberechnung bestimmt werden. Letztendlich werden die einzelnen Fakoren zusammmengefasst in ihrer Rangfolge, und ein Eignungsindex wird eingeführt. Die Modelle zur Bestimmmung der Eignung des Gebietes für Micro- / Macrocatchment-Systeme oder Flutwasserkonzentrationstechniken umfassen 3 bis 4 verschiedene Ebenen: das Ziel, die Kriterien, Subkriterien und die Alternativen der Kriterien. Die Kriterien umfassen potentieller Abfluss, Hangneigung, Bodenklassen, Nähe zu Straßen, Nähe zu Siedlungen und Nähe zu industriellen, militärischen Anlagen und Ödland Gebieten. Die Alternativen der Kriterien betragen z. B. bei dem Kriterium der Nähe oder Nachbarschaft zu industriellen oder militärischen Anlagen oder Ödland die Klassen der Entfernung 0 bis 2,5 km, 2,5 bis 10 km und > 10 km. Diese Klassen werden aufgrund von Erfahrungswerten oder der speziellen Gegebenheiten vor Ort paarweise verglichen und anhand von Zahlen in eine Rangfolge gebracht. So weist die Klasse > 10 km eine größere Präferenz gegenüber der Klasse von 0 bis 2,5 km und wird somit mit dem Wert 7 versehen im Gegensatz zu 1. Der Eigenvektor, der sich dann aus einer Reihe von Werten der Alternativen und deren Anzahl errechnet, wird schliesslich in eine relative Gewichtung überführt. Es wurden bei der Errechnung der Eignung des Gebietes verschiedene Klassen unterschieden: günstigere oder weniger günstige, mehr oder weniger geeignete und ungeeignete Gebiete. Vor allem im südwestlichen Bereich des Untersuchungsgebietes zeigen sich mehr geeignete Flächen zur Anwendung von Wasserkonzentrationstechniken. Im allgemeinen ergab sich eine größere Eignung des Gebietes für den Einsatz von Micro- / Macrocatchment–Systemen. Entlang von Straßen zeigen sich sehr günstige Bereiche für Micro- / Macrocatchment-Systeme. Im Bereich der Abhänge der *Südlichen Palmyriden* eignen sich mehr Bereiche für Flutwasserkonzentrationstechniken. Die aus dem hierarchischen Entscheidungsmodell resultierenden Karten zeigen potentiell nutzbare Gebiete für die Anwendung der Wasserkonzentrationstechniken. Die quantitativ nutzbare Menge an Abfluss, die in durch die Wasserkonzentrationstechniken gesammelt und genutzt werden können, kann durch die vorliegende Analyse nicht ermittelt werden. Hierzu fehlen konkrete Niederschlags- und Abflussdaten von einzelnen Niederschlagsereignissen. Diese würden dann erlauben, einen Abflusskoeffizienten zu ermitteln, der die Dimensionierung einer Wasserkonzentrationsanlage ermöglichen würde. Der Abflusskoeffizient könnte auch durch Regensimulationsanlagen im Gelände ermittelt werden. Mithilfe des CROPWAT-Modells der FAO und den berechneten potentiellen Verdunstungswerten wurde noch der Wasserbedarf einiger Pflanzen unter den gegebenen klimatischen Verhältnissen ermittelt.

Die Methodik des AHP kann auf andere Gebiete übertragen werden. Der AHP innerhalb des GIS erlaubt auch ohne weiteres die Einbindung weiterer Faktoren wie z.B. sozioökonomischer Entscheidungskriterien. Ein Beispiel für sozioökonomische Kriterien wäre der Arbeitsaufwand, der benötigt wird für die Installation und Unterhaltung einzelner Wasserkonzentrationssysteme. Somit ermöglicht die angewandte Methodik, die moderne Techniken wie Fernerkundung und Geoinformationssysteme einschliesst, eine Entscheidungsfindung bezüglich der Anwendbarkeit von Wasserkonzentrationstechniken vor allem in großen, unzugänglichen Gebieten mit wenig bekannten hydrologischen Daten.

Chapter 1
Introduction
1.1 Description of the problem

About half of the world's population lives in semi-arid or arid regions. A major constraint in these areas to any economical development is the lack of water. In Syria, about half of its surface belongs to the low rainfall zones, where sustainable agricultural land use is limited by the availability of adequate water resources. The rapid increase of the population (1980: 8.7 million, Census in 1994: 13,8 Million, 2000: 16.2 Million (FAO 2000a, CBS 1996)) over the past decades, with a growth rate of 3.23% (2.54% in 1995-2000, FAO-MAAR 2001) has forced Syria to develop the agricultural sector in order to ensure self sufficiency of the country in food supply. To meet these challenges, large areas near the main surface water sources, i.e. the *Euphrate*s river and its tributary *Khabour*, have been developed for irrigation. About 95% of the total estimated consumption of water is used in agriculture (FAO 2000b). Since the irrigated areas are planned to be extended and the water of the Euphrates river is shared with Turkey and Irak, it is presumed that after 2010 Syria will face an increasing water deficit (Wakil 1993, FAO 2000b). Population growth is another important justification for the expansion of agriculture into marginal areas. In the marginal areas, agriculture depends on groundwater resources of deeper aquifers whose age reveals the fossil character of the water resources. About 60% of the irrigated area in the country is irrigated with groundwater (FAO 2000b), the remaining area with surface water. The dilemma of increasing demand for irrigation water with declining availability may be solved through use of alternative water resources that have been neglected for a long time. Erratic precipitation with large annual and seasonal variations does often not build up soil moisture and recharge of the ground water due to uncontrolled runoff and evaporation. However, runoff agriculture or water harvesting would be an appropriate alternatives to utilize this unused water. Runoff - or water harvesting-techniques have been used in the Middle East for more than 5000 years. The *Marib* dam in Yemen and the dam at *Al Baridah* in the research area are examples of these traditional technologies and their usefulness and sustainability.

Surface irrigation or treated wastewater irrigation are typical choices for large-scale irrigation. However, for smallholders and pastoralists, water harvesting techniques have proven to be adoptable (Prinz 1995). These traditional technologies also make use of locally available materials and are therefore cheaper to develop and operate than large irrigation schemes. Water harvesting techniques do not induce problems such as water logging or salinization. A social implication of a more reliable water supply is the reduction of migration to the urban areas, thus sustaining agricultural production of the rural communities and conservation of natural resources (Prinz 1994, Barrow 1999). Water harvesting is also a means to combat desertification in marginal lands, thus maintaining and enhancing the productivity of arable areas and rangelands (Prinz 1994). 70% of the rainfed cropland in Syria is estimated to be threatened by desertification (Nasr 1999). About 90% of the Syrian rangelands are considered to be affected by desertification, of which about 67% are considered to be already severely degraded (25 to 50% degradation) (Nasr 1999). Degradation also leads to economic losses, especially if the land is left non-rehabilitated. “Runoff agriculture and the related water conservation approaches have particular value for remote and harsh environments, where other strategies would be either technically impossible, too expensive or ill-advised.” (Barrow 1999, page XV).

A major problem for the initiation and implementation of water harvesting practices is the lack of knowledge to identify potential areas and suitable locations for water harvesting. The semi-arid regions are typically characterized by an underdeveloped infrastructure and the lack of appropriate environmental and socioeconomic data. This is mainly due to the low priority that used to be given to these marginal areas in terms of their importance for agriculture. Also, financial constraints of the public sector led to insufficient investments in equipment for data capture and storage; in addition, politically rooted constraints often limit the accessibility to existing data, which are frequently classified as restricted for public use. However, over the last decade, the development and application of modern technologies, especially remote sensing, has made available tools that help overcome these constraints. Numerous publications illustrate that remote sensing (RS) and geographical information systems (GIS) are capable to address and help to solve a wide range of problems pertaining to hydrology and agricultural water use.

1.2 Objectives of the research

Remote sensing and geographical information systems are modern scientific tools for the determination, assessment and modeling of environmental characteristics and processes. In development projects, remote sensing is e.g. used to commonly applied for regional to develop control strategies for soil erosion or to develop concepts for sustainable agriculture (Komp 1991). In the *Sahel* remote sensing images were used in a large scale to detect vegetation changes with regard to diminishing grazing potential. Rangeland degradation in Australia has been assessed through remotely-sensed data (Pickup et al. 1993). In hydrology remoteley sensed data help in estimating evapotranspiration or precipitation (Engman & Gurney 1991) or the delineation of hydrological similar units within a water catchment (Schultz & Engman 2000). Watershed morphology, outline of drainage systems or the delineation of hydrological similar units within a water catchment are determined with the help of sensor data from satellites (Schultz & Engman 2000, Engman & Gurney 1991). The runoff potential of a catchment that is a crucial design parameter to water harvesting systems can be modeled through the empirical US Soil Conservation Service (SCS) method involving also the use of remotely-sensed data (Engman & Gurney 1991, Nouh 1988). There are limitations to conclusions from empirical models built upon scarce data available in arid remote areas (El-Hames & Richards 1994). Geographical information systems allow the linkage and interrelation with other data which are important to determine potential sites to water harvesting systems. Vorhauer et al. (1996) used GIS to determine potential sites for farm ponds. Tauer & Humborg (1992) used GIS to define water harvesting sites in Mali. Within the current study no field data concerning rainfall runoff events were available. Remotely sensed data and geographical information system were used to overcome this limitation and to draw conclusions on the current runoff potential which is crucial to water harvesting. The analysis of *Landsat TM* data gives information on determinants to runoff generation such as the land cover, soil surface and soil moisture. The data on land cover is amplified through additional information, such as soil analysis. It also helps in determination of relevant parameters to the SCS curve number method. Slope or flow length which also influence runoff behavior are defined by analysis of the digital terrain model. The results of the SCS curve number method are compared to the determination of runoff potential by combining (indexing) the different data layers on slope or soilscape units. The runoff potential either determined by the SCS method or the indexing method is then implemented in a typical decision procedure. Here also the other parameters are included which are important to identify the potential to water harvesting. The developed methodology is practicable and can be adapted to other research sites. It provides a flexible tool to determination of potential sites to water harvesting especially in regions which are difficult to access. The result consists of thematic maps of water harvesting potential. They are basis to further planning and field studies needed for design of water harvesting techniques.

1.3 Approach and outline of the work

- After introducing the project area by describing location and settlement character (Chapter 1) the different parameters important to runoff generation in semi-arid areas are described (Chapter 2). The following paragraphs illustrate how modern techniques such as remote sensing or geographical information system are nowadays used to determine the relevant parameters. A compendium of water harvesting systems which may be relevant to more efficient use of runoff in the project area is also included.
- The third chapter illustrates the methodology which was used in determination of runoff potential in the project area. It incorporates the decision support system which was used to select potential sites for water harvesting structures in the research area.
- In chapter 4 the data sets available for the project area concerning rainfall, soil, land use etc are presented and analysed. This includes statistical analysis of rainfall data, determination of runoff potential by index method and alternatively SCS curve number method and the land use characterization by classification of satellite images.
- The final chapter comprises the results of application of the **A**nalytical **H**ierarchical **P**rocess (AHP) for the determination of potential areas for water harvesting. Discussion and outlook on possible further focus of study finalize this chapter.

1.4 Location and infrastructure of the research area

Syria is located on the eastern side of the Mediterranean sea. Neighboring countries are Turkey in the north and Jordan in the south. It shares the eastern border with Irak, the western with Lebanon and Israel.

The project area is situated east of the *Northern Lebanon* and the green belt of the coastal mountains with settlements dating from early times. It belongs to the central part of Syria comprising an area of about 32,400 km^2, according to the coverage of one *Landsat TM* scene (Fig. 1.1). Within the whole area a research site was chosen which covers an area of 10,500 km^2 (Fig. 1.2). The region belongs to the *Bahdi*a, i.e. the Syrian steppe. It is situated east of the highway *Damascus - Aleppo*, which since Roman times is the major north-south road axis in Syria. Administratively the whole project area belongs to the province of *Homs* and the new province *of Tadmor*.

Main topographic features of the study area are (1) the *Northern Palmyrides*, (2) the plains south of the *Northern Palmyrides* intercalated between the mountain chains of the

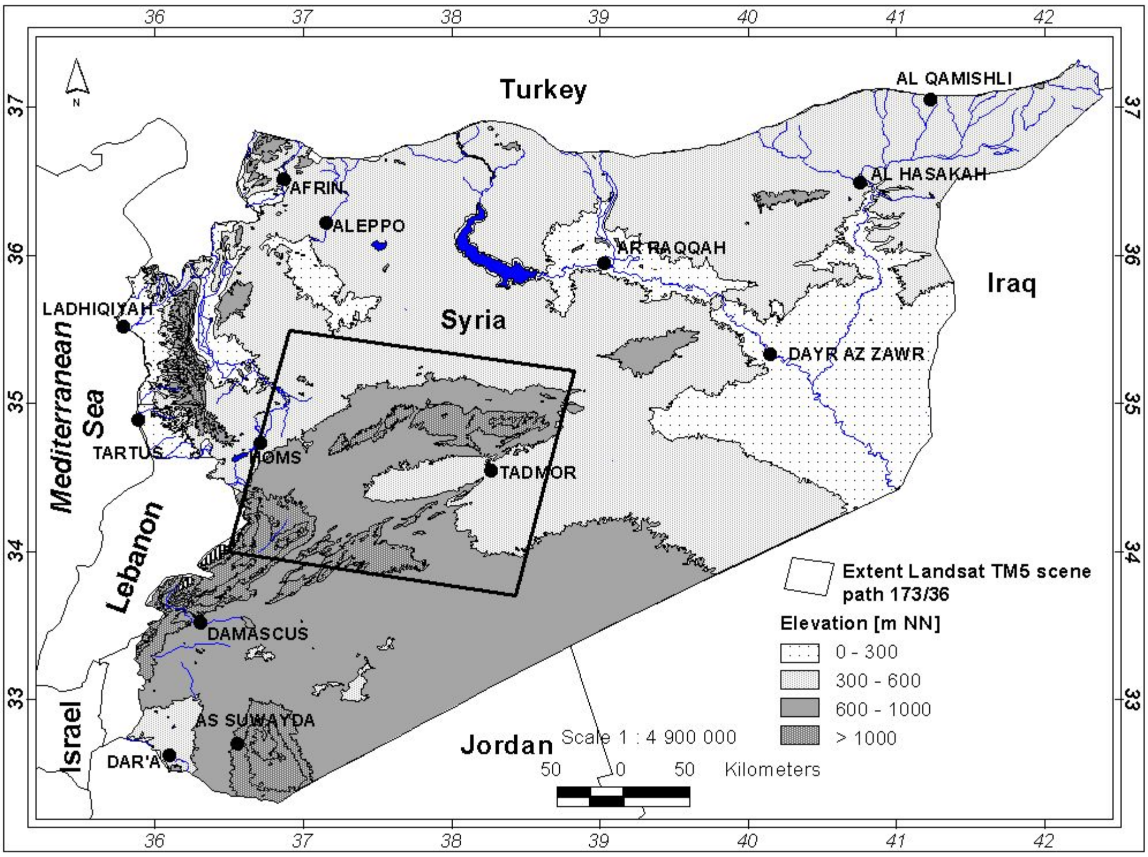

Fig. 1.1 *Location of project area (ESRI 1998b, ESRI 1994)*

Southern Palmyrides, (3) the *Ad-Dauw Basin* and (4) the *Sabkhat al Muh* south of *Tadmo*r. (Fig. 3.2). Perennial streams are missing and the regime of surface flow is governed by the precipitation occurring from November to April. On the northeastern side of the *Southern Palmyrides* the region is highly dissected with deep cutting ephemeral streams further on referred to the Arabic name *wadi*. The area south of *Tadmor* is characterized by depression of *Sabkha Mouh*, a saltpan, covering an area of around 3 km^2 at an elevation of around 300 m a.s.l.. The *Northern Palmyrides* are descending in the North to the plain south of the *Euphrates* and the large reservoir at *Lake Assad*. It can be differentiated into different mountains chains going up to elevations of 1100 to 1200 m a.s.l. : *Jebel Al-Bilaas, Jebel itet Ar-Ras, Jebel ash Shath* and the *Jebel qualat al Hury*. The *Northern Palmyrides* reach elevations of up to 1387 m a.s.l. (*Jebel Hawitet Ar Ras*). Most of the wadis collecting the runoff from the slopes end in the large alluvial fan of the *Ad-Dauw* syncline. The large undulating plains south and east of the *Ad-Dauw* basin are cut by the Southern Palmyrides comprising several NNE - SSW striking mountain ranges intercalated with plains: *Jebel Sharquiyat*, *Jebel Rus at Tiwal*, *Jebel Haymour Jebel An-Nasrani, Jebel Ghattour*.

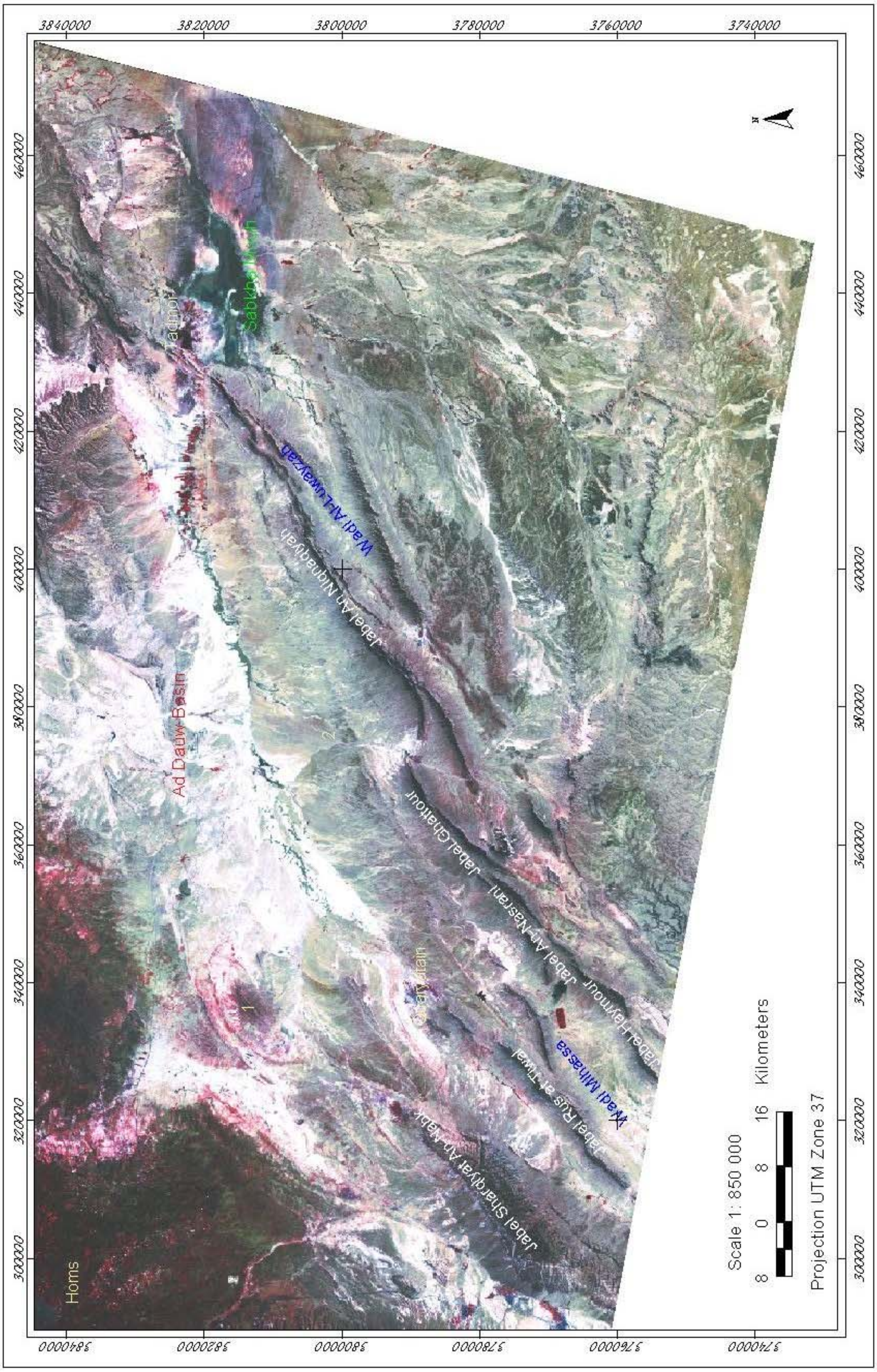

Fig. 1.2 *Location and topography of the research area (Subset of landsat TM scene, path 173/36, 04/04/1994, False colour image, Bands 4,3,2 [1: Hammam Abou Rabah, 2: Quasr Al hir] (Source: ESA 1994a)*

Different *wadi*s are cutting the mountain ranges in north-south direction. The mountains especially in the upper part have the gentle rolling hilly surface unlike the rather ruffed shape of the European Alpine region since the Mediterranean dry climate favours continuous erosion. The lower parts are characterised by steep scree slopes.

The *Landsat TM* scene defining the project area comprises an area of about 32,000 km^2, about the area of *Baden-Wuerttemberg* (35,752 km^2) (federal state of Germany). Main roads within the project area are connections to important settlements, such as *Tadmor* or *Quaryatain*. These are settled since ancient times due to natural springs (oasis) (Fig. 1.3). Since *Tadmo*r has gained growing importance as tourist site during recent years, the road between *Damascus* and *Tadmo*r leading through the southern part of the region is well maintained. One of the major east-west connections is the road *Homs - Tadmor* which follows the old oil pipeline that was constructed during the times of the British oil company in the early 1920s. The road is an important economical link: Trucks are transporting petroleum from the oilfields nearby *Dayr-Ez-Zaur* (oilfield *Jafra* (U.S.E.I.A. 2003)) to *Homs* where major centers of oil industry, including a refinery, are located. The oil industry counts for 20% of the GDP (IFC 1999). To allow shepherds to get their herds more quickly to the steppe area south of the *Northern Palmyrides* a road was constructed recently following a former unpaved path through the mountain from *Salamiyeh* to the *Ad Dauw Basin* and the rangelands of the *Southern Palmyrides*. Small paved roads lead to newly constructed reservoirs or industrial sites such as phosphate mines. Besides 82 km of the highway between *Aleppo* and *Damascus*, 710 km of paved roads are constructed within the area and about 2,380 km of unpaved roads (ESRI 1998b). This means a density of 0.02 km road per km^2 and 0.07 km per km^2 for unpaved roads (compared to *Baden-Württemberg*: 0.79 km of paved primary and secondary roads per km^2 (Statistisches Landesamt Baden-Württemberg 2002). The condition of the unpaved roads is very variable; some consists only of compacted tracks, others are gravel roads. Nevertheless, most of areas within the study region are only accessible during the dry season with time consuming travel. During the rainy season, from November to April, flooding of depressions and valleys makes travelling by car difficult or even impossible. Therefore the use of remotely sensed data was needed to get more economically the needed information within a reasonable time frame.

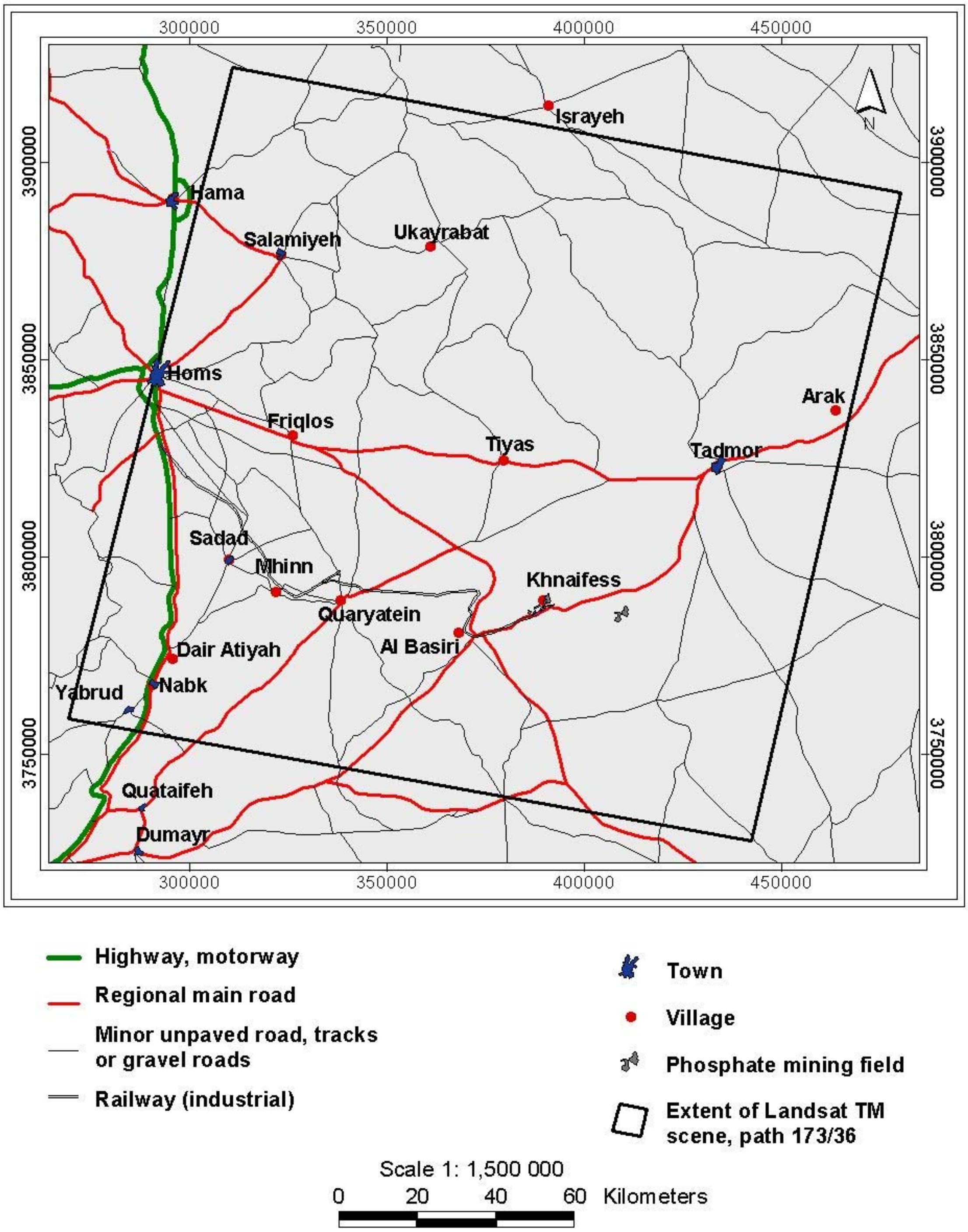

Fig. 1.3 *Infrastructure of the project area (Source: ESRI 1998b)*

1.5 Population and settlement pattern

Syria is a cradle of ancient civilization. The first Neolithic agricultural settlements were founded in the seventh and sixth century BC. A Neolithic archeological site near Damascus shows evidence of agriculture with cultivation of wheat and pulses as well as livestock production with domesticated pigs and cattle .

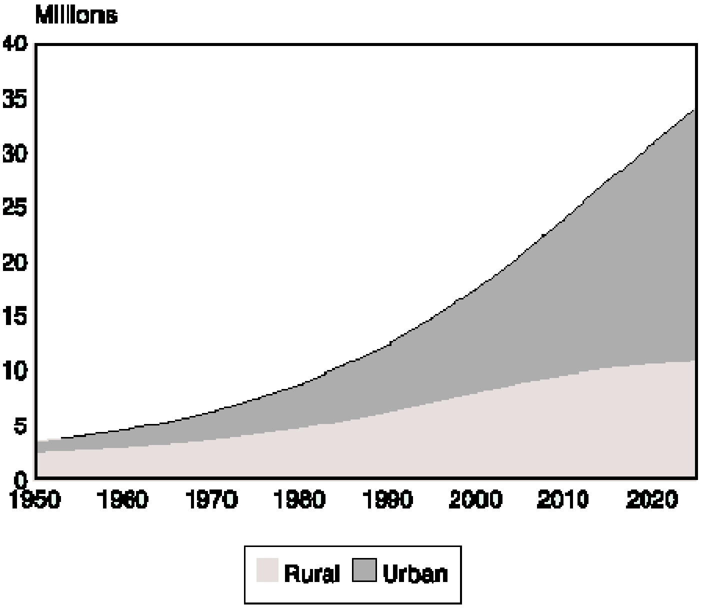

Fig. 1.4 *Increase of population of Syria since 1950 and prognosis for 2025 (WRI 2000)*

The total population of Syria comprises about 16,189,000 in 2000 (FAO 2000a). It doubled in the last 20 years (1975: about 8 millions). The growth rate is about 3.15% (FAO 2000a). About half of the population is below 14 years old, clearly contrasting to the population structure in industrialised countries. The trend is similar to other developing countries, the rate of the urban population has tremendously increased from 1960 to 1990, from 36.9 to 50%: About 53% counts for the urban population in 1997, about 47% belongs to the rural one (WRI 2000) (Fig. 1.4).

Approximately 38% of population are working in the agricultural sector. The project region is mainly belonging to the *muhafazat* (Province) of *Homs*. The population density in the *muhafazat Homs* is the lowest of the country, although it doubled since 1970 (1970: 12.9 inhabitants per km², 1994: 24.8; (Statistisches Bundesamt 1990, CBS 1994)). Since climatic conditions get harsher from the west to the east of the project area the population density is decreasing: Around *Hama* and *Homs* in the north western part and the southwestern part the population density ranges from 50 to 100 inhabitants per km² whereas in the eastern part of the project area the population density is around 2 to 10 inhabitants per km². The population is concentrated in the small towns such as *Quaryatain*, *Salamiyeh*, *Tadmor* or *Sadad*. People are mainly employed in the agricultural sector, only in *Tadmor* (important archeological site and famous tourist site) the percentage of people working in the tourist sector is rising. Main centres of urban population are *Homs* and *Hama* on the western limits of the study area.

The settlement type of the major drier part of the region is characterized by islands of settlements, mainly at areas where natural sources of water exist: The oasis settlements with a lot of irrigated orchards such as *Tadmor* or *Arak* in the east or *Quaryatain* are examples. Other more recent settlements were founded due to commercial reasons: such as *Tiyas* (*T4*) on the road between *Homs* and *Tadmo*r, founded by a British oil company and destinated as more comfortable working camp or *Khnaifess*, that is home to workers of the neighbouring phosphate mines. The construction and arrangement of houses in most of the villages is simple, often concentrated along the roads leading out of the village. The settlement character is also important to planning of water management structures.

Chapter 2

Determinants of runoff generation and their characterization in semi-arid areas - State of the art

2.1 Parameters important to runoff generation in semi-arid areas

2.1.1 Introduction

The overland flow in arid climates illustrates perfectly the hypothesis of Horton which describes the infiltration process depending on rainfall (Horton 1935). Especially during a storm , the amount of usually exceeds the infiltration capacity of the soil, the infiltration rate tends to decrease in an exponential manner and overland flow will occur. During a storm depressions will be filled and afterwards water runs downslope. This simple relationship demonstrates that runoff is not only dependent on rainfall characteristics but also on other parameters such as the soil infiltration capacity. Runoff data are usually scarce in semi-arid areas because of randomness of high irregularity of runoff events and lack of measuring devices due to financial constraints or remoteness of semi-arid areas. Therefore it is essential to thoroughly describe the different parameters.

There have been numerous approaches to describe the different parameters influencing runoff. Cook (1939) used a method that allows the derivation of different classes of susceptibility to runoff with regard to relief, vegetative cover and surface storage attributes. Chow (1988) divided the parameters important to runoff generation into two groups. The first order attributes consist of surface condition and soil type. The other factor refers to basin size, basin shape and slope.

These parameters have also been incorporated within the current study. The following parameters are therefore important to runoff potential (Table 2.1).

Table 2.1 *Parameters important to runoff generation*

Climate	Topographic features	Land cover	Soil characteristics
Rainfall intensity	Slope	Vegetation density	Soil texture
Rainfall amount	Slope curvature	Vegetation characteristics	Soil crust
Soil evaporation	Catchment length	Land use	Soil moisture

2.1.2 Rainfall characteristics

Rainfall amount in total limits agriculture. Cultures are dependent on rainfall amount. and evaporation (see chapter 5.3.2). Water harvesting techniques which collect runoff are not feasible below the amount of 100 mm (Table 2.7).

The threshold of rainfall which produces runoff in semi-arid regions depends mainly on the underground (Table 2.2). No runoff is observed below the threshold of rainfall and the whole amount of rainfall infiltrates or evaporates on the surface.

Table 2.2 *Threshold for daily rainfall events producing runoff (after Humborg 1988)*

Threshold rainfall [mm]	Region	Author
12.7 - 17.8	Southwest of USA	Murphy et al. 1977
8.1	Southwest of USA	Fogel & Duckstein 1973
3 – 4 on dry soil surface 2 on wet soil surface	Israel	Bryan et al. 1978
5 for the dry river beds	Israel	Yair & Klein 1973
1 – 2 (massive rocks) 3 - 5 for scree slopes	Israel	Yair 1983
1 - 2 on stony underground 3 - 5 on sandy soils	Israel	Tenbergen 1991

Studies within the *Negev* (Israel) showed that the threshold for rainfall to produce runoff is 1 to 2 mm for stony underground and 3 to 5 mm for sandy soils (Tenbergen 1991) (Table 2.2). The climate in the study area is comparable with the *Negev* Highlands, where rainfall events are also around 0 to 6 $mm \cdot d^{-1}$. 77% of total annual rainfall occur in storms with intensity of 5 to 10 mm per hour (Tenbergen 1991). Rainfall events of over 10 $mm \cdot d^{-1}$ last for only 15 $min \cdot h^{-1}$. Rainfall intensities in a semi-arid watershed in Jordan range between 5 to 35 mm h^{-1} (Shatanawi et al. 1998). The maximum rainfall intensity in the low rainfall zone in northern Iraq is about 20 $mm \cdot h^{-1}$ for normal storms (Hussein 1996). The small database on rainfall intensity is nowadays amplified and made more publicly accessible by projects like the Regional Rainfall-Intensity Project (USGS 2003). The project which is an activity within the Middle East Peace Process was established in 1999 to build up a regional database on rainfall intensity in the Middle East including the countries Israel, Jordan and Palestine.

2.1.3 Topography

Topographic features are significant to hydrological parameters (Table 2.3). Slope, for example is crucial to runoff rates and amounts. The topography plays a key role in distributed flow and sediment transport models (Bates et al. 1998). The topographic features are the results of terrain analysis of a **D**igital **T**errain **M**odel. The DTM stores different information beside the slope, curvature or aspect (Mattikalli & Engman 2000).

Table 2.3 *Topographic attributes and their significance to meteorology, hydrology and vegetation (Wilson & Gallant 1998; Moore & Agharwal 1998)*

Topographic Attribute	Definition	Significance
Aspect	Slope azimuth	Solar insulation, evapotranspiration, vegetation
Slope	Gradient	Runoff rate, runoff amount, flow velocity
Catchment slope	Average slope over the catchment	Time of concentration of runoff
Catchment area	Area draining to outlet	Runoff volume
Catchment length	Distance from the most upper point in the catchment to the outlet	Overland flow attenuation, transmission losses
Plain curvature	Contour curvature	Converging/diverging flow, soil water characteristics

2.1.4 Infiltration behavior of soils and soil crusts

Since runoff is dependent on the infiltration characteristics of soils a lot of studies exist on the influence of parameters on infiltration. Infiltration in general starts as soon the rainfall intensity exceeds the infiltration capacity of the soil. The infiltration capacity which is dependent on soil texture, structure and antecedent soil moisture declines over the period of the storm event. The texture of the different soil layers influences the infiltration capacity. Soil texture is an important parameter for the hydraulic conductivity and permeability. Generally coarse textured soil have higher saturated hydraulic conductivities than soils with low porosity and smaller pores and higher clay content (Landon 1991) (Fig. 2.1). According to Rawls et al. (1982) mean values of saturated hydraulic conductivity can be estimated according to the soil texture class.

Rainfall simulation experiments on fields of brown earth in the humid area showed that the steady state infiltration rate at the end of the rainfall simulation experiments was higher on fields with higher clay content and lower on fields with lower clay content (Gerlinger 1997). These effects of soil texture are mainly linked to the behavior of soil aggregates. Experiments of Gollany et al. (1991) confirmed these results that aggregate stability increased with clay content especially when linked to higher water content of the soil. Pore interconnectivity also plays a role.

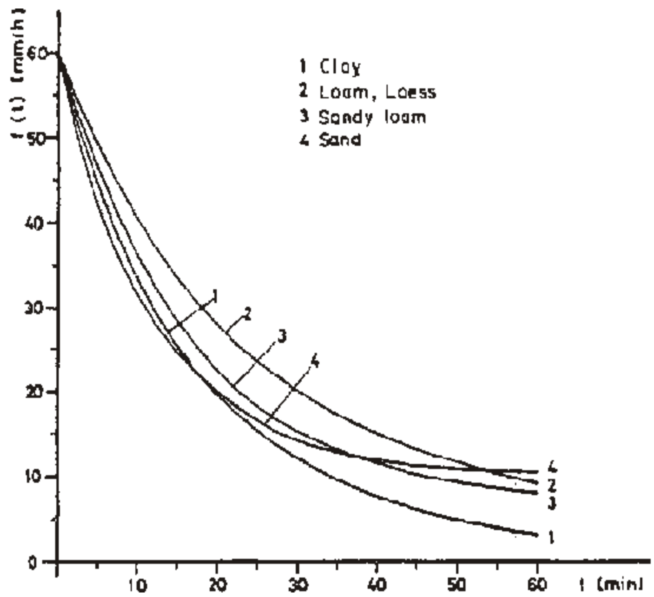

Fig. 2.1 *Infiltration rate dependent on soil texture (Morin 1993)*

Soils are not homogenous units; the top layer of soils often shows a completely different hydrological behavior. Figure 2.2 shows that besides the vegetation cover crusting also influences the infiltration capacity of soils. Crusting often occurs in semi-arid areas. Two different types of crusts can be differentiated, depositional and structural (Morin 1993). Depositional crusts form in depressions and rills created during erosion from increased runoff (Bradford & Huang 1993). These runoff depositional crusts can be differentiated from still depositional crust formed in standing water. Salty crusts mainly consists of sodium and magnesium chlorates and sulfates. Bresson & Valentin (2001) differentiated between different forms of structural crusts: slaking crusts, infilling, coalescing and sieving crusts which are different temporal stages in crust development. Sieving crusts are composed of a layer of loose sand overlaying a thin layer of finer material.

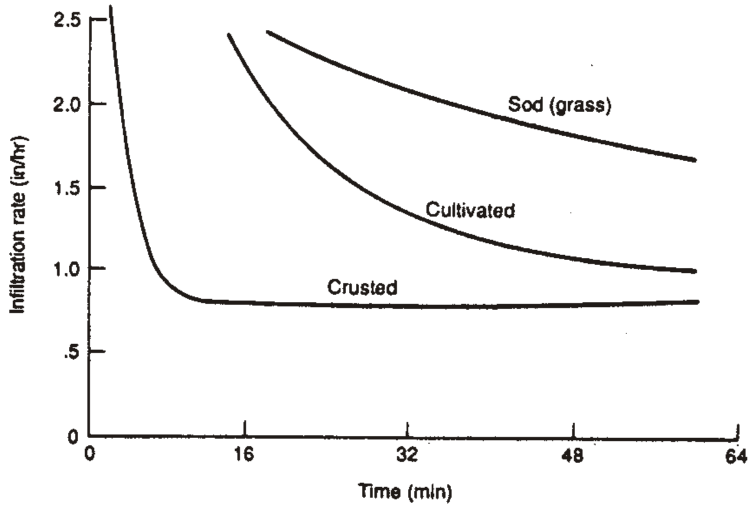

Fig. 2.2 *Effect of parameters such as vegetation and crusting on infiltration rate (Rawls et al. 1982)*

They are mainly formed in sandy loams. A special form is the pavement crust with embedded rock fragments in the crust. Slaking crust are mainly formed within soils of fine particles with patches of broken down clods (Morin 1993). The erosion crust develops either from slaking crusts enriched with finer particles or from sieving crusts where the sandy layer is blown away.

The structural crusts are in the range from < 1 mm to > 10 mm in depth. Reductions of porosity are reported in the range from 30 to 60% and also the mean pore diameter is reduced: Pores from 0.075 to 0.3 mm in a crust occur over a soil with pore diameters of 0.15 to 0.4 mm (Valentin & Ruiz Figuero 1987).

To estimate the soil susceptibility to crust formation different indices are proposed in the literature. They include consistency indices like the Atterberg liquid test (Bresson & Valentin 2001), mechanical strength tests or the strength of a dry-soil aggregate (Skidmore & Layton 1992). Bresson & Valentin (2001) pointed out that crusting processes are mainly correlated with the rainfall patterns and antecedent moisture conditions of the soil. They prefer therefore to use aggregate instability tests instead of consistency tests for soils in semi-arid tropics, which normally dries before the next shower.

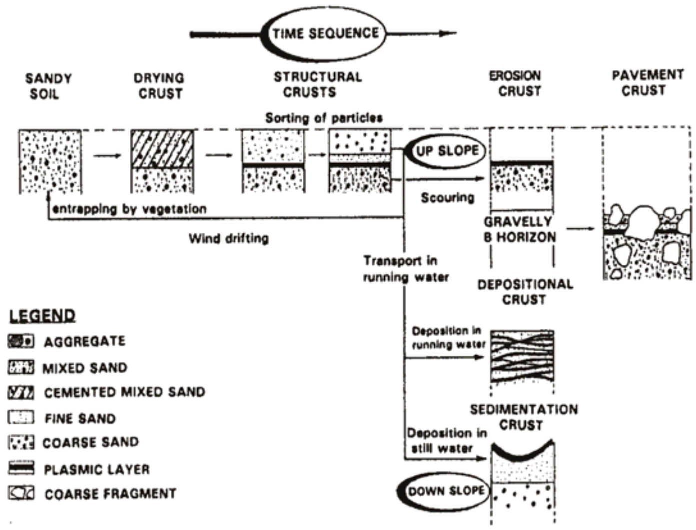

Fig. 2.3 *Sequence of formation of different types of crusts (Bresson & Valentin 1990)*

However, simulated rainfall is the most efficient method to assess the soil crustability. Simulation of rainfall events uses known drop-energy distribution of natural rainfall events.

The formation of this crust is mainly due to two processes: breakdown of the soil aggregates because of the impact of the raindrops and compaction of the crust. Secondly the rain involves the stirring of particles that enhances the chemical dispersion and movement of the clay particles into a “washed in” region with dispersed particles (McIntyre 1958). The layer is about 0.1 to 0.5 mm thick.

The initiation of crust formation is due to raindrop impact causing the break down of soil aggregates and slaking. Fig. 2. 4 shows the different processes during crust formation: chemical dispersion, filtration and physical dispersion of soil aggregates.

Aggregates are important to soil crusting. Aggregates mainly form during the drying process of the soil first due to capillary forces between the particles. They can have different sizes and forms : crumbs (< 2 mm), polyhedres or subangular blocks (0.005 - 0.02 m), or prisms or columns larger than 0.1 m (Horn et al. 1994). Aggregates also influence the pore distribution and pore diameter and the hydraulic properties of the soil. Increase of drying cycles first decreases the finer porosity but may increase it later. The amount of water available to plant will be increased with the improvement of soil aggregation. Also the hydraulic conductivity is influenced by the aggregates. It decreases within the aggregates, sometimes even up to four times due to the lower porosity and tortuosity of the pore system.

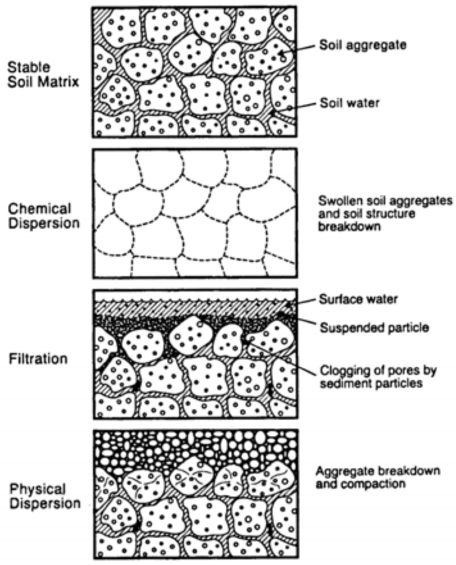

Fig. 2.4 *Processes during crust formation (Baird 1992)*

Also the flow route is changed: The pore water gradient forces the water to flow to the macropores of the torturous system of aggregates in the case of saturation of macro and micropores (Horn et al. 1994). The aggregates can be also stabilized by metabolic production of bacteria. (Horn et al. 1994). Therefore the hydraulic properties determined for the bulk soil do not consequently reflect pore continuity or pore accessibility (Horn et al. 1994, Dunne et al. 1991). Upon increase of soil water content, saturation and due to raindrop impact, soil aggregate disperse. This affects water uptake by the soil, e.g. due to increased sealing and crusting and the destruction of the larger pores that are critical for the uptake of short-term and high-intensity rainfall and runoff. Therefore aggregate stability is important to maintain favourable water-uptake condition during rainfall and runoff events.

The crust formation and the permeability of the soil within the arid climates are dependent on soil characteristics, rainfall characteristics and water quality of the rainwater. Infiltration processes within the semi-arid areas are directly linked to the process of soil crusting (Fig. 2.4).

Table 2.4 gives some characteristic values of kinetic energies of raindrops, calculated on data from the *Vale Formoso Experimental Erosion Center* near *Mértola*, a semi-arid region in Southern Portugal (Coutinho & Tomás 1995).

Table 2.4 *Rainfall intensities (station in Southern Portugal), median drop diameter and kinetic energy of rainfall (Sources: Coutinho & Tomás 1995 (1), Morgan 1986 (2), Lal & Elliot 1994 (3))*

Rainfall intensity [mm·h^{-1}] (1)	Median volume diameter of raindrop size D_{50}[mm] ±stddev (1)	Kinetic energy per unit area and time [J·m^{-2}mm^{-1}], calculated with model of Renard et al. (1992) (RUSLE)[1](2)(3)	Kinetic energy per unit area and time [J·m^{-2} mm^{-1}], calculated with model of Zanchi & Torri (1981)[2](2)
light: 0 - 2	1.13 ± 0.33	9.1 - 10.1	9.8 – 13.2
moderate: 4 - 6	1.70 ± 0.26	11.9 - 13.5	16.6 – 18.6
heavy: 10 - 15	1.98 ± 0.33	16.3 – 19.1	21.1 – 23.1
excessive: 40 - 50	3.25 ± 0.25	26.2 – 27.3	27.8 –28.9

[1] $E=29.0\ (1-0.72e^{-0.05I})$

[2] $E=9.81+11.25\ \log_{10}I$

The raindrop energy which is related to the rainfall intensity needed for breakdown of aggregates depends on the stability of the aggregates. The median drop size is related to the rainfall intensity, such as the median drop size increases with rainfall intensity. Based on works on this relationships, different empirical models have been developed to calculate the kinetic raindrop energy (Table 2.4). The higher the kinetic raindrop energy the higher the disintegration of the aggregates and the effect of slaking and seal formation (Betzalal et al. 1995). On a clay loam soil (40% sand, 28% silt and 32% clay), the infiltration rate at a rainfall intensity of 40 mm·h^{-1} and a kinetic energy of 3 J·m^{-2}mm^{-1} dropped from 15.7 mm·h^{-1} to 2.0 mm·h^{-1} with a rainfall of 27 J·m^{-2}mm^{-1} (Bradford & Huang 1992).

Lange (1999) used infiltration measurements in the watershed *Nahal Zin* within the *Negev* (Israel) and characterized various terrain units according to infiltration characteristics (Table 2.5). Final infiltration rate is the rate established after reaching at steady condition. It shows that the highest infiltration rates are found on steep active slopes, within badland areas, followed by dissected flint plateau. These values could only be estimates, the variability depends on the method of infiltration measurement and on spatial effects. Infiltration can vary by four magnitudes over a site (Radcliffe & Rasmussen 2000). Various measurement methods exists, such as Guelph permeameter or the double-ring infiltrometer. Lee et al. (1985) provide a description and comparison of these methods. But these infiltration measuring methods mainly provide information on infiltration characteristics of flat land. Infiltration characteristics of sloping land are more difficult to measure by these methods (Wilcox et al. 1986).

Table 2.5 *Infiltration characteristics of terrain units within the watershed Nahal Zin (Negev) (Lange 1999; Yair 1983)*

Terrain type	Initial loss of runoff [mm]	Final infiltration rate [mm h^{-1}]
Limestone plateaus	4.5	5
Dissected limestone	7	15
Flint plateau	6	10
Dissected flint plateau	8	20
Marly sediment	9.5	15
Steep active slope	10	30
Badlands	9.5	2

Rainfall simulation experiments lead to a better understanding of the infiltration processes. Especially in areas with sporadic rainfall events they provide a tool for better understanding of the hydrological processes. Since hydrological data are rare within semi-arid regions rainfall simulation experiments offer data in a shorter period of time. The effect of the kinetic energy of raindrops can be measured, and is mainly important within the arid areas with regard to the build-up of crust. Also rainfall simulation experiments allow the measurement of hydrologic parameters on undisturbed soil since e.g. augerhole tests like the Guelph permeameter disturb the soil structure (Byars et al. 1996). The runoff can be measured more exactly on well defined plots.

Fig. 2.2 shows besides the crusting the influence of vegetation cover on the infiltration rate. Nevertheless like the other parameters the influence of only the factor vegetation cover is difficult to discern. Paige et al. (2001) mainly investigated the infiltration rates at rangeland sites which are typical for semi-arid areas. The relationship between rainfall intensity and infiltration rate there varies widely with vegetation and soil type (Paige et al. 2001) (Fig. 2.5). Therefore a single rate of hydraulic conductivity or infiltration capacity cannot be used to model the hydrological response at a semi-arid rangeland site.

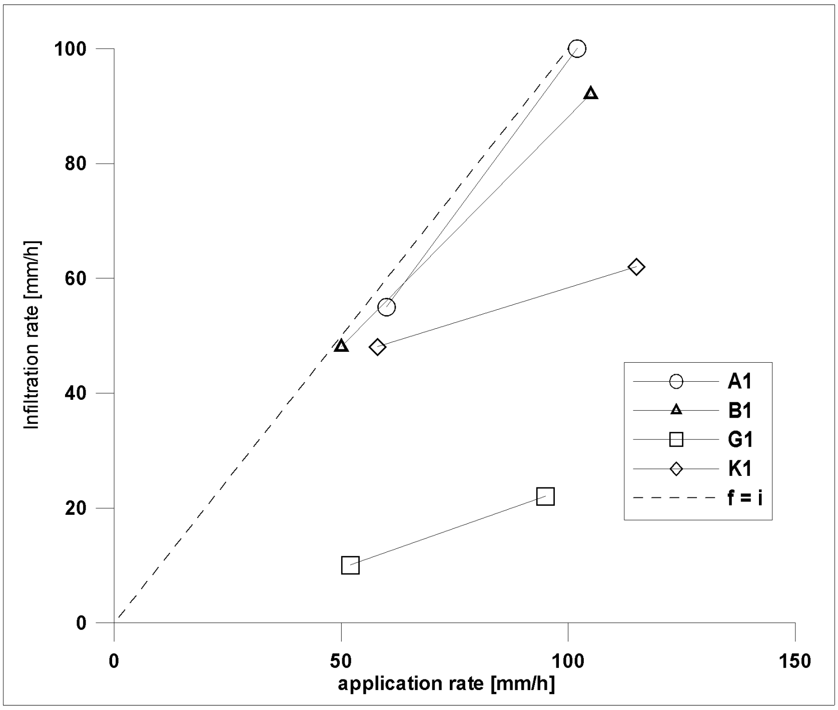

Fig. 2.5 *Variation of rainfall intensity (simulation experiment) with vegetation and soil type on brush dominated rangeland sites (Paige et al. 2001) (A1, B1, G1, K1: rangeland sites of Walnut Creek, described in Table D-1)*

2.1.5 Soil roughness

Soil roughness is negatively correlated with the runoff velocity. This is mainly incorporated in the formula of Manning Strickler which describes the friction component within the runoff flow (Woolhiser et al. 1990). Reduction of the runoff velocity decreases the runoff volume.

$$v = R^{2/3} S^{1/2} n^{-1^{-1}} \quad [2.1]$$

or written as discharge formula

$$Q = AR^{2/3} S^{1/2} n^{-1} \quad [2.2]$$

Q = discharge [m^{-3}]
A = channel cross section area
R = hydraulic radius
S = slope
n = roughness coefficient
v = flow velocity

The Manning's roughness coefficient characterizes the flow resistance (Table 2.6) within a channel or natural stream beds. But the Manning equation is nowadays not only restricted to open channel hydraulics. HEC RAS (U.S. Army Corps 1998) for example uses the Manning equation to handle one dimensional water level calculations and permits delineation of flooded areas adjacent to large stream or rivers (Kraus 2000b). The *Manning* equation is incorporated in the PEPP/HILLFLOW model. The model simulates runoff and sediment transport on hillslopes (Gerlinger 1997).

Table 2.6 *Roughness coefficient (Chow 1988 (1); Morgan et al. 1993 (2); Woolhiser et al. 1990 (3); Engman 1986 (4); Bork 1988 (5); Gerlinger 1997 (6))*

Land cover	**Recommended values of roughness coefficient (Manning values)**
Floodplains (adjacent to natural streams), pasture (no brush) short grass	0.030 - 0.035 (1)
Cultivated areas: Mature field crops	0.04 - 0.05 (1)
Light brush and trees	0.05 - 0.08 (1)
Bare Soil < 25 mm	0.01 - 0.03 (2)
25 - 50 mm	0.014 - 0.033 (2)
50 - 100 mm	0.023 - 0.038 (2)
> 100 mm	0.045 - 0.049 (2)
Eroded loam, no vegetation	0.012 - 0.033 (3)
Cultivated field with crop residues	0.03 - 0.07 (4)
Field cultivated with field crop (cereals before harvesting)	0.1 - 0.3 (2)
Winter wheat	0.4 (5)
Mulch (wheat, straw)	0.05 - 0.25 (2)
Tilled field	0.02 - 0.19 (6)

It has to be considered that the values in Table 2.6 are determined within the humid areas. Probably after a certain saturation of the soil is achieved the values can be also applied to soils within semi-arid areas.

2.1.6 Soil stoniness

Since information on soil roughness is not present for the project area, soil stoniness is the more important parameter. There is a clear relationship between runoff volume and stone clearing (Evenari et al. 1982). In the 1960s Evenari et. al. made hydrological investigations at *Shivta* in the Negev desert and established that the average runoff is about 12 mm, with an annual rainfall of 93 mm. The surface of the soil in this area is cleared and the stones are collected in small heaps. Stone clearing produced a 30% increase in runoff yield. They developed a nomogram illustrating the effect of slope and the importance of stone clearing on runoff generation. The steeper the slope of the area, the higher the effect of stone clearing. (Fig 2.6). This effect can be easily be enhanced to 100% runoff on regions with up to 20% slope. Mainly catchments with rocky surfaces or rock outcrops are chosen for the water catchment system of *alijbes* in Southern Spain (Van Wesemael et al. 1998). The runoff coefficient is very high in these catchments.

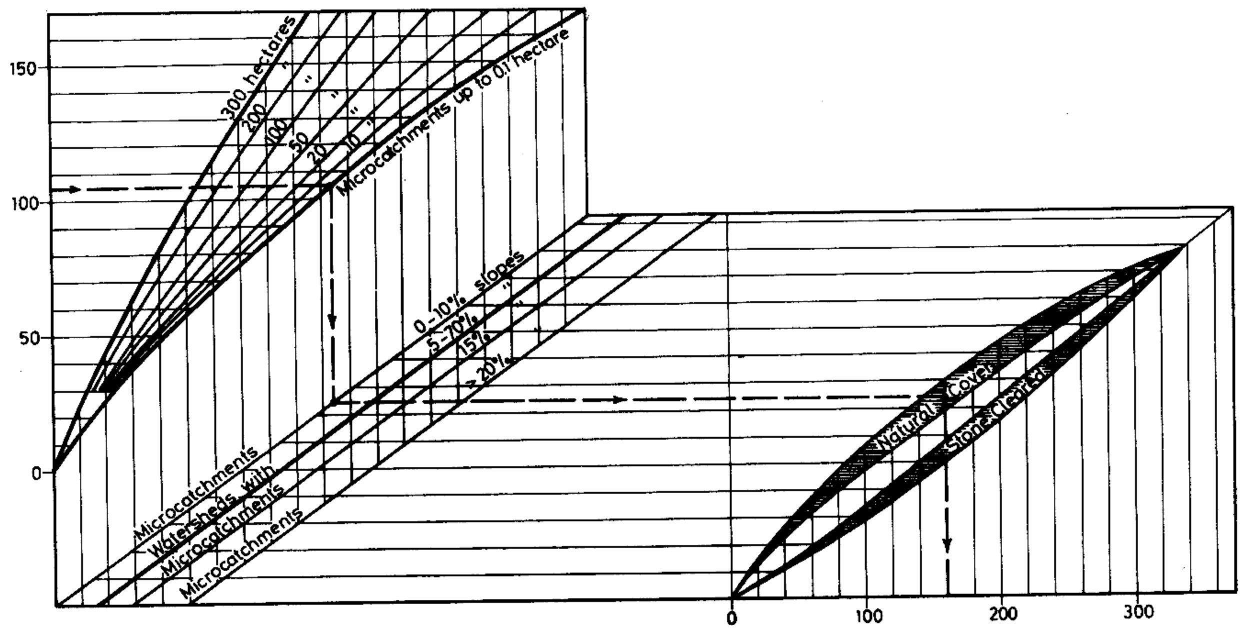

Fig. 2.6 *Nomogram illustrating effect of stone clearing, surface cover and slope on runoff (Evenari et al. 1982)*

When especially considering *alijbes* with very rocky surfaces it was shown that the positive relationship between catchment area and volume is more significant than on catchments with less stone cover. Stone cover protects the soil against the impact of raindrops that causes sealing of topsoil pore spaces. Yair & Lavee (1976) investigated an area in *Sinai* with lithology similar to the Syrian steppe. They studied the talus mantle of scree slopes with a slope of 30% and with an upper layer of loose gravels, cobbles and boulders of 15 to 20 cm diameter, slightly cemented by sand and silt. The area was artificially irrigated by sprinklers and the runoff measured. They measured a rainfall/runoff coefficient of about 25%. There is a negative correlation between the thickness of the gravelly layer and its adsorption capacity (Yair & Lavee 1976). The size of the boulders is positively correlated with the runoff yield. Large boulders offer more surface area to produce runoff than small pebbles.

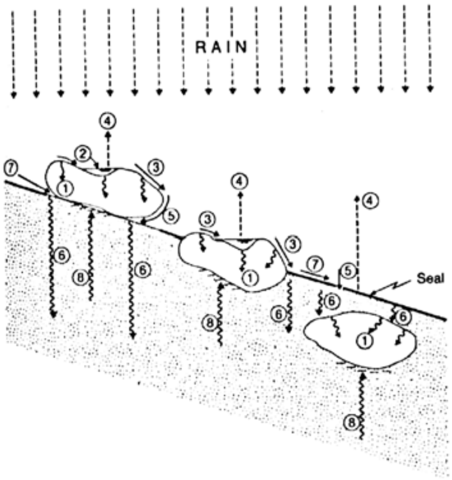

Fig. 2.7 *Different processes linked to runoff from stone-covered soils (Poesen et al. 1998), 1 - infiltration into cracks of rock fragment, 2 - wetting of stone fragment, 3 - runoff from rock fragment, 4 – evaporation, 5 - infiltration into the soil, 6 - percolation, 7 - runoff from soil*

Poesen et al. (1998) conclude that the contradictory results in studies on the relation of rock fragment cover at soil cover and runoff volume is due to different positioning of rock fragments on the soil. They found out that the runoff is higher on soils with embedded rock fragments than on soils with loose rock fragments. This is probably due to the surface area of impermeablized top soil being increased, leading to a higher runoff coefficient. With loose rock cover the runoff coefficient decreases with increasing rock cover because of infiltration into the soil within the fragments. Fig. 2.7 illustrates the different processes linked to runoff on a stone covered soil. Rock fragments protect the soil from evaporation. But the infiltration rate in moist soil is less than on dry soil, therefore the stone cover may produce more runoff in the case of a runoff event. But, if there are plants present, infiltration capacity will be increased (Lavee & Poesen 1991).

The amount of rock fragment cover is additionally related to the gradient of the land. The rock fragment cover with a size over 5 mm and over 25 mm increases with the gradient of hillslopes in Southeast Spain (Poesen et al. 1998). But the rate of increase of large rock fragment cover with increasing slope is lower than for the smaller fraction (Fig. 2.8).

Lithology plays an important role in the size of rock fragments. In areas of volcanic rocks of the research area the size of the fragments is higher compared to the rock fraction on slopes with limestone lithology. The runoff is more irregular here since flow is decelerated by large fragments. Studies on soil loss on slopes with and without rock cover show the protective nature of the rock cover: Soil loss is less on slopes with fragment cover. Therefore runoff amount is smaller on rocky surfaces.

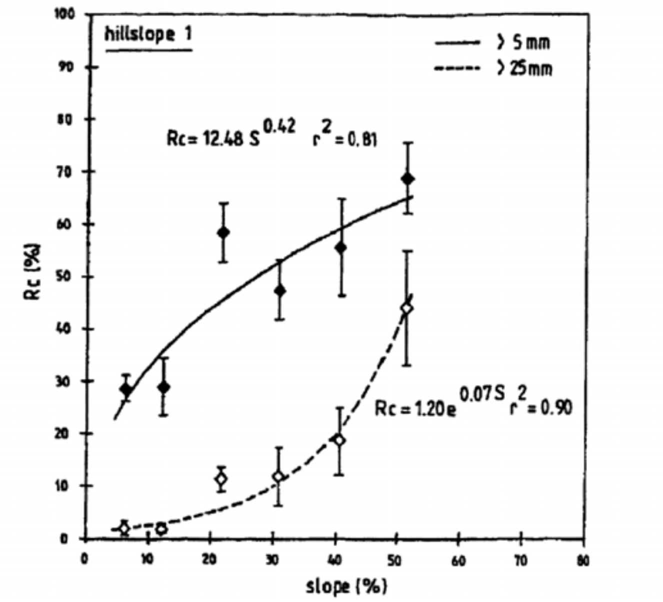

Fig. 2.8 *Influence of hillslope gradient and cover of rock fragments > 5 mm and > 25 mm for a hillsope in a semi-arid catchment in Southern Spain (Poesen et al. 1998)*

Especially in the *Negev*, runoff irrigation farms are mainly found in the area with shallow soils and high stone cover (Yair 1983). In simulated rainfall experiments (rainfall intensities of 15 $mm \cdot h^{-1}$ and 30 $mm \cdot h^{-1}$ for a period of 30 min and 60 $mm \cdot h^{-1}$ for 15 min) the initial infiltration rate on rocky slopes was 40 $mm \cdot h^{-1}$, reducing to around 15 $mm \cdot h^{-1}$ at the end of rainfall application. The experiments also showed that rocky surfaces respond more quickly to runoff than the colluvial slope. A plot with rock surfaces and half the size of a plot within the colluvial slope leads to twice as much runoff. The ratio of exposed bedrock / soil is more important than slope length or stone cover.

Valentin (1993) made similar investigations to Poesen's ones in a north-south transect through the *Sahel*. He recorded the size of rock fragments and the stage of rock fragments within the soil, embedded within the crust or on the surface layer. He adjusted the sprinkling intensity of the rainfall simulation for the analysis of 1-year to 10-year storm events. The runoff plots were subject to 6 rainfall events with intermittent drying periods. The infiltration coefficient was positively correlated with the degree of free flowing fine and medium gravel surface layer and negatively correlated with the surface cover of embedded gravel. Consequently runoff is higher on the surface cover with embedded gravel.

2.2 Efficient use of runoff by application of water harvesting technologies

Most of the runoff in the semi-arid areas is lost due to evaporation and infiltration without efficient use to agriculture. Remnants of well-developed water harvesting systems serving agriculture in the dry regions of the Middle East are found at *Jawa*, Jordan, dating back at least 5000 years (Helms & Flader 1985). There are strong implications that runoff water has already been used for agriculture around 9000 BC at *Beidha* in Jordan within a zone of 170 mm annual rainfall (Bruins et al. 1986). During the *Nabataen-Byzantine* period barley, wheat, grapes, olives, pomegranates and figs were cultivated in the *Negev* and in Jordan under systems of water harvesting (Bruins et al. 1986). During the great period of the *Sabatean* empire (600 BC to 600 AC) agriculture was based on highly developed irrigation schemes such as water harvesting. In North Yemen the enormous dam across the wadi (dry river) *Dahna* was the backbone of agriculture (Kohler 1994). Studies on the reconstructed site of an ancient water harvesting farm in the *Negev* (Evenari et al. 1982) gave the incentive to concentrate more on this ancient technique and to try to implement it within different development projects.

2.2.1 Definition of water harvesting

The terminology for water harvesting for agriculture is vague and different terms and definitions exist which are often used synonymously e.g. flood-water farming, runoff farming or stormwater harvesting. Terms such as stormwater farming are misleading giving the impression that only extreme rainfall-runoff events are used for collecting water. Rainfall harvesting and runoff agriculture are two terms describing the whole processes from collecting the precipitation and then transferring it for the beneficial use in agriculture (NAS 1974; Barrow 1999). Runoff agriculture includes the soil and water conservation techniques used to retain runoff, increase infiltration and counteract soil erosion. It is different to rain-fed agriculture where cultivation depends only on the precipitation and no means are used to explicitly store the runoff. Water harvesting means the more effective use of natural resources for agricultural production (Prinz 1994). “Water harvesting is usually employed as an umbrella term describing a whole range of methods for collecting and concentrating various forms of runoff (e.g. rooftop runoff, overland flow, stream flow, etc.) from various sources (e.g. precipitation, dew, etc.) and for various purposes (e.g. agriculture, livestock, domestic and other purposes)" (Reij et. al. 1988). Water harvesting systems are mainly used in semi-arid to arid regions where runoff is periodical and erratic. "Runoff agriculture and the related approaches ... have particular value for remote and harsh environments where other strategies would be either technically impossible, too expensive or ill-advised." (Barrow 1999, page XV). Often the rainfall in these areas is insufficient itself since the frequency and total amount of rainfall events is not enough to provide sufficient water for plant growth especially during critical growth stages. The storage of runoff or the area where the runoff is directly used is an integral part of the system in combination with an adjacent catchment area characterized by a high runoff coefficient (Prinz 1995).

For the current study, the term "water harvesting" was chosen to implicate the various sources of water, and "harvesting" including the action of storing the water before releasing or using it for irrigation or drinking purposes. Consequently water harvesting also includes the harvesting of dew or fog. Perrier (1988) defines water harvesting as a "process of collecting rainwater from a modified or treated area to either maximize or minimize runoff, whichever technology is to be implemented at a specific site".

There is nowadays a wide range of classification of water harvesting systems depending on different parameters:

- Source of runoff (either rainwater, intermittent streamflow) (Pacey & Cullis 1986)
- Characteristics of catchment area (small catchments with sheet runoff) and storage components in terms of period of storage (short term within the soil profile or ponds) (Pacey & Cullis 1986; Critchley et al. 1992)
- Type of conveyance (water spreading or diversion)
- Principal purpose of use (crop production systems) (Matlock & Dutt 1984)
- Geomorphology (e.g.terraced wadi systems with low checkdams) (Bruins et al. 1986)
- Ratio between catchment area and runon area (Prinz 1994)
- Length of the slope (Reij et. al. 1988)

Concerning the rainfall regime which is suitable to different systems, the point of view was taken that the amount of annual rainfall is of lower importance compared to the quantity of effective stormwater (i.e. runoff) events. The current study is based on the differentiation by Prinz et al. (1998). They distinguish between three groups of water harvesting: rainwater harvesting, floodwater harvesting and groundwater harvesting (Table 2.7).

Table 2.7 *Differentiation of various groups of water harvesting types and techniques according to Prinz & Wolfer 1999*

WH Group	**Rainwater harvesting**			**Floodwater harvesting**		**Groundwater harvesting**		
Type	**Roof and Courtyard WH**	**Microcatchment**	**Macrocatchment**	**Floodwater harvesting within streambeds**	**Floodwater diversion**	**Quanat systems**	**GW dams**	**Special wells**
Techniques	Treated surfaces, e.g. sealed, paved, compacted, smoothed surfaces	Interrow WH	Hillside conduit systems	Jessour type	Wild flooding	Short quanats	Sand storage dams	Horizontal wells
		Negarim / Meskat type WH	Semicircular hoops	Dike type	Water dispersion	Medium-sized quanats	Subsurface dams	Artesian wells
		Pitting techniques	Cultivated reservoirs, tanks	With percolation dams	Water distribution	Long distance quanats		
		Eyebrow terraces	Stone dams					
		Vallerani type WH	Liman terraces					
Storage Medium	Cisterns, ponds, jars, tanks	Soil profile	Soil profile, cistern, ponds	Soil profile		Ponds	Substrate profile	Soil profile, ponds
			Reservoirs	Reservoirs	Ponds			
Aquifer recharge	None	Very limited	Limited	Strong	Very strong	Limited	Medium	Medium

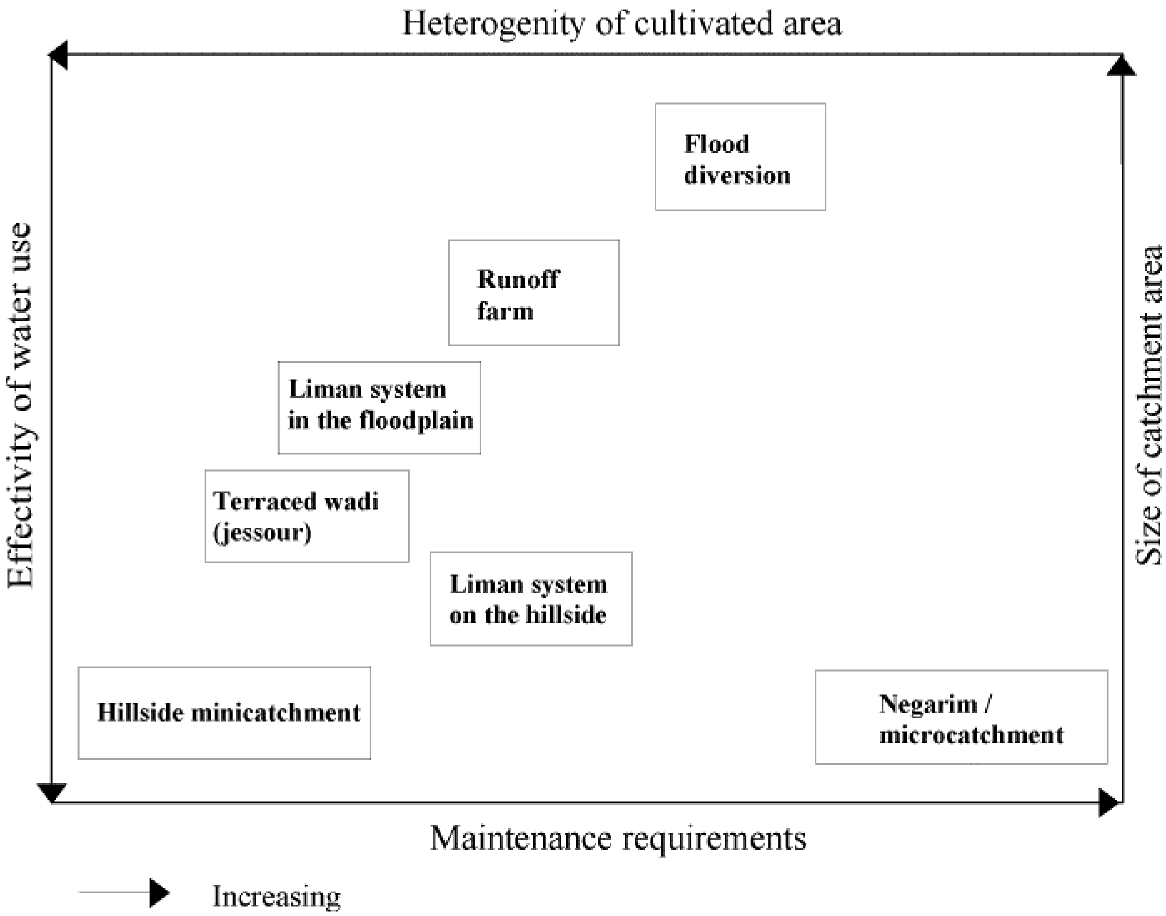

Fig. 2.9 *Comparison of different water harvesting systems used in the Negev with respect to effectivity of water storage, maintenance, heterogeneity of cropping area and catchment area (Sources: Tenbergen 1991, composed according to Herwitz et al. 1988; Evenari et al. 1982, Bruins et al. 1986; Yair 1983,Yair & Lavee 1985, , Yair & Enzel 1987, Yair et al. 1989)*

The amount of required labor and maintenance is different for the various techniques. In an area with limited infrastructure, a skilled labour force is usually unavailable and the financial resources are also low. Then the implementation of simple techniques should be given first priority. Therefore highly costly engineering structures such as concrete dams and reservoirs on rivers are not included in the current description of potential water harvesting systems for the region. Critchley & Siegert (1991) give an overview of needed earthwork/stonework for various water harvesting techniques. Tenbergen (1991) (Fig. 2.9) gives a rough overview of the importance of the different factors like water storage capacity, heterogeneity of cultivation area, size of catchment area and degree of required maintenance for different water harvesting systems. Table 2.8 illustrates the minimal annual rainfall amounts required for the various techniques and the ratio between catchment and cropped area.

Table 2.8 *Minimal annual rainfall amounts and size for various forms of water harvesting (Source: Prinz & Wolfer 1998)*

Water harvesting technique	Minimum annual rainfall required(rainy season in winter)	Typical Catchment area	Ratio Catchment area / Cropped area
Microcatchments	150 - 200 mm	100 m^2 - 1000 m^2	1 : 1 – 10 : 1
Hillside conduit systems/Macro-catchments	150 mm	1000 m^2 - 200 ha	10 : 1 – 100 : 1
Floodwater harvesting	100 mm	200 ha - 50 km^2	100 : 1 - 10000 : 1

Water harvesting structures in the study area are supposed to mainly support the rehabilitation of the rangeland and the production of fodder shrubs and afforestation. A change in the current agricultural (land-use) system (livestock production) would lead to further degradation since already the cultivation of barley in former years led to severe problems of soil and vegetation degradation (see Chapter 4.5.3). The proposed water harvesting systems should not lead to further degradation of the resources which would counteract the sustainable character of water harvesting systems.

2.2.2 Water harvesting systems

Those techniques are described within the current chapter which might be of use in the region. But the presented study focuses on microcatchments and macrocatchments as examples for small to medium scale systems and floodwater harvesting techniques as an example for large scale systems. Details of the design and construction of water harvesting systems are given by Prinz & Wolfer (1999) and Critchley & Siegert (1991).

2.2.2.1 Rainwater harvesting

Microcatchments

"Microcatchment is a method of collecting surface runoff from a small runoff contributing area and storing it in the root zone of an adjacent infiltration basin to meet crop water requirements" (Ben-Asher & Berliner 1994).

Interrow water harvesting or contour bunds **or** ***contour ridges***, is a widespread soil and water conservation technique (Critchley & Siegert, 1991). Bunds are spaced closely and follow the contour. They can be constructed in areas with slopes up to 5%. The ratio between catchment area and run-on area is about 1 to 5 (25 m^2 over 1000 m^2) (Prinz et al. 1999). The spacing between the bunds has to be adapted depending on the slope: the spacing is therefore between 1.5 to 20 m. (Prinz 1999). The capture of soil moisture behind the contour bund is reinforced either by construction of an infiltration pit (Critchley & Siegert 1991) (Fig. 2.2) or the excavation of a ditch parallel to the contour bund (Pacey & Cullis 1986). Spillways may prevent breakage in case of extreme floods. The downslope part of the bund could be reinforced by plants (Prinz 1999). The technique has been successfully implemented in the *Baringo* area of Kenya (Critchley & Siegert 1991) with tree planting. ***Contour bunds*** on the footslopes of *Jebel Mukram* (Kassala, Sudan) have allowed the rehabilitation of grassland in combination with controlled grazing (Ibrahim & Dow El Madina 1986). In the Northern *Palmyrides* in Syria this technique is already used for nurseries of shrubs and trees . The system has to be maintained, ruptures of bunds of the bunds have to be immediately repaired. The contour bunds can also be constructed with stones. Since a stone bund is semipermeable to runoff, runoff is spread more evenly over the whole area. The implementation of stone bunds in the agroforestry program of *Yatenga* (Burkino Faso) led to a doubling of the yield (Critchley & Siegert 1991).

The **eyebrow terraces** or ***minicatchment*** is another technique of microcatchment often used for the cultivation of trees. Tenbergen (1991) used it for cultivation of trees (i.e., *Prosopis juliflora*, *Pistacia atlantica*, *Ceratonia siliqa* and *Pinus halepensis*) in the *Negev*. 300 half-moon shaped depressions, downslope side supported by stone cover, of sizes between 0.1 and 2.5 m^2 and of volumes ranging from 500 to 2500 l have been dug on the slope of the hill. The length of the runoff area above the catchment varied between 32 m and 85 m. The contributing areas were between 100 and 800 m^2 with an average of 265 m^2 (Tenbergen 1991). 50% of the planted trees survived the five years period, also increasing in height. It was also shown that the development of vegetation below the trees was much better in the surrounding areas and down slope compared to sites without minicatchments (Tenbergen et al. 1995). Tenbergen (1991) suggested that the minicatchments should be placed near bare rock surfaces and that the minimum size should be 1500 l with depths greater than 20 centimeters. This technique may be used in the *Northern Palmyrides* or the lower slopes of the *Southern Palmyrides* to grow trees or fodder shrubs. The labour demand for construction is high, but it is easier to be maintained than other techniques.

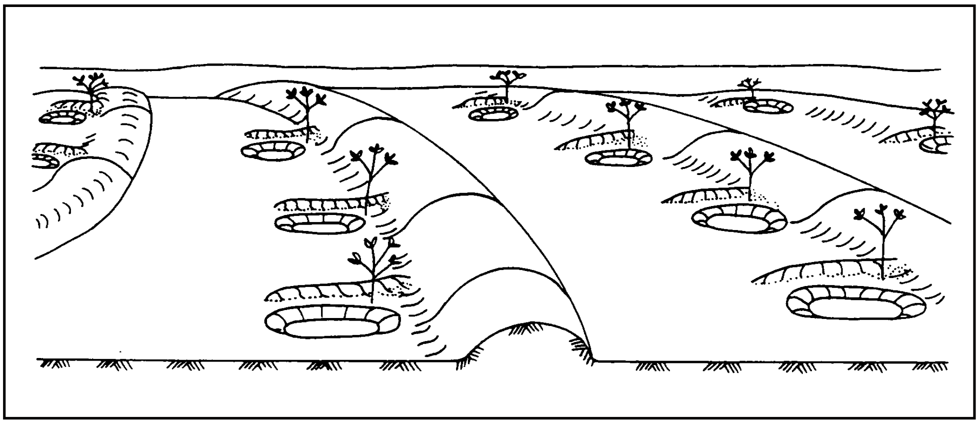

Fig. 2.10 *Contour bunds for cultivation of trees (Critchley & Siegert 1991)*

Semi-circular bunds ("half moons") are widely used in rangeland rehabilitation or fodder production in the semi-arid areas of Africa. The form of the "half-moons" is more efficient than trapezoidal forms in terms of the impounded volume in relation to the soil volume of the bunds volume (Critchely & Siegert 1991). "Half-moons" have been successfully implemented in Niger for the production of millet (Critchley & Siegert 1991). It can be applied on slopes up to 2%. Radii are between 2 to 3 m for smaller structures on slopes up to 1%. To prevent damage in case of extreme floods the wings should be reinforced with stones. In countries like Yemen this technique is a traditional system: *Turats* are half-moon shaped heaps of stones, used for the cultivation of various crops.

Macrocatchments

Macrocatchments comprise techniques harvesting water from long slopes or external catchments (Pacey & Cullis 1988).

Larger semicircular hoops are comparable to the microcatchments of semicircular bunds in terms of structure and layout. The radii of the bund are about 20 m and they can be constructed on slopes up to 2%. They are commonly used for the plantation of fodder shrubs. The construction should be reinforced with stones around the wings to prevent erosion and failure of the construction as was observed in the Turkana district, Kenya (Critchley & Siegert 1991; Reij et al. 1988).

The ***stone bunds*** are similar to the contour earth bunds, constructed on slopes less than 2%. The spacing between the stone bunds is about 15 to 20 m. Since the stone bunds are permeable, spillways are not needed. The construction is labor intensive, but the maintenance required is less than for contour earth bunds (Prinz 1999). They may be used in the steppe area for fodder crops such as pasture legumes. The land in the study area is mainly used for livestock production and stone bunds are more recommended than earth bunds on open rangeland sites since they are less vulnerable to damage by water and animals (Pacey & Cullis 1986).

Simple *hillside conduit systems* comprising stone bunds following the flow direction on steep slopes can be used to direct the water to small ponds at the footslope of the mountains. Stone bunds have been used by former generations of farmers in Syria on the northern slopes of *Jabal al Hass* near the *Jabul* lake, south east of Aleppo (Arab, personal communication).

Hafir (Arabic: hafar = to dig, to spade) is a reservoir constructed within depressions or the lower part of a dry river. *Hafirs* are widely used in the Sudan, Ethiopia and Kenya for storage of drinking water for men and animals (UNEP 1983). In Syria several hafirs exist at the footslopes of the mountains of the *Northern Palmyrides*. The Ministry of Irrigation has already developed a layout scheme for *hafirs* (IFAD 1997). ***Mahfur*** is a similar technique, used in Jordan and Yemen to store drinking water. In drier years when the small reservoir is not filled the soil moisture is at least enough for cropping (Fig. 2.11).

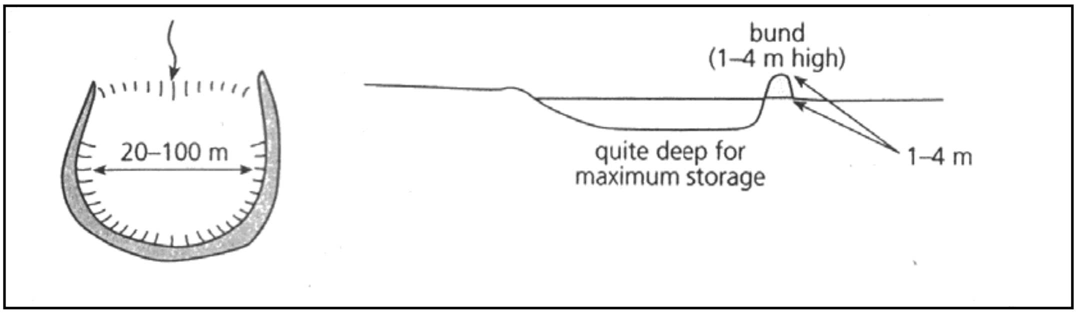

Fig. 2.11 *Layout of Mahfur, (pl Mahafir) (Barrow, 1999)*

2.2.2.2 Flood water harvesting

Flood water spreading

Flood water spreading systems need more maintenance and also the design to construct them is much more complicated. Some of the ***flood water spreading*** systems are "amongst the world's most productive forms of agriculture, include the longest sustainable productive strategies and in most cases require little input, other than flood water and human labour to maintain fertility" (Barrow 1999, page 75). The tradition to use flashfloods is widespread. The Papagos, an Indian tribe in Southern Arizona (USA), in the *Sonoran* desert, cultivated *arroyos* (dry river) deltas, flood water mouth (*akçin*), where the floodwater spreads out. They cultivated beans and barley. The fields were irrigated in the subsurface, and also fertilized by sediments brought in during flooding (Nabhan 1986).Brush dikes were constructed to divert the water and to check the water through a field. Through wings they divert the water into pockets of fields.

The flood water spreading structure at the archeological site of *Marib* (Yemen) is famous. A wall 620 m long, 16 m high and 60 m wide dams up the floodwater of the wadi *Dhana* (dry river). Calculated from the height of the accumulated lime of 30 m and the sedimentation rate of 1.2 cm per year the system was in operation for about 1200 years (Kohler1994; Brunner & Haefner 1986). The water stored by the dam was diverted into two primary channels which fed secondary and tertiary channels irrigating about 9600 ha. The average supply of water was estimated to be about 87.5 Million m^3 (Kohler 1994). Since the main dam has to withstand large flashfloods, the requirements for the engineering structures are higher. The costs for planning and designing the structure are consequently higher. Simple stone dams can be constructed within the streambed to divert the water. Instead of concrete weirs, spillways can be build as *gabion* structures (Prinz & Wolfer 1999). In Morocco and Tunisia small dams ("*barrages collinaires*" or "*lac collinaires*") have been constructed to provide water for animals and irrigation water (Siegert 1995).

A simpler application of ***flood water harvesting*** within the streambeds of flat wadi*s* are *percolation dams* (Fig. 2.12) since they have a low hydrological impact on larger floods (Vlaar 1992). Infiltration dams in Burkino Faso at the valley bottoms lead to higher grain yields for Sorghum (Vlaar 1992). Percolation dams (Fig. 2.12) have a positive effect on groundwater and soil moisture. For half of the growing season the root zone is between excess field capacity and saturation compared to the downstream side with wilting plants (Vlaar 1992).

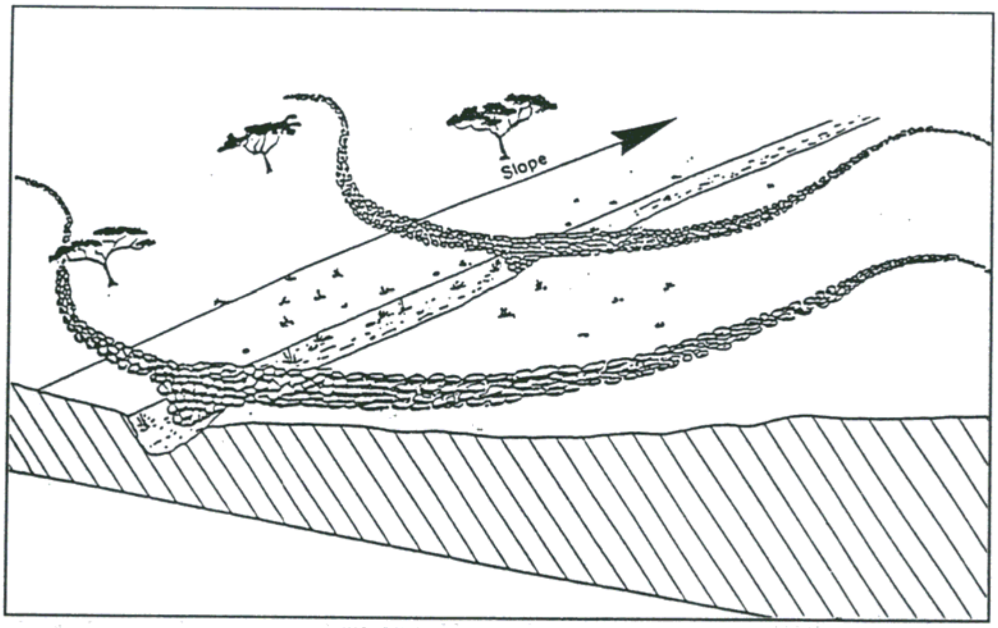

Fig. 2.12 *Percolation dams (Reij et al. 1988)*

Flood water diversion

Flood water diversion allows cultivation of almost any crop (Prinz et al. 1999). The catchment area is the watershed of a large wadi (Fig.2.13). Stone dams or concrete dams divert flashfloods onto the fields. In the *Turkana* district (Kenya), diversion dams have been constructed in the fifties to divert floodwater onto sorghum fields. Sometimes these constructions have to withstand extreme flashfloods (Reij et al. 1988). If the structures are simple they can be easily repaired or reconstructed after damage. Examples of floodwater diversion system are found in Pakistan (*Sailaba* system) or in Somalia (*Caag* system) (Critchley et al. 1992; French & Hussain 1964). The *Caag* system allows small- scale cultivation from 1 ha upwards. On slopes of less than 0.5% straight bunds are constructed to spread the water; slopes of 0.5 to 1% require graded bunds (Critchley & Siegert 1991).
In Australia water spreading schemes are widely used for rangeland rehabilitation (Hudson 1987).

At *Mihassa*, a *wadi* about 130 km northeast of Damascus, a floodwater spreading system was established during the nineties by the Syrian government with the help of foreign aid (UNEP, IDRC) (Soumi & Abdul Aal 1999).

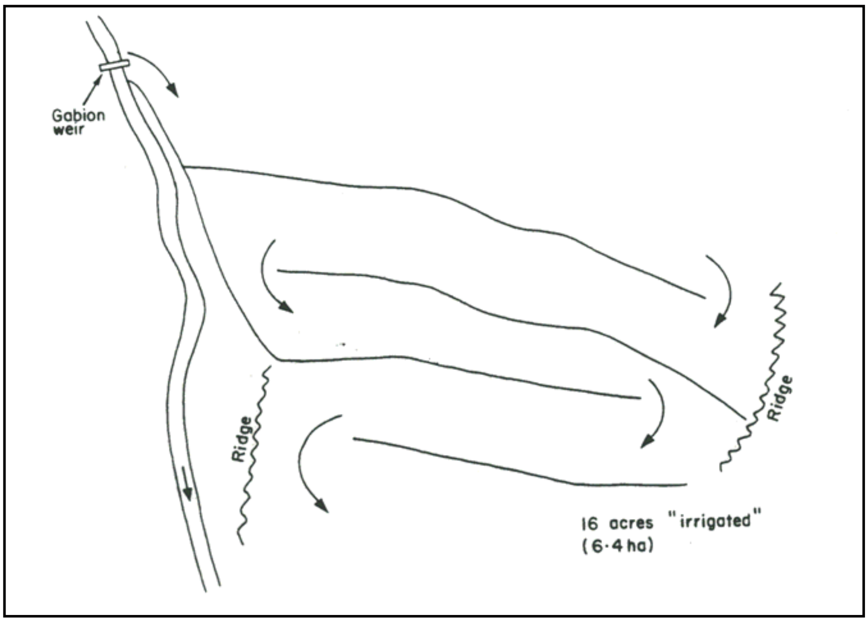

Fig. 2.13 *Layout of a typical flood water diversion system (Fallon 1963)*

2.2.2.3 Groundwater harvesting

Qanats

Qanats are of Persian origin, dating back 2000 years. In the Middle East and North Africa they are known as *Foggaras*. In the 1960s these systems provided about 75% of the domestic and agricultural water supply in Iran. *Qanats* with a common length of between 8 and 16 km are mainly located on footslopes. They consist of sloping subsurface tunnels whose extensions meet the water table within an alluvial fan on the footlslope of a mountain. The tunnel itself serves as infiltration gallery and is often ending in an oasis. The *Foggaras* at *Sebkha di Timimoun* in the *Algerian Sahara* are fed by channels coming from a fossil drainage system on the eastern side of the oasis. In Syria *qanat* systems supplied the northern *Damascus* oasis (Cressey 1958) and the *Al Sukhneh* oasis (Wirth 1971). A still functioning system is found at *Sfireh, Khanasser* valley. A ***qanat*** system has to be very well maintained otherwise the channels become silted up. Cressey (1958) gives an overview of the traditional way of construction of a ***qanat***. Since the construction needs trained people and also a lot of maintenance, it can be used only in the vicinity of larger settlements in the area to meet the requirements for drinking water. But there is the risk of well overpumping.

Sand-filled reservoirs

Sand-filled reservoirs or sand-storage dams are constructed within the streambed of ephemeral streams (Fig. 2.14). Sand brought in by floods fill the space behind the constructed weir or is brought in during construction (Nilsson, 1988). Since flash floods may choke up a usual reservoir, sand-filled reservoirs withstand them. Other advantages include the double-functionality of the storage place as grazing area and the reduced evaporation losses. The construction period may take several years to store a large volume of soil and sand. The dam at *Al Baridah* (Fig. C-9) in the research area is an example of this. Although the function was a different one during its construction: The dam was constructed in Roman times and silted up until today. Sand-filled reservoirs have been used in Namibia, too (Beaumont & Kluger 1973).

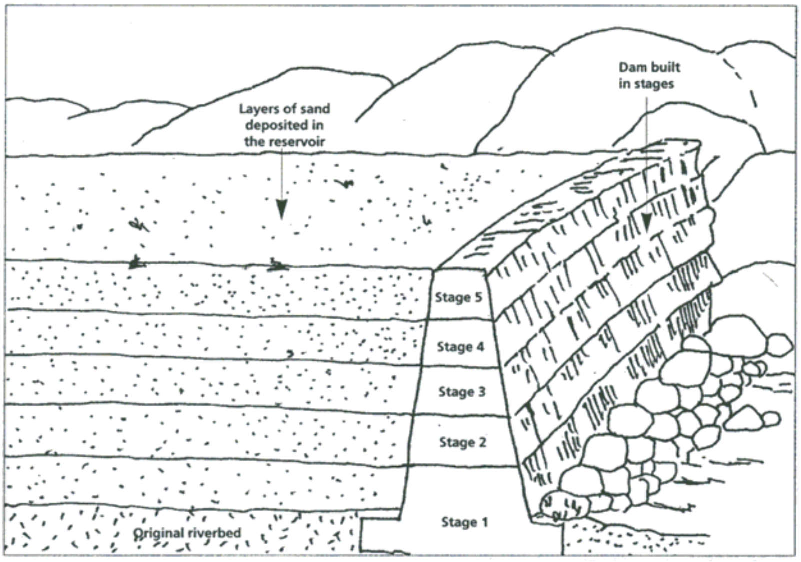

Fig. 2.14 *Typical stages of construction of sandfilled reservoir (Nilsson 1988)*

Groundwater dams were proposed or constructed in areas with similar climatic conditions such as *Biskra* in Algeria (180 mm annual rainfall; 1330 mm annual potential evapotranspiration), *Tarfaya* in Morocco (110 mm annual rainfall; 850 mm annual potential evapotranspration) or *Moudjeria* (Mauritania) (170 mm annual rainfall, 1870 mm annual evapotranspiration) (UN 1973). Dam heights have to be kept small but the storage volume should be also be sufficiently large. This is mainly achieved on gentle slopes. Thus many sand-storage dams are constructed on gentle gradients (3-4% in *Machakos*, Kenya, 0.5 to 3% in Namibia, 1% in Botswana) (Nilsson 1988). The height of the dam is between

1 and 4 m and the material used for the construction of the dam consists of stones, gabions or a clay core mantled by gabions. Spillways should be constructed for the overflow and the wings might protect the banks. The groundwater dam is constructed in different stages where the height of any subsequent stages can be adjusted according to the sedimentation in the reservoir. The dam itself can be constructed with block masonry or gabions. To avoid erosion of the banks of the sand storage dam the dam should be constructed along rock bars.

2.3 Use of Geographical Information Systems (GIS) in hydrological analysis

Geographical **I**nformation **S**ystems (GIS) are management tools supporting policy makers in finding solutions for problems such as soil erosion within the field of land management. Table 2.9 illustrates the capacity of geographical information systems and the tasks of the manager using the GIS.

Table 2.9 *Capacities of GIS as management tool (Bartelme 1995)*

Capacity of GIS	Tasks of manager or user
Visualization of data and relationship	Definition of the problem
Illustration of planning alternatives	Check of suitability of data
Comparison of different alternatives	Check of suitability of analysis methods
Support of arguments	Check of results
Visualization of argumentation	Visualization of relationships of results
Support of interdisciplinary work	Check of costs (data, infrastructure, analysis)

A geographical information system can be defined as follows:
"a tool for planning development and environmental control as well as an instrument of decision support. On the one hand, it consists of a Georeferenced Database, on the other hand of techniques for data acquisition, actualization, processing and visualization of the results. The semantic data are geometrically related to an homogenous georeferenced coordinate system allowing controlled interrelation of the information." (Bähr 1999) (Fig. 2.15). Therefore every expert defines GIS according to his field: a remote sensing specialist refers to GIS in the terms of data processing.

De Roo (1993a) provides an overview of current GIS use in catchment hydrological and erosional modeling. GIS techniques can be directly used for soil erosion risk assessment by calculating important parameters such as slope gradient, aspect or local drainage direction or the definition of the point of contributing.

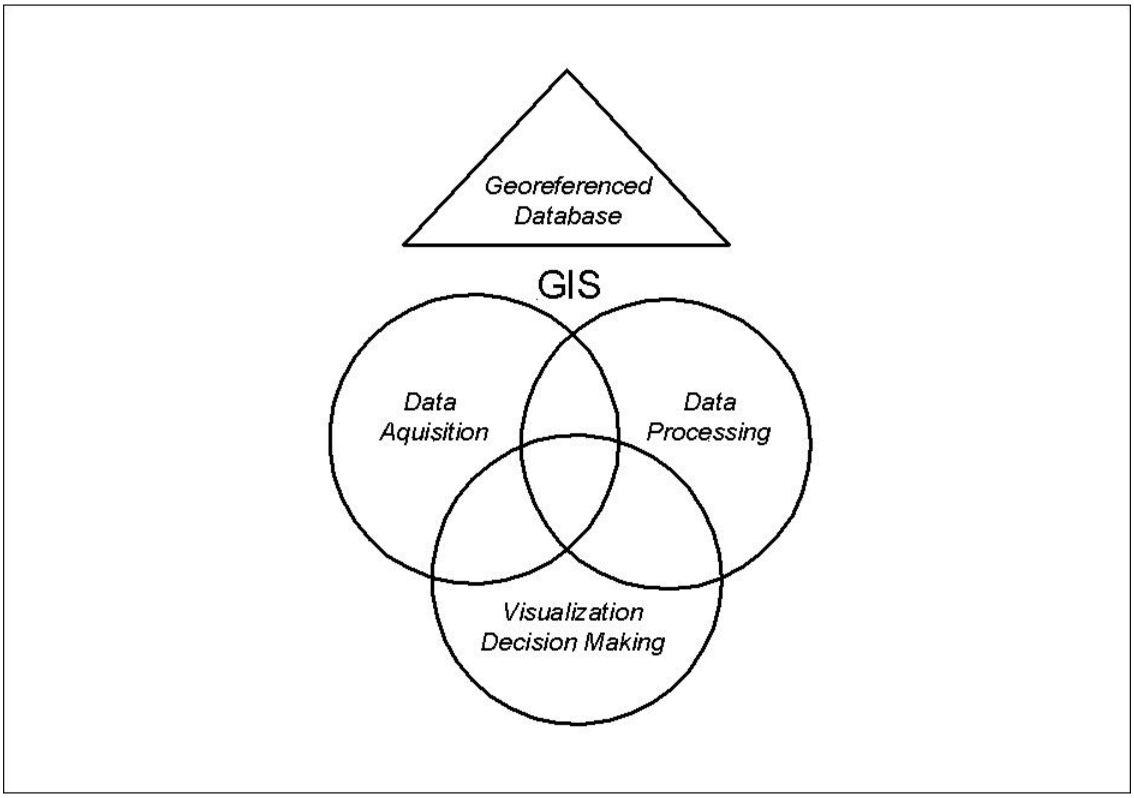

Fig. 2.15 *Definition of GIS (modified after Bähr 1999)*

Vögtle (1999) used a simple decision matrix to determine runoff irrigation sites in Mali. They superposed three layers including a classified image, a distance model for accessibility and an inclination model. They defined two slope classes, one less than 10% and one steeper slope class. The accessibility map comprises different levels of distance from the settlements to the neighboring field sites. They mainly used the decision factors which relate attributes to suitability to use the land for micro or macrocatchment. They used a decision hierarchy including the classified image for water storage, the distance model for accessibility and the digital terrain model used to identify the slope.

GIS provided a tool for siting farm ponds used as drinking water for animals (Vorhauer & Hamlett 1996). They characterised reservoir area limitations and aquifer-fed pond limitations within the pond suitability attribute table. They created different coverages including information about streams, slopes, roads and land use. Their approach additionally included a water balance for each potential site. The volume of runoff was calculated with the SCS curve number method.

Costick (1996) indexed watersheds for their potential for soil erosion and contribution to sedimentation: he defined a **N**atural **E**rosion **P**otential *I*ndex (NEPI) and a **S**edimentation **H**azard **I**ndex (SHI). He used a ranking system assessing the potential of each watersheds in the central *Sierra Nevada* mountains of California. The model assumes a hierarchical analysis. The sensitive watershed ranking is the numerical summation of the different indexes: the Natural Erosion Potential Index (A100), the Sedimentation Hazard Index and the hydrologically and geologically sensitive units. The hydrological model is an overlay of annual precipitation and snow zones with mean rainfall isohyets. The geological layer comprise the drainage density and the tectonic background. Costick (1996) points out that there are many sophisticated models to determine rates of erosion or sediment movement. But they often consider a localized area where an attempt is made to predict a sedimentation rate from a single storm event. In particular the scaling up of these models to the watershed or region level is then a major problem.

2.4 Modeling rainfall-runoff processes in semi-arid regions

2.4.1 Overview

Rainfall-runoff modeling provides the chance to easily simulate the response of a watershed. It provides an option for better water management in the semi-arid regions (Gaaloul & Aurouze 2001). The research on the rainfall-runoff model is extensive. Generally rainfall- runoff models can be differentiated into lumped and distributed models. Lumped models use averaged parameters over the whole model area. Distributed models divide the whole catchment into smaller units with parameters of different values. The advantage is the more realistic spatial differentiation of hydrological parameters. Most models are deterministic, using output from one simulation with a defined set of input parameter set. Stochastic models consider randomness of variables.

Some of the models emphasize the hillslope processes more and the routing within the ephemeral channels less (SCS curve number method (SCS 1972)). HEC-RAS 1 (U.S. Army Corps of Engineers 1998) bases mainly on the channel routing. In the humid temperate areas GIS provides an efficient tool in flood controlling. Floodplains limits can be automatically and accurately mapped by using ArcView the mapping software and HEC-RAS the modeling software (Kraus 2000b), developed by the U.S. Army Corps of Engineers. Doan (2000) includes terrain analysis, data visualization and exploration and project documentation as the role of GIS. Terrain analysis provides data on flow accumulation, stream delineation, stream links and watershed delineation and the automatic generation of outlets. These data are then used within the hydrological model of the watershed. The flow within the different subbasins of the watershed is then simulated with the HEC-1 model and the HEC-2 water surface-model. It was also combined with the NEXRAD rainfall, where rainfall is estimated on radar observation Models developed in humid regions, e.g. TOPMODEL emphasizes the baseflow or the saturated subzone which is less relevant to hydrology in arid regions. The main problem for sophisticated rainfall-runoff modeling in arid regions is the dearth of high quality field data. Therefore rainfall-runoff modeling in drylands is less abundant than in humid areas. Models which lay stress on the infiltration component within runoff process in semi-arid areas are more suited to the semi-arid area. Al-Turbak (1996) used a geomorphoclimatic model with a physically based infiltration component to simulate the hydrological response of three catchments in Saudi-Arabia. It incorporates an infiltration module calculating the rainfall excess intensity and duration which is the input for the geomorphic instantanteneous unit hydrograph GIUH. This hydrograph then results in peak discharge and quantity of the discharge. Data which are needed are topographic information, climatic variables and the estimates on soil data and infiltration characteristics. Nouh (1987) combined GIUH and SCS for study of 32 catchments in southwest region of Saudi Arabia. He calculated size and slope on catchments by means of topographic maps 1:25 000. Time average intensity of rainfall was computed by the isohyetal method. Infiltration was simulated according to the *Philip* equation. Main influencing parameters are the size of catchment and rate of infiltration. His model overestimated the time to peak flowrates and total runoff volumes, but underestimates peak flowrates. Since the accuracy of prediction declined with increasing size of catchment, Nouh (1987) recommended the method only for catchments below 400 km² and highly permeable catchments.

Example of a distributed parameter model is the ANSWERS (**A**real **N**on-point **S**ource **W**atershed **E**nvironments **R**esponse **S**imulation) (De Roo 1993b). Runoff is higher when used within the distributed case (using all pixels) compared to the lumped version where only few representative areas are used.

Gao et al. (1993) used GRASS and a distributed rainfall-runoff model to compute the hydrological response of a semi-arid watershed to a storm event. The model was fully integrated within the GRASS system including several modules, e.g. the Green-Ampt infiltration formula and the 2D-overland flow module. The input was done using numerical modules. Some of the information is lost due to resampling to a larger resolution. Validation of the model could not be done since the costs for grid overland depth or average grid infiltration rates are high. They propose to use these models to specify the amount of further data collection.

Michaud & Sorooshian (1994) investigated the output of different model approaches within a semi-arid catchment of *Walnut Gulch*, Arizona (150 km²) since the only excellent database within a semi-arid catchment exists there. The *Walnut Gulch* catchment is an operational experimental semi-arid watershed supervised by the USDA-ARS Southwest Watershed Research Center. Michaud & Soroshian (1994) compared the simple distributed model SCS (Soil Conservation Service) model with KINEROS (Woolhiser et al. 1990). This is a complex distributed model especially developed for semi-arid catchments (Smith et al. 1995) using the Smith-Parlange infiltration equation (Beven 2001) linked to one-dimensional kinematic routing. In KINEROS it is possible to simulate a two - layer soil profile with different saturated hydraulic conductivities (Smith et al. 1995). This allows integration of crusted soil into the modeling process. Also the process of rainfall prewetting is included within the model. It permits adjustment of the initial soil moisture content used in the infiltration equation calculation. To describe the infiltration behavior of a soil, KINEROS needs the field effective hydraulic conductivity, the capillary drive and the porosity. The overland flow is based on the Hortonian concept within the model and simulated by a one-dimensional kinematic wave equation. The Manning roughness coefficient is considered. Slope and surface length of the catchment have to be introduced. Channel routing is also included within the model. KINEROS assigns transmission losses within channel beds by an empirical expression called "effective wetted perimeter". KINEROS can also simulate soil erosion by rainfall and sediment transport within the overland flow.

Within the study of Michaud & Sorooshian (1994) 6 runoff events were used for calibration and 24 events were used for validation. Without calibration the KINEROS results are superior to the results obtained with the SCS models. With calibration the SCS model showed more accurate coincidence with the observed runoff events. The authors emphasized that the KINEROS model needed more time for implementation and two magnitudes more computer time compared to the SCS model. Although both models use different approaches to predict runoff routing (KINEROS: non-linear kinematic routing, *SCS* model: unit hydrograph routing) the prediction of shape and timing was quite similar. They concluded that complex approaches such as KINEROS are of limited use for large catchments (100 km² and more). It is presumed that these difficulties emerge from the poor spatial resolution of varying rainfall, soil moisture and other hydrological parameters at larger scale and the missing simulation of channel processes becoming more important on larger scales (Michaud & Sorooshian 1994, Smith et al.1995) added to it. Smith et al.

(1995) showed that the simulation results of a calibrated KINEROS model of 20 events illustrate the nonlinearity of hydrological response with increasing scale: the quality of simulation for the small catchments (0.34 and 4.4 ha) was higher than for the large one (6.11 km^2). Wheater et al. (1993) used a distributed two parameter rainfall-runoff model within the Walnut Gulch catchment. Both the runoff and the timing of the peak discharge could be simulated. Tests on small catchments within the *Walnut Creek* showed a good agreement between simulated and observed runoff data (0.1 km^2), tests on greater parts showed more disappointing results (Woolhiser et.al. 1990). Results of a simple semi-distributed model THALES including infiltration excess and subsurface runoff components within the *Walnut Gulch* watershed were disappointing (Grayson et al. 1992).

Other models concentrate more on water storage: El-Hames & Richards (1994) used a semi-distributed runoff-routing (RORB) which calculates discharge from the storage. The calculation takes into consideration channel properties including width or cross-section geometry. The catchment is divided into different subcatchments. It is based on hillslope infiltration calculated by the Richard's equation, the channel routing is based on *St-Venant* equations and uses the kinematic wave propagation for the flow routing. "Palaeoflood hydrology" uses slackwater deposits which are evidence of former floods and give indications on the physical behavior of the floodwave. Estimation of different roughness coefficients and the delineation of the various cross-sections allow the modeling under HEC-RAS 1.

The CEQUEAU model, a distributed model, was successfully applied in the *Muwwaqar* watershed, Jordan (Morin et al. 1998). The CEQUEAU model uses the water balance method. It embodies two discretization levels, the whole squares and the partial squares. The partial squares allow to simulate the streamflow within a drainage network between the whole squares that are congruent areas of similar hydrological behavior. The flow is simulated between the various squares. Input data comprise meteorological, geometrical, flow data, information about infiltration properties of the soil. Precipitation is calculated by Thiessen polygons. The model was calibrated with four months of data and simulated with a time step of day. Two grid sizes were used 1 km and 100 m. The 1 km grid was used for the whole basin. The calculated water balance was slightly higher than the observed values.

Boers (1994) employed the SWATRE model to calculate the water budget on microcatchments within arid and semi-arid zones. It calculates runoff based on kinematic wave propagation. He compares the kinematic wave model with a non-linear recession model, which is applied for the phase after rainfall has stopped. The third model constitutes a linear regression storm-runoff depth model. It is based on the assumption that there is a linear regression between annual rainfall and runoff data.

Nevertheless, often the mathematically sophisticated especially the physical correct programs do not show better results than lumped models. Many parameters needed for the physically correct models are often unavailable and have to be estimated. Data are often missing for validation of models. Therefore GIS raster based rainfall-runoff models with limited key variables and detailed DTM may produce better results (De Roo 1993a).

Lange (1999) used a noncalibrated rainfall-runoff model for the large arid catchment *Nahal Zin* (1400 km²) in *Negev*, Israel. Input of the model is rainfall, measured by radar. He characterized different terrain units responsible for runoff generation. The percentage of runoff within these terrain units was determined by measuring infiltration capacities. The hydrological response function of sub-reaches were used to estimate the runoff concentration.

The characterization of channel segments for channel routing and transmission losses provide information on channel routing and transmission losses which were simulated using the Muskingum-Cunge technique. The model enables successful simulation of two high-magnitude floods in October 1979 and October 1991. The flow volume was a bit overestimated. The fit of peak discharges seemed reasonable within the frame of reconstructed field values (Gauging stations were destroyed).

If the landscape is divided into areas with similar hydrological response it results in the model of HRUs (**H**ydrological **R**esponse **U**nits). The overlay of different maps such as soil maps, geological maps or DTMs (Digital Terrain Model) provides information relevant to hydrological modeling. The overlaying allows the definition of units of similar hydrological response (HRU) (Beven 2001). The SLURP model of Kite (1995) uses this approach.

Osman (1996) integrated different data layers into an hydrological model of the Sudanese Red Sea. He calculated the rainfall for the whole area. He integrated data by means of a digital elevation model and Landsat TM analysis.

2.4.2 Example of rainfall-runoff model: SCS curve number method

The curve number method is widely used for the determination of runoff in watersheds. It is a conceptual method for the prediction of runoff, based on empirical data of runoff from small catchments and hillslope plots monitored by USDA (Beven 2001). It predicts the volume of storm runoff after some initial retention before beginning of the runoff. It responds to major parameters important for runoff production within a watershed including soil type, land use or treatment and surface condition. The *SCS* curve number method assigns for each part of a watershed the curve number based on the land use, antecedent moisture condition and hydrologic soil group. The curve number presents a specific relationship between storm rainfall and percentage of runoff (Fig. 2.16).

The SCS curve number method was successfully applied in the dry areas of Yemen (Farquaharson et. al. 1997) and Australia (Dilshad & Peel 1996). Colombo & Sarfatti (1997) estimated runoff within two subcatchments of the *Marib* river in Eritrea by choosing the appropriate runoff curve number through analysis of remotely-sensed data. (Landsat TM and SPOT). Abu-Awwad & Shatanawi (1997) used the SCS method for calculation of runoff volumes of the *Wadi Bhutum* (Jordan) (140 km^2) and a rainfall amount of 100 to 150 mm/a. They used rainfall equivalences of return periods of 2,5 and 10 years. Farquaharson et al. (1997) pointed out that especially with low rainfall, runoff coefficient are mainly dependent on watershed characteristics such as soil cover or slope.

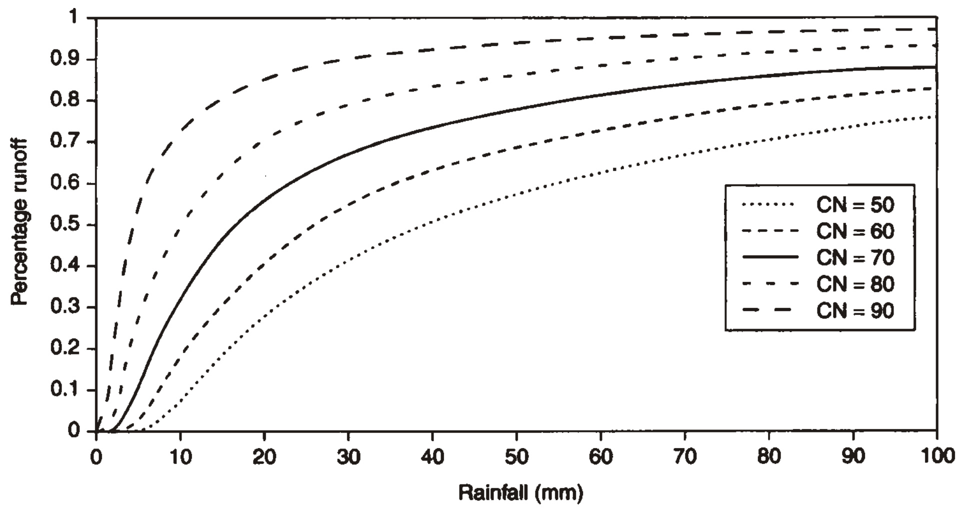

Fig. 2.16 *Relationship between storm rainfall and percentage runoff predicted by the USDA curve number method (Beven 2001)*

Drake et al. (1999) used the SCS curve number method in the context of modelling soil erosion at global and regional scales using remote sensing techniqes and GIS techniques. The SCS curve number method has been incorporated into various rainfall-runoff models such as CREAMS (**C**hemicals, **R**unoff and **E**rosion from **A**gricultural **M**anagement **S**ystems model), WEPP (**W**ater **E**rosion **P**rediction **P**roject) and the **S**oil **W**ater **A**ssessment **T**ool (SWAT) (Beven 2001). Ponce & Hawkins (1996) pointed out that advantages of the method were is simplicity and predictability. A major disadvantage is the unclear definition of the antecedent moisture condition. Baten (1994) used the curve numbers to define the role of land cover in the runoff generation process within a version of knowledge processing for watershed flood runoff simulation in an object-oriented data environment. Mattikalli et al. (1996) used the US SCS classification of land use and soils within an integrated geographical information system including a runoff and water quality model. The runoff is estimated in terms of volume of precipitaton and potential maximum storage or retention. The SCS method is based on the empirical assumption that the ratio of actual to initial runoff is equal to the ratio of actual retention ot the potential retention.

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad [2.3]$$

Q = runoff [mm]
S = potential maximum retention after runoff begins
I_a = initial abstraction ratio
P = rainfall [mm]

Considering purely physics this relation is not justified (Beven 2001). This method is a good representation of the influence of the Hortonian concept. During further modifications a factor was added to the potential retention. I_a, the initial abstraction, is the factor responsable for interception, initial infiltration, surface depression storage and evapotranspiration. It is related to retention by a linear dependance:

$$I_a = \lambda \ S \qquad [2.4]$$

λ = initial abstraction ratio
S = potential maximum retention after runoff begins [mm]
I_a = initial abstraction [mm]

The overland flow in a rainfall event or the effective rainfall is then computed as follows:

$$Q = \frac{(P - \lambda S)^2}{(P + (1 - \lambda)S)} \qquad [2.5]$$

Q = runoff [mm]
S = potential maximum retention after runoff begins [mm]
λ = initial abstraction ratio

The initial abstraction ratio is mostly set to the empirical value of 0.2. Ponce & Hawkins (1996) critized this adoption of the initial abstraction ratio to 0.2 in their review of the SCS curve number method.They referred to other studies showing variing values of the initial abstraction ratio. If P is lower than I_a the runoff is nil. The maximum potential soil water retention is then computed according to:

$$S = (\frac{1000}{CN} - 10) * 2.54 \qquad [2.6]$$

CN = curve number
S = storage volume [mm]

CN is the curve number which can be taken from published data and is a dimensionless number. Popularity of the method mainly comes from the dimensionless number CN which is tabulated for various soil types and conditions (SCS 1972; USDA-SCS 1985). To account for the spatial variability of soil moisture, the original USDA procedure adjusts the CN value on the total rainfall of 5 preceeding days. Therefore values for wet humid and dry conditions are suggested. Further studies showed that this adjustment is ambiguous since the dependance on antecedent soil moisture is impossible to be defined on a function (Sommer 1997). Other approaches realised within the CREAMS model adjust the storage factor by using a ration of actual to saturated water content. Under dry soil moisture condition the factor of storage is only dependant on the maximum infiltration rate (Sommer 1997).

Wood & Blackburn (1984) found out that the antecedent moisture is an important factor using the SCS curve number method on data of 1600 runoff plots in Nevada, Texas and New Mexico and found big differences between computed and observed values. At dry conditions the method slightly underestimate the runoff, but under wet conditions the runoff is strongly overpredicted. They also found out that the results were better on plots with low vegetation cover approaching bare conditions under crop cover than on plots with denser vegetation cover. Low vegetation cover approaches the conditions of soil used for cultivation of crops. Wood & Blackburn (1984) pointed out that the crust formation in soils under semi-arid climate often deludes the results: A sandy loam with an impeding crust, classified as hydrological group B had 60.5% more runoff than a soil classified as hydrological group D. Therefore the hydrological soil group definition should be modified according to rangeland conditions (Table 2.10).

Table 2.10 *Possible modifications of the hydrologic soil group definition for SCS procedure in rangelands (Wood & Blackburn 1984) (A – D: Hydrological soil group)*

Hydrological soil group	Description
A	Sandy texture or well-aggregated granular structure with vesicular pores
B	Massive or weak platy structure with few to common vesicular pores
C	Moderate platy structure with common vesicular pores, massive with many vesicular pores, or clayey and weakly structured
D	Strong platy structure with many vesicular pores or clayey and massive

If more information on soil crusts would be available for the different soils within the project area, the differentiation into the hydrological soil groups could be improved.

Table 2.11 *Influence of antecedent soil moisture (AMS) on curve numbers*

Curve Number	**5 day antecedent rainfall (mm)**	
	Growing season	**Dormant season**
CN1 (AMS I)	< 36	< 13
CN2 (AMS II)	36 - 53	37 - 48
CN3 (AMS III)	> 53	> 28

Farquaharson et al. (1997) adjusted the CN value dynamically over the year according to antecendent precipitation ratios. They calibrated their model on the rainfall and runoff records of six wadis in Yemen over a period of about five years. The runoff coefficient did no fall below 5%.

Since the hypothesis of the antecedent soil moisture is not very clear. Mishra et al. (2003) developed a modified *SCS-CN*-Method based accounting for the static portion of infiltration and the antecedent moisture. They included the soil characteristics by soil-moisture content and the hydraulic conductivity-moisture content. They postulate that the modified method approximates more the physically based infiltration process. Nevertheless the method has still to be more tested. On the contrary to the original method it requires additionally the prior knowledge of the minimum infiltration rate.

The runoff is mainly dependent on the basin characteristics and the antecedent rainfall conditions. This is especially true since the magnitude of rainfall storms is independent on the average rainfall. Another approach could be the composite one, using an average CN number for the project region. The results of the distributed approach are higher than the composite approach (Grove et al. 1998) who investigated different watersheds. Grove et al. (1998) who investigated different watersheds showed that with higher curve numbers the difference between composite and distributed CN gets smaller.

Some authors tried to combine the *SCS* method with other parameters such as slope length (Sommer 1997). Sommer (1997) introduced a new factor to the calculation of the rainfall-runoff curve number: the slope length. Since the rainfall-runoff curve number do not take into account transmission losses, slope length may be one of the parameters accounting for these losses. He introduced a formula according

$$Q = e^{-a(100-CN)^b - L^\beta} * (P - T) + (1 - e^{-a(100-CN)^b - L^\beta}) * \frac{CN}{100} * Q_{CN,T} \quad [2.7]$$

for P > T

with

$$Q_{CN,T} = 25.4 * \frac{(P/25.4 - T/25 - 4)^2}{(P/25.4 + S - T/25.4)} \quad [2.8]$$

A, b, β = coefficients
L = slope length
T = threshold for runoff generation
P = precipitation [mm]
Q = runoff [mm]

He calibrated the formula according to measured data within rainfall-runoff plots situated at *Tel Hadya*, Syria. The constants were determined by regression analysis of the observed data. Since the calibration with runoff data is needed this approach could be only used in areas where sufficient data on runoff amounts exist.

2.5 Application of remote sensing in hydrology

2.5.1 Experiences in semi-arid regions

Fields of application of remotely sensed data are biomass monitoring (Bastiaanssen 1998), range management (Pickup et al. (1993), mineral exploration (Komp 1991, Geerken 1991) and control of erosion and land degradation (Gomer 1994; Belz 2000). Remote sensing provide data for planning of water management needed for arable and pastoral farming (Komp 1991). Bastiaanssen (1998) gives an excellent overview of the application of remote sensing in water resources management. Seasonal satellite data (dry season / rainy season) for example allowed the derivation of maps of pastoral potential in different regions of Algeria. Remote sensing can be used indirectly for determination of watershed geometry and drainage classes (Dubayah et al. 2000). Satellite images help to identify drainage pattern in the Sultanate of Oman, which is the basis for identification of potential sites for reservoirs for rainwater and floodwater harvesting (El-Baz & Koch 1998). The combination of Landsat TM, SPOT and SAR ERS-1 images permitted detection of palaeochannels of an ancient wadi system in the *Tanezrouft* plateau (Western Sahara) (Chorowicz & Fabre 1997).

Landsat TM data have been also used to characterize water catchment areas in Burkina Faso (Vine 1997). Different hydrological landscape units were demarcated, including e.g. thalweg depression with impermeable soils where the infiltration rate is very low. Guillet (1997) used SPOT images to characterize different soil surface features according to the “état de surface” ,which is a classification of soil cover complexes in the *Sahelian* landscape (Casenave & Valentin 1989). Van Dijk & Reij (1994) used *SPOT* images to detect areas under floodwater spreading (small earth dams) in Yemen.

The delineation of land use classes by remotely sensed data is used for the determination of runoff coefficients. The land use classes or homogeneous land cover classes can then be used in combination with model parameters. Remotely sensed data are therefore used in combination with model approaches such as the SCS runoff curve number method. This method was successfully applied in two subcatchments of the *Mareb* river in Eritrea (Colombo et al. 1997).

Puech et al. (2000) detected bare soil patches and classified land use in the *Imiga* water catchment in Burkina Faso on *SPOT* images by also applying classification and principal component analysis.

Study of the tectonic setting of crystalline rocks on Landsat TM scenes illustrates possible underground drainage courses on the Ivory Coast (Savane et al. 1997). In Tunisia, *SPOT* images have been used for the determination of possible sites for flood water spreading techniques within the drainage courses (Daoud & Trautmann 1997). These sites would also be used for recharging the groundwater.

2.5.2 Choice of satellite system : Characteristics of Landsat TM system

In 1994 Landsat TM images were the first choice for use of satellite images. The first system of Landsat satellites started in 1972 (MSS), the Landsat 5 with TM sensor was launched in 1984. Landsat TM is a “Leitfossil” of remote sensing (Bähr 1998). Nowadays the choice is much wider and in recent years satellite products have become much cheaper and easier to get, probably due to the general lowering of costs for image processing and the availability of a wider range of sensors. Main criteria for the choice of a sensor system is the relationship resolution and repetition cycle (Konecny 1996). Modern tendency is towards development of the higher geometric resolution. They have most potential in agriculture (precision farming) comprising governmental and commercial satellite systems, examples are the Indian satellite IRS-ID with a resolution of 5.8 m (Panchromatic) and a repeat cycle of 5 days or commercial satellite systems such as IKONOS-2 with four multispectral bands at a nominal ground resolution of 4 m. These high resolution systems may be used in precision farming or urban planning. However, for the current topic the use of satellite images still requires a high financial effort. An alternative to the used Landsat TM system could now be, for example, the Landsat ETM+7 (Lillesand & Kiefer 1999). The main criteria of application in developing countries is availability and quality (Bähr 1998). The repeat cycle plays a major role, since a high repeat cycle enhances the chance of obtaining data just after a rainfall event. Nevertheless costs for satellite images are often a crucial factor in project management in developing countries. These costs may be reduced by using images from archives.

The data of the Landsat system are normally obtained from the European Space Agency, obtained from the *Fucino* ground station in Italy. The data were transmitted from the second generation of Landsat satellites 4 and 5, launched in March 1984 into sun-synchronous near-polar orbits at 705 km, providing a 16 day cycle (Richards & Jia 1999) at 14.56 orbits per day. Landsat satellites belong to the category of sun synchronous satellites near polar orbits allowing a smaller distance than the weather satellites on polar orbits (Richards & Jia 1999). There is a complete coverage of the earth covered after sixteen days with the ground tracks of every orbit about 2752 km apart at the equator (Lillesand & Kiefer 1999). The MSS sensor and TM sensor of the satellite are equipped with the primary imaging optics, scanning mechanisms, spectral band discrimination optics, detector arrays, radiative cooler, in-flight calibrator and required operating and processing electronics. The swath width of the Landsat sensor is 185 km. The dynamic range of the sensor signal is 8 bits over 256 digital numbers resulting in a fourfold increase of the older MSS sensor. Data are transferred to the ground receiving stations per S- and X band antennas. The ground resolution cell for six of seven spectral bands of the thematic mapper is 30 by 30 m, for the thermal band 120 by 120 m, for the MSS sensor the ground resolution is 79 by 79 m. 16 detectors record data per scan, resulting in 16 scan lines (Draeger et. al. 1997), the scanning is done in east-west and west - east direction. The moving speed of the mirror is lower on the TM sensor compared to the MSS system, allowing a longer response to brightness. Communication of the data depends on transmission to ground stations or via geosynchronous TDRS (**T**racking and **D**ata **R**elay) **S**atellites. The data from the project area were received at the ground station at *Fucino*, Italy. A TM full scene consists of 5667 scan lines, each 185 kilometers in the scan direction. Each scan line has 6167 pixels. With seven bands per scene, there are 244, 600, 000 pixels per scene. Since the MSS sensor is more suitable for rough overviews on scales of 1 : 1 million and 1 : 200,000 and retrospectives TM sensor still offers an interesting alternative to other sensors even nowadays. SPOT data have been regarded as alternative sensors at the beginning of the project. The resolution is higher and there are stereophotographs available allowing the calculation of DTM. If there are special missions, there are even repetitive images. Due to its lower cost and the widespread application of the Landsat TM system and the broader spectral range the Landsat TM system was selected. From the scientific point of view the SPOT system is a competitive system (Puech et al. 2000; Vine 1997).

Spectral range of Landsat TM system

The spectral coverage of the TM sensor is shown in table 2.12 . The figure 2.17 show the spectral sensitive ranges of various earth targets (Vonder & Clevers 1998). Since mid 1998 data from the Enhanced Thematic Mapper sensor are available that belongs to the new generation of Landsat 7 satellite with an enhanced spatial resolution of the thermal band and an resolution of 10 m for the HRMSI. Landsat TM 7 data were not used a for the current study since the satellite images were purchased during the first project phase in 1995.

For the calibration of the spectral bands three different stages can be differentiated according to the period related to the launch of the satellite. Pre-launch-calibration is done at the lab by lamps emitting light within the specific spectral range. There is also on-board-calibration with three different lamps and filters and temperature controlled blackbody source (Thome 1994).

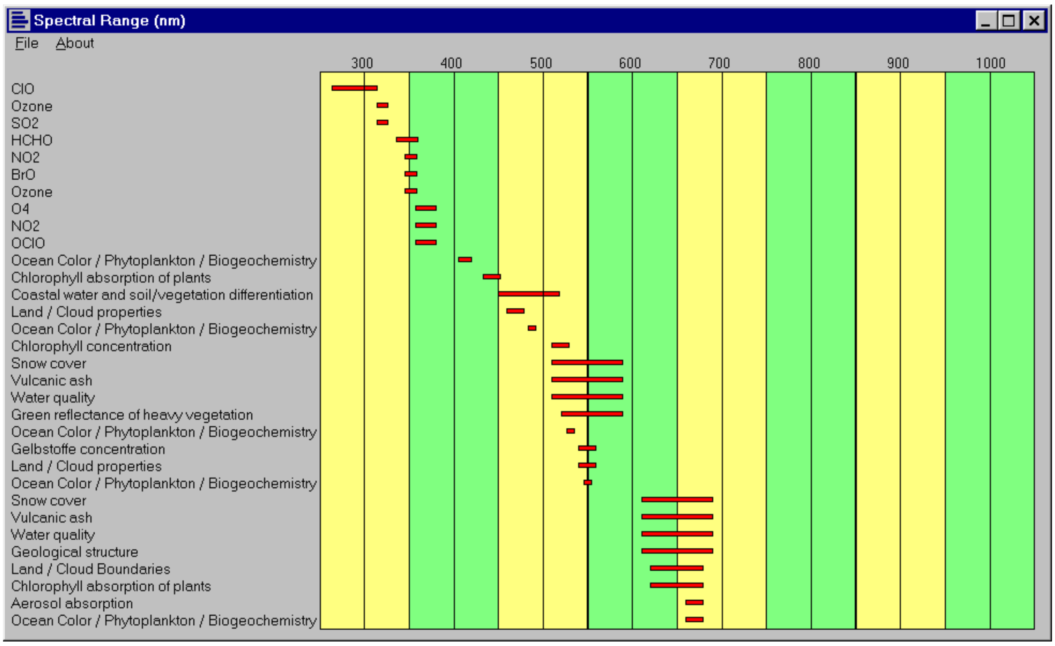

Fig. 2.17 *Sensitive spectral range within the visible range (250 to 700 nm) for various earth targets (Vonder & Clevers 1998)*

Table 2.12 *Radiometric range, spectral bands, spectral resolution and principal application of TM sensor (adapted from Lillesand & Kiefer 1999 and Mika 1997)*

Band	Wavelength [μm]	Reso-lution [m]	Nominal spectral location	Principal Applications
1	0.45 – 0.52	30	Blue	Coastal water mapping, clear water bathymetry, soil/vegetation discrimination, forest type mapping, cultural feature identification
2	0.52 – 0.6	30	Green	Vegetation discrimination, vigor assessment, sediment estimation, turbid-water bathymetry, cultural feature identification
3	0.63 – 0.69	30	Red	Chlorophyll adsorption, plant species differentiation, cultural feature identification, crop classification, ferric iron detection, ice and snow mapping
4	0.7 – 0.9	30	Near infrared (NIR)	Determination of vegetation type, vigor and biomass content, delineation of water bodies, soil moisture discrimination
5	1.55 – 1.75	30	Mid – infrared/Short wave infrared (SWIR)	Identification of vegetation and soil moisture content, snow-cloud differentiation
6	10.4 – 12.5	120	Thermal infrared (TIR)	Plant stress, urban/non/urban land use discrimination, soil moisture discrimination, thermal mapping applications
7	2.08 – 2.5	30	Mid – infrared / Shortwave Infrared (SWIR)	Discrimination of mineral and rock types, hydrothermal mapping, vegetation moisture content

2.5.3 Vegetation indices

Vegetation indices have been widely used to monitor biomass changes or to identify processes of land degradation. The amount of vegetation cover in semi-arid rangelands undergoes dramatic changes during the year. Pickup et al. 1993 report about 7 to 51% on a calcareous shrubby grassland in response to rainfall in one year. Pickup et al. (1993) developed e.g. the PD54 (Perpendicular Distance band 4 - band 5) for Landsat MSS data and estimated the percentage of vegetation cover in arid range lands in Australia.

A vegetation index indirectly identifies the presence of chlorophyll. The absorption of plants is characterized by a strong adsorption of chlorophyll in the visible range and adsorption of the liquid water at wavelengths longer than 1.4 :m. The plant cell structure reflects most within the range of 0.75 :m to 1.4 :m (near infrared) . This sudden change in reflectance behavior between visible range and near infrared is called “red edge”. Fig. 2.18 shows a typical spectrum of vegetation besides the spectral reflectance characteristics of soil and water.

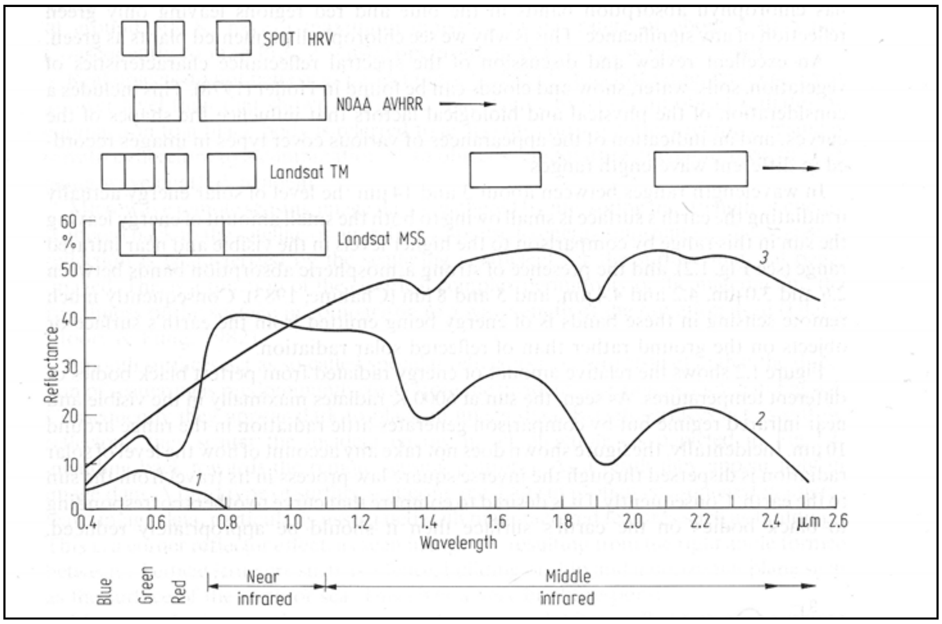

Fig. 2.18 *Spectral reflectance characteristics of water (1), vegetation (2) soil (3). Spectral range of instruments of different satellite systems (Richards & Jia, 1999)*

Multispectral ratios of NIR to visible bands can enhance radiance differences between soil and vegetation (Schowengerdt 1997). The difference between red and NIR reflectance is minimum for low amounts of photo synthetically active green biomass. It reaches a maximum asymptotic level for high green biomass amounts. An overview of the different vegetation indices is given in Table 2.13. The most common vegetation index is the **N**ormalized **D**ifference **V**egetation **I**ndex (NDVI):

$$NDVI = \frac{NIR - red}{NIR + red} \qquad [2.9]$$

The NDVI is nowadays widely used to monitor vegetation on a regional and a global scale. The NDVI is not affected by illumination such as the difference (DVI) or ratio *(RVI)* vegetation indices (Gorte 2000). There is often a good correlation between the amount of vegetation cover and the NDVI index. The NDVI index is mostly used qualitatively, mainly to monitor changes or degradation on a global scale. Phenological differences among vegetation types, reflected in temporal variations in NDVI derived from satellite data, have also been used to classify land cover at continental scales (Vonder & Clevers 1998). To derive these temporal variations a satellite system with high temporal resolution is needed: The orbital period of the NOAA satellites with the **A**dvanced **V**ery **H**igh **R**esolution **R**adiometer (AVHRR) is only 102 minutes producing 14.1 orbits per day. The NDVI is calculated through the reflected radiation in channel 1 (0.58 to 0.68 micrometer) and channel 2 (0.73 to 1.10 micrometer). The data are resampled to 8 km * 8 km pixels and a 10 days composite consisting of the highest values within this period is provided for the public. The U.S. Agency for International Development uses these data to monitor vegetation changes over Africa which is embedded in the project of FEWS (Famine Early Warning System). The data represent one piece of information in the definitive answer to food security conditions on the ground (U.S.A.I.D. 1996).

Huete (1988) introduced the **S**oil **A**djusted **V**egetation **I**ndex (SAVI) (Table D-2), which is a superior vegetation index for low cover environments. He showed that for some ground data the vegetation isolines do not converge at the origin. He assumed that the converging point is at a distance from the origin. Several soil adjusted vegetation indices are calculated, including MSAVI (**M**odified **S**oil **A**djusted **V**egetation **I**ndex).

The sensitivity to atmosphere is increasing with the increase in insensivity to the soil . There are several indices developed which are less sensitive to atmosphere (ARVI-**A**tmospherically **R**esistant **V**egetation **I**ndex (Kaufman & Tanre 1992); GEMI – **G**lobal **E**nvironment **M**onitoring **I**ndex (Pinty &Verstraete 1992))(Table D-2).

Purevdor et al. (1998) compared different vegetation indices (NDVI, SAVI, MSAVI and TSAVI) on spectral reflectance measurements with vegetative cover of desert steppe areas of the Central Asia region. Data were derived from measurements with simulated Advanced Very High Resolution Radiometer (AVHRR). They found out that the **T**ransformed **S**oil **A**djusted **V**egetation **I**ndex (TSAVI) provides the most accurate estimate of vegetation cover. The Transformed Soil Adjusted Vegetation Index also belongs to the soil-line based vegetation indices and compensates not only soil background but also senescent grass effect. Senescent grass covers the semi-arid steppe area especially in spring after the last rainfall events of the rainy winter season.

$$TSAVI = \frac{a(NIR - aRED - b)}{(RED + aNIR - ab)} + 0.08(1 - a^2)$$ (Baret & Guyot 1991) [2.10]

a = slope of soil line
b = intercept of soil line

An overview of the different vegetation indices gives Table D-2.

2.5.4 Determination of soil moisture

Considering soil moisture, mainly the upper 10 to 50 cm of the soil are considered. This moisture is used by plants like barley or corn. This is far less than the area used by trees like eucalyptus or olive trees. In a semi-arid rangeland site in South-eastern Arizona soil moisture measurements showed that the recharge in normal winter season with about 30% of the whole annual rain of 350 mm/a reaches a depth of at least 0.5 m depth in winter rains under grass and a sand loamy soil. This is also the case because the vegetation is senescent and does not use water (Scott et al. 2000).

There are different remote sensing techniques that allow soil moisture to be measured (Table 2.13). Belz (2000) used a visible/near-infrared technique, the procedure of principal component analysis, the Tasseled Cap Transformation: The digital values of the different bands are multiplied by a fixed matrix. This transformation is based on the recognition of a triangularshaped scatter diagrams of Landsat MSS data between band 4 and 2 on scenes of agricultural scenes of Midwestern USA (Kauth & Thomas 1976). The first component of the linear transformation leads to the soil brightness. The axis orthogonal to the soil line is the greenness value. The third component shows the degree of maturing of the crop, called "yellow stuff" or indicator of wetness. The transformation can be applied in the same way to other regions such as semi-arid regions. However not all components of the image are represented in the transformation, e.g. the non-green vegetation in the semi-arid region. (Crist & Cicone 1984).

Table 2.13 *Remote sensing techniques used to quantify soil moisture (Engman 2000)*

Wavelength region	Property observed	Advantages	Disadvantages
Gamma radiation	Attenuation of naturally emitted radiation	Existing airborne program. Averages over a line.	Limited spatial resolution. Limited to low elevation
Visible/near infrared techniques	Albedo, index of refraction	data available	No unique relationship between spectral reflectance and soil moisture. Surface only. Clouds
Thermal infrared	Surface temperature, measured diurnal range of surface or crop temperature	High spatial resolution, wide swath. Relationship between temperature and soil water pressure independent of soil type	Bare soil only. Clouds. Surface topography and local meteorological conditions can cause noise. Surface layer only
Active micro-wave	Backscatter coefficient, dielectric constant	All weather, high resolution	Surface roughness, vegetation, topography, limited swath width. Radio frequency interference
Passive micro-wave	Brightness temperature, soil temperature, emissivity, dielectric constant	All weather, wide swath, good sensitivity can compensate for moderate vegetation	Limited spatial resolution. Radio frequency interference with dense vegetation

Other techniques for investigating the soil moisture by remote sensing are the use of the thermal infrared data (channel 6) of the Landsat TM sensor. Shih & Jordan (1993) differentiated soil moisture status for an area in South-western Florida according to the thermal sensor response and overlaid these results with a landuse classification. This allowed the classification of different moisture statuses within various landuse categories.

Courault et al. (1993) investigated the influence of properties of the bare soil surface on the response to spectral measurements. Using ground measurements like *Munsell* color, soil water content and surface roughness, soil water was the most influencing factor. They monitored the surface stages of slaking of soil due to simulated rainfall On wet soils the reflectance of the red and near-infrared spectral band of the *SPOT* satellite simulation radiometer (red band: 600 to 690 nm, near-infrared band: 790 to 900 nm) was reduced. The slope of the soil lines of wet or dry soil are different due to water adsorption in the near-infrared.

Nowadays microwave techniques are used to determine the soil moisture. These techniques are based on the different dielectric constants of dry soil and water. The dielectric constant of dry soil is between 1 and 10 whereas that of water is 81. Therefore an increase in soil water implies an increase in the dielectric constant. For a loamy soil the increase in soil moisture from 01 to 0.3 signifies a fourfold increase of the dielectric constant (5, 19) (Engman 2000). Neusch (2000) investigated the active microwave techniques. A functional relationship between dielectric constant and volumetric soil water content could be not found, only empirical models exist (Neusch 2000).The microwaves are sensitive to surface roughness. The penetration depth of the microwaves depends on the frequency and the soil moisture (0.2 to 0.008 for soil moisture of 0.05 to 0.4 g/cm^{-3} at a frequency of 1.3 Ghz) Engman 2000, Ulaby et al. 1986). Empirical or semi-empirical models exist to explain the backscatter of the radar signal by soil roughness and soil moisture. The prediction of the soil moisture by these models varies widely (up to 12%) (Neusch 2000). Also vegetation attenuates the microwave signal (Engman 2000). Neusch (2000) studied sensitivities of models for prediction of soil moisture from L-Band to surface roughness and standing vegetation in agricultural fields in Southwestern Germany. Semi-empirical or empirical models are strongly site dependent: Adaption of the empirically algorithm coefficients is needed if using these models in areas with different terrain characteristics (Neusch 2000). Therefore to exactly determine soil moisture the effects of surface roughness, vegetation and terrain (especially active systems like *SAR* are sensitive to it) have to be considered. Nevertheless it is difficult to exactly quantify the contribution of soil moisture to the backscattering of the radar signal in distinction to other biophysical parameters such as vegetation or soil texture distribution (Neusch 2000). Although the current software packages nowadays include image processing modules for radar images a precise terrain model which is needed is frequently unavailable. In addition, standing non-green vegetation often found in semi-arid rangelands interfere with the backscatter of SAR (Moran et al. 2000). Therefore new approaches are tested nowadays like measurement of soil moisture based on radar combined with optical measurements such as based on the temperature measurements in the mid infrared channel of Landsat 5 or 7 (Engman 2000).

Chapter 3
Methodology to determine water harvesting sites in the research area

3.1 Main problems and open questions

Since reliable data on water resources are scarce or even missing in the project area more reliable data resources have to be found. The literature review has shown that new technologies allow this gap to be filled. The tool 'Geographical Information System' finally combines the fields of data acquisition, data processing and the decision process.
First of all data on rainfall within the research area have to be analyzed to consider the problem if there is enough rainfall to guarantee the success of water harvesting techniques. Then the influence of the various parameters presented in the previous chapter should be analyzed and quantified by means of remotely sensed data. Other parameters influencing the choice of water harvesting have to be considered. All these factors that have an impact on the choice of potential water harvesting sites should be incorporated in a decision process model. This model should be flexible enough to adapt it easily to other conditions.

Mainly the natural resources were considered in the current study. Social issues have to be the scope of other studies. The result is a map presenting potential sites for water harvesting. This map could be a planning tool for implementation of water harvesting in the research area.

3.2 Determination of runoff potential

Runoff is one of the crucial parameters in determination of the potential for water harvesting. Direct rainfall runoff measurements are not available for the project area. Only information on runoff events within the ephemeral rivers of the project area exists. Dry rivers are characterized by short extreme runoff events. Fig. 3.1 shows a typical hydrograph with a steep rising limb at the beginning and end of the runoff event within the *Wadi Luwazeh* south of *Tadmor*.

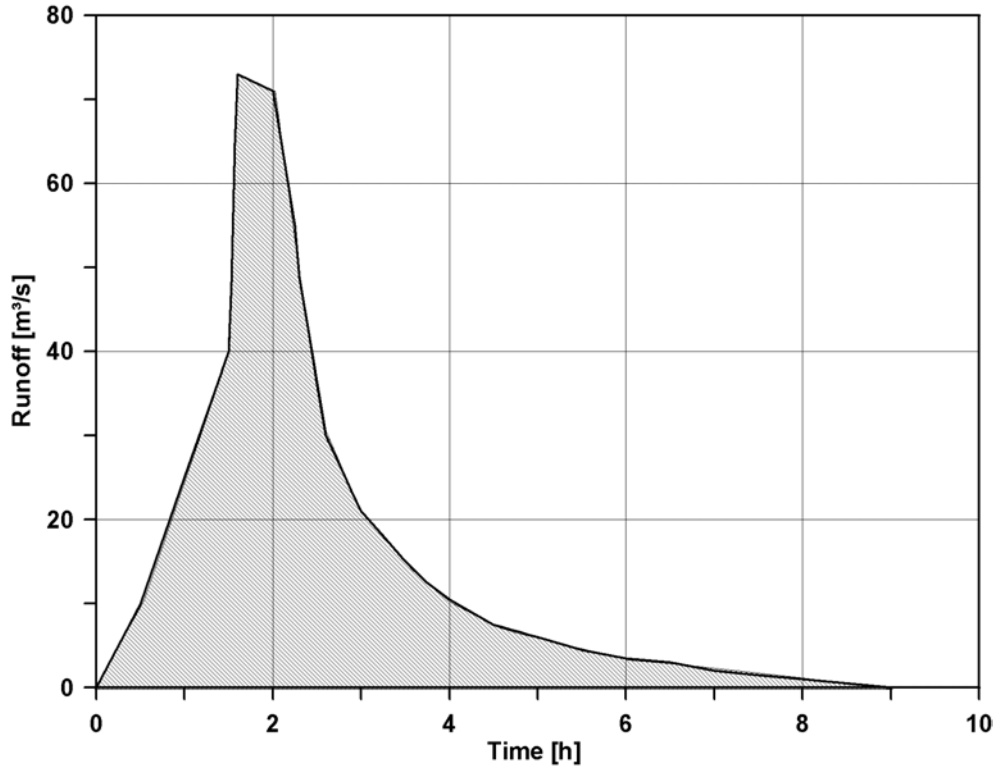

Fig. 3.1 *Runoff in wadi Al-Luwaszah south west of Tadmor on November, 10, 1984 (Lengiprovodhoz 1987)*

Vetter (1998) differentiated various hydrological landscape types on the Northwestern coastal area in Egypt. He characterized them according to their water balance (based on rainfall runoff data) and the potential for cultivation, and suggested different techniques. He noticed that 56% perennial crops grow on lands with a level up to 1%, 23% of the cultivation area of perennial cultures. About 80% of the area of low level land are cultivated by barley. 13% of the gentle sloping area (1 - 2%) are cultivated with barley and 23% of the area in this category are covered by perennial cultures. His analysis was based on rainfall runoff data.

Without the information on runoff events on the arid hillslopes in the research area, the assessment of the hydrological behaviour has to be based on the evaluation of the parameters influencing the runoff process. This lead to the differentiation of soilscape units that vary in their runoff behavior.

Table 3.1 *Hydrological landscape types on the Northwestern coast of Egypt (Marsa Matruh) (Vetter 1998)*

Hydrological landscape type	Characterization of water balance	Potential to cultivation	Possible techniques
Channel of dry river	Inflow predominates to a large extent	High	
Down slopes dry rivers	Inflow predominates to a large extent	Changing	Strip farming, micro catchment
Middle part and upper slopes	Runoff predominates	Very low	
Low level land of uplands (slope of 1%)	Inflow predominates	Middle	
Gentle sloping land of uplands (slope of 1 - 3%)	Runoff predominates	Low	
Delta of dry river on the coast	Inflow predominates to a large extent	High	

The runoff potential was determined through two different methods: One method included the SCS method, the other one comprised the indexing method.
Within the index method the various parameters for runoff generation were identified according to their importance to runoff generation. A data layer in the raster format was made for each parameter. The values of each layer were classified and assigned an index weight according to their importance to runoff generation. Osman (1996) successfully used a similar method in the arid lands of Sudan. The layers within the current study include:

- Slope
- Soil texture
- Vegetation cover
- Stoniness and roughness of soil
- Antecedent soil moisture by the wetness index of Tasseled Cap evaluation
- Flow length

Two scenarios were evaluated within the index method, one including all the layer (Scenario A). The other scenario excludes the layer of flow length (Scenario B). The layer of flow length mainly emphasize the areas of runoff within the dry rivers. Therefore this scenario is important to evaluation of potential areas for floodwater harvesting. The areas within the project area which are assessed according to their importance to runoff are assigned various weights according to the ranking.

Within the SCS method the assignment of the curve numbers was carried out according to the outcome of the soil analysis and the land use classification of the satellite image which results in the definition of soilscape units. The determination of the runoff potential was then based on the rainfall of 2 year return period.

3.3 Decision process to decide on suitability to water harvesting: Use of an Analytical Hierarchical Process (AHP)

3.3.1 Definition of AHP

To identify suitable sites for water harvesting the differences have to be considered and ranked. Different methods are used for decision processes in the GIS. Márkus (1999) points out that the decision-making process is not fully coerced in the GIS. He developed a spatial decision-support system (SDSS) which provides the framework for integrating (1) analytical modeling capabilities; (2) database management systems; (3) graphical display capabilities; (4) tabular reporting capabilities; and (5) decision makers' expert knowledge. He defines the decision process based on criteria which can be differentiated into two groups, (1) factors and (2) constraints. Constraints limit the suitability of a method or a site, factors enhance the suitability or detract from its suitability. To come to a decision, factors and constraints have to be considered within a decision rule linking all the alternatives. The decision rule can be fulfilled within a geographical information system.

One example of a decision procedure is the decision tree which was used by Tauer & Humborg (1992) to determine runoff irrigation sites in Mali. Here the classified satellite image for water storage capacity, the distance model for accessibility and the inclination model for the different types were superposed according to the decision tree (Fig. 3.2).

The analytical hierarchical process AHP was used to meet the complexity of the multi-criteria decision process to the suitability of land for water harvesting. This method was developed at the beginning of the eighties (Saaty 1980) and since then it has been widely used. The AHP presents an excellent technique for dividing the complexity of a problem into smaller units.

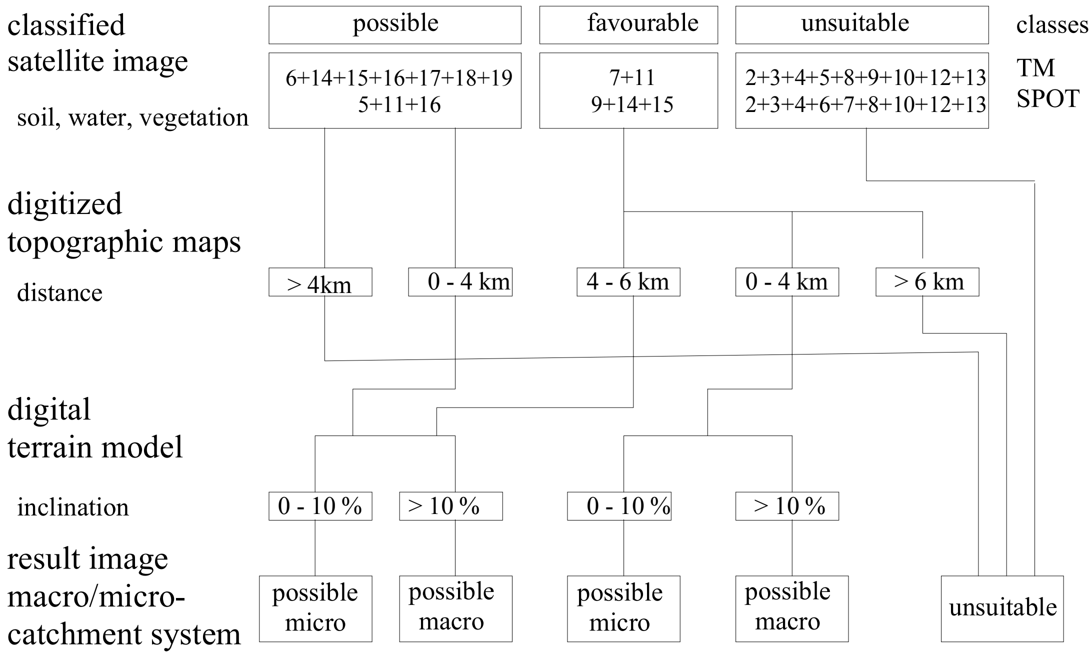

Fig. 3.2 *Decision tree for determination of runoff irrigation sites in Mali (Tauer & Humborg 1992)*

The AHP is widely used in decision processing in environmental planning in industry, politics and urban planning. It is effective in structuring complicated decision processes in business and evaluation of energy systems (Mohsen-Mousa & Al-Jayyousi 1999). AHP involves five basic steps, i.e. (1) objectives have to be clearly defined; (2) the different factors associated with the problem have to be clarified and determined; (3) to get a decision hierarchy the factors need to be structured in a decision hierarchy; (4) measure the importance of each factor on the decision process according to the eigenvector calculation; and (5) aggregate the factors according to their ranking and assign a suitability index.

Therefore different questions have to be set resulting in the typology of an AHP :

- Who are the decision makers?
- Are there only a few or a lot of alternatives?
- Is there only one criterion or are there many criteria?
- Is the context certain or more uncertain?
- Is the spatial distribution an essential part of the problem (Haurie 1998)?

The top level of the decision hierarchy is the overall objective; this is followed by the other levels that consist of the different factors or perceived alternatives to the problem. The attributes of the alternatives are part of the lowest level of the hierarchy. First, the criteria and sub criteria are compared with each other and the preference of one criterion to another (in pairs, one by one) is assessed (Table 3.2). Comparisons of pairs are then computed for all possible pairs. The weight ratios are preferences on a 1-9 scale. The sub criteria are compared on the same level within the hierarchy. The comparison of pairs is carried out at each level of the hierarchy and is expressed in relative weights. First the eigenvalue - or eigenvector - is calculated by multiplying all fractions of the comparison of pairs in one row and taking the n^{th} root of the product (''n' is the number of row elements). The relative importance weights are then the division of each eigenvector by the sum of all eigenvectors. The different levels within the hierarchy are then compared by linear combination.

Table 3.2 *Linguistic measures of preference (From Siddiqui et al. 1996; Saaty 1980)*

Linguistic expression of relative importance of one member of comparison pair relative to another	**Number assigned to linguistic expression**	**Explanation**
Equal preference or indifference	1	Two elements have equal importance regarding the element in the next higher level
Weak preference	3	Experience or judgement slightly favors one element
Strong preference	5	Experience or judgement strongly favors one element
Demonstrated preference	7	Dominance of one element proved in practice
Absolute preference	9	Highest order dominance of one element over another
Intermediate values	2,4,6,8	Compromise is needed

3.3.2 Use of AHP in hydrological studies

AHP has been used in site-evaluation procedures or models focussing on a single parameter. DRASTIC is such a model (Noble 1992). The DRASTIC model assesses aquifer vulnerability. It is a standardized system for evaluating ground water pollution potential of aquifer systems. It consists of seven layers, i.e**.**, **d**epth to water (D), **r**echarge (R), **a**quifer media (A), **s**oil media (S), **t**opography (T), **i**mpact of the vadose zone (I) and hydraulic **c**onductivity (C). Weights assigned to each layer reflect the effect of each of these seven parameters on the vulnerability of the aquifer. The so-called DRASTIC index is simply the sum of the ratings and weights of each of these layers. Thirumalaivasan & Karmegan (2001) extended this index by using GIS and the Analytical Hierarchical Process (AHP) to evaluate the risk of groundwater pollution in northern India by effluents from tannery industries. In Jordan, Mohsen-Mousa & Al- Jayyousi (1999) used the AHP to identify the optimum desalination method for brackish water. The criteria considered through the different levels within the decision hierarchy are of environmental, economic and political character. The different desalination processes were ranked according to their importance with regard to the above-mentioned criteria.

Siddiqui et al. (1996) used it to postulate a reasonable decision hierarchy for siting a landfill site. El Awar et al. (2000) used a four-level model to decide on possible locations of water harvesting reservoirs, including major criteria, sub-criteria and attribute classes. Level 1 of the decision hierarchy structure comprises the reservoir suitability index. Land cover and potential storage are the major decision criteria, which are more classified through the sub-criteria including potential runoff, topographic characteristics and soil characteristic. The highest level then involves the attribute classes, which are characterized by hydrological modeling and GIS application classes. The reservoir suitability index was computed by multiplication of the sum of relative weights of each level.

3.3.3 Use of AHP to determine potential sites to micro- / macrocatchment and floodwater harvesting systems in the research area

A model was developed since the Analytical Hierarchical Process allows consideration and ranking of alternatives. The model includes either three or four levels, including (1) the objective, (2) the criteria, (3) the sub-criteria and (3) or (4) the alternatives of criteria. Different water harvesting systems were chosen to illustrate that the selected decision process could be easily adapted to different techniques. Microcatchments are exemplary for small scale systems. If the catchment area of the microcatchment system is too small for harvest of sufficient water to meet the crop water requirements macrocatchments could be used on the longer slopes of the research area. Floodwater harvesting schemes belong to large scale systems. These techniques are already applied or tested within the project area. Contour ridges are used for rangeland rehabilitation within the area of the *Northern Palmyrides*. Floodwater spreading is applied at *Mihassa* (Soumi & Abdul Aal 1999). Level 1 of the AHP comprises the suitability index of land to be used for micro- / macrocatchment or floodwater harvesting systems. The criteria of level 2 additionally include for the micro- / macrocatchment and for the floodwater harvesting techniques suitability index:

- Runoff potential
- Slope
- Proximity to military or industrial sites
- Soilscape unit
- Proximity to settlement
- Proximity to roads

The last criterion, the proximity to roads is only relevant as single criteria to the micro- / macrocatchment suitability, since it allows inclusion of runoff from the roads for irrigation of cultivated patches in the ditches adjacent to the roads. Within the floodwater harvesting scheme, the proximity to roads and settlements are combined. The suitability to floodwater harvesting systems is a four level model since the main criteria comprise the proximity to runon areas. Slope etc. comprise the subcriteria.

All these criteria or subcriteria are classified into alternatives which are compared in pairs. The factors are not based on experiments, but on the experiences made in the study area or areas with similar hydrological condition. The eigenvectors and finally the importance values, show the ranking of the different classes of one criterion. The sum of the product of the importance value of the second level and the ranked class or alternative of criteria then leads to suitability of the land to micro- / macrocatchment (Fig. 3.3) or floodwater harvesting systems (Fig. 3.4).

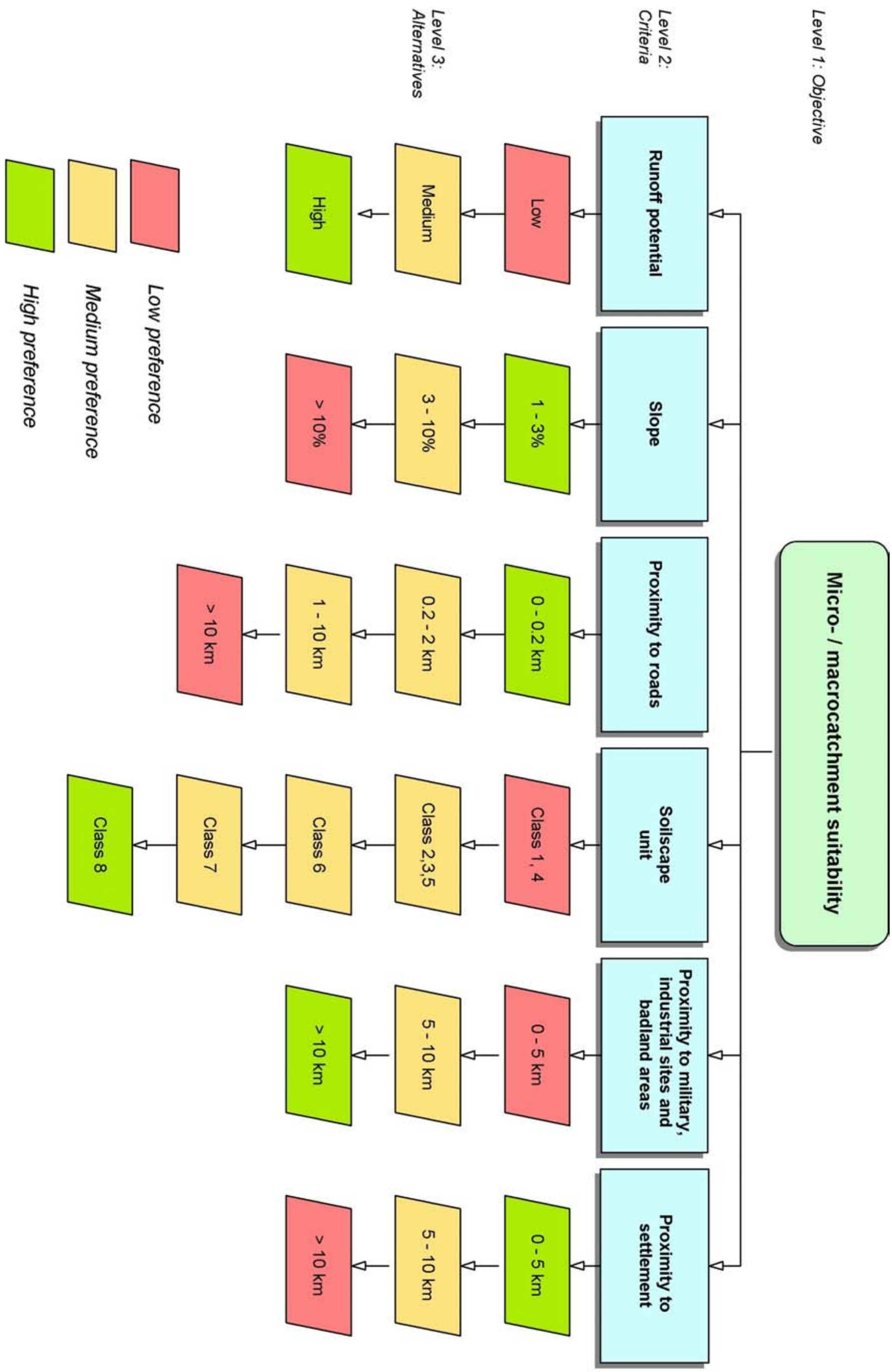

Fig. 3.3 *Criteria and alternatives within AHP for micro- / macrocatchment suitability*

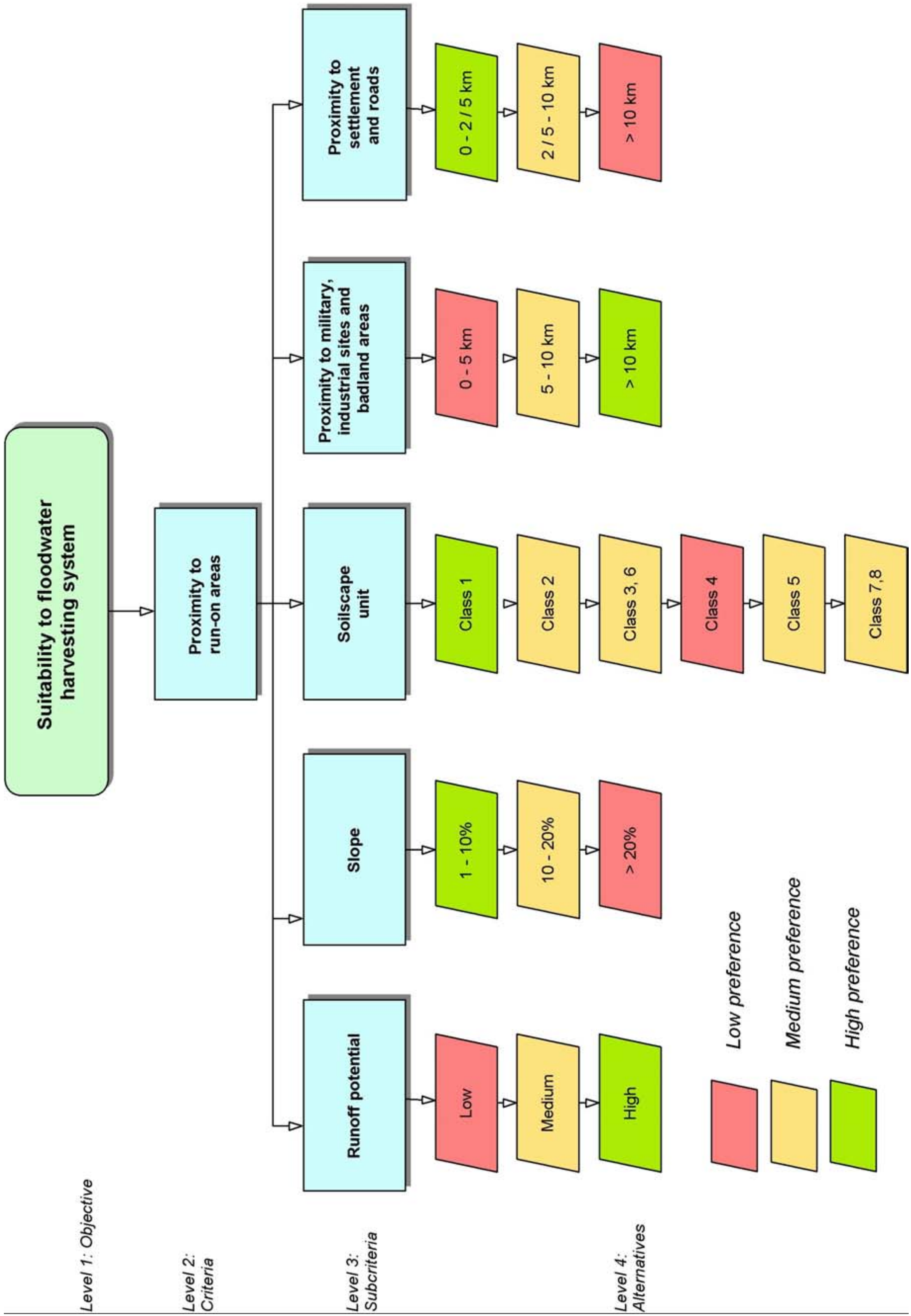

Fig. 3.4 *Criteria and alternatives within AHP for suitability to floodwater harvesting system*

Chapter 4
Data and Analysis
4.1 Climatic characteristics of the research area

One of the principal components of climate in arid regions is the fact that annual evaporation exceeds by far the precipitation (Table 4.1; Kutsch 1982). According to the definition of Kutsch (1982), the project area belongs to the semi-arid to arid region: Evaporation exceeds rainfall by about a factor of 2 or 3. The rainfall is low and erratic, and there are extensive fluctuations in temperature and precipitation.

Table 4.1 *Climatic classification according to precipitation (P) and potential evaporation (E_0) (Kutsch 1982)*

P/E_0	**Classification**
> 0.5	Humid
0.5 to 0.3	Semi-arid
0.3 to 0.1	Arid
< 0.1	Fully arid

The climate in Syria is typical Mediterranean, characterized by a rainy season in winter, e.g. from October to April, and a dry season in summer. The character of the precipitation regime is cyclonic. Orographic precipitation on the western side of the Lebanon range hampers the rain from reaching the central area of Syria. The cyclones triggering precipitation in winter mainly come from the Mediterranean sea. The cyclones are produced in the Tyrrenian sea (i.e. between Italy and Corsica), the Adriatic sea and along the Algerian coast (Wirth 1971). The area is located within the semi-arid region with an average annual rainfall ranging from 250 $mm \cdot yr^{-1}$ in the northwest to 100 $mm \cdot yr^{-1}$ in the south east (Meteorological Department, S.A.R. 1978) (Fig. 4.1). These data are based on observations at 16 principal climatological stations with observations per 24 or 8 hours, 84 climatological stations with observation every 3 hours and 175 precipitation stations with daily observations over the period from 1955 to 1969. Data concerning daily precipitation records for a period of about 19 years (1978 - 1996) were available from about 23 stations (Fig. 4.1).

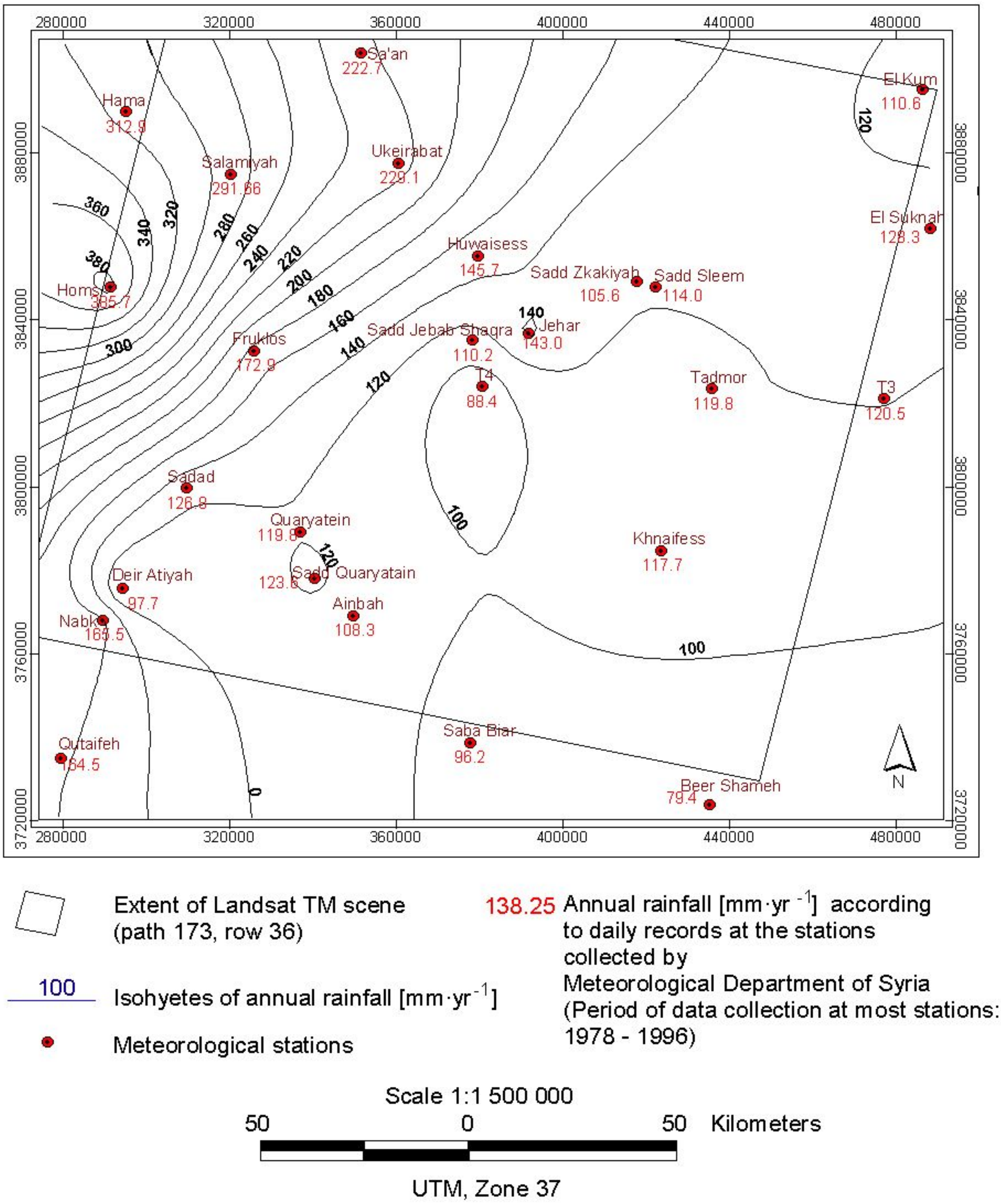

Fig. 4.1 *Isohyetes of annual rainfall (interpolation by kriging) (Source: Meteorological Department, S.A.R. 1996)*

4.1.1 Temperature

Transition seasons like autumn and spring are only short in the Mediterranean climate and characterized by a sharp change in temperature. Data on temperature were available for about 11 stations of the study area and was statistically analyzed. Mainly data were available from a period of about 20 to 30 years (Table A-1). The average air temperature is about 16 to 17°C in the mountain ranges of *Northern* and *Southern Palmyrides*, the station of *Tadmor* shows higher values (18.6°C).

The summer in the steppe area within the project area is characterized by temperatures exceeding 30°C (IFAD 1997). The annual average maximum temperature is about 18°C in the *Southern Palmyrides* mountains and up to 25°C at *Tadmo*r. Going towards the east within the project area, the number of days with a maximum temperature > 35°C increases: at *Quaryatain* there are about 40 days > 35°C increasing to 80 days at *Tadmor* (IFAD 1997). The absolute maximum temperature in summer is between 42.5°C at Homs (38 years of observation) and 46.5°C at *Tadmor* (36 years of observation) in July or August. Hottest months are July and August (Table A-1).

The climate in winter is rather cold :the average minimum temperature in winter season in *Tadmor* is about 6°C. The annual average minimum temperature increases from about 9°C in the eastern part of the study region (*Khnaifess*) to 13°C in the northwestern part (*Ukeirabat*). The absolute minimum monthly temperature ranges from -6.6°C at *Ethriyeh* to -12.1°C at *Tadmor* or even - 13°C in *Fruqlos*. The absolute minimum temperatures occur during December to February. Between 20 to 40 days of frost occur in the areas of *Quaryatain*. In the area south of *Tadmor* and the region between *Homs* and *Tadmor* there are less than 20 days of frost (IFAD 1997; Meteorological Department, S.A.R. 1978).

4.1.2 Wind

The main direction of wind in summer is from the north blowing from the Anatolian highlands, the so called *Etesian* winds (Wirth 1971). Maximum wind speeds mainly occur during the summer months (up to 415 $km \cdot d^{-1}$), minimum wind speeds are in winter, i.e. November or December (FAO 1991). The average wind speeds are in the range from 179 to 340 $km\ d^{-1}$ (2 $m\ s^{-1}$ to 4 $m\ s^{-1}$). These wind speeds are explicitly above the threshold of wind speed, i.e. 0.01 to 0.22 $m\ s^{-1}$, that is needed to dislodge soil particles. The drifting clouds of soil particles in summer or in winter which hamper the driving in the steppe area, illustrate this fact.

Dislocation starts at wind velocities of 0.3 to 0.35 m s^{-1} (25 to 30 km h^{-1}) at levels of 30 cm above ground (Sterk 1998). Wind erosion is therefore a major problem within the project area. Soil losses can be high, especially in the rangeland areas where the protective cover of vegetation is removed due to overgrazing. Protective plant cover decreases the soil loss to 60 to 70% for various soil types (Bielders et. al. 1998). Degradation by wind erosion due to cultivation of the steppe soils has been clearly shown within the *Bishri* mountains situated northeast of the study area north of the main road *Tadmor-Dayr-Ez-Zaur*. It led to the initiation of a project funded by the Federal Ministry of Germany for Economical Cooperation to control degradation within the steppe area of the *Bishri* mountains (Geerken 1997). Since the main action of wind is during the summer months, cultivations should be placed at wind protected sides or behind shelterbelts of trees or bushes. This form is already practiced within the study area; irrigated barley cultivation within the *Ad Dauw* basin is often surrounded by olive trees. Dunes can be observed in the vicinity of *Tadmor*. This implies that there are enough sand particles to be blown out to from dunes.

4.1.3 Rainfall

Annual rainfall

Rainfall occurs mainly during the winter months, which is characteristic for the Mediterranean climate. The first rainfall events occur in autumn, usually beginning in mid October. The rainfall period ends in April. Sometimes single rainfall events occur in May or even June. The duration of the dry period from June to October is between 180 and 250 days. In winter the cloud coverage is 5/10, in summer only 1/10 (Wirth 1971). The average total precipitation is about 100 to 150 mm in the southern part of the project region, rising to 200 mm in the *Northern Palmyrides* (Table A-2). The range of the annual precipitation is between 80 mm in the very southeastern part of the project area (*Beer Shameh*) and 223 mm in the northwestern part (*Salamiyah*, Fig. 4.1). The isohyetes are calculated according to the *Kriging* procedure using the average annual based on data from a period of about 10 to 20 years.

The depression zones bring three to six days of rainfall and then a cloudless period. The weather in winter is characterized by east-west drifting cyclones. In contrast to the climate in North Africa such as Tunisia, the precipitation at the various stations show only one maximum (Wirth 1971). Most rainfall events occur in December, January or April. More than 20 days in average rainfall events exceed 1 mm.

The annual rainfall is highly variable (Fig.4.2): The annual rainfall at *Tadmor* varies between 55 mm and 212 mm with an average annual rainfall of 119 mm for the period 1978 to 1996. Also the monthly sum of precipitation varies to a large extent: At *Nabk* the deviations from the mean for December and April are within the range from -14 to +35 mm (Fig. 4.3). These variations show that the region is not suitable to rainfed agriculture without rainwater harvesting.

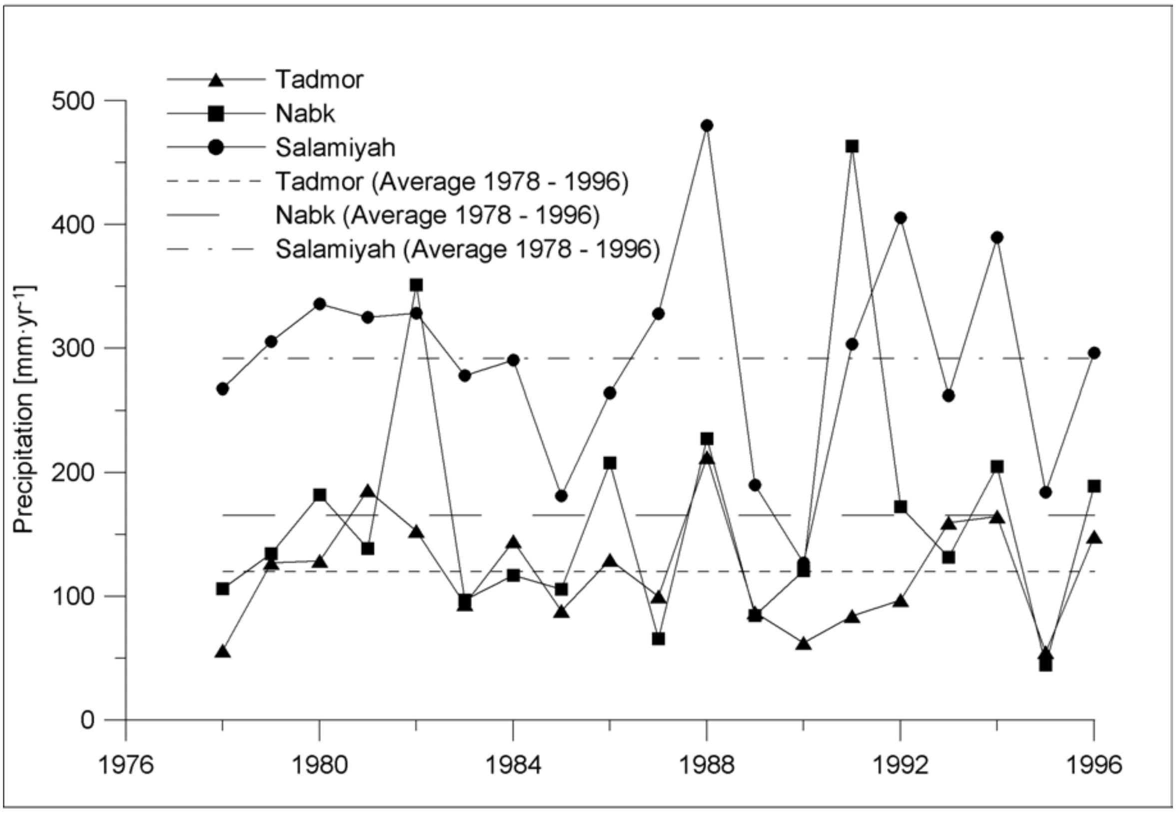

Fig. 4.2 *Fluctuation of average annual rainfall for Tadmor, Nabk and Salamiyah meteorological stations (1978-1996) (Source: Meteorological Department, S.A.R. 1996)*

The amount of annual rainfall for the semi-arid areas is not as important as the number of rainfall events (Mortimore 1998). In semi-arid regions of Africa with seasonal rainfall of 250 mm "the reduction of one or two rainfall events can make the difference between a bumper crop and a catastrophe" (Mortimore 1998, p. 14) (see following paragraphs).

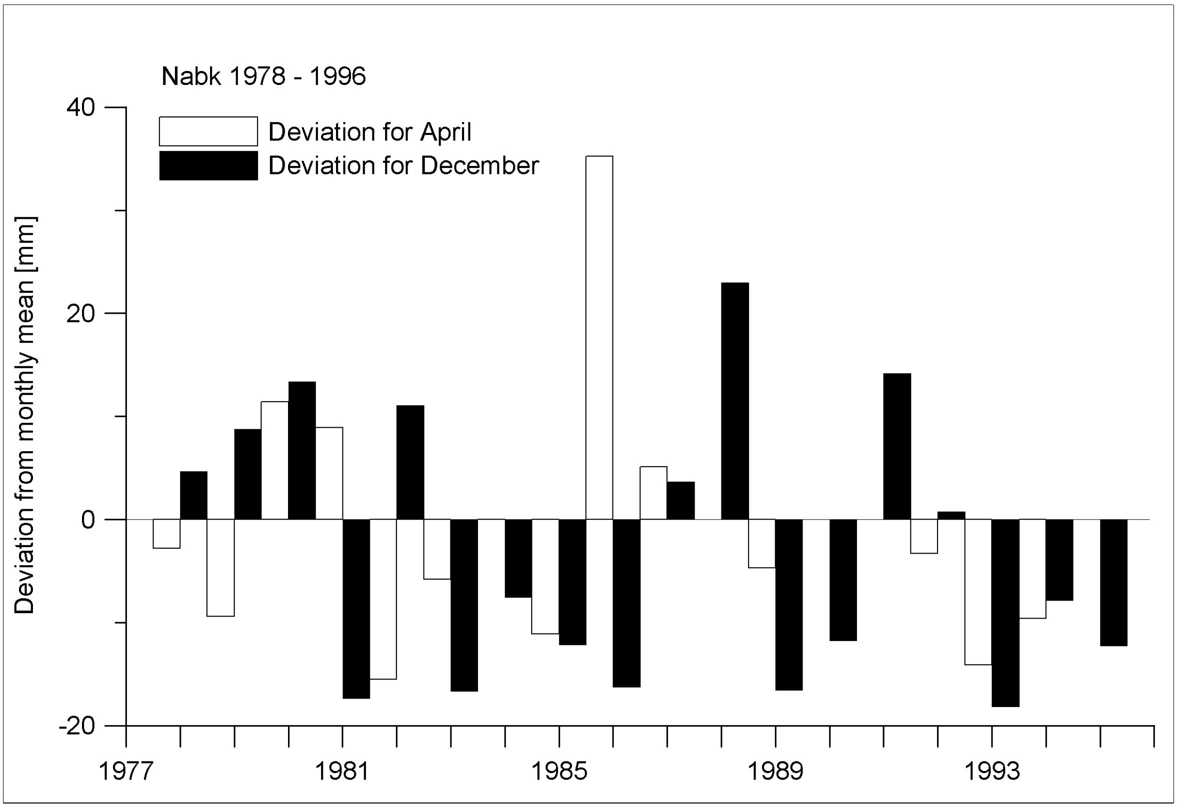

Fig. 4.3 *Deviation of monthly rainfall from average at Nabk station (1978-1996) (Source: Meteorological Department, S.A.R. 1996)*

Effective rainfall and rainfall intensity

The determination of the threshold of rainfall to produce runoff in Jordan has been based on the analysis of only five seasons (1993/94, 1994/95, 1995/96, 1996/97, 1997/98), where between four to eight events over 5 mm d^{-1} were producing runoff. However at least one rainfall event of over 5 mm did not produce runoff which illustrates the shortcoming of daily records. The temporal resolution is too low since daily rainfall of 5 mm may consist of several low intense rainfall events with hourly interruptions. No runoff is observed below the threshold of rainfall and the whole amount of rainfall infiltrates or evaporates on the surface. Studies within the *Negev* showed that the threshold for rainfall to produce runoff is 1 to 2 mm h for stony underground and 3 to 5 mm for sandy soils (Tenbergen 1991) (Table 2.2).

The climate in the study area is comparable to the *Negev*-Highlands, where rainfall events are also around 0 to 6 mm d^{-1}. 77% of total annual rainfall occur in storms with intensities of 5 to 10 mm h^{-1} (Allison & Hughes 1983). Rainfall events of over 10 mm d^{-1}

last for only 15 min per hour. The maximum rainfall intensity in the low rainfall zone in northern Iraq is about 20 mm h^{-1} for normal storms (Hussein 1996). At *Mihassa*, an area within the study site, situated west of the road *Damascus*- *Dumayr-Quaryatain*, and a test site for water harvesting structures, rainfall intensities from 1 to 5 mm h^{-1} were recorded (Soumi & Abdul Aal 1999). Rainfall events of 5 to 10 mm·d^{-1} there normally comprise several single storms with intensities between 0.5 and 5 mm h^{-1} (DVWK 1988). Single rainfall events predominate in semi-arid environments, but days with light, long-lasting showers of low intensities are also found (Dunkerley 2000).

Characteristics of rainfall

The analysis of the rainfall events within the study area shows that there is a strong correlation between the cumulative rainfall of events exceeding 5 mm d^{-1} and the total annual rainfall. Knowing the regression function for a station, the amount of rainfall events over 5 mm·d^{-1} can be estimated. The regression coefficients vary between 0.90 and 0.98 (Table A-4). The percentage of the cumulated rainfall exceeding 5 mm d^{-1} is in the range between 50% and mostly over 80% of the annual rainfall (Table A-3). The correlation between the number of rainfall events exceeding 2 mm and annual rainfall is not as good as for the events exceeding 5 mm d^{-1}. The same correlation was also found for other semi-arid areas: Vetter (1998) illustrated for *Marsa Matruh* (Northwest coast of Egypt) with an average annual rainfall of 140 mm that there is a strong correlation between the cumulated sum of events over 5 mm and the annual rainfall.

The values for the number of rainfall events and also those within the classes of 2 or 5 mm, have been interpolated by Kriging with a linear trend using the Surfer Software package (Golden Software 1999). Fig. A-1 and following up to A-3 show the interpolated isolines of number of rainfall events within the different classes. The average number of days with rainfall is in the range of other arid regions such as *Khartoum*, Sudan (18 rainy days, 164 mm·yr^{-1}) or *Keetmanshoop* in Namibia (19 rainy days 147 mm·yr^{-1}or *Gafsaa*, Libya (29 rainy days with 160 mm·yr^{-1}). Rainfall exceeds 5 mm on 5 to 20 days per year (Fig: A-3). The number of rainfall events exceeding 5 mm d^{-1} decreases going further southeast within the project area. *Homs* and *Hama* on the wetter western side receive on average 20 to 25 events over 5 mm; at *Sadd Quaryatain* and *Tadmor* only about one third of these number occurs. It should be noted that the spatial interpolation technique, i.e. Kriging, can give only a rough estimation of the spatial variation of the values over the study area. Due to high spatial variability of rainfall, data on rainfall events in semi-arid areas are only valid for limited areas (e.g. 2.5 km² for rainfall events in semi-arid areas of

USA; Murphy et al. 1977).

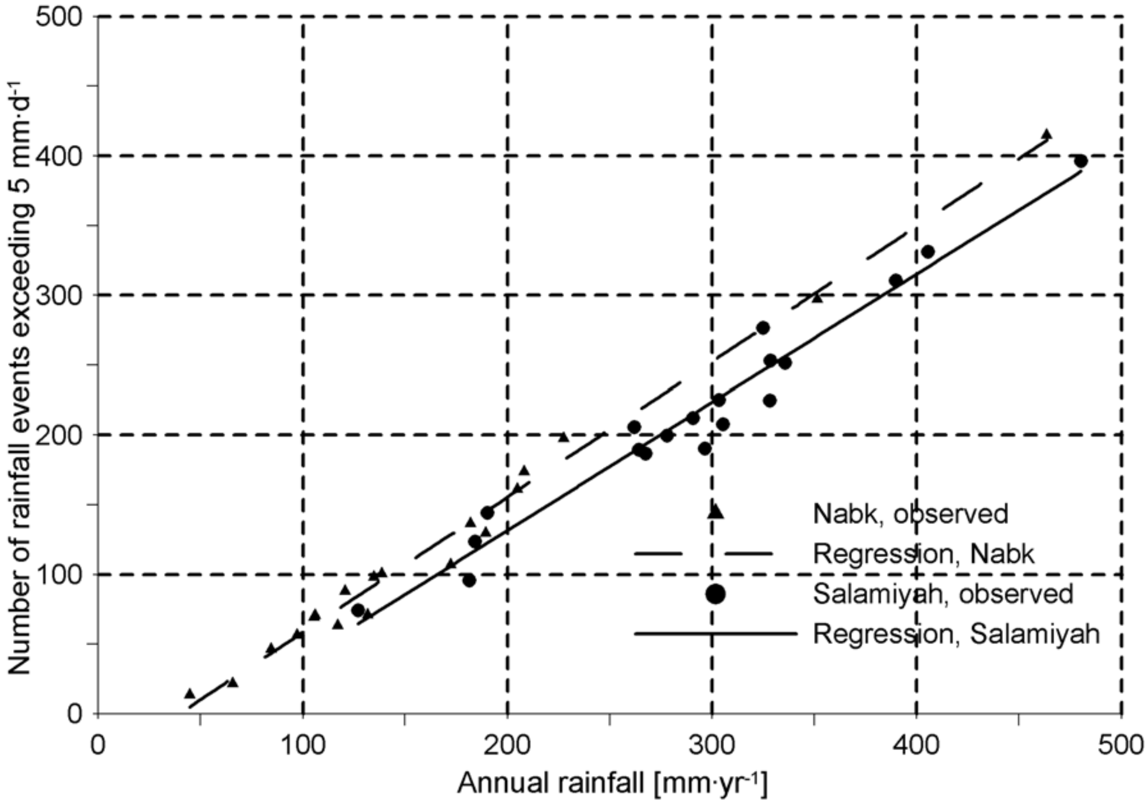

Fig. 4.4 *Correlation between number of rainfall events exceeding 5 mm·d^{-1} and annual rainfall (regression coefficients for Nabk: r^2= 0.95, a=0.97, b=-38.38 and for Salamiyah: r^2=0.98, a=0.92 and b= -52.02 (Source: Meteorological Department, S.A.R. 1996)*

Extreme rainfall events are defined as those events significantly exceeding average rainfall. In humid areas the research on probability of rainfall events is based on the estimate of the risk of flooding. In low rainfall areas, extreme events contribute most to the effective runoff to be used for water harvesting. It is also relevant to plan control measures protecting water harvesting structures from damage. Morin et al. (1998) presented and discussed different methods and models for the rainstorm probability analysis: California method, Chow method and Gumbel method. Gumbel (1958) suggested that for extreme values the predicted value for any probability is based on exponential relations.

For stations in Western Mali with 400 mm annual rainfall, Tauer (1994) showed that the probability of extreme rainfall can be expressed through log-normal distribution or the Gumbel-distribution. A probability analysis was done for the stations in the study area, using the “Extremprogramm”software (IHW 1988). The probability that an extreme rainfall event occurs is often expressed by the return period: for example at the station of *Tadmor* the analysis shows that a rainfall event of 20 mm d^{-1} is of 2-year return period: Half of the daily rainfall events exceeds this value. But 90% of daily rainfall amounts at *Tadmor* will be lower than 28 mm d^{-1} (Fig. 4.4). The first line in Fig.4.4 illustrates the plotting position, which is the relative abundance of a value transformed into a empirical probability (Tauer 1994). The last column in Table A-4 gives the amount of extreme events considered within the analysis, mostly one maximum per year within a series of 19 years. The estimated rainfall amounts are based on the probability function of Gamma distribution, which predicts extreme events well. The choice of best-fit distribution was done by the Kologomoroff-Smirnoff test within the software program. Partial series were used for some stations since the sample period was too short in some cases. For these cases the extrapolation for return periods exceeding 200% of the period of investigation should not be considered.

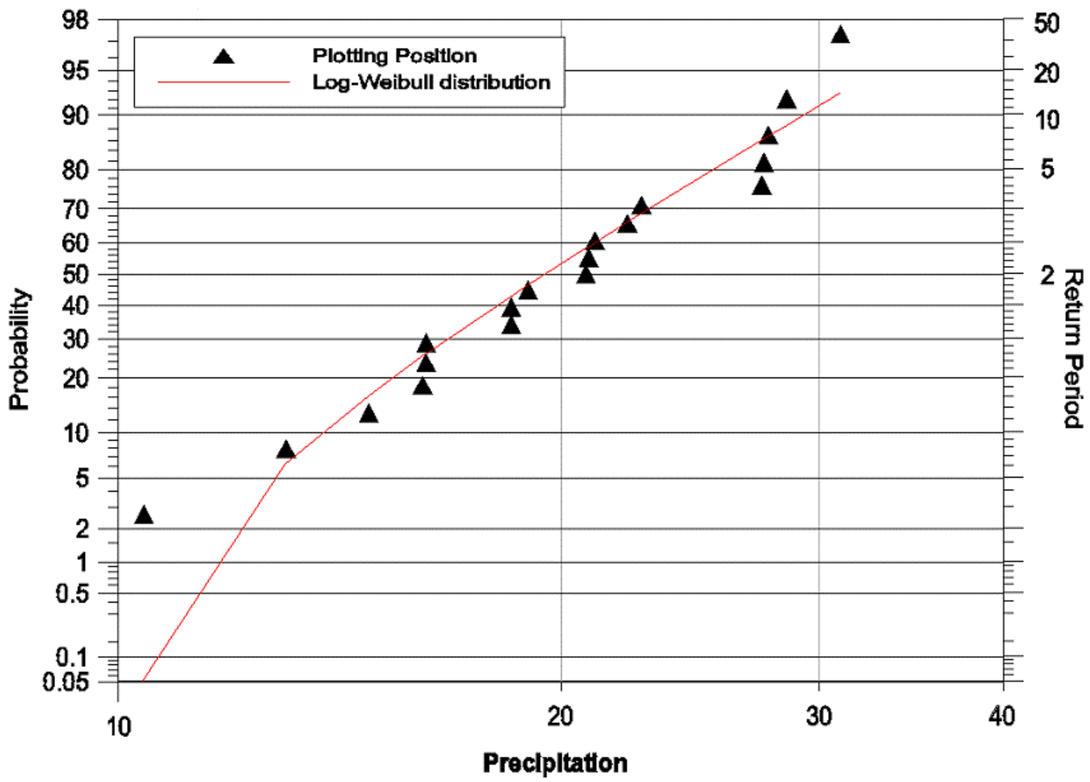

Fig. 4.5 *Extreme values of daily rainfall and Weibull distribution at the station of Tadmor for the time period from 1978 to 1996 (Source: Meteorological Department, S.A.R. 1996), based on analysis of data using the "Extremprogramm" software (IHW 1988)*

For Syrian steppe stations the log-normal, the log Gumbel, Weibull or Gamma distribution best describes the probability of exceedance at most stations (Table A-4).. The upper extreme values are often underestimated (Fig. 4.4). Fig. A-4 and A-5 show the interpolated isolines for the return period of 5 and 10 using the spatial interpolation technique of *Kriging* using *Surfer* (Golden Software 1999). For the return period of 5 years values between 25 to 40 are not exceeded with a probability of 90% .

Frequency of dry periods between rainfall events

The time resolution of the data is too low to differentiate the rainfall events of two successive days. Therefore the frequency analysis of dry periods between the rainfall events is also measured in days.

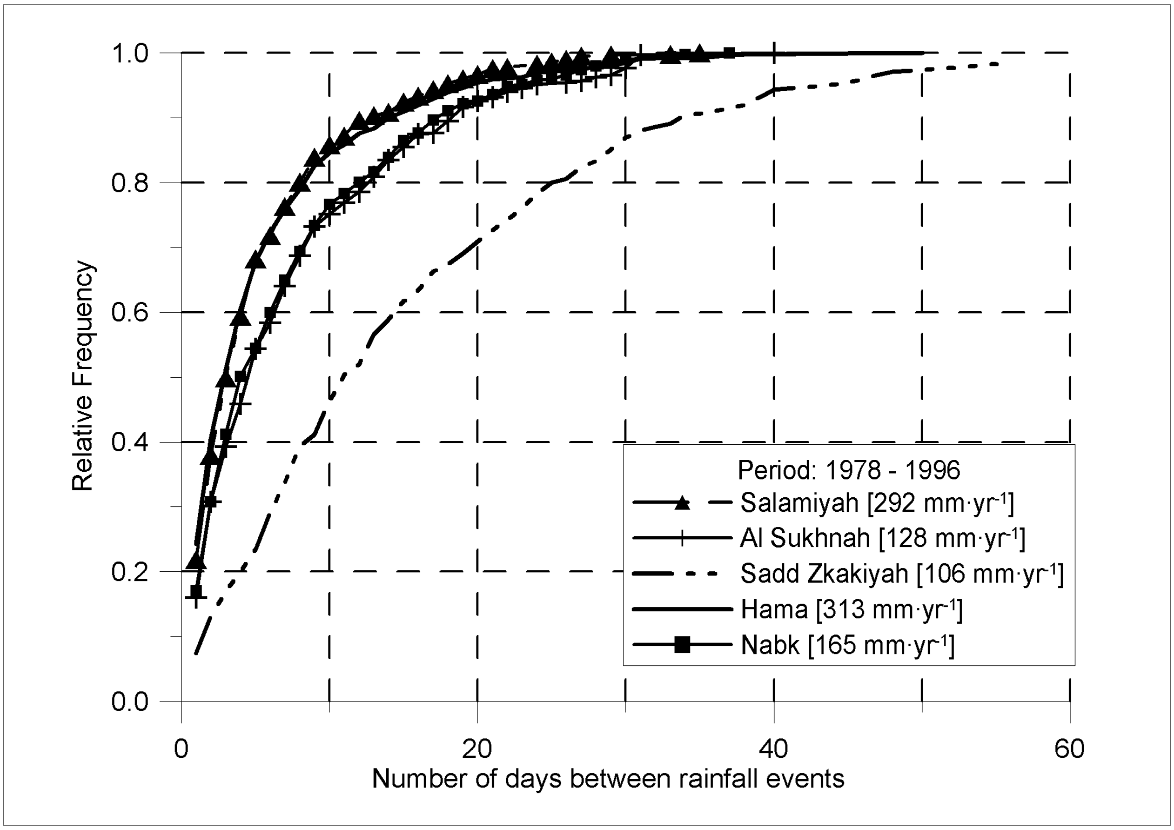

Fig. 4.6 *Relative frequency of dry days between rainfall events at different stations within the project area (Average annual rainfall (period 1978 - 1996) is included) (Source: Meteorological Department, S.A.R. 1996)*

The frequency of days without rain shows a clear distribution. The distribution is more normal in the wetter regions towards the west; in the drier regions the distribution is more left-sided as the relative frequency shows (Fig. 4.6). Comparing the "wetter" station *Salamiyah* (average annual rainfall of 292 mm·yr^{-1}) with the drier station *Sadd Zkakiyah* (average annual rainfall of 106 mm·yr^{-1}) it becomes evident that a high number of dry days between two rainy days is more frequent at the drier station *Sadd Zkakiyah.*

Considering the number of dry days between rainfall events surpassing a threshold value of 2 or 5 mm d^{-1} the number of days between the single events is higher for events of 5 mm d^{-1} than for those events lower than 2 mm d^{-1}(Fig. 4.7). The frequency of dry periods between rainfall events surpassing 2 mm d^{-1} illustrates, that these more extreme events are situated mostly within a period with single events below this threshold. Furthermore this is confirmed by the frequency distribution for days between events exceeding 5 mm·d^{-1}.

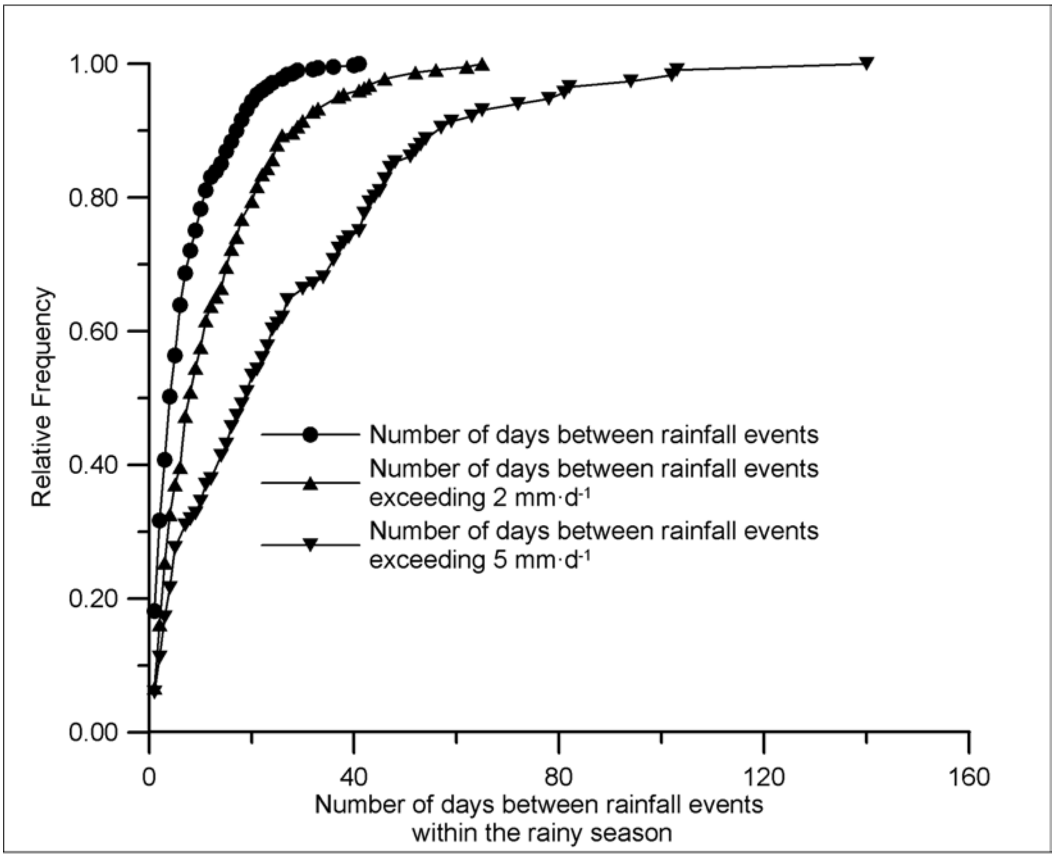

Fig. 4.7 *Relative frequency of days between rainfall events of different maximum height at Tadmor (Source: Meteorological Department, S.A.R. 1996)*

4.1.4 Calculation of potential evapotranspiration

Potential evaporation signifies the maximum water loss from bare surfaces under current climatic conditions. Evapotranspiration is the combined evaporation from the soil, water and plant surfaces and transpiration through the leaves. Water loss from land surface is related to the actual evapotranspiration. Potential evapotranspiration is experienced only with an adequate water supply at all times. This can be measured through the water flow in the atmosphere, heat transfer from land to the atmosphere and the water flow in the soil column (Menenti 2000). Different methods allow direct measurement of evaporation: evaporimeters such as Class A pan, or lysimeters. Class A pan measurements are only relevant to a small area of water surfaces and for restricted areas, about to 1 ha within a period of hours to a year (DVWK 1991). A Russian version of evaporation pan, *GGI 3000* (0.685 m deep round cylinder with a surface area of 0.3 m^2 sunken into the soil and water surface on ground level (DVWK 1991)) was used during the 1980's for evaporation measurements within the study site. They range from 60 mm $month^{-1}$ (January), to 130 to 220 mm $month^{-1}$ in spring (March /April) and maximum of 560 mm $month^{-1}$ in August at the *Tadmor* station (Lengidrophodoz 1987).

Lysimeters are a costly and time consuming method to measure evaporation and are designed for long-term measurements (DVWK 1991). Determination of the water balance of small reservoirs in the study area would allow estimation of the potential evaporation for the watershed area surrounding the reservoir. The withdrawal of water from the reservoir for animal consumption by shepherds has to be controlled.

Allen et al. (1989) emphasized that at least 50 different methods exist to calculate the evapotranspiration. Empirical methods like the Haude or Thornthwaite methods require fewer input parameters than the Penman-Monteith procedure, which requires the input of much data that are often only available on fully equipped climatic stations (Table 4.2).

Table 4.2 *Parameters needed for different methods to calculate evaporation (DVWK 1991, DVWK 1996)*

■ Parameter needed ■ Parameter may be calculated

Ta = average temperature, Rh = relative humidity, U2 = wind speed at a 2 m level above ground
Rg = global radiation, Ts = surface temperature, P = daily percentage of daylight hours for Northern Hemisphere

Method	**Measured parameters**					
	Ta	R	U2	Rg	Ts	P
Penman	■	■	■	■		
Thornthwaite	■					
Haude	■	■				
Turc	■	■		■		■
Blaney-Criddle	■					■

The empirical method of Thornthwaite was used for a first estimation of the evapotranspiration. Thornthwaite (1948) explained the potential evapotranspiration as “the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation”. The potential evapotranspiration according to Thornthwaite is correlated with the air temperature and the sunshine hours, calculated as follows (DVWK 1991):

$$ETO = f * 16 * \left(\frac{10 * T_a}{I}\right)^a \qquad [4.1]$$

where

ETO = potential evapotranspiration
T_a = average monthly temperature
f = correction factor according to total sunshine hours dependant on the latitude and month

$$a = (0.0675 * I^3 - 7.71 * I^2 + 1792 * I + 49239) * 10^{-5} \qquad [4.2]$$

where I = annual heat index :

$$I = \sum_{k=1}^{12} i_k \qquad [4.3]$$

where i_k = monthly heat index

$$i_k = (\frac{T_a(k)}{5})^{1.514}$$ [4.4]

The calculations are based on average monthly temperature data measured and collected by the Meteorological Department (Meteorological Department, S.A.R. 1996). The difference between maximum and minimum potential evapotranspiration is increasing from west to east (e.g. *Hama* in the western part of the project area: 18.26 mm·month^{-1} (January) to 102.88 mm·month^{-1}(July); Tadmor in the eastern part: 7.81 mm·month^{-1} to 208.62 mm·month^{-1} (July)) (Table A-5).

Another common method is the empirical method of Blaney-Criddle, which also belongs to the widely accepted evapotranspiration methods besides FAO Penman equation, radiation method (revised Makkink equation) or pan evaporation recommended by the FAO (Allen et al. 1998). The Blaney-Criddle equation is often used in irrigation management. The general form of the *FAO Blaney-Criddle* formula is as follows (Allen et al. 1986) which is slightly modified in comparison to the original:

$$ETO = \{a + b[P(0.457T + 8.128)]\}[1 + 0.1(\frac{Elev}{1000})]$$ [4.5]

where

P	=	mean daily percentage of total annual daytime hours for a given time period and latitude
T	=	mean average daily temperature [°C]
Elev	=	elevation above mean sea level [m]
a,b	=	correction factors for relative humidity, mean daytime wind speed, mean ratio of actual to possible sunshine hours

Allen et al. (1989) showed for a region in Idaho (USA) that the Blaney-Criddle formula slightly underestimates the evapotranspiration in spring and fall without calibration of the formula for the correction factors a and b. For the calculation of ETO in the project area the original formula (DVWK1996) without calibration factors was used, since information on relative humidity or mean daytime wind speed were missing for most of the stations:

ETO = $[P(0.457\ T + 8.128]$ [4.6]

As expected the highest values of evapotranspiration occur in summer (5 to 9 mm d^{-1}), lower values are found during winter months (2 to 3.5 mm d^{-1}). For the *Mihassa* station in the southern part of the project area the data of three seasons (Soumi & Abdul Aal 1997) are available to calculate the monthly evapotranspiration according to Blaney-Criddle*;* this is between 47 mm (January) and 260 mm (August) (Table A-6).

Jensen et al.(1990) compared different methods. He found that the Penman-Monteith formula gave the best correlation for 11 lysimeter experiment results in arid climate. For the temperature methods the Blaney-Criddle method gave the best correlation. The *FAO*-Penman-Monteith method is the most widespread method for calculation, although it needs quite a number of parameters as input. The Penman method is based on a combination of theoretical energy balance and wind speed. The penman method combines the physical prerequisites of the climate with the maximum use of water by crops. For the calculation of ETO the Penman-Monteith formula was used as recommended by the Expert Consultation on the revision of FAO methodologies for crop water requirements (Allen et. al. 1998). The original form of the Penman-Monteith equation was changed concerning a radiation term and an aerodynamic term and comprises the rate of evapotranspiration from a hypothetic crop with an assumed crop height of 12 cm, a fixed canopy resistance of 70 s m-1 and an albedo of 0.23 (Allen et al. 1998) as the reference evapotranspiration.

$$ET_0 = \frac{0.408\Delta(R_n - G)\gamma \frac{900}{T+273} U_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \qquad [4.7]$$

The different terms include:

ETO	=	latent heat flux of evaporation [MJ $m^{-2}\cdot d^{-1}$]
Rn	=	net radiation flux at surface [MJ$\cdot m^{-2}\cdot d^{-1}$]
G	=	soil heat flux [kJ$\cdot m^{-2}\cdot d^{-1}$]
ρ	=	atmospheric density [kg$\cdot m^{-3}$]
U2	=	wind speed measured at 2 m height [m$\cdot s^{-1}$]
(ea-ed)	=	vapor pressure deficit [kPa]
Δ	=	slope vapor pressure curve [kPa°C^{-1}]
γ	=	psychrometric constant [kPa°C^{-1}]

The values according to the Penman Monteith formula are calculated using the CROPWAT software Version 4.2 (Smith et. al. 1998). The evaporation is lower during the rainy season (1-3 mm d^{-1}) compared to the classification of Critchley & Siegert (1991) concerning the aridity of the region (4 - 5 mm d^{-1}) at temperatures below 15°C (Table A-7, A-8). The stations located in the eastern part of the study area confirm the definition of classes for semi-arid region with 7 to 8 mm d^{-1} during seasons with medium (15 to 25°C) and 9 to 10 mm d^{-1} during high temperatures (more than 25°C).

Table 4.3 shows that the potential evapotranspiration according to Penman-Monteith is within the rate of 1600 to 2000 mm·yr^{-1}. The amounts calculated by Thornthwaite seem to underestimate. The values of Blaney-Criddle are lower than those given for zone 3 (around *Hama* and *Homs*) with more than 2020 mm·yr^{-1} and for zone 4 and 5 with 2000 to 2319 mm·yr^{-1} (Soumi 1987). These values seem to be too high, compared to 1600 to 2000 mm·yr^{-1} of mean annual potential evapotranspiration (GRID-Nairobi 1992).

Table 4.3 *Average yearly potential evapotranspiration [*mm·yr^{-1}*] calculated with different methods (see Fig. 4.1 for location of stations) (Source: Meteorological Department, S.A.R. 1996)*

Station	Penman-Monteith	Thornthwaite	Blaney-Criddle
Hama	1610	698	1406
Homs	1451		
Ethriyeh	1625		
Ukeirabat	1514	880	1597
Salamiyah	1470	937	1616
Fruqlos		902	1578
Quaryatain	1777	905	1578
Nabk	1543		
Khnaifess	1889	853	1619
T4	1916	1071	1645
Tadmor	1989	880	1714
T3	2110		
Mihassa	1813		

The reference crop evapotranspiration can be used to calculate the evapotranspiration of specific crops by multiplying it with a specific crop coefficient, k_c (Allen et. al. 1994b, 1998). The crop coefficient represents the empirical ratio between measured crop ET to reference crop ET (Allen et al. 1998). The coefficient is used to adjust the potential evaporation, incorporating climatic data and solar radiation, to the actual evaporation of the plant. The crop evapotranspiration allows computing of crop water requirements crucial to irrigation planning and design. The Thornthwaite method clearly underestimates the evapotranspiration, the values comprise 30 to 40% of the values calculated by the Penman-Monteith equation. The Blaney-Criddle method underestimates the evapotranspiration in summer compared to the Penman-Monteith approach, but shows higher values during the rainy season.

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4.2 Topographic features and their influence on runoff generation

4.2.1 Introduction

Osman (1996) successfully used a similar method in the arid lands of Sudan. Some of the parameters are explained with regard to physical laws and are also incorporated in the few models such as *KINEROS* successfully applied to semi-arid implication on runoff generation.

Topographic features are significant to hydrological parameters (Chapter 2.1.3, Table 2.3). Aspect allows identification of areas of higher insulation. Slope e.g. is crucial to runoff rates and amounts. Differentiation of land suitability to microcatchment or floodwater harvesting systems is based on slope classes. The topography plays a key role in distributed flow and sediment transport models (Bates et al. 1998).

The topographic features are results of terrain analysis of a **D**igital **T**errain **M**odel. The DTM stores information besides the slope, curvature or aspect (Mattikalli & Engman 2000). Often the slope data of a DTM are merged with other data to derive further information. Fortin & Bernier (1991) used SPOT derived DEM and satellite images for the definition of homogeneous hydrological units. The information on slope and aspect is later combined to the other information within the geographical information system.

4.2.2 Calculation of Digital Terrain Model (DTM)

Source of data of the DTM were contour lines of maps in the scale of 1 : 100 000 were digitized by the software package ArcInfo Version 5.2 software package (ESRI 1995a). These maps of rather low scale have been the only available source for data on elevation within the study area. The elevation rises towards the south going from 300to 400 m up to about 700 to 750 m above sea level. The northeast trending mountain ridges of the *Southern Palmyrides* reaches elevations of about 1000 to 1100 m a.sl. Most of the wadis (flow courses) have flat valleys (e.g. *Wadi at Luwazah*), some of them are more deeply incised (up to 80 m) such as the one nearby *Al Basiri* blocked by the *Kharbaquah* dam built within the 2nd century.

One of the possibilities for calculating a DTM are based on the *Delaunay* triangulation where the different points of similar elevation are connected through an irregular network. Advantages of the *Delaunay*-Triangulation are the possibility for determination of volumes. Also fault lines could be taken into account. Irregularities in measurements of altrimetry could not be filtered. Especially in the flat areas of the project area the approximation of flat triangles would be too inaccurate. The current DTM (Fig. B-9) was calculated using the TOPOGRID function of ArcInfo, Version 7.2.1 (ESRI 1998a). The TOPOGRID function incorporates different powerful features: the interpolation of elevation from contour lines is based on identifying lines of steepest descent between contours. Points of maximum curvature are determined since they represent drainage paths and ridges (Hutchinson 1996). The algorithm is based on an iterative finite difference interpolation method, where areas of local maximum in each contour are calculated. A thin plate spline algorithm (Wahba 1990) is incorporated allowing incorporation of ridges and streams. This method results in a DTM with a continued surface often created from interpolation methods such as Kriging. Kraus (2000a) showed that Kriging could be described with a multiquadratic algorithm. This algorithm calculates a DTM with regularly spaced grid sets where information on drainage paths can be included. Compared to TIN, the accuracy in elevation of DTM calculated by TOPOGRID is similar (Wise 1998). Drainage paths were digitized on the screen according *to* Landsat Thematic Mapper images of April 1994 and 1995 and were included in one of the TOPOGRID calculations. To test the automatic extraction of the drainage network, two grids were calculated: one incorporating the digitized information on drainage channels and another grid without this additional information. In some cases the automatic extraction and the digitized drainage network fits well although the accuracy of the topographic maps is low.

4.2.3 Slope

The grid derived from the TOPOGRID function was used to calculate the slopes for the region (Fig. 4.8). Slope classes of over 40 to 50% only occur to a smaller amount within the mountain ridges such as *Jabel an Niqniqiyah* or incised drainage courses in the southern part. Classes in the range from 0 to 1 % are predominant, covering an area of about 9100 km², which means one half of the whole area. Since the resolution of the grid is low, slope may fall in reality to higher classes. The comparison of different resolutions of DTM of an area at the research sites of the Walnut Gulch watershed in south-western Arizona (Goodrich et al. 1994) and watersheds in Oregon and California (Zhang & Montgomery 1994) illustrated that with lower resolution the slopes are smoothed, since the small variations are averaged to the larger cells. Zhang & Montgomery (1994) reported a declination of mean slopes from 0.65 for a 2 m size to 0.45 for a 90 m grid DTM.

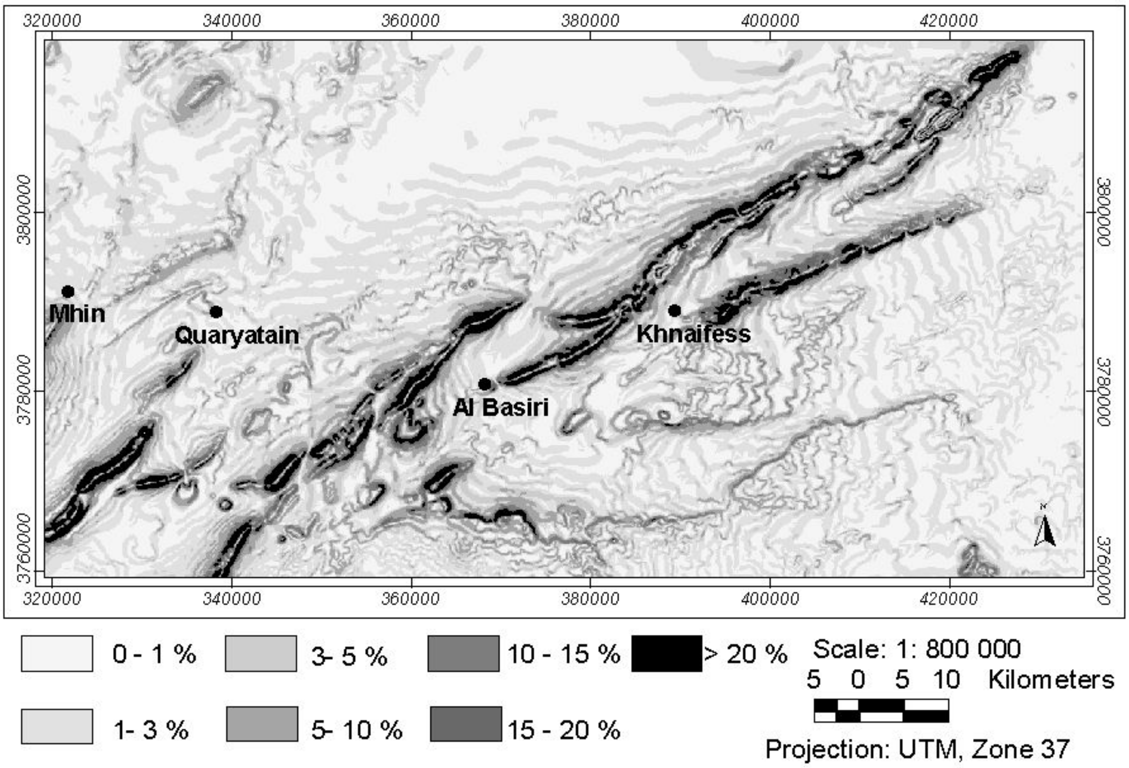

Fig. 4.8 *Slope, based on DTM calculated on contours of 1 : 100 000 maps (Source: Cartographic Department, S.A.R. 1976)*

Table 4.4 *Slope classes within the research area (Source: Cartographic Department 1976)*

Slope (%)	Area (km²)	Percentage (%)
0 - 1	9193	66.5
2 - 3	2285	16.5
3 - 5	906	6.5
5 - 10	775	5.6
10 - 15	272	1.9
15 - 20	171	1.2
20 - 30	166	1.2
> 30	52	0.4
Sum	*13824*	*100*

Therefore the DTM loses its ability to resolve the slope characteristics of especially more dissected topography with increasing size of the raster cells of DTM. The vertical resolution of the DTM is low, since it is derived from digitized contours 10 m apart and 5 m apart within the flatter areas. Since also geodetical points of elevation were digitized and introduced in the interpolation process the vertical resolution is higher, especially in the flatter areas.

Considering the aspect of slopes, only small maxima of slope are exposed either to the northeast or the northwest (Fig. 4.9). Photogrammetric work on aerial images that are unfortunately not accessible to the public in Syria due to political and military constraints, would provide further information on topographic features.

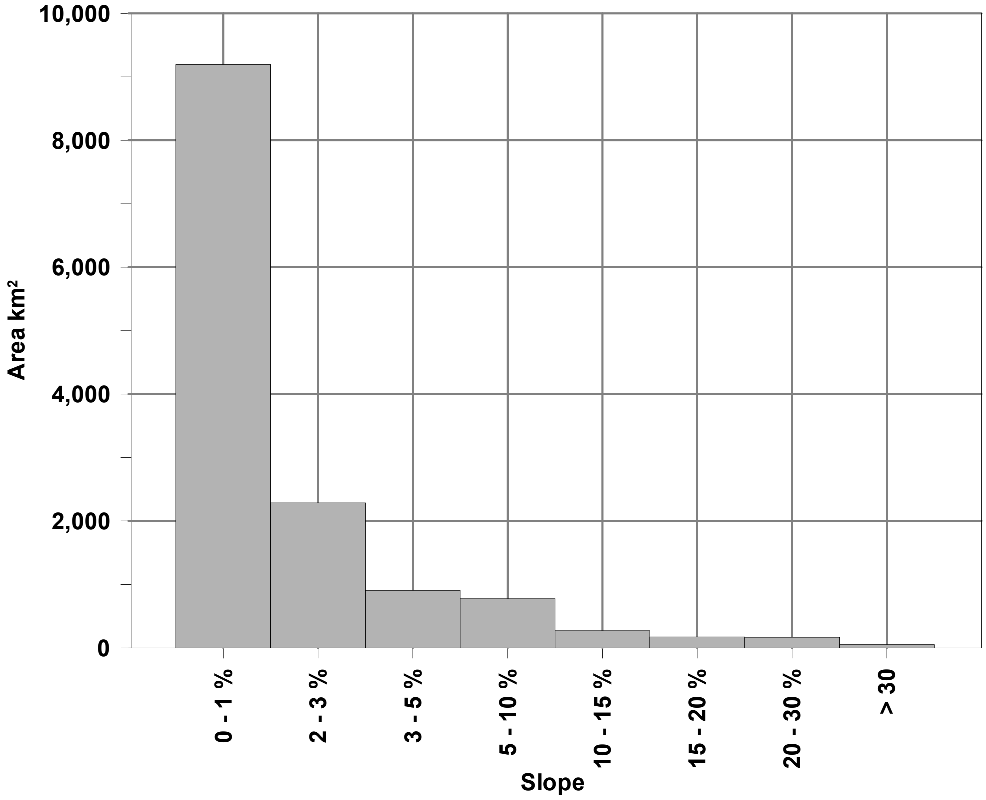

Fig. 4.9 *Slope classes for the southeastern part of the study area according to the 100 m-DTM (Source: Cartographic Department, S.A.R. 1976)*

4.2.4 Curvature

The curvature is calculated on the same algorithm as the aspect. The planiform curvature provides information on the convergence and divergence of flow. The profile curvature was not calculated since the information on flow acceleration or deceleration is more important to the point of view of sediment transport and erosion modeling.

4.2.5 Aspect

Aspect is one of the topographic features correlated with the insulation effect. It is important for evapotranspiration since the amount of solar insulation is higher on slopes facing south or southwest. Wang & Takahashi (1999) found higher soil moisture content on north facing slopes within the semi-arid loess plateau (China) than on south facing slopes. They calculated the evapotranspiration based on solar radiation, altitude and azimuth of the sun. The results confirmed the expectation: on northfacing slopes the amount of evapotranspiration is higher than on south facing slopes. Therefore the potential to runon areas for water harvesting is generally higher on north facing slopes. At least, the soil water within the profile is less than on north facing slopes.

The aspect function within ArcInfo version 7.2.1 (ESRI 1998a) determines the downslope direction of maximum rate of change of the cell to its neighbours. The aspect is calculated on the basis of the algorithm of Zeverbergen & Thorne (1987), fitting partial quantic equation to nine points within a 3×3 window (Fig. 4.10).

The slopes are quite equally distributed concerning the aspect. A clear distinct maximum of aspect values can not be distinguished, about 20% of the area is occupied by northwestfacing slopes (Table 4.5).

Table 4.5 *Aspect classes (Source: Cartographic Department, S.A.R. 1976)*

Aspect (Degrees)	Area (km²)	Percentage (%)
226 - 270	8.68	6.28
181 - 225	11.96	8.65
271 - 315	14.28	10.33
46 - 90	17.51	12.66
136 - 180	18.23	13.19
91 - 135	18.94	13.70
0 - 45	22.22	16.07
316 - 360	26.42	19.11
Sum	**138.24**	**100**

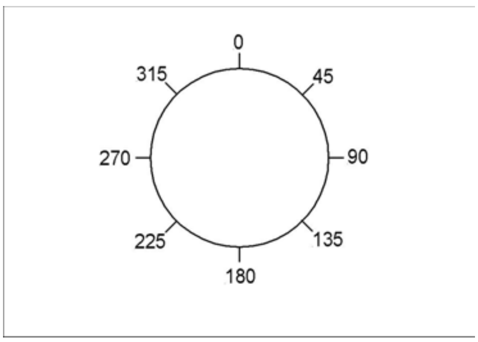

Fig. 4.10 *Aspect values (ESRI 1998a)*

4.2.6 Identification of drainage paths

The identification of the drainage system is important since the delineation of the water course has to be known for some water harvesting techniques such as check dams water courses. For other techniques, these areas should be avoided or only included as runoff or catchment areas, since the erosion is high and the risk of damage to structures within the winter and spring storms is high.

Before the hydrological analysis the grid underwent the process of filling all sinks. The filling process recalculates the elevation of the sinks by filling it to the elevation of the lowest overflow point out of the sink (Garbrecht & Martz 2000). The so called breaching method was not applied based on the approach that sinks result form obstruction of flow paths by overestimating the elevation (Garbrecht & Martz 2000). This analysis was also done by the GRID module of the ArcInfo software package Version 7.2.1 (ESRI 1998a). The algorithm used for the determination of flow direction is based on the method presented by Jensen & Domingue (1988). The flow path is determined by encoding the cells surrounding the center cell in different ways as follows (Jensen & Domingue 1988) (Fig. 4.11).

32	64	128
16		1
8	4	2

Figure 4.11 *Eight valid output values for the eight neighboring cells (Jensen & Domingue 1988)*

The method is based on an algorithm solving the cell to cell flow directions by determining the path of steepest descent between a cell and its eight neighbors (D8 procedure). The steepest descent is calculated according:

$$sz = \frac{\Delta z}{d} \qquad [4.8]$$

sz = steepest descent

Δz = change in elevation

d = distance to neighboring cell

Since a hydrologically coherent digital elevation model was produced the amount of cells without distinct flow direction are minor. (These cells show values different from the values in Fig. 2.1). The flow path shows a slight preference to the northwest (Fig. B-16). It displays the geomorphological characteristics, northeast trending ridges and channels within a gentle sloping landscape. The histogram of flowdirection shows a major component towards southwest. In the south the flowdirection reverses towards the north.

The D-8 procedure has the disadvantage that it allows only one flow direction, away from a cell. However, there multiple flow paths exist on convex slopes. The flow direction algorithm which routes flow just in one direction (Wise 1998) results in a large number of parallel flow lines within the predicted drainage system. Nevertheless the D8 procedure provide the most appropriate technique to delineate water catchment areas for large areas (Garbrecht & Martz 2000) since it is already fully incorporated within the ArcInfo software packages used during the present work (ESRI 1998a). The flow direction grid was used to calculate the flow accumulation grid. Both were used to extract the grid of stream length. Table 4.6 represents the results of stream length routine where the stream lengths are differentiated according to the *Strahler* order: the stream order only increases when two streams of the same order intersect (Strahler 1964).

Nevertheless flow routing is also dependant on the soil properties, therefore these results are only preliminary and have to set into the context of other parameters. Other options are the automatic derivation of drainage network from digital terrain models by implication of threshold values (Tarboton et al. 1991). According to the same statements made for the smoothing of slopes due to the low resolution high resolution DTM are the first choice for preciser channel networks with a more complex routing. However the present results are a basis for further analysis combining different parameters within the geographical information system to extract the necessary hydrological information.

Table 4.6 *Stream length of automatically extracted channels in the project area of about 14 000 km² (Source: Landsat TM scene, path 173, row 36, April 4, 1994, April 7, 1995, ESA (1994a, 1995))*

	Automatic extraction of drainage channels, length in km
Length of Stream order 1	4990
Length of Stream order 2	2020
Length of Stream order 3	630
Length of Stream order 4	140
Length of Stream order 5	0.7

The streams are divided according to the *Strahler* order of the river network: a second order stream is created by the junction of two first order streams which have no upstream junctions. The *Strahler* order is also used in the concept of the geomorphological unit hydrograph. Here third order stream have contributions of runoff from local hillslopes and second-order and first-order streams. The GUH (**G**eomorphic **U**nit **H**ydrograph) includes parameters such as length ratio of the network and the average catchment area of streams of a specific order. Nevertheless the GUH is still a hypothesis which is not fully tested in practice (Nash & Samseldin 1998).

Other methods which implicate hydrological functions on the DTM are the topographic index (ln (A/tanβ). A is the area drained per unit contour and β is the local surface gradient. Here the assumption that the upslope area is equal to the contribution of flow in any part of the DTM gives ambiguous results (Lamb et al. 1998). Anderson & Kneale (1982) showed the inapplicability of such an index to different slopes.

Tillage sometimes changes the flow path predicted according to DTM. The flow path is then a function of topographical flow direction, tillage direction and the soil surface roughness (Ludwig et al. 1996). This factor also has to be considered within the steppe area where barley was planted in vast areas south of the *Ad Dauw* basin. But in some areas the spring flooding may have already obliterated these small variations in change of flow direction due to tillage especially since cultivation is banned in the steppe area.

4.3 Soilscape units

The topographic investigation already showed that most slopes are smooth and the land slope is relatively flat. Geology plays a role in creation of soils and abundance of groundwater.

4.3.1 Geological strata

The Syrian territory belongs to the northern edge of the Arabian Platform (Krasheninnikov et. al. 1996) consisting of the inner zone of a stable shelf and a more mobile zone in the north belonging to the mobile shelf. The stable inner zone comprises the southern part of Syria with the Jordan uplift, the *Drouz* depression and the *Rutba* anteclise. The study region belongs to the mobile shelf, where the *Ad-Dauw* basin and the *Balas* uplift (Fig. 4.12) can be differentiated within the folded area of the *Palmyrides* (aulacogene). The folded zone is surrounded by the *Northern Palmyrian* fault and the *Southern Palmyrian* fault which is the most prominent with vertical displacements up to 1000 m. The northern part of the zone is composed of large folds complicated by smaller anticlines (Fig. 4.12).

The southern subzone shows asymmetrical linearly extended anticlines (10 – 25 km) with gentle sloping western limbs (10 to 20 °) and steep south-eastern limbs (up to 30 ° to 40 °) and faulty. *Cretaceous* sediments and *Jurassic* rocks are present in the core, P*aleogene* sediments are characteristic for the limbs. The subzone is bordered by the *Dimachq* fault in the southwest and the *Ad-Dauw* Basin, filled with *neogene-quate*rnary sediments in the north.

In the *Northern Palmyrides* mainly sediments of *Cretaceous* age are found. The oldest sediments outcropping in the *Palmyrides* belong to the *Jurassic* age. A section of about 60 to 100 m of dolomites, the largest outcrops in Syria of the *Middle and Upper Jurassic* are found in the *Palmyrides* at *Jebel Naqnaniyeh* (*Bajocian* sediments: dolomites of about 180 m) and *Jebel Ash Shath* (*Callovian* sediments, several 10 m thick: limestones and marls and *Oxfordian* beds, consisting of dolomites and clayey limestones of about 60 m) (Ponikarov et al. 1967). The upper slopes of the *Palmyrides* are mainly constituted of *Cretaceous* sediments. The lower slopes are constituted of *Paleogene* age. The rock outcrops of the younger and middle *Cretaceous* are limestones and dolomites. The layers of *Upper Cretaceous* are characterized by mergelic limestones with glauconites and geodes.

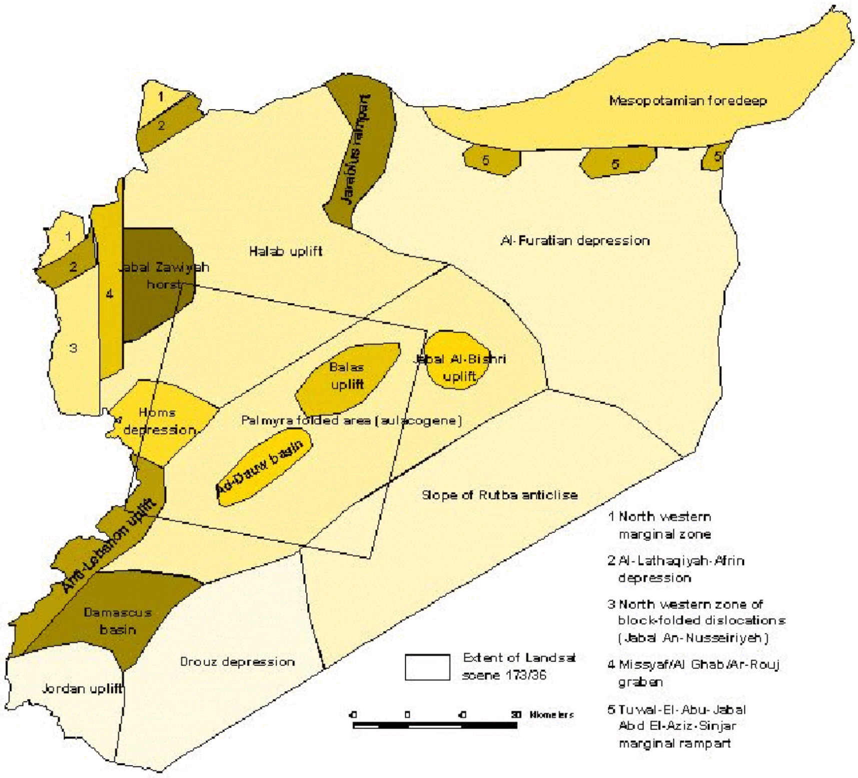

Fig. 4.12 *Tectonic subdivision (Krasheninnikov et al. 1996)*

The outcrops of the *Cretaceous* formation are between 200 to 300 m thick in the *Northern* and *Southern Palmyrides*. The lithofacies is mainly limestones and sandstones, intercalated partly with gypsum beds and organo-granular phosphate intercalations. In the other areas the *Cretaceous* rocks are overlaid by *Paleogene* sediments.

The series of the *Paleogene*, exposed southeast of *Tadmor*, are dated according to planktonic and benthonic small foraminifera. The *Paleogene* consists of calcareous marls and clayey limestone. The clay content is highest in this lower *Palaeogene* sequence. Flintstones of nodular type are mainly found here in nodular type. The *Palaeogene* formation is mainly consistent in depressions like in the Wadi *El-Bardeh*. The *Lower Eocene* sequence of limestones, marls, alternating with flints can be differentiated from the *Upper Cretaceous*. The *Middle Eocene* is characterized by softlike chalky limestones and organic limestones with large nummulites sometimes with beds of marls with glauconite and phosphate nodules and flint streaks. In the upper part of the *Middle Eocene* chalk-like limestones with block-jointing are present, in some places containing large baryte concretions. The *Upper Eocene* is composed of chalk like limestones and nummulitic limestones.

According to the investigations based on geochronological methods (radiometric: K-Ar isotopes, Rb-Sr, and foraminifera zones) (Krasheninnikov et. al. 1996) the *Paleaogene* of Syria is characterized as follows: *Lower Eocene* sediments comprise foliated calcareous clays, marls. The uppermost *Lower Eocene* and *Middle Eocene* show an alternation of limestones with black and brown cherts forming independent questas or ridges. The flints are mainly chalcedonic which means that the transition from gel-liquid to calcedony is complete. Nevertheless the chert content of some of the Eocene formations do not exceed 3% (Krasheninnikov et al. 1996). White and grey chalky limestones and marls with planktonic microorganisms typifies the *Middle Eocene* and an alternation of chalky massive biogenic and softer fine-grained pelitic limestones can be distinguished for the *Upper Eocene*. *Oligocene* sediments with a thickness of about 120 m are present on the southern and northern footslopes of the *Northern Palmyrides* and in the region of the *Ad-Dauw* Basin. The lithofacies is characterized by massive coarse layered limestones containing coral colonies, pelecypods, foraminifera, intercalated especially in the higher layers with sandy limestones, sandstones and clays.

In the area of Wadi *El-Bardeh* the *Oligocene* sediments consist of sandy limestones and sandstones with vertical burrows of different shapes filled with siliceous concretions. Oligocene sediments consist of shallow water massive coarse – layered, fine-grained, aphanitic and biogenic limestones with terrigeneous sediments like sand and clay rocks at the top. Facies and thicknesses varies with respect to tectonic structure. Most of the sediments comprises glauconite horizons and the planktonic foraminifera allows subdivision of the sediments according to the 26 subglobal based on the *Paleogene* formainiferal zonal scale of the Caribbean basin within deep sea drilling project research in 1968.

The Lower Miocene sediments present west of *Tadmor* comprises continental, sometimes silicified sandstones and limestones. *Middle Miocene* sediments are gypsum beds, limestones and sandstones nearby and west of *Tadmor*. *Upper Miocene* sediments are not present in the project area. Pliocene sediments, mainly conglomerates and sandstones with small beds of clays and marls, containing freshwater mollusks shells fill depressions in the mountain ranges like the *Ad-Dauw* basin.

Proluvial *quaternary* sediments are mainly found in the southeastern part of the study area and the intermontane basin of *Ad-Dauw*. They are composed of debris cones, i.e. pebble and gravel beds, comprising local rocks. *Upper Quaternary* proluvial deposits are most widespread within the quaternary deposits consisting of rocks with loam debris and pebbles. Bedded clay, loam and sandy marls form the *Upper Quaternary* sediments in the *Tadmor* basin.

Miocene volcanic rocks probably from ocean floor volcanism are found in the Wadi *Mihassa* where a dolerite sill, detectable for 4 km, within the *Middle Miocene* Series . *Pliocene* basalt cone is found on *Paleogene* sediments near *Mihassa*. These are remnants of volcanic cones in dissected tableland and consist of numerous interbedded lava flows 4 – 50 m thick. The basaltic outflows form very blocky material which obstructs water flow. The red sands on the road *Palmyra-El Basiri-Damascus* seem to be decomposed basalt remnants. The red sands are quite abundant and can be used as construction material

4.3.2 Hydrogeological situation

Most of the water resources exploration is often concentrated on the development of groundwater resources, which are then subject to overexploitation. About 20 000 ha are projected for the steppe area where the withdrawal of groundwater resources will probably be enlarged. The directorate of the *Badia* Basin of the Ministry of Irrigation estimates the groundwater resources to 196 million cubic meters (IFAD 1997). However, the hydrogeological situation is not well known and there are only few studies. Nearby *Tadmor* the German Geological Survey (Brunke 1997) carried out a study concerning the use of a groundwater model simulating the current situation. Main aquifers which are found in the region are in the *Neogene* and the lower *Cretaceous* strata. There are two principal aquifers at the *Palmyrian* basin: the lower aquifer from the *Cenoman-Coniac* formation covering the whole area and a second shallow aquifer within *Neogone* sediments. The aquifers are separated by the aquiclude of *Santonian* to *Palaeogenian* age. The lower aquifer is therefore confined, its top is approximately at 280 m depth within the *Palmyrian* syncline. The water from the deep aquifer cannot be used for drinking because of the high sulfuric content. About 16 deep wells are known within the steppe area of *Homs*. One example is the deep well at *Khnaifess* (depth of 380 m a. sl.) (IFAD 1997). The water level of the deep aquifer is constantly dropping , illustrated by the decline of head at sulfuric spring such as at *Tadmor* from 416 m a.sl. in 1970 to 408 m a.sl. in 1997 (Brunke 1997). The closure of the sulfuric bath in the mid of nineties at the entrance of *Tadmor* nearby the ruins is one of the consequences of this process. Other deep springs are found at *Al Bardeh* and *Quaryatain*, and *Al Mhin* east of *Quaryatain*. Within the *Ad Dauw* basin which is separated from the *Palmyrian* syncline by a antecline the groundwater resources of the shallow aquifers within *Pliocene* and *Miocene* deposits are intensively used to pump water for irrigation purposes with yearly pumping rates between 50 000 and 600 000 m^3 (ACSAD 1984).

The only hydraulic interconnection between the two aquifers is at *Tadmo*r. Here a groundwater flow from North to South is possible. The shallow aquifer is probably recharged by water flow through fissures and cracks within the mountains. But the decline of water level such as at wells at *Mihassa* illustrates that the recharge is not sufficient to compensate the higher amount of pumped water in recent decades (drop-down of water level at *Mihassa* from 820 m a.s.l. in 1970 to 740 a.s.l. in 1997 (Brunke 1997)). Table A-9 in the appendix shows characteristics of the main aquifers within the region.

4.3.3 Description of typical soil profiles

Several soil investigation have been made in the project area , based on different soil classifications. They all give an overview over the present soil types and are based on a large scale, 1: 100 000. The soil catena along a hillside and possible changes due to human activities are not taken into consideration (Mulla & McBratney 2000). A soil survey in the scale of 1: 500 000 has been made within the Syria Land Classification and Soil survey Project, a technical assistance project of the United States Agency for International Development (U.S.A.I.D) and the Syrian Arab Republic. The study bases on the interpretation of false color Landsat TM images and extensive ground checking. The study is amplified by soil analysis of chemical and physical soil properties. The classification is based on the USDA soil classification. The area is differentiated into various soilscape units (Fig.4.13) which takes into account the geomorphological setting besides the general pedological characteristics. These are described further in the following paragraphs. The report gives also short recommendations on the potential of the soil for agriculture.

In 1997 and 1998 the effort at ICARDA was undertaken to relate these soilscape units (according to the USDA Soil Taxonomy Classification) to the soil classes such as they are used on the FAO-UNESCO world soil map with the revised legend of 1988 (FAO 1988, FAO-ISRIC-ISSS 1998). The FAO soil map is based on the principle of diagnostic horizons which are in relation to the soil forming process and to management purposes. Climatic parameters are not included in the classification (FAO –ISRIC-ISSS 1998).

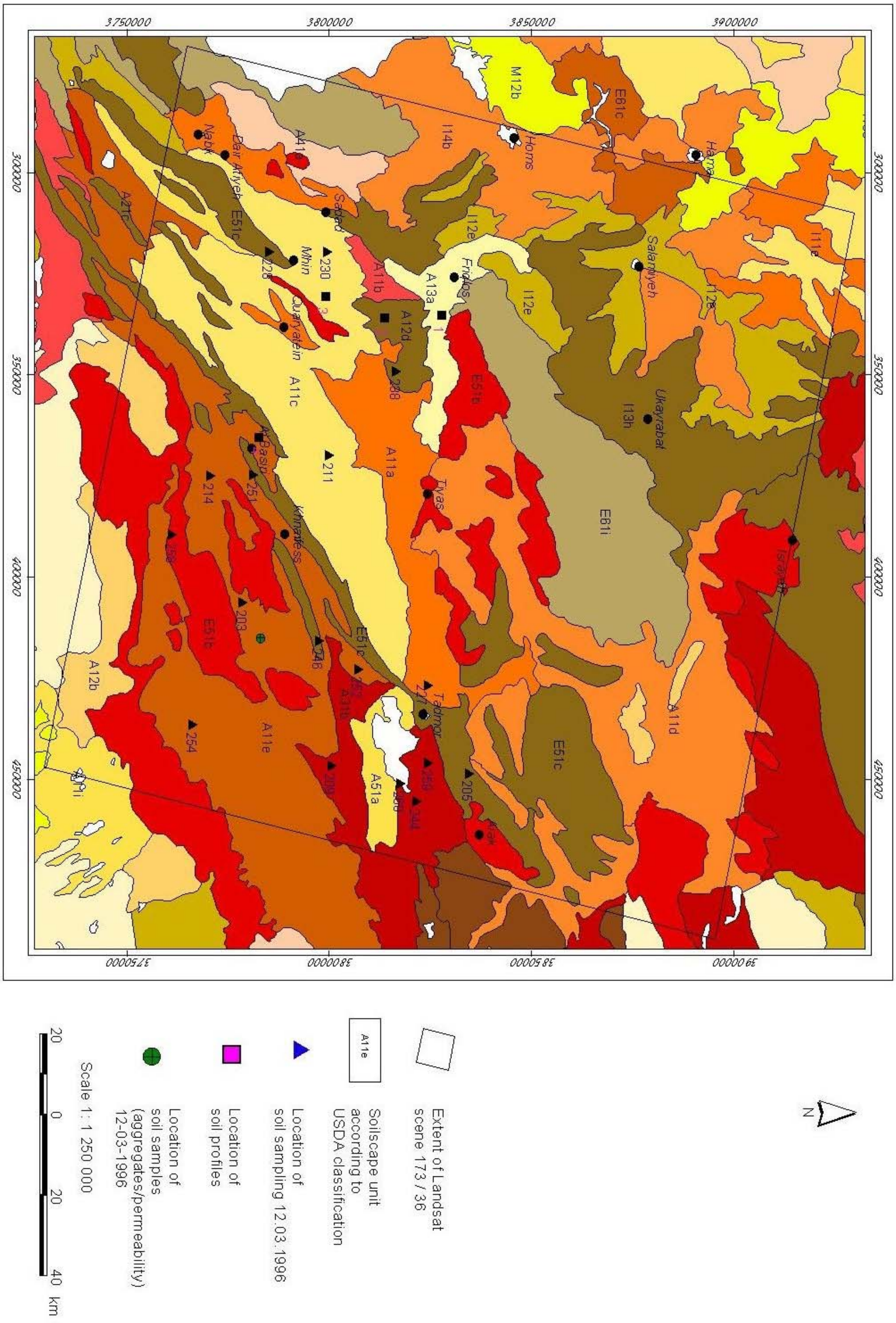

Fig. 4.13 *Soilscape units of the project area (FAO–ISRIC-ISSS 1998)*

A third study was done through Russian scientists end of the eighties, based on the classification of the former USSR. In general they characterized the main features (Lengiprovodkhoz 1987) of the soils in the steppe area as having a high content of carbonate and the presence of rock debris in most soil profiles. The depth of soil formation is not exceeding 0.6 to 1 m. Often the soils are truncated to a depth of up to 0.3 m. Loamy soils with a well defined heavy texture are predominant. The content of humus is low (2 to 2.5%).

Main soilscape units (A12d, A13a,A11a to d, A31b, E31b, E31c) in the central part of the project area comprise soil units of the USDA taxonomic group of *Aridisols* (*Calciorthids* and *Cambiorthids*) and of *Entisols* (*Torriorthents*) (Fig. 4.13). Per definition *Calciorthids* have a calcic horizon within the 1 m of the surface and are calcic in all horizons. Like most *Aridisols* they are not saturated with water for more than 90 consecutive days in a year (Soil Survey Staff 1987). The organic content is low, below 0.6% . They do not have reddish peds in the lower parts of the soil profile. Neither do they have a horizon within the 1 m of the profile with a content of over 20% of durnodes in brittle matrix. *Lithic Calciorthids* are shallower than the *Typic Calciorthids*. *Typic Cambiorthids* differ from *Calciorthids* in having as a *cambic* diagnostic horizon. A *cambic* horizon shows evidence of alteration in a regular decrease of organic carbon, in cracks below the surface of 1 cm or more width, stronger chroma in the lower horizons and evidence of removal of carbonates. The *Typic Cambiorthids* on the other hand have a darker color and are developed on *Quaternary* sediments with gravels of more recent deposits. The surface layer is thicker about 17 cm. The B horizon is also slightly thicker and is more yellowish brown . These soils are stonefree compared to the ones, mentioned in the upper paragraph, but the stoniness on the surface can exceed one percent. In a revised taxonomy *Cambiorthids* and *Calciorthids* are referred to as *Calcids* and *Cambids* (Southard 2000).

The *Typic Torriorthents* belong to the group of *Orthents* within the group of *Entisols* that is a group with mineral soils with low pedogenic development. *Torriorthents* are mainly found in desertic environment (Southard 2000) according to the *torric* regime (desertic regime). They are found on steep slopes often together with rock outcrops (Southard. 2000). Table 4.7 describes the main characteristics of the soilscape units found within the project area.

Table 4.7 *Soilscape units and their characteristics within the research area (U.S.A.I.D.1982)*

SC	Lithology	Geology	Description	Landscape	Slope	Stoniness	Soil depth	Typical soil profile	Soil suitability
A11c	Limestones and colluvial, alluvial fan deposits	*Paleogene, Neogene*	Loamy, calcareous deep soils often with a soil crust, often intercalated with pebble beds at C, horizons not clearly discernable	Piedmont plain, alluvial fans and very dissected low hills, badlands on gently slopes facing *Al Dauw*	Very gentle, gentle	Few	Deep	*Quasr al Hir*, slope nearby dry riverbed crossing road *Mihinn/Quaryatain*	Not suitable for rainfed or irrigated agriculture
A11e	Limestones, gravel deposits	*Qaternary Paleogene*	Medium to fine-textured, gravelly and stony soils of gravels deposits and limestones	Undulating plateau shaped desert plains	Gentle	Few	Deep	Dry river west of road *Damascus-Tadmor*	High potential for rangeland, irrigation of cotton, legumes and non-rosaceous trees
E51b	Limestones intercalated flintbeds, gypsum layers	*Paleogene, Neogene*	Fine textured soils often alternating with rock outcrops with a high stone cover	Slightly undulating	Gentle	Abundant	Shallow	*xxx*	Very low
A11a	Limestones	*Paleogene, Neogene*	Fine textured deep soils with a sticky firm B horizon	Gently undulating intermontane basins	Very gentle, gentle	Very few	Deep	*xxx*	With irrigation medium to high potential
E51c	Limestones	*Paleogene, Neogene*	Very shallow fine textured soils with sub-rounded gravel within the soils, high stone cover	Upper slopes and summits of the Southern Palmyrides mountains	Steep	Abundant	Shallow	On the road from *Khnaifesss*	Not suitable for rainfed or irrigated agriculture
A31b	Fluvial and lacustrine beds	*Neogene*	Medium textured sticky soils, petrogypsic substratum	Gentle undulating plains	Very gentle	Very few	Deep	South of *Sabkha Mouh* and *Tadmor*	Suitable to rangeland, but salinisation
A51a	Lacustrine deposits	*Holocene*	Fine-textured, imperfectly drained saline soils	Flat lacustrine basin	Very gentle	No	Deep	*xxx*	Not suitable, saline
A12d	Limestone	*Paleogene*	Shallow fine-textured soils, very gravelly on soil surface	Medium-height hills	Steep, very steep	Abundant	Shallow	Road *Fruqlos* to *Quasr al Hir*	High potential for rangeland

A typical soil report of a deeper *Calciorthid* (Table 4.8) is described in the Russian report of a study within the steppe area (Lengiprodhoz 1987). The Russian soil classification is not based on a hierarchical structure with a key of diagnostic horizons such as the FAO System. It is based on the recognition of the soil forming process (Spaargaaren 2000).

Table 4.8 *Typical soil profile of deeper Calciorthid nearby Quasr Al Hir (Lengiprodhoz 1987)*

0.5 to 2 cm	Thin loamy-layered crust
A 0 to 8 (12) cm	Pale yellow with cinnamon shade or brownish with grayish shade, loam, lumpy-silty, calcareous, abundance of thin roots in the upper portion (2 to 3cm) below drastic diminution
$\mathbf{B_1}$Ca 8 (12) to 30 (38) cm	Pale yellow-brown or cinnamon shade, loam, lumpy-fine nutty, calcareous, few large roots.
$\mathbf{B_2}$Ca 30 (38)to 65 (80) cm	Brown or cinnamon, generally with distinct reddish shade, mostly heavy and medium loam, fine porous, dense, calcareous with abundance of dingy white soft spots, transition to other horizons clear.
BC_{ca} 65(80) to 100(105) cm	Brown or reddish-brown loam, angular lumpy, medium skeleton content, floury calcium carbonate pendants or under faces of rock debris and pebbles , few roots, transition abrupt
C_{ca} 100 (150) cm or deeper B	Mostly proluvial, alluvial-proluvial deposits of pebble beds, rock debris, fine stone with loam or sandy loam filler, calcareous, frequently well cemented by calcium carbonate, floury pendants of calcium cuts, on the under the faces of stones, sometimes local inclusions of varigrained gypsum, no roots

A typical soil profile of this soil scape unit (Fig. C-10) is found nearby *Mihinn*, within a wadi crossing the road *Mihinn* - *Quaryatain* (No.3 Fig. 4.3). A reddish brown, sticky firm horizon with layers of gravel are presented within the about 2 m deep profile. The soil surface is covered with small stones. The soil profile is found within gentle sloping hills.

4.3.4 Evidence of soil crusting

The *Calciorthid* at the agricultural station of *Quasr al Hir* (Table 4.8) is characterized by a 2 cm thick loamy layered crust. Depositional crusts can be observed in the project area along the banks of the road where runoff accumulates in depressions. They also form at footslopes along the ridges of the *Southern Palmyrides.* Depositional crusts form in depressions and rills formed during erosion from increased runoff (Bradford & Huang 1992). These runoff depositional crusts can be differentiated from still depositional crust formed in standing water. During drying the crust often breaks into plates. These depositional crusts can be observed within the depression of *Wadi Ar Dauw*. The area is often widely flooded here after heavy rainfall showers. Also small water ponds develop where the infiltration capacity is already lower due to crusting. The still depositional crust is formed here. Salty crusts are formed within the saltpan of *Sabkha Mouh* south of *Tadmor*. They mainly consists of sodium and magnesium chlorates and sulfates.. Pavement crusts with embedded rock fragments are found south of *Tadmo*r within the hills surrounding the *Wadi Luwayezeh*. .

4.3.5 Soil texture

Samples within the representative soil profiles of the different soil map units were taken for detailed analysis. The location of the soil samples is illustrated in Fig. 4.13. The soil samples were taken on the upper 20 cm to maximum 50 cm of the soil profile.

Particle size distribution determines the texture which is an important parameter for e.g. hydrological behaviour of soil. Particles above 50 µm were separated by wet sieving using sieves of different diameter (Skopp 2000, Ryan et al. 1996). Smaller particles were determined by the hydrometer method. Soil particles are dispersed in water and the reduction of density of the fluid due to settling is determined through the float or hygrometer (Skopp 2000). According to the USDA texture classification most soils can be characterized as loam (18 to 38% clay, 38 to 42% silt and 39 to 42% sand) (Table A-10). Extremes are sandy loams (70% sand, 10% clay, 19% silt) found within the soilscape unit A51a and clayey soil (44% of clay, 33%, 23% of sand) (A12d) and silt loam (25% clay, 54% silt and 21% sand) in soilscape unit A11e.

Soil texture is an important parameter for the hydraulic conductivity and permeability. Generally coarse textured soil have higher saturated hydraulic conductivities than soils with low porosity and smaller pores. According to Rawls et al. (1992) mean values of saturated hydraulic conductivity can be estimated according to the soil texture class. But the hydraulic conductivity is a factor sensitive to many different soil parameters such as e.g. pore interconnectivity. This is especially true for soils that form a crust, occurring in the project area, having different conductivities according to the layer considered.

4.3.6 Important soil chemical properties

The analysis comprised the content of calcium carbonate, electrical conductivity, potassium, nitrogen and organic matter and pH-value (Table A-11).

Calcium carbonate, pH and electrical conductivity

The Calcium carbonate is a basic constituent of these soils on lithological units of limestones. The content of $CaCO_3$ was determined by the titrimetric method using the hydrochloric acid and the *phenolphthalein* indicator.

The content of calcium carbonate is high, the values are in the range from 40 to 50% , on average 45%, which is higher than at other Syrian sites (e.g. *Maragha* and *Tel Hadya*) according to the soil analysis of Ryan et al. (1997) (20 to 30%). The high $CaCO_3$ content is also reflected in the strong alkalinity such as pH-value of around 8.7. The electrical conductivity is generally below 1 $mS \cdot cm^{-1}$ which is below the value of 4 $mS \cdot cm^{-1}$ causing salinity damage to crops (Ryan et al. 1997). The soil samples at soil unit A 12 d (No. 238) within the hills near *Fruqlos* show higher values (11 $mS \cdot cm^{-1}$), these sites are only suitable for planting with soil tolerant crops, e.g. *Atriplex*. The electrical conductivity values of soils within the *Sabkha Mouh* (saltpan) south of *Tadmor* are the highest as expected (96 $mS \cdot cm^{-1}$) Soil samples taken from soils near the *Sabkha Mouh* (No. 244, No. 259) also show higher values as expected.

Organic matter

The determination of organic matter is based on the measurement of oxidizable organic carbon which is then converted to percentage of organic matter. The results are converted into the content of organic matter by assuming that organic matter contains 58% carbon. During the measurement procedure the organic carbon is reduced by potassium dichromate. Then the unreduced dichromate is measured by titration with ferrous sulfate

(Ryan et al. 1996). The organic matter is low, between 0.45 and 1.45% (2.1). This is much lower than in temperate regions (3-4% organic matter). But it is usual to semi-arid areas: a whole range of soils at other Syrian sites such as *Maragha* (0.8%) within the northern part of the Syrian steppe or even within zones of higher agricultural productivity such as at *Tel Hadya* (0.8 to 1.5%) show similar values (Ryan et al. 1997).

Phosphorus

Most of the soil samples show plant available phosphorus over 6 ppm. Lower values are considered to be deficient. Areas in the rainfed region of above 10 ppm are considered to be suitable to cropping without P fertilization. The plant available phosphorus was determined by the *Olsen* test (available phosphorus is extracted by $NaHCO_3$ (Ryan et al. 1996). Deeper soils of soilscape unit A11d, A11e and A31b show higher values of phosphorus. The values of phosphorus can be considered to be adequate for soils suitable to agricultural activities.

Nitrogen

The total nitrogen was determined by the *Kjeldahl* procedure involving digestion and distillation. Soil is digested in the sulfuric acid H_2SO_4. The ammonium which is produced is distilled and then collected in H_3BO_3 and tritrated (Ryan et al. 1996).
Total nitrogen contents are in a wide range between 218 to 1326 ppm being in the range from 400 to 1000 ppm for different soil types in Syria (Ryan et al. 1997). The *Kjehldahl* nitrogen gives the whole range of nitrogen, including the smaller parts of plant available nitrogen like nitrate or ammonium.

4.3.7 Soil aggregation

To estimate water stable aggregates soil samples were taken from a location south of *Tadmor* (Location see Fig. 4.13). The soil samples were taken from a transect within the soilscape unit A11e which comprises deep fine-textured soils on gentle sloping hills. The soils often alternate with rock outcrops. Starting at 50 m below the top of a medium height samples at three transects were taken at a east facing slope. The 3 transects (S, W, D) run parallel to contour of the ridge. They differ in height by 50 m and are 500 m (S), 1000m (W) and 1500 m (D) long. The subscripts refer to the location n – north, m - middle position, s - south.

According to the texture the soils are loam or silt loam (Table 4.9). The soil samples were sieved and the part of the soil smaller than 2 mm was used for the determination of aggregates. The soil samples were put into water and sieved again afterwards. For soil samples of the soilscape unit A11e about 17% of water stable aggregates are in average larger than 0.5 mm, about 23% were of a size between 0.2 and 0.5 mm. In the case of smaller aggregates a trend was visible: the soils of the footslope (Dn, Dm) have a larger amount of smaller aggregates (0.2 to 0.5 mm) than the soils from the top (Sn, Ss) (Table 4.9).

Table 4.9 *Texture and aggregates stability of soil samples within the research area*

Location	Clay (%)	Silt (%)	Sand (%)	Total water stable aggregates < 5 mm (%)	Total water stable aggregates < 2 mm (%)
Sn	20	42	38	11.4	22.8
Ss	18	38	45	12.6	22.8
Wn	25	37	37	19.7	21.5
Wm	24	39	37	16.2	23.8
Ws	11	62	27	33.9	15.4
Dn	21	34	46	13.3	29.6
Dm	24	40	36	11.2	26.3
Ds	22	36	43		

This is mainly due to the rapid wetting of the soils in the arid climate after a shower. The intra-aggregate pores increase in diameter resulting in more macroscopic flow of water. The abundance of smaller aggregates on the foot slopes is probably due to erosion of the finer particles from the upper slopes. The soils on the top (Sn, Ss) also consequently show a higher percentage in sand. Clay particles at the footslopes are also an indicator of rapid wetting and drying cycles.

Perennial vegetation such as forages have a beneficial effect on soils by increasing the formation of soil aggregates. However the type of forage is also important (Kay & Angers 2000). Release of nutrients or polysaccharides in the vicinity of the roots of grasses increase aggregate stability. (Kay & Angers 2000). A maximum aggregate stability due to forage introduction was reached for alfalfa or red clover (Chantigy et al. 1997).

4.3.8 Soil roughness and stoniness

No data were available concerning the soil roughness . The soil stoniness was assessed only qualitatively according to the land use or land cover data in context with field records on the training areas for the classification of satellite images (see Chapter 4.7.3).

4.4 Land cover and land use

4.4.1 Introduction

Four datasets of full Landsat TM scenes of path 173, row 36 were available for the current study. To especially study the hydrological parameters data during the rainy season would be most suitable. Due two high cloud cover during the rainy season and the repetition cycle of 16 days the availability of useful datasets is limited. These datasets of the rainy season were compared with the datasets of the dry season: 25-07-1994 and 10-10-1993.

Land cover includes the physical appearance of the earth. Land use describes the purpose for which the land is used (Addink 1997). Land cover classes such as bare soil can be consequent to human land ‘overuse’: destruction of the vegetative cover and the consequent delation of the upper soil cover. Before the classification process is explained the current land use is presented in the following paragraphs.

Table 4.10 *Available datasets of Landsat TM, full scene, 173/36 (Source: ESA 1993, 1994a, 1994b, 1995)*

Date	Time	Sun altitude	Solar azimuth
October 10, 1993	7:26	41.24°	142.50°
April 4, 1994	7:24	48.62°	127.08°
July 25, 1994	7:22	56.92°	108.04°
April 7, 1995	7:13	47.68°	123.23°

The agricultural sector is important for the country's economy. Agriculture still accounts for 27% of the GDP (Turner 2002), it decreased only slightly from the standard of 30% in 1963 (Al-Ashram 1990). Major agricultural products are cereals, cotton for export and fruit and vegetables produced for local markets and export (IFAD 1997). About 32% of Syria's land mass is arable land (6 million hectares), with about 92% (5.5 million hectares) cultivated (CBS 1994). The main part of this area is cultivated with annual crops (4.27 million ha), and the rest has permanent crops (e.g. olive trees.) (FAO 2004). Table 4.11 shows the land use within the provinces partly covered by the project.

Table 4.11 *Land use within provinces where the project area is located (in percentage of area, 2nd column) (1 = arable land, 2 = cultivated land, 3 = uncultivated land,4 = non-arable land, 5 = buildings and roads, 6 = lakes, swamps, 7 = rocks, bare soil, 8 = rangeland, 9 = forest) (CBS 1994)*

Province	Area [million km²]	1	2	3	4	5	6	7	8	9
Homs	6.67	23.1	23.1	0.1	13.5	8.6	0.2	4.0	63.6	0.4
Homs(Al Maghrim)	3.11	23.5	23.5	0.0	4.6	1.3	0.7	2.6	24.2	1.6
Tadmor	38.8	2.1	2.1	0.0	18.1	0.1	0.0	18.0	54.5	0.2
Salamiyah	5.68	29.8	21.9	7.9	10.9	1.7	0.2	8.9	49.9	2.2

Over 50% of the project area is rangeland according to official statistics. Only a quarter of the area is considered to be arable land and is cultivated. Most part of the project area belongs to the province *Tadmor*. About 20% of the land within the province *Tadmor* is assigned to bare soil and bare rock as the land cover. The low importance of agriculture to the economy of the province are illustrated by only 2% of cultivated land.

4.4.2 Rainfed and irrigated agriculture

According to the general rainfall pattern different "settlement zones" within the country were defined by specific cropping patterns and agricultural practices (Al-Ashram 1990) (Table 4.12).

The major part of the project area belongs to zone 5 of the settlement or agricultural zones which are based on the isohyetes of mean annual rainfall (Fig. 4.14). Within the project area the major sites of agricultural production are east of *Hama* and *Homs*, belonging to the zones 2, 3 and 4. The region there is characterized by fertile brown soil and is mainly cultivated with olive trees, pistachio trees, fruit trees, wheat and barley. The transition from the rainfed zone is clearly visible on the satellite image, especially on the false color image where the limit of the rainfed zone with brown soils and dense vegetation cover can be easily differentiated from the rangeland zone with only sparse vegetation.

Table 4.12 *Different settlement or agricultural zones in Syria according to mean annual rainfall range (Compiled according Al-Ashram 1990)*

Zones	*Mean annual rainfall range*	*Crops and cropping pattern*
1a, b	> 350 mm (subzone a: > 600 mm)	wheat, pulses and summer crops, at least 2 harvests per season
2	250 - 350 mm, not less than 250 mm during two thirds of the years	every 3rd year two barley crops, wheat, pulses, melons
3	> 250 mm, not less than 250 mm during half of the years	one or two barley harvests every two years
4	200 - 250 mm	barley[1] or permanent grazing land
5	< 200 mm	not suitable for rainfed crops

[1]Number of barley harvests cannot exactly be defined, very erraticly

In the whole area of Hama and Homs the production of annual crops such as wheat or barley is between 1 to 4% of the whole country production. (Table 4.13).

The agricultural system in Syria is officially based on socialist planning economy since 1973. For a period of five years a plan regulates the production of the agricultural sector. Since certain production goals have to be officially fulfilled, the official statistic may not always represent realistic production numbers or yields. Especially in the first and second agricultural zones (see below) this regulation system includes ”cultivation licenses”, the setting of production goals and plans, mandatory sale of all important agricultural goods to the state, control of wholesale prices, standardized credit regulations all over the country, introduction of a fixed wage scale, control of prizes for agricultural products, limitation of tenure rights in the form of restriction on property ownerships within the scope of land-reform regulation (Hopfinger 1991). It is not quite clear how much of this socialistic system still persists. Also the agricultural economy seems to be in transition. Since the beginning of the nineties foreign investment is possible allowing agribusiness farms e.g. the small Saudian cooperation farm within the project area. Most of the agricultural area (61.5%) is nowadays under private farms (Al-Ashram 1990), 31.7% under cooperatives and only a small part under state-owned farms.

Table 4.13 *Percentage of production and cultivated area of different agricultural commodities in the different provinces of the project area in relation to whole production of Syria (CBS 1996)*

Province	*Wheat*		*Barley*		*Cotton*		*Olives*	
	Prod. (%)	*Area (%)*	*Prod. (%)*	*Area (%)*	*Prod. (%)*	*Area (%)*	*Prod. (%)*	*Area (%)*
Homs	3.68	4.72	2.54	4.88	0.63	0.75	4.83	5.54
Hama	4.50	4.38	7.82	8.18	3.79	3.43	5.77	3.87
Damascus	2.41	1.76	0.20	0.62	0.77	0.74	3.04	2.38

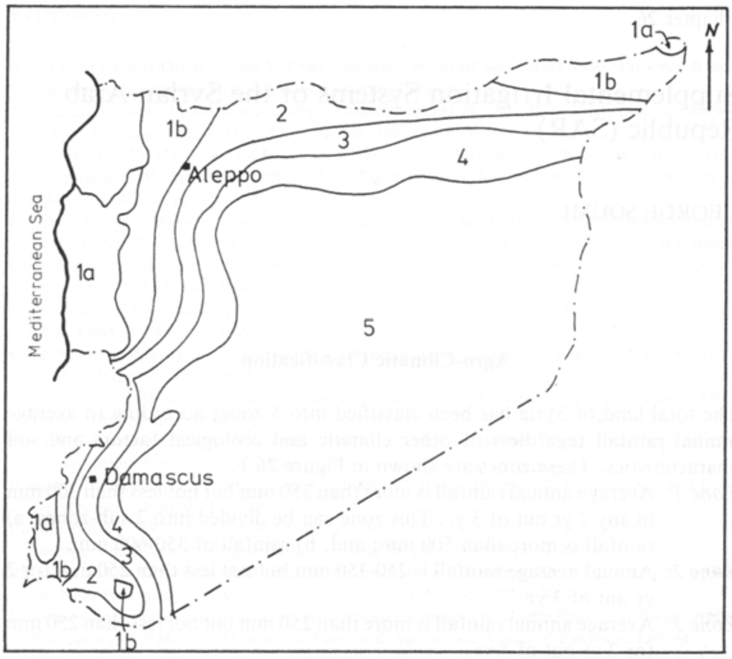

Fig. 4.14 *Differentiation of settlement or agricultural zones according to isohyetes of mean annual rainfall (Source: Soumi 1987) (see Table 4.12)*

Within zone 5 in the project area irrigated fields of crops (barley, olive trees, cotton) are found on the oasis plantations at *Tadmor* and *Quaryatain* and along the *Ad-Dauw* basin where groundwater resources are exploited and used for irrigation. At *Tadmor* extensive plantations of olive trees and palm trees are found. The rather low quality dates are sold on the local market. In the *Ad Dauw* basin groundwater resources are used for the cultivation of barley on about 5060 hectares (CBS 1994).

The farms are situated along the road between *Homs* and *Tadmor*. The farmers cultivate mainly barley, often planted inside small olive orchards. The farmers are resettled former nomads who often have no experiences in farming practices. Hopfinger (1991) describes a similar situation at newly reclaimed areas at the *Khabour* in the eighties. Farmers who have been nomads are often helpless with the cultivation of sensitive crops, such as vegetables or legumes that need a lot of experience and manual work. They prefer therefore to cultivate crops which require less manual work such as barley or cotton. Most of the cultivated sites are irrigated within the project area. The technique used is basin or furrow irrigation. Most of the time the farmers dig their own wells. About 44% of all wells (1994: 122 276, FAO 1997) are estimated to be private and non-registered wells. In the region north of *As-Sukhneh* at *Al-Kum* even vegetables are grown with irrigation water from springs and wells. The fields can be used only for 3 to 4 years due to salinisation problems or depletion of soils (personal communications with farmers around *Tadmor* and in the *Ad- Dauw* basin). Salinization occurs due to irrigation technique and the absence of any drainage system. According to official statistics about 6% of the total irrigated area in Syria is affected by salinization which is an area of about 60 000 ha (officially 1 million hectares are irrigated). South of Palmyra even cotton is found, a plant that has a high water requirement. It was not investigated how farmers perceive and deal with the low organic matter content of the soils.

In some patches rainfed agriculture has been practiced in the *wadi* beds such as *wadi Ar Rauw*. The nomads prefer to cultivate barley as a fodder than to utilize range landsince more fodder per unit area can be obtained from barley cultivation than from the range lands. A yield of about 200 $kg \cdot ha^{-1}$ dry matter is normal for range land. The dry matter production of barley is double that amount (Wirth 1971).

Investigations in the eighties within the drier parts of the *Raqqa* and *Aleppo* provinces have shown the effect of a change of the agriculture system from pure livestock production to irrigated agriculture. Severe drops in the barley yields have been triggered by the decline of soil organic matter which was not replaced. Stubble grazing after harvest removes all the organic matter from the harvested fields and no inputs like manure are used to replace it (Jaubert 1983). The organic matter of the soils in the study area is below 1% . Soil degradation is accelerated by wind erosion. This process can be seen in the assessment of remotely sensed data on the *Bishri* mountains situated west of *Dayr-Ez-Zaur* (Geerken 1997*)*. A time series of satellite images showed the encroachment of sand dunes. On 6/12/1994 the government prohibited completely the cultivation of barley in the *Bahdia* (Syrian expression of rangeland area in Central Syria) (IFAD 1997). Tillage is not allowed east and south of the 200mm isohyet. The prohibition was already declared in 1973, but the government enforcement was low. Even in 1988 after a heavy rainfall the ploughing and cultivation tillage in the steppe area was once again allowed by a decree from the agricultural ministry after a heavy winter rainfall. The prohibition since 1997 seems to be more controlled (personal communication from farmers and Bedouins near *Quasr al Hir*, farmers in the rangeland of the *Aleppo* province). Nowadays abandoned farmlands within the banned area of the northwestern steppe area is recultivated with perennial forages often using water harvesting pits (ICARDA 2002).

It seems that large agrobusiness companies start to discover the steppe area for production of agricultural commodities. A Syrian - Saudian company uses an area south of *Al-Basiri* for the cultivation of different crops by irrigation using groundwater.

4.4.3 Livestock production and rangeland utilization

About 8.3 million ha are classified as pasture in the official statistics. About 54% of the district of *Tadmo*r is rangeland (Table 4.15). The main type of livestock in Syria is sheep. About 13.1 million head were officially counted in 1996 (CBS 1996). The FAO statistics estimate sheep at 15 million in 1998. Since in the nineties there was a constant rise of flocks with the peak in 1998 with more than 15 million heads of sheep, the number is now reducing (2004: 13.5 million) (FAO 2004). These fluctuations maybe resulted from economical difficulties. Apart from fluctuations due to climatic conditions (Al-Ashram 1990) there has been steady rise of sheep herds during the last 20 years (1975: 5.8 million). For the provinces of *Hama* and *Homs* the statistics list 1.3 and 1.6 million head of sheep respectively. For the project area of the IFAD project (main part of the current study area), 3.4 millions sheep are counted. Most owners have flocks of less than 100 breeding ones. (The type bred in Syria is the *Awassi* sheep which is mainly for the local market). But probably there are more sheep grazing in the area than officially registered. During the short months of the rainy season the sheep are transported by truck to their grazing areas in the rangeland for three months, March, April and May. In summer and autumn they graze crop and cotton residues in agricultural zones 2 and 3; in winter (December to February) they are hand fed with barley grains or wheat bran (Wachholtz 1996). The migratory tribes move their sheep at the start of the wet winters (November) to the steppe area, IFAD (1997). Wachholtz (1996) studied the migration behavior in the *Aleppian* and *Hama* province in the marginal and steppe areas north of *Esriyeh*. Three distinctions are made regarding tribal migration patterns: fully migratory tribes completely abandon their winter base during grazing time; semi-sedentary tribes see half of the families migrating for a four and a half month period and settle seasonally in small hamlets in the *Bahdia*; mostly sedentary ones located in areas of high rainfall retain half of their family members at home.

The migration period starts in May or June and ends in November or December. These flocks are mainly concentrated on stubble grazing of harvested fields of winter crops and later on summer crops. The herds wander 50 to 200 km during grazing (Meyer 1984). Meyer (1984) investigated the situation of smallholders in the *Ghab* region who are former nomads yet still own flocks of sheep. Between August and October sheep are grazed on the stubble of harvested cotton fields. Their grazing period in the steppe runs from November or December through late May, early June. Some of the shepherds occasionally interviewed during field trips, confirmed this behavior. There are also small milk processing units installed in the steppe area, producing cheese not only to sustain local need, but also to sell on the markets in *Hama* (center famous for the typical *Syrian* cheese processed from sheep milk).

Table 4.14 *Livestock in the project area (CBS 1994)*

Province	District	Population	Number of cows	Number of sheep	Number of goats
Hama	*As Salamiyeh*		1 375	670 503	11 141
Homs	*Tadmor*	53 048	1 296	241 600	15 700
Homs	*Al Maghrim*	38 896	22 635	27 744	5 735
Homs	*Homs*	814 201	70 865	708 521	31 174

Other livestock within the project comprises goats, cattle, sheep and camels (about 8000 of the latter) (IFAD 1997). Goats and cattle comprise only about 5% the number of sheep, camels comprise only 0.5% . The number of camels has been tremendously reduced. In 1930 the number of camels was estimated at 200 000 in whole Syria together with 2.5 million sheep. In 1965 there were only 40 000 camels and 6.5 million sheep (Wirth 1971). The rearing of camels (4000) has declined further in recent years being grazed only on land which does not support sheep. But the number of camels nearly doubled in the last seven years (1995: 6711, 2002: 13 500; FAO 2004) showing a growing importance. Bedouin tribes who formerly reared camels shifted to sheep (Rae 2000). These remaining camels satisfy in part the demand for camel meat. Investigations in the semi-arid thornbush Savannah in Northern Kenya have shown that sheep mainly graze the herb layer with grasses, herbs and small dwarf shrubs, whereas camels utilize larger shrubs, bushes or trees (Schwartz 1988). Maybe the steppe area with its low vegetation cover does not offer enough forage. First increases in sheep flock size have been triggered by the introduction of mobile water tanks brought in by trucks. Some other factors in recent years influenced and changed the form of livestock production in the area. With the motorization of transportation, allowing further intrusion into the steppe area; camel rearing became better with the larger availability of animal feed, greater availability of crop residues due to the expansion of irrigated areas nearby the *Orontes*, *Khabour* and *Euphrates rivers*, water supply improvement through the building of dams and government wells. But abandoning camel rearing may have led to further degradation of the steppe vegetation since camels graze more sensitively than sheep: roots of vegetation are not pulled out and the impact of the hoods of sheep on the soil and vegetation cover is larger (Schwartz 1988).

Nevertheless the high number of sheep has led to continued degradation of the steppe vegetation. The grazing capacity of the Syrian steppe is quite low. Already in 1965 Van der Veen (1967) estimated that maximum carrying capacity for the Syrian rangeland that does not lead to degradation is at 12 million sheep for one month (or 2 million sheep for 6 months). In 1965 about 33 million sheep per one month were already grazing (Wirth 1971). Nordblom (1992) estimated that only about 9% of feed ration for sheep are provided by steppe and fallow areas in the northwestern areas of the steppe area. About 92% comes from concentrates and aftermath (residues). Therefore control of grazing is needed.In an area of 75,000 ha of the *Mihassa* watershed (Fig. 3.1) about 40,000 sheep during high rainfall years and about 6,000 sheeps in dry years are estimated. Most of them are fed by additionally feed resources since the rangeland is degraded (Tutwiler et. al. 1997). There is also a gap of 16% between existent feed resources and optimal performance of livestock in 1991 (IFAD 1997). The rise of livestock and the impact on steppe degradation is probably partly due to subsidized state feed policy and the access to free drinking water and free veterinary services (Masri 2001). After an ecological disaster in the 1960s, where over two million sheeps died because of a three-year drought, a UN project was launched to revitalize the livestock sector (Chatty 1998). The traditional Bedouin system of *hema* was reintroduced and *hema* cooperatives were founded. Cooperative rules within the *hema* system control stocking rates and fix movement of herds within cooperative borders. It also includes a system of rotational grazing. Violations of rules were pursued by judicial police. In 1996 about 60 000 with 60% of the total sheep population in Syria (7.5 million sheep) belonged to *hema* cooperatives (Syrian Arab Republic Steppe Directorate 1996). Benefits for the members are access to managed grazing, preferential feed prices and credit facilities. How much the degradation process of the Syrian steppe vegetation could be reduced is not clear. Chatty (1998) describes the concept of *hema* cooperatives as improvement over former uncontrolled grazing or strict governmental obligations in consideration of the Bedouin participation. Other approaches to controlled grazing are the total exclusion of areas from grazing, done within the project for establishment of the wildlife reserve in *Al-Taliba* east of *Tadmor* (Masri 2001). There are dams around the wildlife reserve not allowing the Bedouins to enter the reserve with their herds. The improvement of vegetative cover show the success, but the acceptance of such conservation measures within the Bedouins population is small (Chatty 1998). Only because of severe drought the reserve offered open access to the herders in winter 1998/99 (Triulzi 2001). The control of grazing within the mountains of *Northern Palmyrides* shows the same progress, but also only under strict control. Investigations of Rae (2000) in the northern steppe area (north of *the Northern Palmyrides)* have shown that there are enough customary laws within the tribes regulating the grazing through cooperatives of the *hema* system. These cooperative structures are regarded as future control of grazing within the area since they regulate access to grazing areas and water and facilitate customary resolutions of disputes. They garantee the responsibility to needs of state and community (Rae et al. 2001). It is not quite clear how much this *hema* system functions south of the *Northern Palm*yrides within the project area. Baas (1998) states that free access predominates with state owned areas and the breakdown of the traditional Bedouin system. Here degradation is more likely since control is less.

4.4.4 Non-agricultural land use

Oil production is one of the major sectors of the Syrian economy. There are no oilfields within the project area: they are concentrated on fields east of *Dayr-Ez-Zaur* and the North-eastern part of the country. More important are industrial site for phosphate production within the project area and the military base.

Phosphate production

In the world production Syria ranks low with an annual production of 2,392 million tons of phosphate rock in 1997. The United States accounts in the same period for 30% of the world production, 45.9 million tons of phosphate rock (gross weight) (USGS 1999). The main phosphate producer in the Middle East is the Jordan Phosphate Mining Cooperation accounting for 5.9 million tons. About 90% phosphate rock is used for the production of nitrogen/phosphorus/potassium-fertilizer used worldwide for food crop production. Phosphate rock is mined and processed either by solubilizing to phosphoric acid or smelting to phosphoric acid or elemental phosphorus (USGS Geological Survey 1999).

Quarries of two mines exists in the area, nearby *Quaryatain* and *Khnaifess* (see Chapter 1.4, Fig.1.3). Phosphate beds are found within Cretaceous sediments, in the *Campanian* series. The deposit at *Khnaifess* has been estimated at 17 million tons (Wirth 1971). The impact of phosphate mining is high on the landscape: The mine at *Khnaifess* occupies an area of 17.34 km^2 where the exploitation is now concentrated on two places 25 km apart .The mine near *Quaryatain* only occupies only a small area of 0.56 km^2. For transportation of the material a railway was constructed linking the different production plants in the area to *Homs.* Newly constructed water harvesting sites have to be kept at a distance from the industrial sites. The sites were identified during the field trips and their extension is digitized on the satellite image.

Military sites

The budget of the Syrian state includes important expenses on the military sector, about 8% of the GDP is estimated to be defense expenses (CIA 1999). Since the steppe area is only sparsely populated, it is a convenient place for military installations and operation sites. Two small airports, one on the road *Homs - Palmyra*, one on south of the road *Dumayr - Saba Biar* exist in the area. The steppe area is often used for military exercises or testing of new instruments. Any operation in the steppe area is suspiciously observed by the military. New constructions have to be kept at a distance from military sites. The extension of the military sites was determined by visual interpretation of satellite images and definition of location by GPS during field trips.

4.5 Vegetation cover in the research area

4.5.1 Characterization of vegetation

The main part of the study region belongs to natural grazing lands. There is only one vegetation map covering the whole country based on definition of vegetation climax groups (Sankary 1977) and of limited use on the grazing potential of rangeland. Wirth 1971 described a geographical classification differentiating the Syrian vegetation into four different regional vegetation zones: the *Mediterranean* in Western Syria, the *Euro-Siberian* in the mountains in the Northwest, the *Irano-Turanian* in Central and East Syria and the *Sahara- Indian* zone in South-East Syria. With this system 70% of the flora species of the steppe area are part of the *Irano-Turanian* botanical region, 30% transitional (mainly found in the region SE of *Sabkhnet Mouh*), belonging to *Sahara Indian* subregion. This differentiation is also congruent with the fact that the *Irano-Turanian* region belongs to zones of rainfall regime within 80 to 300 mm (Tenbergen 1991). Characteristic plants of the *Irano-Turanian* zone are *Pistacia atlantica*, *Artemisia herba-alba*, *Stipa barbata* and *Poa sinaica*. Typical plants of the *Sahara-Indian* zone include those of oasis plantations such as palmtrees or *Haloxylon salicornicum*. In relation to the growing habitat the steppe area is characterized by different geomorphological and geological conditions. Various habitats have been schematized for the *Negev* steppe (Fig 4.15). This scheme is partly transfer group associations found in the different environmental subunits or growing habitats of the Syrian steppe and illustrates the potential for grazing.

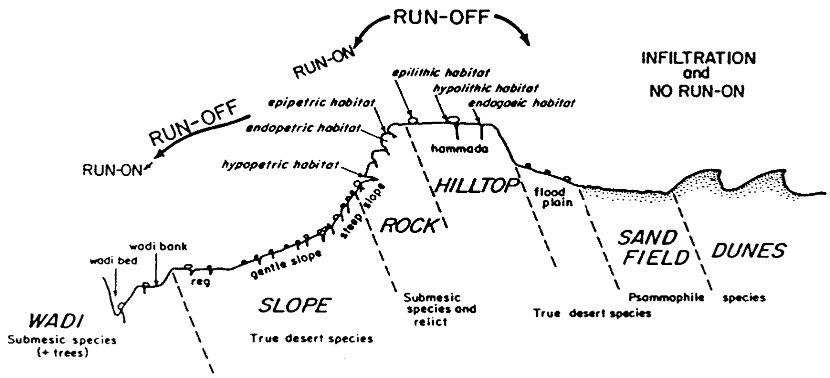

Fig. 4.15 *Different growing habitats for plants in the Negev (Tenbergen 1991)*

Main vegetation groups are fodder shrubs (e.g. *Atriplex spp*., *Haloxylon spp*., *Anabasis spp*.), dwarf shrubs (*Noaeo mucronata*, *Artemisia herba alba*) or annual grasses (*Poa sinaica*). Some of these plants are fodder plants such as *Atriplex halimus*, others are quite resistant to grazing (*Artemisia herba alba*).

Table 4.15 *Different plant species and their typical geomorphological setting in the steppe area, palatability, FU/ha = equivalent of energy produced by 1 kg of barley grain when digested by ruminants (Lengiprovodkhoz 1987, IFAD 1997)*

Rangeland type	Geomorphological setting	Palatability	Feed unit per hectare (FU/ha)
Artemisia herba alba, *Noaea mucronata, Achillea fragramtissima, Anabasis ssp., Atracylis serratuloides, Astragulas spinosa*, Annuals like *Poa bulbosa, Koeleria spp., Scorzonera undulata, Diplotaxis ssp., Plantago ovata, Erodium glaucophyllum*	Rocky calcareous area, ploughed area in the plains		70 (30 and 120)
Noaea mucronata, accompanied by *Haloxylon articulatum, Peganum harmal, Stipa parviflora, Poa spp., Carex spp.*	Flat plains, undulating hills	Advanced degradation of group of Artemisia herba alba	35 (15 and 70)
Haloxylon salicornicum	Gypsiferous soils	Low palatability, in a high degradation stand	35 (10 and 70)
Anabasis articulatum	Heavy loamy soils, depressions where run-off accumulates	Aggressive invader species, not eaten by sheep	25
Haloxylon articulatum accompanied by *Plantago albicans, Carex stenophylla, Schismus arabica, Arnebia decumbens, Launaea spp.*	Gypsiferous soil	Only eaten if no other forage available	50 (0 and 80)
Astragalus spinosus		Indicator of severe land degradation	80 (20 and 160)
Annuals and grass	Plains, recent fallow along foothills		90 (0 and 200)

Pasture legumes are another large group of plant species found in the steppe area. They are adapted to climatic extremes and due to coexisting Rhizobia important for the soil fertility (Abd El-Moneim 1992, Cocks & Osman 1996, Osman et al. 1991, Russi et al. 1992). There were about 60 sites at the steppe within the precipitation range of 300 mm to below100 mm. Khattach (1995) identified legumes belonging mainly to the genus of

Astralagus (about 50%), *Trigonella* (20%), *Medicago* (13%), *Trifolium* and *Onobrychis*. These pasture legumes have also been found during a field trip at the end of March 1998 (Khatib 1998). The distribution of the species depends on climatic and endaphic conditions. Most of the species show a dependance on the annual rainfall. *Astragalus spp.* and *Trigonella spp.* are mainly adapted to drier conditions, below 100 mm annual rainfall. In regions exceeding rainfall of 100 mm *Medicago spp.*, *Onobrychis spp.*, *Hippocrepis* spp. and *Vicia* spp. were the most important genus.

The spatial variation of various species is high. During a field trip in March 1998 about 15 to 20 species were found on every site. On a site on a southern footslope of *Jabel an Naqniqiyah* (*Northern Palmyrides*) up to 58 species were found (Khatib 1998).

4.5.2 Degradation of the rangeland

Vegetation cover in the region is very low; even during the vegetation climax at the end of March 1998 vegetation cover of only 30 to 40% on different sites around *Tadmor* were estimated (Khatib 1998). The interpretation of satellite images taken at the end of the rainy season show a high percentage of vegetation cover in flooded depressions. And in summer, vegetation on the plains or scree slopes is so scarce and so sparsely distributed that the spectral response of the soil totally dominates the response due to vegetation.

Pabot (1955) proposes that formerly the steppe area was covered by a dense vegetation of high grasses with wooden shrubs or trees such as juniper or pistachio. The unique trees of *Pistachio atlantica* found at *Jebel Bilas* (*Northern Palmyrides*) seems to confirm this hypothesis. Because of population pressure and the consequent increase of flock size of sheep, rangelands in Syria have suffered considerable deterioration. Primary causes include uncontrolled and prolonged grazing, uprooting of shrubs for fuel and encroachment of cereal cultivation on rangeland. The biomass production of the Syrian steppe is only about 400 $kg \cdot ha^{-1}$ whereas normal Mediterranean rangeland production is about. 2000 $kg \cdot ha^{-1}$ (Leybourne et al. 1994).

The impact of grazing on plants is very complex. Primary causes are the effect on the impact on reserves of carbohydrate synthesized from sunlight through photosynthesis. Therefore the timing of grazing is crucial. If the leaves are defoliated too early, growth of plants is hampered. Adding to the complexity the threshold for defoliation without damage has to be determined for each plant species (Ffolliott et al. 1995).

The negative effect of uncontrolled grazing is also visible in the distribution of seeds in the soil of the *Bahdia*. The highest rate of seeds per hectare soil of *Trigonella spp*. and *Medicago spp.* was found in areas with low pressure of grazing such as protected areas

(*Wadi El Azib*) or military grounds (Khattach 1995).

4.5.3 Planted rangeland and regeneration potential of steppe vegetation

The Ministry of Agriculture started a program in 1987 for establishing a system of public grazing reserves (*Mahmiat*). In these 28 reserves on about 240 000 ha grazing is limited to two periods of two months during the winter and spring and the stocking rate (sheep per hectar) is restricted (IFAD 1997). A fourfold increase in forage was achieved within a few years (IFAD 1997).

Osman et al. (1991) studied the effect of stocking pressure on planted rangeland at Maragha (Province of Aleppo) and native rangeland. The rangeland was rehabilitated with native edible shrubs, such as *Salsola vermiculata* and *Atriplex halimus*. During most of the time animals grazing on native rangeland needed more extra feeding than those on planted shrubs.

In the southern part of the study region two reserves are located east and south west of *Tadmor*. The fenced natural reserve east of *Tadmor* (*Al Tilal*) is mainly replanted with *Atriplex spp.*, *Salsola spp.* and *Tamarix spp.*. In winter season the vegetation in the reserve is grazed by camel flocks coming from Jordan.

Results from experiments with protected fenced vegetation plots in the *Khanasser* valley in Aleppo province that are characterized by annual rainfall regime of about 200 mm showed that vegetation rehabilitation on degraded rangeland is fast. Although the annual precipitation in the *Khanasser* valley is slightly higher, the results are comparable. Nevertheless the vegetation recovered beyond 50% after only two growing seasons. Plant species also increased on the protected sites (Zoebisch & Masri 2002).

Potential to other plants include plants like *Astragalus spp*. which deliver tragacanth gum (dried exudate from stems of *Astragalus spp.*) which is used in pharmaceuticals, cosmetics, industrial textile sizing and as thickening agents in foods for syrups, dressings etc. (Le Houérou 2001). It is found in run-on areas within wadi-depressions and could probably be grown with additional irrigation in a commercial way.

Fodder shrubs can provide an important part of the livestock diet. The Great Basins desert rangelands provide 50 to 70% of the sheep diet (IFAD 1997). *Populus spp*. and *Juglans spp*. have been already planted in Syria under very dry climate. They can be seen as live fence around irrigated crops (*Juglans spp*.) or interplanted with crops (*Populus spp*)

The irrigation with water especially harvested by water harvesting has to be thoroughly planned since every crop has its critical periods for soil water stress. Barley has its critical periods in the early boot stage, olives before flowering and fruit enlargement (Doorenbos

& Pruitt 1984). Also the soil depth is important to successful growing of plants.

4.5.4 Vegetation indices

To provide better estimates of plant biomass and cover in semi-arid regions soil background effects have to be removed to give better estimates (Richardson & Everitt 1992).Bare soil in the spectral space within the red and infrared range forms a line, the so-called soil line. Different vegetation indices are based on the soil line. The *perpendicular vegetation index* (*PVI*) assumes that the perpendicular distance of a pixel from the soil line is linearly related to vegetation cover (Richardson & Wiegand 1977):

$$PVI = \frac{NIR - aRED - b}{SQRT(1 + a^2)} \qquad [4.9]$$

a = slope of the soil line
b = intercept of the soil line

Training areas of bare soil provide the data on reflectance of the visible red channel (TM 3) and the near infrared channel (TM 4). Data were taken within the training areas in April 1994 and April 1995. The soil line is a trend line whose function describes the data points within the spectral space. Fig. 4.16 shows the soil lines derived from data of the scene in April 1994 and April 1995. Geerken (1997) adjusted the soil line within the Bishri mountains with a spectrometer and could identify different forms of vegetation. The coefficients of the soil line of both images are in the same range. Comparison of the PVI and the NDVI index does not give much more information than the conventional classification.

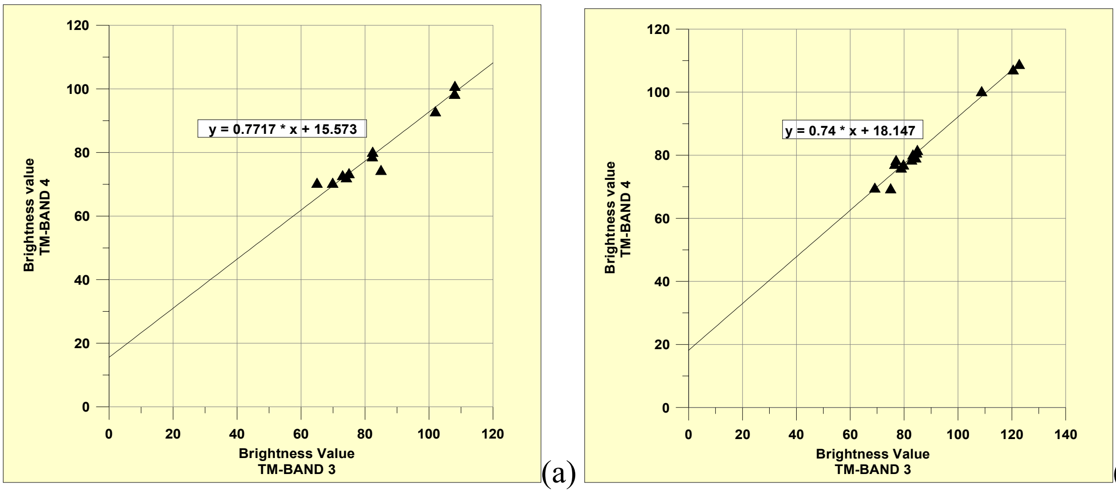

Fig. 4.16 *Soil lines derived from reflectance characteristics of areas of bare soils of the Landsat TM scene of April 4, 1994 (a) and April 7, 1995(b) (Source: ESA 1994, 1995)*

All the vegetation indices which are found in literature mostly give formulas with specific coefficients. Nevertheless it is doubtful to transfer the coefficients within the formulas directly to sites different from the study site where these formulas were implemented. The comparison of the results of the NDVI and PVI image (Fig. B-7, B-8) does not show very specific distinctions leading to the preference of one to another. At least the PVI image shows more clearly the natural dense vegetation within the wadis in contrary to the NDVI image.

The darker regions on the NDVI or PVI image represents the agricultural areas, e.g. pistacchio and wheat fields around *Homs* on the north-western fringe of the image or the irrigated barley fields in the *Ad-Dauw* basin. Denser vegetation within the drainage channels or on the protected rangelands such as the *Al Talil* reserve near *Tadmor* could also be easily detected. The areas on the slopes of the mountains, which are covered by grasses and herbaceous plants can also be easily detected.. Nevertheless, statements on the quantity of vegetation cover are impossible since ground-based data on vegetation and their reflectance characteristics especially within the spectral range of Landsat Thematic Mapper are missing in contrast to the study in the *Bishri Mountains* (Geerken 1997). Therefore the vegetation indices only provide a confirmation of the results of the supervised classification. They only give qualitative information on the abundance of irrigated areas, major drainage channels within the dry rivers , heavily degraded rangeland areas (with no vegetation in the spring scenes) and less degraded areas and protected rangeland areas. This information is confirmed through the supervised classification and the choice of training areas. Therefore the vegetation indices based on the analysis of the Landsat TM images do not provide more information than the visual interpretation of the satellite image and the spectral classification such as the supervised classification. Therefore the vegetation cover which is incorporated in the GIS analysis is qualified according to the land cover classification (see 4.6.2). Within a project at Yale University NDVI data of the AVHRR Pathfinder are used to find an approach to improve range management and detect degradation by e.g. improved distinction between perennial and annual plants (Bonneau 2001).

4.6 Determination of soil moisture

4.6.1 Use of adsorption of Thermal Infrared (TIR) and Tasseled Cap component analysis

The TIR channel of Landsat TM has its sensitivity in 104 to 12.5 :m. The images of the thermal channel show cooler regions in the darker grayscale. These cooler regions correspond to the wetter regions like at the *sabkha* or the irrigated fields in the *Ad-Dauw* basin. The image in July shows very few dark areas such as the irrigated fields (Fig. B-6).

On the subsets of the Landsat satellite scenes of the project area the first components of the Tasseled Cap component analysis show the soil brightness, the lighter are mainly areas with bare soil surfaces, often degraded. The second component of greenness has the highest values in the areas of natural vegetation in the wadis or the irrigated fields such as *Wadi Ad-Rauw* south and north of the road *Tadmor - Homs* (Fig. 4.17). The wetness component shows higher values in the irrigated fields and the wadis. Higher values are also visible on the northwestern slopes of the *Palmyrides*, probably showing drainage channels. About 79% of the variance is explained through the first component, about 8% by the second. The component of soil brightness is more evident in the scenes of the dry season of October 1993 and July 1994. The highest percentage of variance in the third component in wetness is found in April 1995. Rainfall events have been there about 5 to 6 days before, according to precipitation records at stations within the research area (Table 4.17). Here the area of the sabkha shows the highest values in the third component, one of the wettest areas of the region. But wet areas are also visible within the drainage areas of the large wadis of *Ad Dauw* and south of *Tadmor*. Especially in the dry scenes in July 1994 or October 1993 only the irrigated fields show more wetness. These results are comparable to the evaluations of the *Chott el Hodna* in Algeria (Belz 2000). He showed in the comparison of measured data on soil components influencing the soil moisture, that regionalization of these factors will not consequently give more information on soil moisture than the interpretation of satellite images.

Table 4.16 *Percentage of variance showed by the different Tasseled Cap components (Source: ESA 1993, 1994a,1994, 1995)*

	Landsat TM scene, Subset Tadmor of Date			
	Oct 10, 1993	**Apr 4,1994**	**Jul 25, 1994**	**Apr 7, 1995**
Comp. 1 :Soil brightness	86.61	81.74	84.82	79.37
Comp. 2: Greenness	3.09	5.54	4.69	6.06
Comp. 3: Wetness	6.34	8.03	4.74	12.53
Comp. 4: Haze	2.07	2.8	3.59	0.02

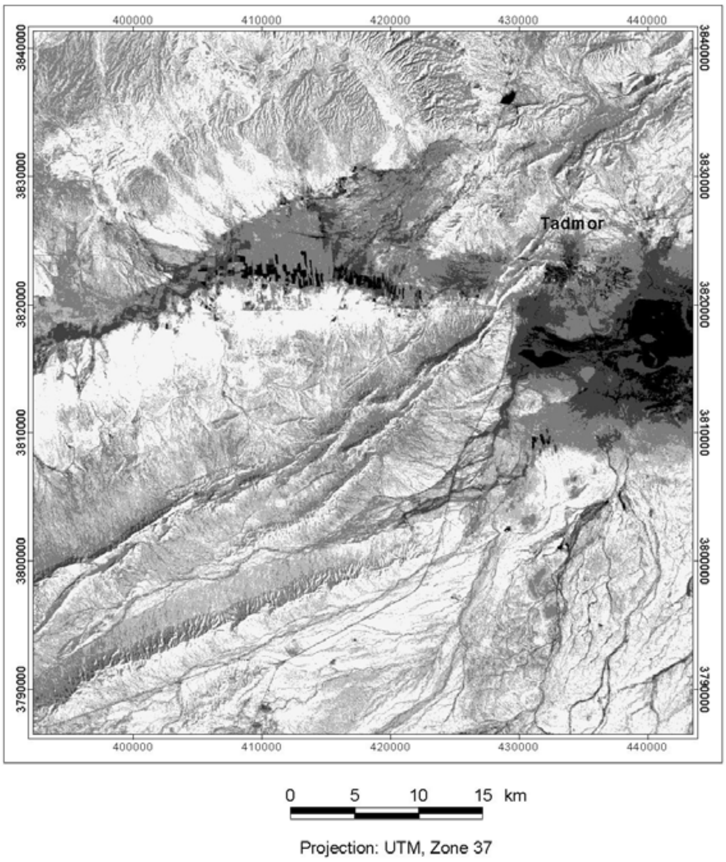

Fig. 4.17 *Tasseled Cap transformation, wetness component of the Landsat TM scene of April 4, 1994, showing area around Tadmor (Source: ESA 1994a)*

Table 4.17 *Rainfall events of the last ten days before recording date of scenes of rainy season (4/04/1994 and 4/07/1995) (Source: Meteorological Department, S.A.R. 1996)*

	Rainfall events before April 4, 1994 [mm·d^{-1}]		**Cumulative rainfall of season 93/94[mm]**	**Rainfall events before April 7, 1995 [mm·d^{-1}]**		**Cumulative rainfall of season 94/95 [mm]**	**Average annual rainfall [mm·yr^{-1}]**
Tadmor	3/30/1994	1.1	112.7	4/01/1995	8	104.6	119.75
	3/31/1994	6.4		4/02/1995	1.2		
	4/01/1994	7.2					
Nabk	3/29/1994	0.3	204.8				165.45
Homs	3/29/1994	0.8	432.6	4/02/1995	0.2	207.7	385.74
	3/30/1994	2.9					
	3/31/1994	4					
El Saan	3/29/1994	1	283.5	3/26/1995	55	146	222.69
	3/30/1994	4		3/27/1995	45		
	3/31/1994	10		4/02/1995	1		
	4/01/1994	7.5		4/04/1995	1.5		
Sadad	3/29/1994	5.5	221.5		none	38	126.75
Sadd Quaryatein	3/25/1994	0.2		3/26/1995	3.2		123.58
	3/30/1994	3.7		3/27/1995	1.6		
	3/31/1994	6.3					
	4/01/1994	0.6					
Salamiyah	3/29/1994	2.7	389.6	4/02/1995	38	184.1	291.66
	3/30/1994	1.6					
	3/31/1994	16.8					
Sadd Zkakiyah	3/30/1994	16	123.5		no data		105.61
Ukeirabat	3/29/1994	0.5	358	4/02/1995	1	178	229.12
	3/30/1994	27		4/03/1995	1		
	4/01/1994	21					
T3	3/29/1994	2.5	174.4	4/02/1995	16	113.6	120.47
	3/30/1994	30		4/03/1995	0.7		

4.7 Determination of land cover by classification of *Landsat TM* scenes

4.7.1 Atmospheric correction

The effect of atmospheric scattering on remotely sensed data influences the data quality and the comparability of datasets of different periods. Haze compensation methods were undertaken to minimize the effect of path radiance effects and to allow the comparison of classification on images of different dates. The dark-object subtraction technique was used to correct for the haze in the images. Other haze correction methods include the empirical line method. The empirical line method requires field measurements of spectres to be done under almost similar atmospheric conditions that predominate during the overpass of the satellite. These spectres were not available for the images. Concerning the Dark Object Subtraction all information needed is available within the image itself (Chavez 1988). The method is based on the assumption that in every image there are areas which have to be completely dark. These areas include regions such as clear water or dark basaltic rocks. The basaltic area south of *Al Basiri* west of the road *Tadmor-Damascus* proved to be the better choice for this image since the water in the reservoirs showed some algae blooming. The histogram technique combined with the relative scattering model (for a clear atmosphere) was adopted. A starting value in the first band was chosen and then the factors according to the model for clear atmospheric conditions chosen (Chavez 1988). In the current study the corrections of spectral intensities by contrast enhancement is included. To compare the remotely sensed data of different dates different images are calibrated. Edge improvement or noise reduction was not included.

4.7.2 Geometrical correction

To incorporate global data within the geographical information system all the datasets were transferred into a geographical coordinate system. For the projection of the different maps the Universal Transverse Mercator *Projection* with the geodetic datum of WGS84 was chosen. The projection of the geoid always produces distortion, but the conformal projection by retention of true direction and local shape was already the most convincing one for the mariners 400 years ago. The UTM map projection was developed by the U.S. military after World War II and used on a global basis since the adoption by the NATO (North Atlantic Treaty Organization) (Colvocoresses 1997). The UTM projection comprises 60 zones each covering 6 degrees between 80 E S and 84 E N latitude which results in a distortion within every zone of 1:1000. It is a transverse form of the Mercator cylindrical projection, with a 90 E rotation of the cylinder from vertical polar axis to intersect with the central meridian of the specified zone (ERDAS 1994).

Polynomials of first power has been sufficient for solution of the geometric model to geocorrect the scenes.(For large datasets algorithms up to the third power could be used (Jacobs & Sties, 1995)). The root mean square error (RMS) is a statistical value, taken from the distance between input (source) location of ground control point and location of the same GCP after the transformation. The RMS error was normally 0.7 to 0.9 pixels. The UTM-coordinates of the ground control points were determined in the field by GPS. The position of the ground control points well distributed over the image was determined in the field by receivers outfitted to measure dual frequency carrier phase signals from satellites of the **G**lobal **P**ositioning **S**ystem. The signals are emitted from about 21 satellites, orbiting at an altitude of 20.000 km in six orbital planes inclined at 55 degrees to the equatorial plane with 12 hour periods. With this a minimum of 4 satellites are visible for the spectator per 24 hours. The principle is based on the fact that everybody can orientate himself by defining the distance between himself and three satellites with known orbital positions (Dixon 1991). For the measurement in the field a 3-channel handheld receiver, the Scout master Trimble GPS was used. The accuracy (Trimble 1995) is in the range of 100 m for the two dimensional RM*S*. An additional error is added since the satellites transmit a misleading signal in the politically sensitive region especially during the Gulf War.

To solve the mapping polynomials, the correction of the geometric distortion, based on ground control points has to be determined. About 10 to 15 ground control points (Table A-14) were found per quarter scene of the Landsat TM scene. The exact UTM coordinates for the ground control points were determined in the field. An usual alternative to ground control points determined in the field is normally maps, but maps available for the study areas are mostly dating from the sixties or seventies. Therefore, many newly constructed features such as roads do not exist. Also the size of villages or small towns changed tremendously within this period.

Easily recognizable features were chosen as ground control points, such as

- road junctions
- road-railway intersections
- constructions (e.g. race course for camels and horses at *Tadmor*) Houses were often not so easily to recognize in the image since the construction material is taken from the surroundings or covered by soil
- rock escarpments, especially volcanic rocks

To exactly define the center point of a crossing Jacobs (1998) suggested the method of delineation of the line features by calculating polynoms of 1 to 3rd grade through the dependant points. Since the GPS measurements were within an accuracy of 100 m and the accuracy of the maps used for calculation of the DTM even less such procedures were not undertaken.

The spatial resampling was done with the nearest neighborhood algorithm causing a dislocation of half a pixel. The other scenes of April 1994, July 1994 and October 1993 have been registered to the 1995 image. This registration process is especially recommended for scenes with few control points (Jacobs 1998).

4.7.3 Process of classification

There are different approaches to classify and minimize the full amount of information in order to only consider data relevant to the current problem setting. In general image classification "means assigning image pixels to well defined classes which may be very different in nature (Bähr 1999).

One form of classification is the spectral one which includes unsupervised classification or supervised classification, neural network classification and the classification tree, statistical procedure within a decision making environment. The classification is an arbitrary process since the thresholds between the classes are defined by the observer. Probably not every pixel can be assigned to a specific class (Bähr 1999). Unsupervised classification allows an unbiased assessment of the total of the raw data. It can be used on the first hand to identify the main classes and then check the information in the field (Richards & Jia 1999). The method is often preferred if area is very large and field data are lacking. Unsupervised classification can used as preprocessing prior to supervised classification to get an idea of dominant classes. It also illustrates that a priori knowledge of the human observer is needed to assign the pixels to classes.

Another form of preprocessing is the principal component analysis. This is a statistical method, trying to find those data which are most relevant to the statistical variance. An advantage is the summary of all information from all channels into one image (if using a composite of the first three components). Therefore no information is lost. Nevertheless the interpretation of the meaning of the different components is not straightforward and needs a lot of experience. About 20 different soil types within a watershed *Oued Mina* in Algeria were characterized with the help of inverse principal component analysis and verification on site and in the laboratory inventory (Gomer 1994, Belz 2000).

The spectral classification involves the process of analytical separation of the clusters which are formed in the feature space or multispectral vector space with n-dimensions of the image with n-spectral classes (Richards & Jia 1999). The classification process is a sort of coding: the pixel vectors within the image are labeled according to training areas which are samples of pixels for every class. During the following classification process the distribution of the digital values within the feature space of two different bands were compared to garantee the clear discrimination of pixels between different classes. The training data or the signature data set are then used for the probability model for the whole dataset. Each class shows a specific distribution based on the Gaussian functions for normal distribution (Bähr 1999). The unknown parameters of the Gaussian functions (mean variance and covariance matrix) are computed for the training data or fields. There is a range of algorithms which can be used for the classification process: the maximum likelihood classification, the minimum distance classification, the parallelepíped classification and the Mahalanobis classifier and nearest neighborhood classifier (Bähr 1999, Richards & Jia 1999). They use different designs of the covariance matrix. The assumption that the population from which the training samples are taken, have a normal distribution is certainly not true for remotely sensed data (Mather 1999, Bähr 1999). Therefore alternatives are nowadays used such as the **A**rtificial **N**eural **N**etwork **C**lassifier (ANN).The training of the network is time consuming, but afterwards the computation is much faster. The neural network classifier belongs to the non-parametric procedures which do not use exact model approaches to describe the classification algorithm (Segl 1999). Mainly the MLP (**M**ulti-**L**ayer **P**erceptron) (feedback neural network) and the RBF (**R**adial-**B**asis-**F**unctions) are nowadays used (Segl 1999).

Before classification of scenes taken during different periods the brightness values of one histogram have to be calibrated against the other. In most cases the brightness value of extreme endpoints like the brightness value of water comprises the reference point for the calibration process. To have a good representation of the details of an image the histogram should have a uniform shape, a procedure which is called histogram equalization (Richards & Jia 1999).

The classification of the remotely sensed data for the study area was an iterative process. First easily recognizable areas have been delineated on the satellite images. Polygons were digitized on the screen and assigned to different classes. They represented the first training areas which have then been checked within a field trip. Other training areas were chosen during the first and the following field trips. All the training areas have been put in a small database with attribute features: location, soil cover, photos taken during the field trip. About 90 training areas were defined and entered into the signature file within the classification module of ERDASImagine. Afterwards the histograms of the different training areas belonging to one class were compared. To guarantee good separation between the classes the distances within the distributions within the feature space are measured. This separability analysis was done using the Jeffries-Matusita distance due to application of the maximum-likelihood classifier (Schowengerdt 1997). The training areas were slightly modified by excluding or including neighbouring pixels to garantee the homogeneity of the classes.

The **m**aximum **l**ikelihood **c**lassifier (MLC) is the most common classifier (Richards & Jia 1999). The maximum likelihood classifier is considered to be one of the most accurate classifier since it describes the mean vector and covariance matrix of each spectral class. Main disadvantages of the maximum likelihood classifier is the computational intensity and the parametric procedure based on the assumption of normal distribution of spectral classes. Therefore some researchers recommend nowadays the use of nonparametric classifier such a s neural network classifier (Fauzi et al. 2001, Atkinson & Tatnall 1997) since it improved e.g. the accuracy on classification of forest area in Indonesia using Landsat ETM+7 data. Paola & Schowengerdt (1995) concluded on urban land use classification of Landsat TM images within dry areas that neural network classification provides a visually more accurate image. Neural network classifier is less sensitive to mixtures of land cover spectral signatures and training site heterogeneity. Probably residential areas within the steppe area which proved to be difficult to detect by the maximum likelihood classifier within the research area could be more easily differentiated by the neural network classifier (individual houses within foothills in dry areas of Tucson, Arizona could be more easily detected with neural network classifier). Frizelle & Moody (2001) compared maximum likelihood classifier (MLC) and network classifier on a classification of Landsat TM scene in California. Especially in an area with barren land and grassland both classes were better differentiated by the MLC classifier than the network classifier. Nevertheless the results are not convincing often the accuracy of classification is not improved by using nonparametric classifiers (Skidmore & Layton 1992).

The remotely sensed data within the study were used to characterize the land cover and land use. Land cover includes the physical appearance of the earth. Land use describes the purpose which the land is used for (Addink 1997). Since the human impact on nature is quite omnipresent both terms could not be clearly separated: land cover classes such as bare soil can be consequent to human land ‘overuse’: destruction of the vegetative cover and the consequent delation of the upper soil cover. In some areas specific classification schemes have been developed such as e.g. the European CORINE (**CO**o**R**dination of **IN**formation on the **E**nvironment) land use / land cover classification (Brown et al. 2002) or the *LGN4* system in the Netherlands. The latter one is based on the supervised classification of land use in the Netherlands. It consists of five superclasses (Water, urban area, nature area, forests and agricultural area) which are divided into 25 subclasses (e.g. the forest class includes the class of deciduous and coniferous forest) (De Wit 1999). 13 classes of land cover/land use were differentiated within the research area (Table 4.19).

The classes were mainly chosen according to the spectral characteristics of the different soil surfaces: rock outcrops show different spectral behavior than the dense vegetation within the wadis. Since main purpose of the classification process was also to illustrate the various parameters influencing runoff behaviour the classes were chosen according to these characteristics. Vegetation cover, rock cover or human influenced areas which are even irrigated. Soil surface classification systems have been already compiled for a region in West Africa using Landsat TM and SPOT data (Lamachère & Puech 1997). This catalogue of soil surface classes refers to the system of "etats de surface" developed by Casenave & Valentin (1989), but this system is developed for a different climatic region and has to be widely changed to be transferred to the current project area. Geerken (1997) differentiated terrain units by parameters of vegetation density, vegetation type, soil type and occurrence of sand cover within the *Bishri* Mountains. He used imaging spectrometers to attain more information on the spectral response of soil surfaces or vegetation. This method was not available during the current field campaigns. The comparison of these measurements with satellite data from the same date would probably allow better distinction between different soil surfaces.

Different difficulties were encountered during the classification process. The dense vegetation within the *wadis* often overlapped with the spectral signatures of the agricultural fields cultivated with barley. The classified image was recorded just half a year (6/12/1994, IFAD 1997) after the ban of barley cultivation in the steppe area. Therefore barley cultivation is probably found outside clearly to be distinguished barley fields, showing late emerging barley plants.

Major groups are scree slopes and the sparse vegetation on scree slopes. Since the vegetation is so low, it is difficult to distinguish it clearly from the soil background. It was difficult to roads and settlement areas due to soil particles from the surrounding areas covering road pavements and roofs of houses. Roads and main settlement areas were therefore digitized, borders of villages determined by ground control points measured in the field. To also evaluate the separability of the different classes scatter plots were used showing the feature space between two bands (Appendix B, Fig. B-1 – B-5).

The higher percentage of area covered by dense vegetation within the wadis in the image of 1994 could not be explained by a different rainfall intensity before the images were recorded (Table 4.17), since at most stations the season 1993/1994 seems to be wetter than the season 1994/1995 according to the cumulative rainfall. But the slightly higher percentage of sparse vegetation on the scree slopes in the classified image of April 1994 might be taken to confirm wetter conditions. But it is difficult to assess correctly the sparse vegetation on the scree slopes because it consists of widely scattered bushes. A pixel represents the mixture of spectral response of different features. In the rangeland of Central Syria, the spectral signature is a mixture of different features such as vegetation and background soil. This is the major constraint to vegetation monitoring in dry areas by remote sensing. Vegetation consists of sparse fodder bushes often scattered over a wide area. Ray & Murray (1996) clearly showed that the reflectance of the background soil and the bush are not part of a linear mixing of the spectral signals. They should be better conscribed to the nonlinear mixing which does not even allow the distinction between background soil and vegetation by application of linear models. To exactly distinguish a feature the area occupied by a feature has to be at least larger than 4 pixels (Puech 2000). Puech (2000) studying an area of patches of bare soil in Burkina Faso pointed out that only the percentage of patches over a threshold of 1600 m² on a SPOT image with 20 m resolution should be considered as a significant parameter in hydrological analysis. For Landsat TM images this threshold would be 0.36 hectares. Therefore patches of bare soils within agricultural land are not found and as mentioned above, the clustered bush vegetation of the area is often not detectable by the Thematic Mapper sensor. Remotely sensed data with a higher spatial resolution will allow to differentiate better between these features. Perhaps also soft classifiers such as the fuzzy classifier or neutral network classifier may offer a new opportunity for classification in the semi-arid areas.

Classification results are illustrated by the confusion matrix (Table B-2): The accuracy of classification is around 97% , labels of pixels of ground truth sets were compared with the labels of pixels determined by the classifier. The pixel of ground truth sets were chosen adjacent to training areas.

The difficulty is that the maximum likelihood classifier belongs to the traditional classifier based on rigid discrete classes. Pixels may enjoy a partial membership to different classes which is probably true for classes such as vegetation and soil in the arid areas. The *fuzzy* classification technique provides another possibility to take this different assignment into consideration. A *fuzzy* classifier is therefore a sort of soft classifier compared to the hard classification processes (Mather 1999). *Fuzzy* classifiers are nowadays available in most image-processing software tools .

Table 4.18 *Land use / land cover classes within the research area (Numbers refer to Fig.4.19) (Source: ESA 1994a, 1995)*

Land use / land cover classes
1 - Saline soils within the *Sabkha*, covered with saltcrust
2 - Gypsiferous salty soils, covered with salty crusts
3 - Bare ground, low stone cover, no vegetation cover
4 - Soil surface covered by flintstones
5 - Scree slopes, degraded area (cover < 5%)
6 - Sparse vegetation within the steppe area
7 - Dense vegetation within the wadis
8 - Limestones, basaltic rocks
9 - Brown clay enriched soils within the flooded area
10 - Agricultural brown soils
11 - Reservoirs
12 - Orchards of datepalms, olive trees
13 - Irrigated agricultural areas within rangeland (mainly barley or wheat)

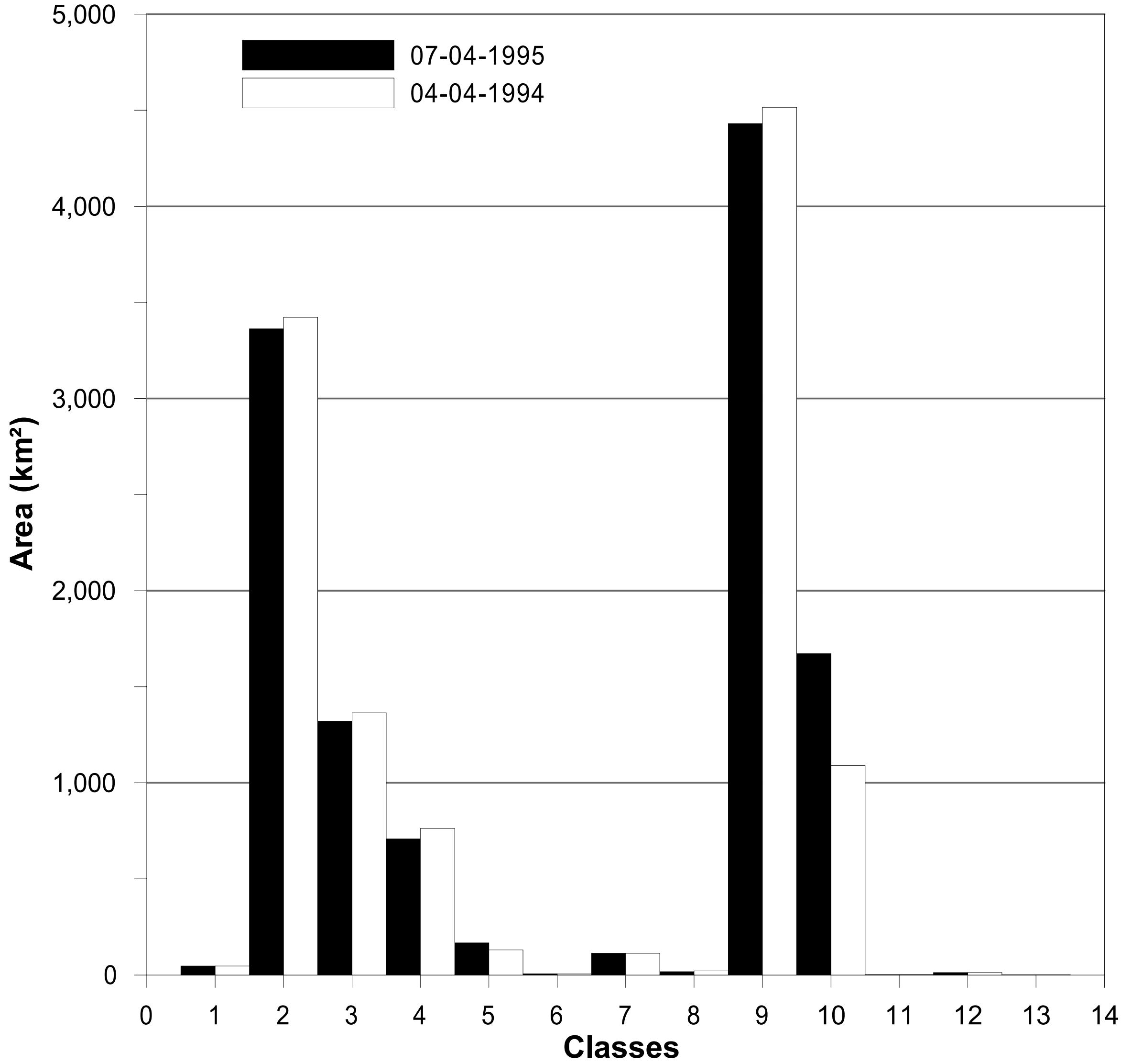

Fig. 4.18 *Area in km² for the different classes for Scene 04-04-1994 and 07-04-1995 referred to the area as shown in Fig. 4.19 (Source: ESA 1994a, 1995)*

1. Rock outcrops: Limestones and volcanic rocks
2. Scree slopes , degraded area (cover < 5%)
3. Soil surface covered by flintstones
4. Bare ground
5. Saline soils within the sabkha, covered with salt crust
6. Gypsiferous salty soils, covered with salty crusts
7. Brown clay enriched soils within the area ,flooded during rainstorms
8. Agricultural brown soils
9. Sparse vegetation within the steppe area
10. Dense vegetation within the wadis
11. Orchards of palm- and olive trees
12. Irrigated agriculture within the rangeland
13. Reservoirs, surface water

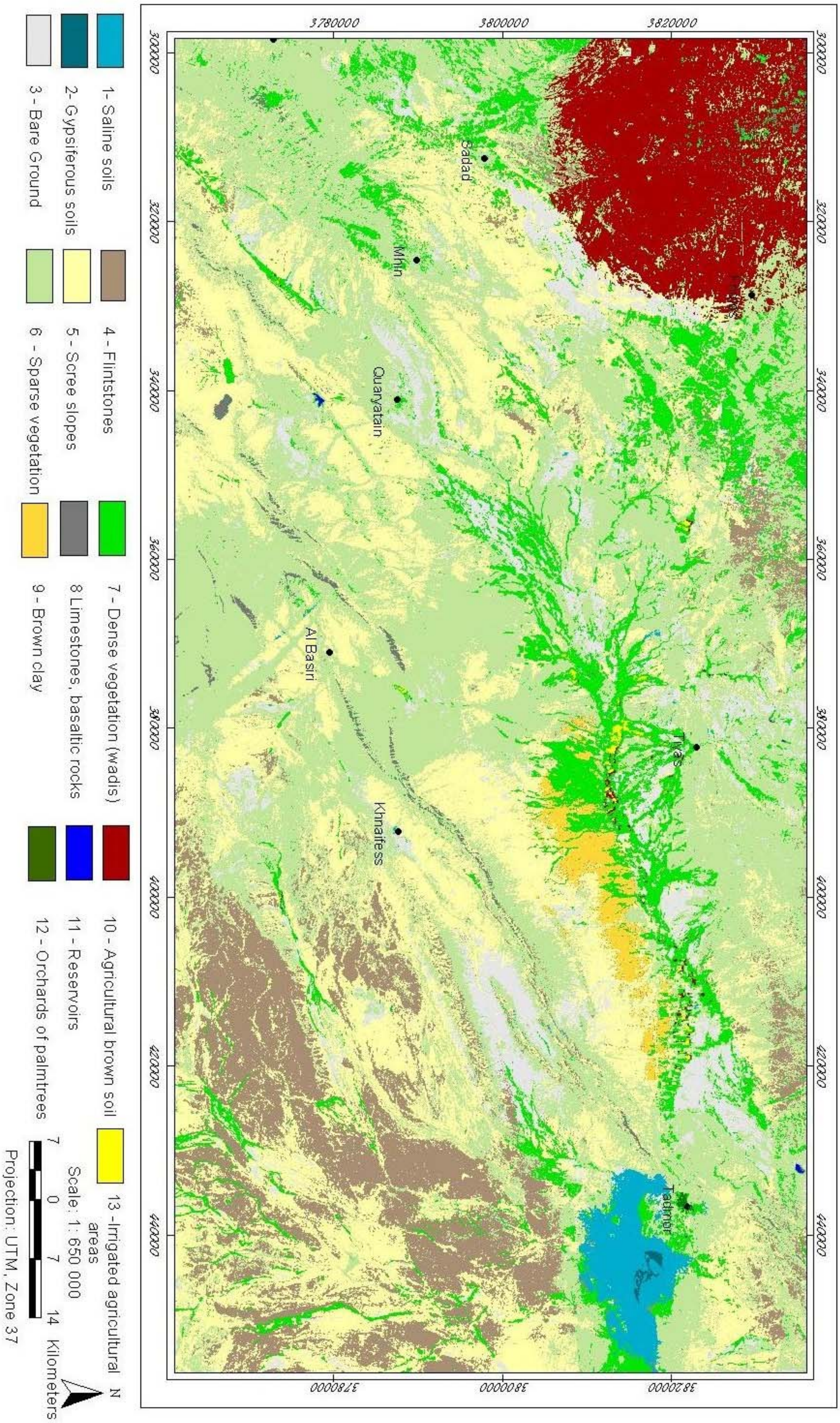

Fig. 4.19 *Land use and land use within the research area according to MLH classification on Landsat TM image (path 173/row 36) of 4/04/1994 (Source: ESA 1994a)*

Chapter 5
Results, discussion and outlook

5.1 GIS analysis of the runoff potential

5.1.1 Procedure of indexing

The different parameters for runoff generation were identified according to their importance. For each parameter a data layer in the raster format was provided for each parameter. The values of each layer were classified and given an index weight according to their importance to runoff generation. Osman (1996) successfully used a similar method in the arid lands of Sudan. Vögtle & Tauer (1991) applied this method to derive result maps for potential site for runoff irrigation in Mali. The layers which were used within the small geographical information system include:

- Slope
- Soil texture
- Vegetation cover
- Soil stoniness
- Antecedent soil moisture by the wetness index of Tasseled Cap transformation
- Flow length.

There were two scenarios evaluated, one including all the layer (Scenario A) (Fig. 5.2) without the layer flow length. The other scenario includes the layer of flow length (Scenario B) (Fig. 5.3). The layer of flow length mainly emphasizes the areas of runoff within the dry rivers. Therefore this scenario is important for evaluation of potential areas to floodwater harvesting. The different layers were indexed resulting in the composite layer or map of potential to runoff. The areas within the research area which are assessed according to their importance to runoff are given various weights according to the ranking. The area showing the highest runoff potential was given the highest rank with 1, the lower potential areas to runoff are assigned a value between 0 and 1. The maximum weight per parameter or layer in Scenario A (with five layers) is at 0.2 (1:5), in scenario B 0.167 (with 6 parameters) (Fig 5.1). The resulting map represents the sum of key numbers of all layers. The indexing method was applied by using the GIS analysis functions of ArcView (ESRI 1995b). The susceptibility to soil crusting is partly shown through the assessment of texture (see Chapter 2.1.4 and 4.3.7) .

The assessment of vegetation and stoniness was based on the land cover classification and field observations (Table 5.1). The vegetation cover which is incorporated in the GIS analysis of runoff potential is based on the land cover classification. The land cover classes, considering the parameters vegetation or stoniness, are ranked according to their contribution to the runoff potential. The dense vegetation within the dry rivers is considered to contribute less to runoff than the scree slopes with sparse vegetation.

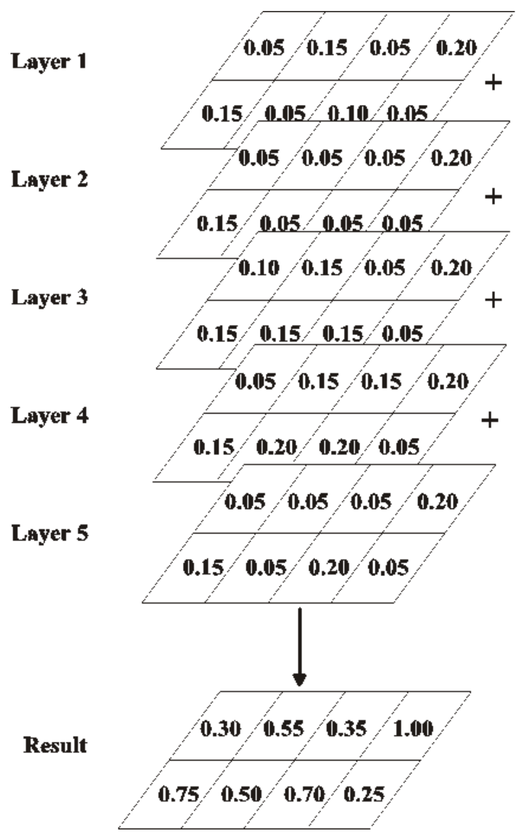

Fig. 5.1 *Calculation of output values by using indexing method for the different layers*

Considering e.g. stoniness, the soils covered by flintstones are considered to have less runoff potential than bare ground. Table 5.1 shows the ranking of the different land cover units according to their stoniness index and plant cover. This assessment is mainly based on the experiences published in the literature or observations during field visits. These assumptions must be proven in the future through direct field measurements of rainfall-runoff relationship on the different land use classes. Transect surveys in a catchment in Burkina Faso provided a catalogue of soil-cover complexes with different hydrological characteristics (Lamachère & Puech 1997b).

The wetness index was incorporated since the satellite images of April 1994 and 1995 were taken just few days after rainfall events recorded at most stations (Table 4.17). The wetness indexes taken from the Landsat TM scene in April 1994 and April 1995 illustrates two conditions of soil moisture (Table 4.16), but a comparison between calculations made with wetness index either of April 1994 or April 1995 did show only minor differences. This allows to take one wetness index as representative for soil moisture condition in the area few days after rainfall events.

The resulting maps (Fig. 5.2 and 5.3) show areas with a high runoff potential mainly on the northwest facing slopes of the mountain ranges of the *Palmyrides*. Here the drainage density is also higher and often leads to gully erosion resulting in badland areas. In the scenario incorporating the flowlength, the beds of the ephemeral streams also show high runoff potential. The ridge at the northwestern corner of the study area (location of a hot spring: *Rutba hamman*) is also characterized by a high runoff potential. The flat rangeland areas north of *Quaryatain* or south of *Tadmor* show lower runoff potentials. Especially the hillslopes covered with flintstones show a low runoff potential since the loose stone cover hampers the runoff.

Table 5.1 *Ranking of surface cover within the research area according to potential to runoff (1 = very low, 2 = low, 3 = high, 4 = very high)*

Land use / land cover classes	Plant cover	Stoniness
Saline soils within the Sabkha, covered with saltcrust	2	4
Gypsiferous salty soils, covered with salty crusts	2	4
Bare ground, low stone cover, no vegetation cover	4	3
Soil surface covered by flintstones	4	1
Scree slopes, degraded area (cover < 5%)	4	1
Sparse vegetation within the steppe area	3	2
Dense vegetation within the wadis	1	3
Rock outcrops: Limestones, basaltic rocks	1	2
Brown clay enriched soils within the area, flooded by	2	4
Agricultural brown soils	1	4
Water	0	0
Orchards of palm- and olive trees	1	4
Agricultural fields	2	4

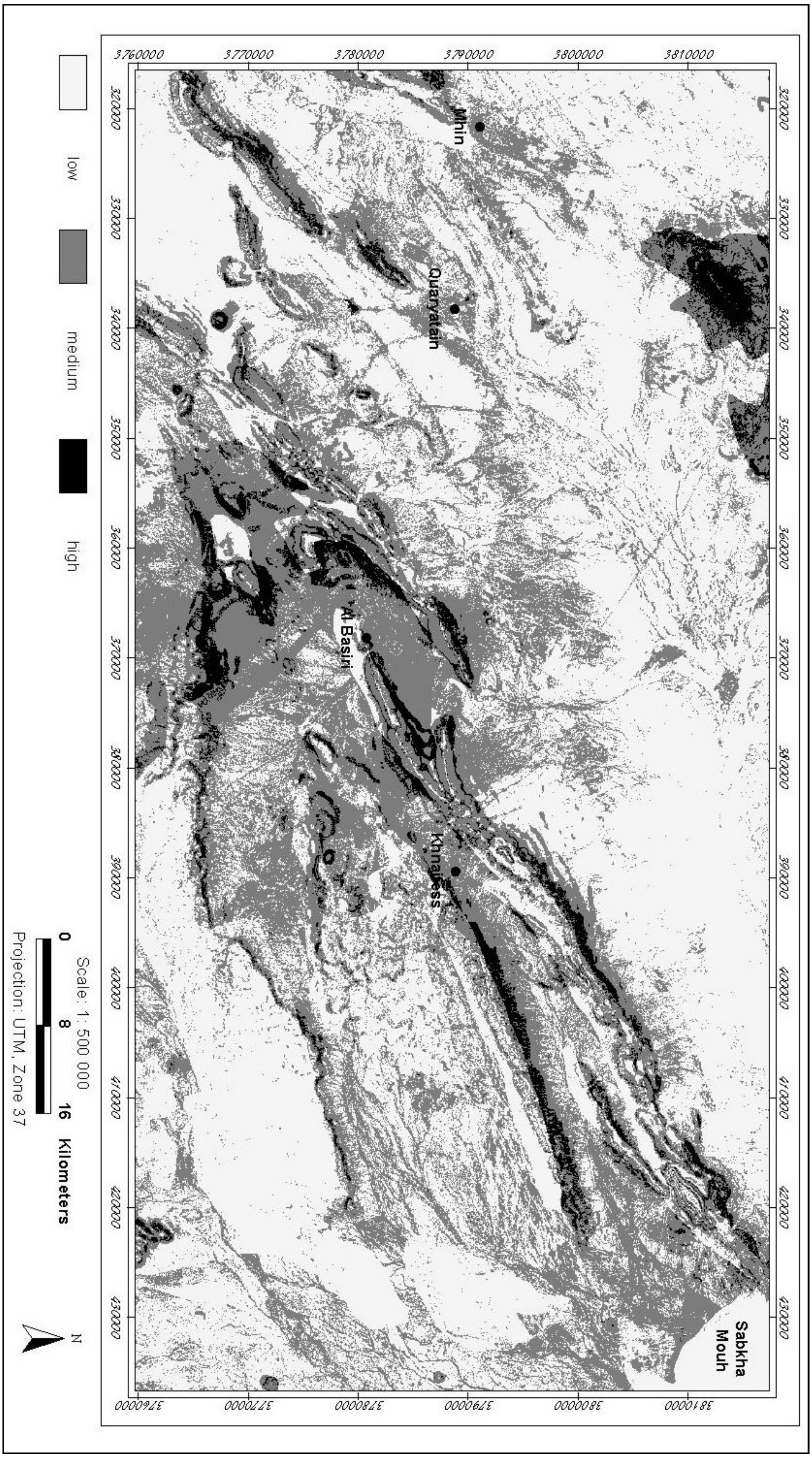

Fig. 5.2 *Potential runoff calculated by indexing method (Scenario A)*

Fig. 5.3 *Potential runoff calculated by indexing method, including the layer of flow length (Scenario B)*

5.1.2 Use of the SCS curve number method

The curve number is dependent on factors such as land cover, soil type and soil texture. The soil is differentiated into 4 hydrological groups (Pilgrim & Cordery 1993) A,B,C,D. The hydrological soil group depends on physical characteristic including soil texture, hydraulic saturated conductivity and soil depth (Table 5.2). According to laboratory and field results the soils of the project area were assigned to different soil groups. Mainly soils of group B and C occurred within the research area. Soils of group B are characterized by moderate infiltration, and a soil texture of moderate fine to moderate coarse, e.g. sandy loam. The clay loams of the flood plain are characterized by slow infiltration, belonging to group C. Soils of group D with slow infiltration such as swelling and plastic clays are only occurring within the *sabkha* area south of *Tadmor*.

Table 5.2 *Hydrological soil group and association of soils within the research area to the hydrological soil group (Rawls et al. 1982)*

Hydrological soil group	Description	Soilscape unit within research area
A	High infiltration, low runoff as for deep sand or loess, aggregated silts	
B	Moderate infiltration, as for moderately fine to moderately coarse-textures soils such as sandy loam	
C	Slow infiltration, as for fine-textured soil such as clay loam, shallow sandy loam, soils low in organic content	A 11 a, A11e, A11c, A12 d E 51 b, E 51 c
D	Very slow infiltration, such as swelling and plastic clays and claypan	A 51 a, A 31 b

Table 5.3 illustrates the different curve numbers which could be applicable within the research area (USDA-SCS 1985) derived from the land use according to classification of the Landsat Thematic Mapper scene (Chapter 4.7) and the hydrological soil group. Since the runoff curve numbers mainly apply to land cover types in North America, other sources have to be considered. Colombo & Sarfatti (1997) adapted the runoff curve numbers to conditions within the semi-arid *Marib* catchment in Eritrea (Table 5.3).

Table 5.3 *Runoff curve numbers for average antecedent moisture condition (AMC II) and I_a = 0.2 S) (SCS 1972; USDA-SCS 1985; ² Colombo & Sarfatti 1997; Rawls et al . 1982) (A-D Hydrological soil group); hydrologic condition: Poor: < 30% ground cover; Fair: 30 to 70% ground cover, Good: > 70% ground cover.*

Land use, crop and management	Hydrol. Cond.	A	B	C	D
Pasture	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Degraded areas (veg. cover < 5%)²	Poor	77	86	91	94
Semi-arid: herbaceous mixture of grass, weeds and low-growing brush, with brush the minor element, poor hydrologic condition	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	35
Sagebrush with grass understory	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub - major plants with saltbush, greasewood, cresotebush, blackbrush, bursage, paloverde, mesquite and cactus	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84
Cultivated with crop rotations Row crops with poor management		72	81	88	91
Irrigated agriculture (furrow irrigation) ²		72	81	88	91
Roads, hard surfaces and roof areas		74	84	90	92
Brush, brush-weed-grass mixture		48	67	77	83
Poor woods, grass combination (orchard)		57	73	82	86
Sabkha		92	94	96	98

Within the project area, the antecedent soil moisture was characterized as dry and average, AMS I and AMS II. The curve numbers for the project area mainly show values around 86, determined on the hydrological soil group and the land cover. Table 5.4 shows the runoff curve numbers for the different land use classes within the project area. The definition of CN values is based on the classification of the Landsat TM scene of April, 4. 1994.

The potential annual rainfall is not useful for the application of the method since the water harvesting design is based on single rainfall events. Therefore the calculation was based on extreme rainfall events with a 2-year return period (Fig. A-4). The calculation process was done using the geographical information system analysis by ArcView (ESRI 1995b). Fig. 5.4 shows the resulting map of potential runoff for the project area. Maximum potential runoff is around 20 mm in the southern part of the research area and the *Ad-Dauw* basin (North western part). Around *Tadmor* the potential runoff volume is lower (10 – 14 mm).

Table 5.4 *Curve numbers of land use classes within the research area*

Land use / land cover classes	Curve number	Hydrological soil group
Saline soils within the Sabkha, covered with saltcrust	98	D
Gypsifereous salty soils, covered with salty crusts	96	C
Bare ground, low stone cover, no vegetation cover	91	C
Soil surface covered by flintstones	88	C
Scree slopes, degraded area (cover < 5%)	91	,C
Sparse vegetation within the steppe area	81	C
Dense vegetation within the wadis	74	C
Rock outcrops:limestones, basaltic rocks	90	C
Brown clay enriched soils within the area, flooded during rainstorms	79	C
Agricultural brown soils	77	C
Water	88	
Orchards of palm- and olive trees	82	C
Irrigated agricultural fields within rangeland	88	C

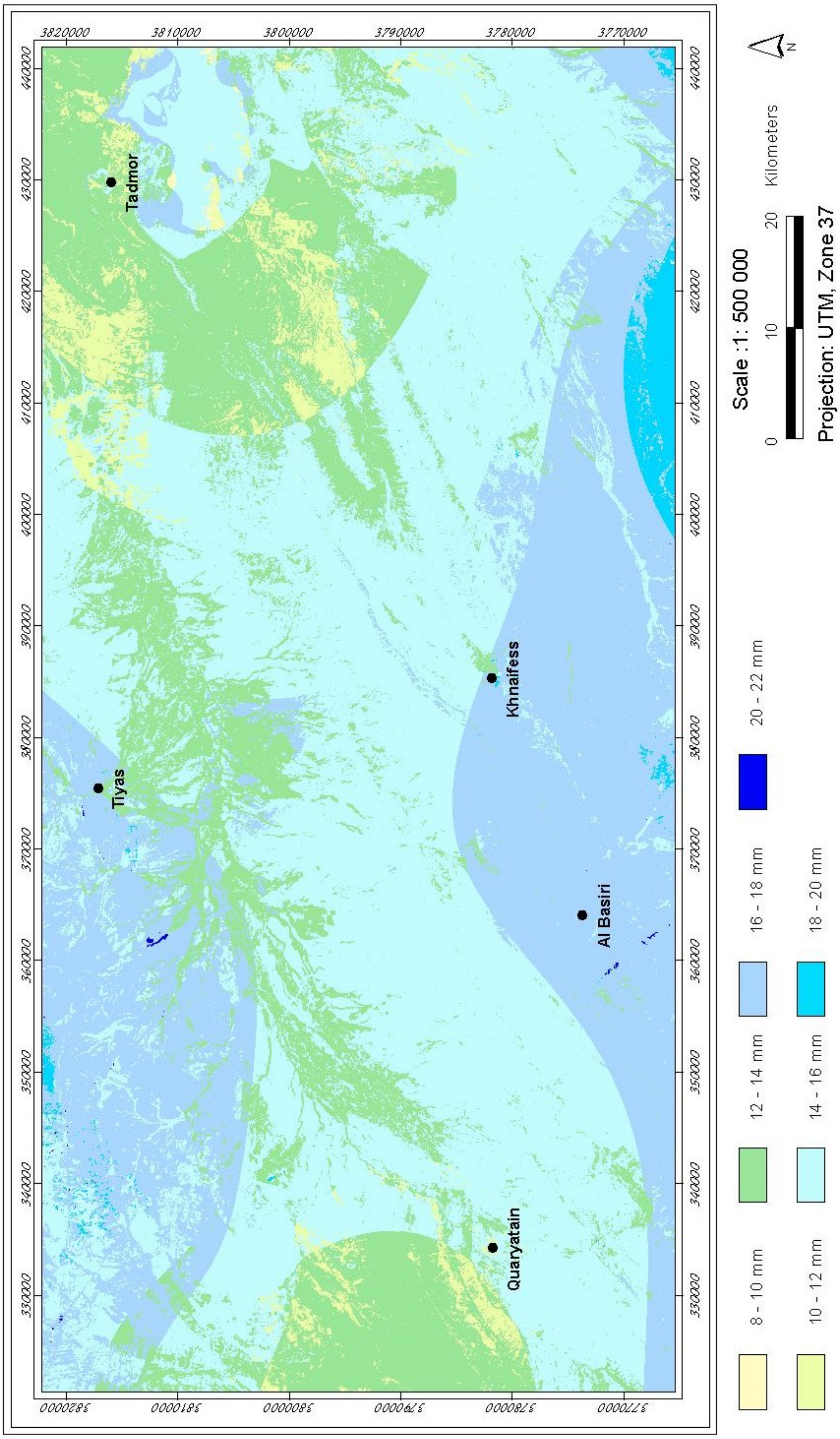

Fig. 5.4 *Potential runoff calculated by SCS method*

5.1.3 Comparison between the two methods

The indexing method illustrates the natural prerequisites for runoff. It shows if a site would probably produce more or less runoff. The quantity could not be assessed by the indexing method. If measurements of local rainfall/runoff events are available, runoff coefficients for the sites could be computed and then regionalized considering the results of the indexing method.

Runoff coefficients relate the runoff amount to a certain rainfall event (see Chapter 5.3.2):

$$R = r_c * P \qquad [5.1]$$

R = runoff volume [mm]
P = effective rainfall amount [mm]
r_c = runoff coefficient

The results of the SCS method reveal information concerning the potential quantity of runoff: Here the values rise to 17 to 18.5 mm runoff calculated with a rainfall of a 2-year return period. It shows less runoff potential around *Tadmo*r than the indexing method. Also around *Quaryatain* and *Mhin* the runoff potential is estimated less than by the indexing method. The runoff potential from the mountain ranges is also underestimated within the SCS curve number method. The SCS curve number method depends on regionalized rainfall which is extremely difficult to determine in semi-arid areas where rainfall is scarce. Rainfall measurements at one station are therefore only valid for a small area around the station itself. Therefore the network of stations where rainfall data are available for the research site is insufficient to show the real variations of rainfall. Therefore the indexing method should be preferred in the research area since it considers the determinants on runoff generation such as topography better.

5.2 Use of AHP

5.2.1 Method

A three and a four-level model have been chosen for the present study, including (1) the objective, (2) the criteria, (3) the sub-criteria and (3) or (4) the alternatives of criteria. A suitability index of land to be used for micro- / macrocatchments or floodwater harvesting systems has been developed. The criteria are classified into alternatives which are compared in pairs. The factors are not based on experiments, but based on the experiences made in the research area or areas with similar hydrological conditions. The eigenvectors and finally the importance values show the ranking of the different classes of one criteria. The sum of the product of the importance value of second level and ranked class or alternative of criteria then leads to suitability of the land to micro-/ macrocatchment (Chapter 3, Fig. 3.3) or floodwater harvesting systems (Chapter 3, Fig. 3.4).

One of the criteria is based on the exclusion of sites to be used for the construction of water harvesting structures. This refers to military or industrial sites, such as the phosphate mines within the project area. Additionally, a buffer zone of 2 km and areas of badlands with deep erosion channels are also excluded from the analysis. The buffer zone around industrial sites within the region which are mainly the phosphate mine is greater than 2 km since the mining activities need more space (deposition of slag heaps, etc.). They are mainly situated within the mountain ranges of the *Southern Palmyrides*. The zones of military areas or industrial sites were directly digitized using the satellite scene and background information collected during the field trips. The badland areas can only be partly depicted on the satellite image. Here rough GPS measurements were used to demarcate the areas. The buffer zones were established using the GIS system ArcView (ESRI 1995b). Afterwards the vector layer is converted in raster format. The relative importance weights for each zone were added within an attribute table to the vector layer (Fig. B-11).

Table 5.5 *Ranking of alternatives of criteria proximity to industrial and military sites and badlands*

Proximity to industrial and military sites and badland areas	0 – 5 km	5 - 10 km	> 10 km	Eigenvector	Relative importance weight
0 - 2.5 km	1	1/5	1/7	0.31	0.07
2.5 - 10 km	5	1	1/3	1.19	0.28
> 10 km	7	3	1	2.76	0.65

The proximity to roads is important to access water harvesting sites, e.g., to deliver construction materials. In case of micro- /macrocatchment suitability, the proximity to roads also allows inclusion of runoff from the roads for irrigation of cultivated patches in the ditches adjacent to the roads. 200 m is a sufficient distance from the road to avoid direct pollution but still to guarantee enough runoff volume. Different classes were defined and their relation to each other is determined. The different classes are ranked according to the importance weights (Table 5.6). The buffer of 200 m and more along the roads (Fig. B-

13) was made similarly to the definition of the layer of military sites and industrial sites.

Table 5.6 *Ranking of alternatives within criteria proximity to the road, used in defining the potential areas to micro- / macrocatchment systems*

Proximity to road	0 - 0.2 km	0.2 – 1 km	1 - 10 km	> 10 km	Eigenvector	Relative importance weight
0 - 0.2 km	1	3	5	7	3.20	0.56
0.2 – 1 km	1/3	1	3	5	1.50	0.26
1 - 10 km	1/5	1/3	1	3	0.67	0.12
> 10 km	1/7	1/5	1/3	1	0.31	0.06

The importance of the different alternatives is evaluated in pairs for each level. Two scenarios were evaluated for the potential runoff: one scenario was calculated with the outcome of the SCS method (Scenario 1) (see Chapter 5.1), the other one with the results of the indexing method (Scenario 2). The areas of runoff potential were classified into low, medium and high potential (Table 5.7).

Table 5.7 *Ranking of classes of runoff potential determined by use of SCS method (Scenario 1) or indexing method (Scenario 2)*

Runoff potential	Low	Medium	High	Eigenvector	Relative importance weight
Low	1	1/5	1/9	0.28	0.05
Medium	5	1	1/7	0.89	0.17
High	9	7	1	3.97	0.77

The land cover classes determined by use of remotely sensed data (see chapter 4.7) were combined with the soilscape classes (Table 5.9). These terrain units are only regarded in function to hydrological parameters. The infiltration characteristics and runoff behavior leading to the classes of soilscape units have already been thoroughly discussed in chapter 4.3.

The suitability of the different soils to be used for cropping regarding parameters such as organic matter is not considered and has to be explicitly investigated with regard to the crop system for cultivation.

For the terrain units, two different classifications were evaluated, one for the suitability as a catchment area and another one for the suitability to water concentrating area. The suitability index of terrain unit to water concentrating area was chosen in the case of micro- / macrocatchment suitability (Table 5.8). Concerning floodwater harvesting systems, the suitability index to catchment was considered (Table 5.10) within level 4 of the AHP.

The terrain unit area covered with flintstones mainly belongs to the soil unit of E51b (see chapter 4.3). The soils are shallow and fine-textured. Since the flintstones presents a rather high dense pavement on soil surface, they are more useful for catchment areas. The flint plateaus in a watershed in the Israelian *Negev* desert show lower infiltration rates, around 10 mm h^{-1} (Greenbaum 1986). Neighboring areas with sediments on Pleistocene beds show higher infiltration rates (up to 20 mm h^{-1}) (Greenbaum 1986; Lange 1999).

The bare ground and the rock outcrops within the mountains of the *Southern Palmyrides* are within the soil unit *E51c*, characterized by soils of a depth of 20 to 30 cm. They are considered to be of very low use to water concentrating areas and are therefore characterized by a higher suitability to catchment areas. The rock outcrops within the *Southern Palmyrides* are comparable to the limestone plateaus within the *Nahal Zin* watershed in the *Negev* with very low infiltration rates (5 mm h^{-1}) (Lange 1999). A lot of colluvial material is found at the bottom of the slopes with rock outcrops with higher infiltration rates and less runoff (Yair 1983).

The scree slopes and rangeland area east of the axis *Tadmor - Al Basiri* are mainly characterized by soils of the unit *A 11c*. These soil are characterized by a texture of 20% clay, about 40% each of silt and sand. This soilscape unit is mainly characterized through deeper soils, often fluvial sediments with higher infiltration characteristics.

The areas of dense vegetation in the dry ephemeral channels are nine times more suitable as water concentration areas than the rock outcrops of limestones or basalts on the soil units of the *Torrifluvents* of soil unit *E51c*. The irrigated barley fields within the steppe area have a five times greater preference as water-concentration area than the rangeland areas with sparse vegetation. The factor five has to be understood as a relational factor. It is not based on experimental data such as infiltration values, but illustrates the importance of the values compared to the others. The eigenvector values and the relative importance weights provide the rankings of the different values.

Table 5.8 *Comparison of pairs of terrain units designed for the determination of potential areas for water-concentration*

	Classes 1, 4	**Classes 2, 3, 5**	**Class 6**	**Class 7**	**Class 8**	**Eigenvector**	**Relative importance weight**
Classes 1, 4	1	1/3	1/5	1/7	1/9	0.25	0.03
Classes 2, 3, 5	3	1	1/7	1/8	1/9	0.36	0.04
Class 6	5	3	1	1/3	1/5	1.00	0.12
Class 7	7	8	3	1	1/7	1.88	0.23
Class 8	9	8	5	7	1	4.79	0.57

Table 5.9 *Characterization of soilscape units used within the analytical hierarchical process*

Terrain unit	Land cover	Soilscape unit	Soil texture	Soil surface	Topography	Runoff and infiltration characteristics
Class 1	Rock outcrops of limestones or basalts	*E51c*			Steep slopes	Low infiltration, high runoff rates
Class 2	Bare ground, degraded area (< 5% vegetation cover)	*A11c*	Sandy, clayey loams	Soil crust	Flat terrain, gentle slopes	Infiltration rates vary extremely, high runoff rates at beginning of rainstorm
Class 3	Hillslopes covered by flintstones	*E51b*	Clayey loams	Pavement of small stones	Gentle slopes	Pebbles often embedded, higher runoff rates
Class 4	Sabkha sediments	*A31b, A51a*	Silty loams	Soil crust, salt crust	Flat terrain, gentle slopes	High infiltration rates, low runoff rates
Class 5	Scree slopes, rangeland	*A11c, A11b, A11e A12d*	Sandy, clayey loams	Intercalating with rock outcrops, size of rock fragments varies, colluvium at the foot	Steep slopes	Runoff rates depending on steepness of slope, amount of rock outcrops
Class 6	Sparse vegeation on rangeland and scree slopes	*A11c, A11a*	Sandy, clayey loams	Size of rocks smaller than class 5	Steep slopes	Runoff rates lower than on scree slopes without vegetation
Class 7	Dense vegetation within ephemeral streams	*A11c*	Conglomerates, pebble beds	Size of rock fragments varies	Flat terrain	Infiltration rates vary, depending on clayey channel beds, high runoff rates during extreme events
Class 8	Agricultural area	*A11c*	Silty, clayey loams	Clayey soil crust, especially if irrigated	Flat terrain, gentle lopes	High infiltration rates, low runoff rates

Table 5.10 *Comparison of pairs of terrain units designed for the determination of potential areas for catchments*

	Class 4	Class 7, 8	Class 3, 6	Class 5	Class 2	Class 1	Eigenvector	Relative importance weight
Class 4	1	1/2	1/3	1/3	1/5	1/9	0.33	0.03
Class 7, 8	2	1	1/5	1/3	1/7	1/9	0.36	0.03
Class 3, 6	3	5	1	2	1/3	1/7	1.06	0.11
Class 5	3	3	1/2	1	1/5	1/5	0.75	0.08
Class 2	7	7	3	5	1	1/3	2.50	0.26
Class 1	9	9	7	5	3	1	4.52	0.47

The proximity to settlements is one of the criteria also used in both processes for determination of suitability (Table 5.11). In the case of suitability to floodwater harvesting systems it is combined with the proximity to roads (Table 5.10).

Table 5.11 *AHP matrix for the criteria of proximity to settlements*

Proximity to settlement	0 - 5 km	5 - 10 km	> 10 km	Eigenvector	Relative importance weight
0 - 5 km	1	5	7	3.27	0.67
5 - 10 km	1/5	1	5	1.00	0.21
> 10 km	1/7	1/5	1	0.58	0.12

Another important criteria to differentiate between suitable areas to micro-/ macrocatchment or floodwater harvesting systems is the topography, the slopes. Table 5.12 and 5.13 show the ranking of the various slope classes. The slope classes of lower ranges are preferred in the case of micocatchment systems , whereas more inclined slopes are more suitable in the case of floodwater harvesting systems.

Table 5.12 *Suitability of land to floodwater harvesting systems according to slope classes within AHP*

Slope	1-3%, 3-10%	10-20%	> 20%	Eigenvector	Relative importance weight
1 - 3%, 3 - 10%	1	7	9	3.98	0.58
10 - 20%	1/7	1	7	1.91	0.28
> 20%	1/9	1/7	1	1.00	0.15

Table 5.13 *Slope categories according to suitability to micro-/ macrocatchments within AHP*

Slope	1-3%	3-10%	10-20%, > 20%	Eigenvector	Relative importance weight
1-3%	1	7	9	3.97	0.78
3 - 10%	1/7	1	3	0.75	0.14
10 - 20%, > 20%	1/9	1/3	1	0.33	0.06

Table 5-14 and Table 5-15 show the matrix of criteria used to determine potential sites for micro- / macrocatchment and floodwater harvesting systems within the project area. To identify the potential areas for floodwater harvesting systems it is also necessary to consider the proximity to water concentration areas.

Table 5.14 *Matrix used to assess suitability of land to micro- / macrocatchment systems within the project area. (A = settlement, B = proximity to military, industrial sites and badland areas, C = terrain unit, D = proximity to roads, E = slope, F = runoff potential)*

	A	B	C	D	E	F	Eigenvector	Relative importance weight
Settlement	1	3	5	1/5	1/7	1/5	0.36	0.13
Proximity to military, industrial sites and badland areas	1/3	1	3	1/5	1/5	1/5	0.38	0.14
Terrain unit	1/5	1/3	1	1/3	1/5	1/7	0.39	0.15
Proximity to roads	5	5	3	1	1/3	1/5	0.58	0.21
Slope	7	5	5	3	1	1/3	1.00	0.37
Runoff potential	5	5	7	5	3	1	1.72	0.63

Slope and runoff potential are the most important citeria on the selection of potential areas for micro- / macrocatchment and floodwater harvesting systems. The terrain unit is then the next most important criterion whereas the criteria of proximity of the site to settlement was considered to be the least important. In the current study mainly the natural constraints are considered. Since most of the micro- / macrocatchment or floodwater harvesting systems within the scope of the study are understood to be used for fodder production or to improve rangeland vegetation the distance to settlement areas is less important. Additionally the rangeland is mainly used for livestock production for the Bedouins who nowadays use trucks to transport their flocks to the grazing areas. Since socioeconomic data have not been available during the studies, the importance of the natural constraints are probably overestimated. Different scenarios have been evaluated with different ranking of the criteria, but the scenarios presented in Tables 5.14 and 5.15 seemed to be the most appropriate. The calculation was done using the Analysis Function of ArcView (ESRI 1995b).

Table 5-15 *Matrix used to assess suitability of land for floodwater harvesting systems within the project area. (A = settlement, B = proximity to military, industrial sites and badland areas, C = hydrological terrain unit, D = slope, E = runoff potential)*

	A	B	C	D	E	Eigenvector	Relative importance weight
Settlement/roads	1	3	1/5	1/7	1/7	0.41	0.06
Proximity to military, industrial sites and badland areas	1/3	1	1/5	1/5	1/5	0.31	0.04
Terrain unit	5	5	1	1/3	1/5	1.11	0.15
Slope	7	5	3	1	1/3	2.04	0.28
Runoff potential	7	5	5	3	1	3.50	0.48

5.2.2 Results

The resulting maps (Fig. 5.5 – 5.8) only show proposals where water harvesting systems can be established. It is impossible to draw conclusions on how much water could be harvested on the various potential sites. The information needed for this quantification could only be found by making experiments such as runoff simulation experiments.. Concentration on the influence of the main parameters has allowed the major conclusions to be made. The maps only depict potential to water harvesting, further on-site investigation will provide more basic information such as e.g. the influence of soil crust.

The outcome of the evaluation is shown in Fig. 5.5 , 5.6, 5.7 and 5.8. The results are classified into five suitability classes,

- more favourable
- less favourable
- more suitable
- less suitable and
- not suitable.

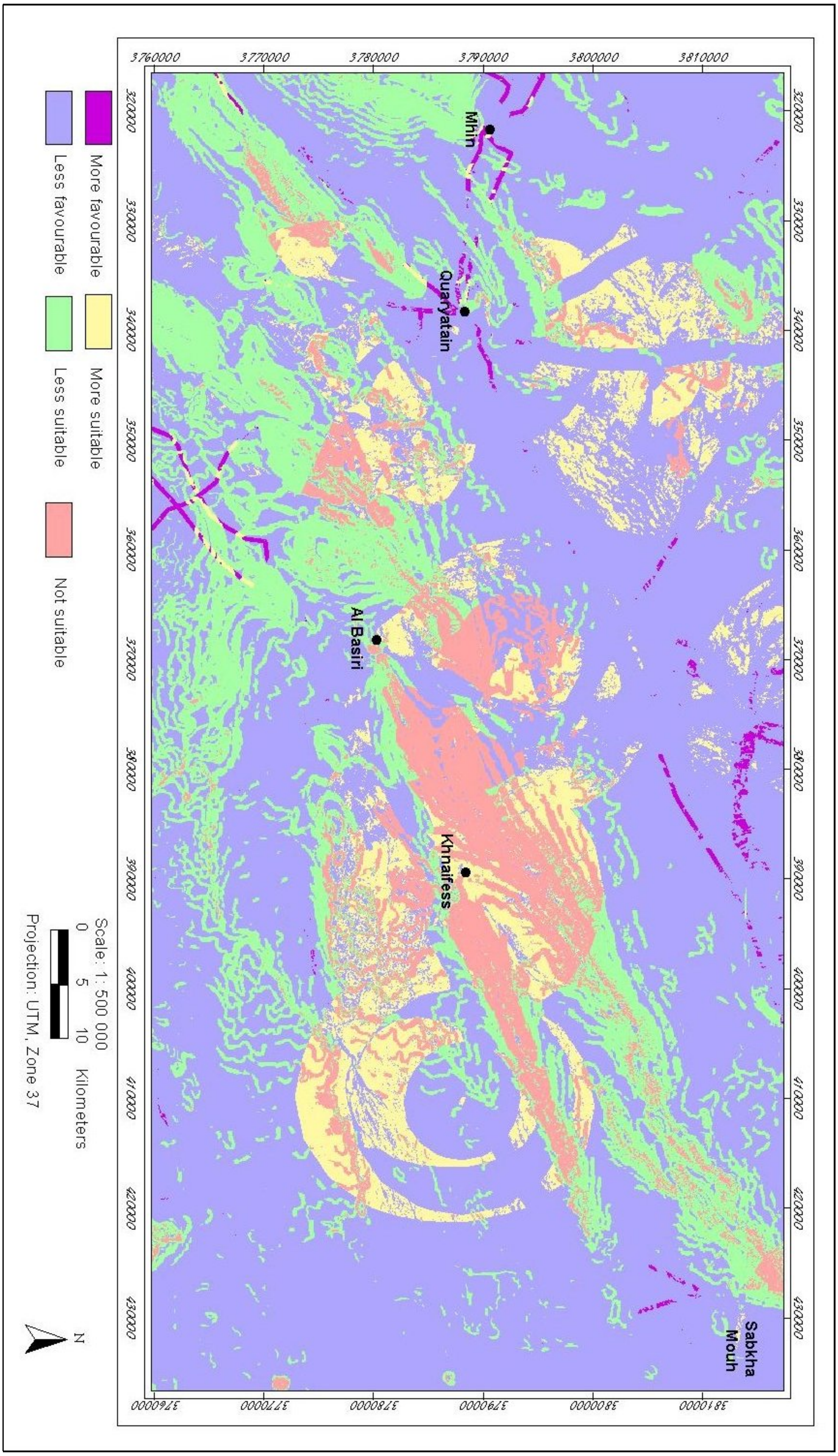

Fig. 5.5 *Potential areas of micro / macrocatchment systems, Scenario 1 (calculated with runoff potential, resulting from SCS method)*

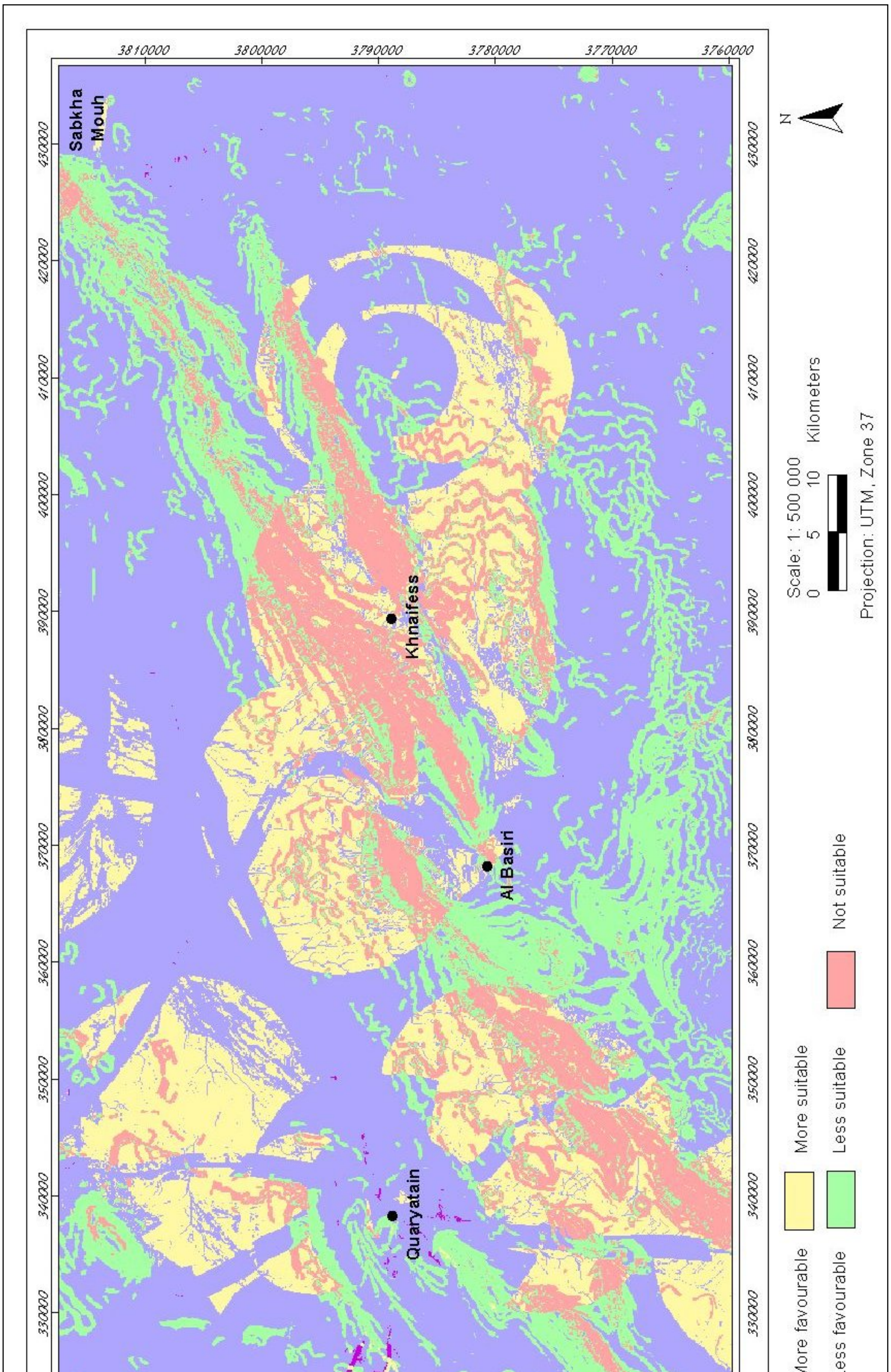

Fig. 5.6 *Potential areas of micro- / macrocatchment systems, Scenario 2 A (calculated with runoff potential, resulting from indexing method)*

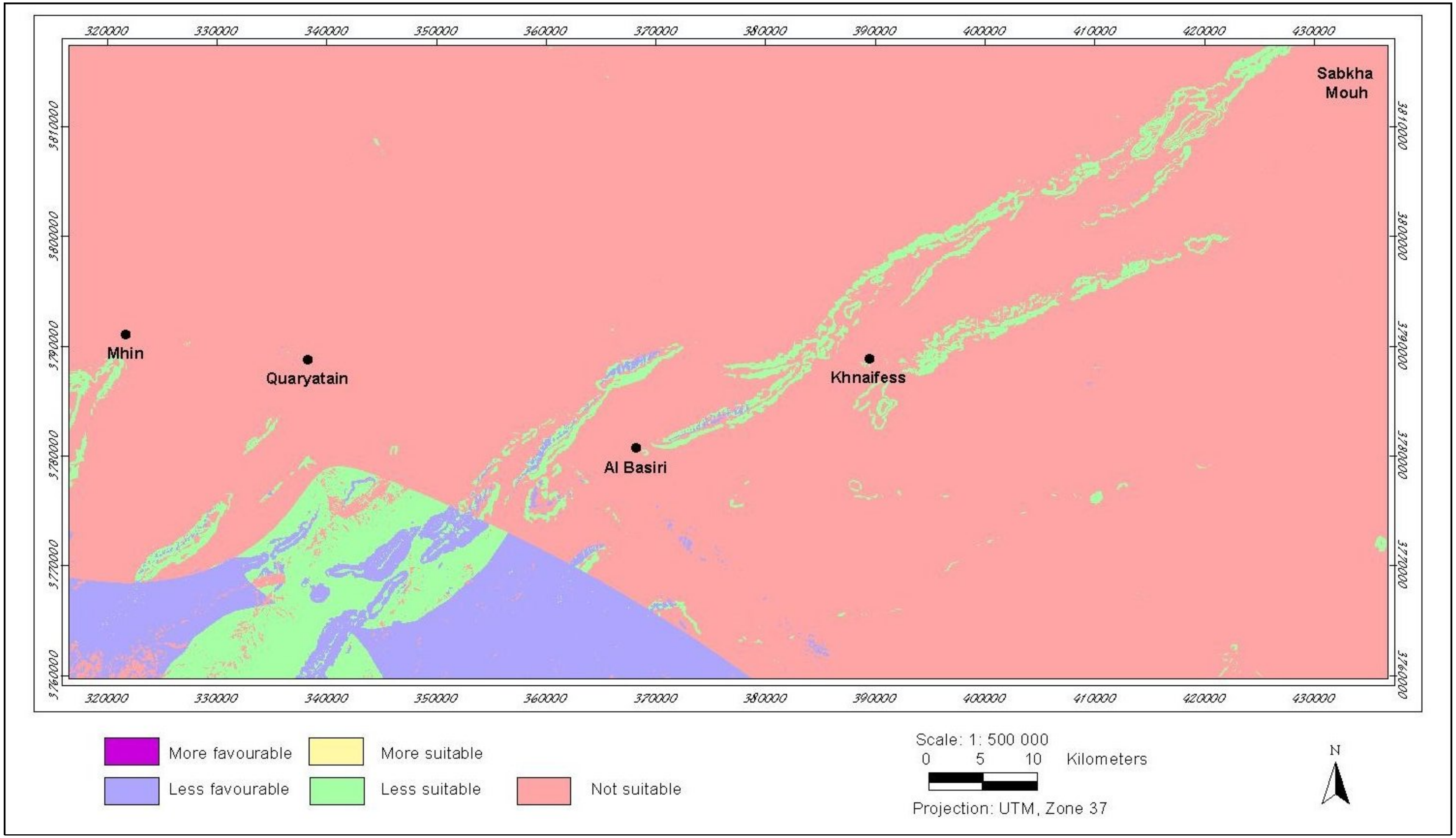

Fig. 5.7 *Potential areas for floodwater harvesting systems, Scenario 1 (calculated with runoff potential, resulting from SCS method)*

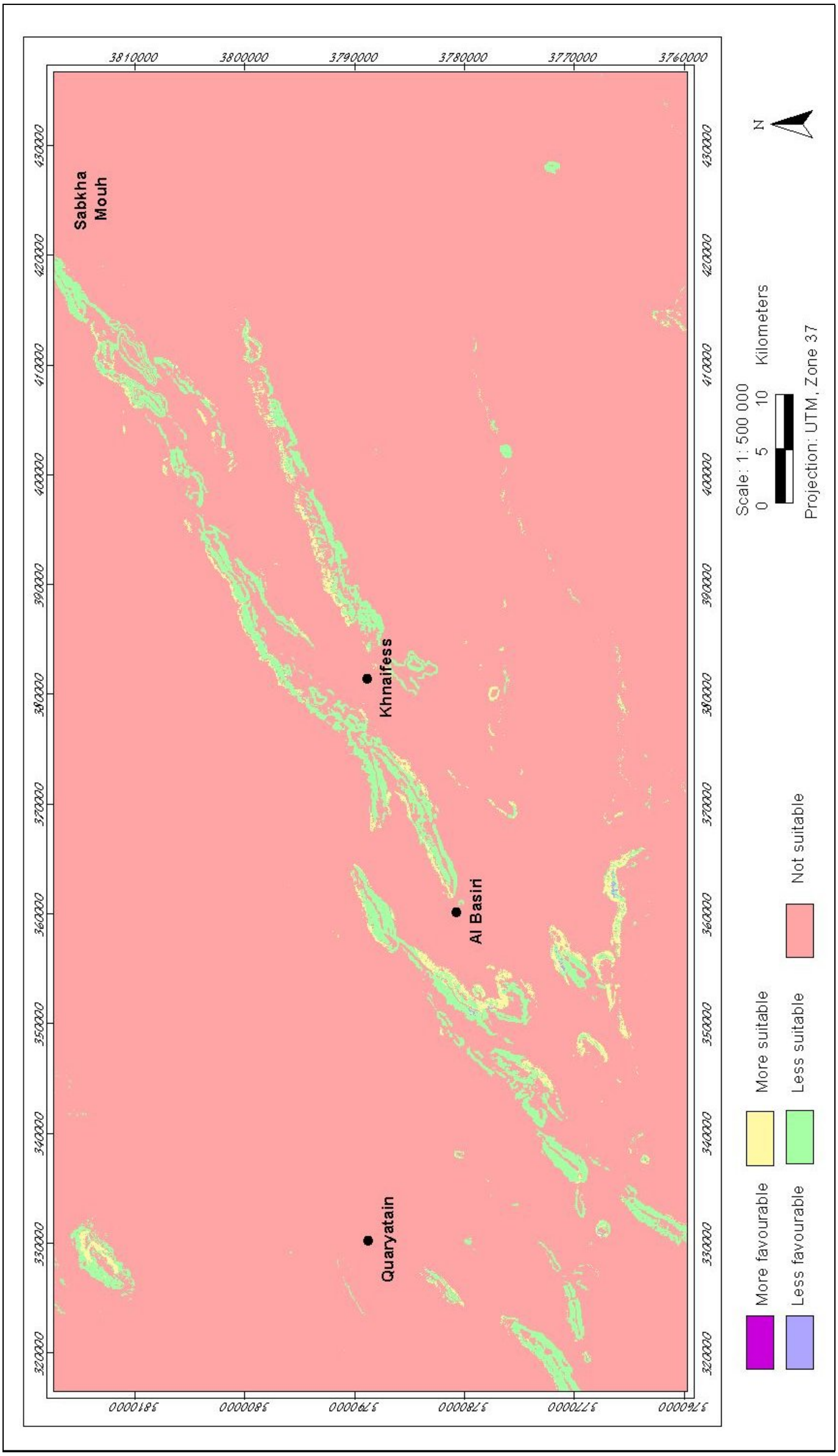

Fig. 5.8 *Potential areas for floodwater harvesting systems, Scenario 2 A (calculated with runoff potential, resulting from indexing method)*

The more favourable areas to both systems are found in the southwestern part of the project area. Most of the flatter terrain south of *Tadmor* is favourable for use for micro- or macrocatchment systems. Unsuitable areas are mainly the rock outcrops and upper slopes of the *Southern Palmyrides*. The region of *Wadi Ar Rauw* is also classified as favourable. More favourable areas are found according to the analysis along the roads near *Quaryatain*. The differences between the two scenarios are few. The area east of *Khnaifess* is classified less suitable than the surrounding areas. This is probably due to the layer of interpolated rainfall volumes. Since the slopes are based on a Digital Elevation Model with a resolution of 100 m and the slopes are therefore exaggerated.

The results of the two scenarios differ more concerning the suitability for floodwater harvesting systems. Both recognize the mountain ranges as the more suitable areas. In the southwestern part there is a more suitable area for floodwater harvesting systems according to the analysis with the SCS derived runoff potential. This is probably due to the favourable rainfall distribution in this part.

5.3 Discussion

5.3.1 Use of new remotely sensed data products

The current study has led to results concerning the potential suitability of the region to water harvesting systems. The use of remotely sensed data from other sensors allows improvement of the knowledge on hydraulic parameters. The temporal resolution of the Landsat system is restricted: the repeat cycle of 16 days is often too long to attain data shortly after a rainfall event. The Indian satellite IRS (repeat cycle of 22 days) or the satellite SPOT (repeat cycle of 26 days) are no alternatives. Airborne multispectral scanners are an alternative such as the **T**hermal **I**nfrared **M**ultispectral **S**canner (TIMS) offering an alternative for exact definition of the time of data acquisition, angle and spatial resolution. Due to spectral emission features of the thermal infrared, clay silicates in soils can be detected by the TIMS. This maybe permits distinction between different soil types (Richards & Jia 1999) if there is no vegetation which will reduce field campaigns. Drawbacks are the high costs and the political restrictions concerning airborne missions in some areas.

To attain more information on soil crusts, the use of imaging spectrometers (e.g. CASI, Itres Research) 288 channels over the visible and near infrared range (0.4 to 0.9 µm) within the field would be convenient. The comparison of these measurements with satellite data from the same date would probably improve distinction between different soil surfaces. Geerken (1997) differentiated terrain units by parameters of vegetation density, vegetation type, soil type and occurrence of sand cover within the *Bishri* Mountains. He compared the radiometric measurements of the handheld spectrometer with the spectral classes of the Landsat TM images. The comparison of these measurements with the spectral classes fund within the Landsat TM images might improve the classification of the Landsat TM images.

Information on soil moisture is nowadays investigated using the microwave techniques (see chapter 2.5.4). MONSOON 90 and 91 have been research campaigns investigating the effects of changing soil moisture on the hydrologic behavior of a semi-arid rangeland catchment, the Walnut Gulch Experimental Watershed. Passive microwave soil moisture measurements were compared to measured rainfall and modelled soil moisture to reach conclusion on the antecedent soil moisture (Goodrich et al. 1994). The most promising systems in investigating soil moisture for studies in watersheds have active systems, transmitting electromagnetic waves towards the target. The reflected waves are recorded and analysed in order to derive information on the physical behavior of the target. The Canadian RADARSAT, the Japanese earth resources satellite JERS-1 (ESA 2003a)and the European ERS 1,2 (ESA 2003b,c) provide spatial resolutions in the range of 18 to 30 m. Data of JERS-1 or ERS-1,2 could be obtained for the project area (ESA 2004). But the active microwave systems have a high sensitivity to roughness, topographic features and vegetation (Engman 2000). Then software has to be used being capable of correcting the effects of terrain on the data. Up to now no algorithm is known which allows to extract directly volumetric soil moisture from the microwave measurements in every area (Neusch 2000, Engman 2000). Most models are only valid for a specific area. But the high sensitivity to roughness of the microwave systems might allow accurate measurements of another parameter important to runoff over large areas: soil roughness or stoniness of the soil.

Since data on hillslope gradient are one of the most important criteria for the selection process for water harvesting sites, the accuracy of the SRTM is important. The current available digital elevation model has only a vertical resolution of 10 m and a horizontal resolution of 100 m which results in a rough estimate of the slope, especially in flatter areas. The calculation of a DTM with the stereo *SPOT* images produces a DTM with 10 m horizontal resolution and a vertical resolution up to 5 m in ideal cases (Case 1989, Dubayah et. al., 2000).

Nowadays modern techniques such as inferometric **S**ynthetic **A**perture **R**adar (SAR) allow generation of high quality DTM. Multiple sensors survey the ground and are then combined into the resulting image. The resolution is typically between 3 and 70 cm according to the X-band and P-band. Since the microwave reflectance is dependant on soil roughness and vegetation cover, this so-called back scatter coefficient would influence the accuracy of the DTM. With the low level land the accuracy of a terrain model would be sufficient but with high sloping lands of the *Palmyrides* the level of accuracy would probably coincide with the accuracy of the current DTM.

Another alternative is the digital elevation model performed according to data from the X-band of the **S**huttle **R**adar **T**opography **M**ission (SRTM) on February 11-22, 1999. The continental set on Western Eurasia is available since beginning of 2004 (NASA 2004). The digital elevation model will have a horizontal resolution of 17 to 25 m with an elevation range of 1 m (DLR 2002a) without vegetation cover. Studies have already been launched investigating e.g. the further application of the X-SAR data (DLR 2002b). With inferometric SAR accuracies of 5 (aeroplane) and 10 m (satellite) have been achieved (Kraus 2000b) But the inferometric SAR is still in the pre-operational stage.

Laser altimetry has been successfully used during the last years within the Rhine valley. In Germany, data were generated with a grid size of 1 m used for hydrological applications such as flood plain determination along the Rhine valley (Toposys 1998). The laser (wave length of 1540 nm, (Toposys 1998, Kraus 2000a)) is installed on the plane. A differential GPS is needed to calculate the polar coordinates within the terrain. The accuracy of the differential GPS also defines the accuracy of the resulting DTM. Since the laser reflects at vegetation such as trees or bushes, in highly vegetated areas complex filtering processes are needed to reach the earth surface. Therefore this technique could be successfully applied, especially in an area with low vegetation such as the research area.

Therefore this techniques would provide an alternative to intensive geodetic fieldwork and would allow to derive an accurate DTM over an large area. It could be then also used within the process of design and outline of water harvesting sites after selecting pilot study areas.

5.3.2 Use of rainfall-runoff experiments to determine runoff coefficients needed for design of water harvesting systems

The differentiation of terrain units within the study area could be improved by experimentally investigating the hydrologic behavior: The set up of rainfall simulation experiments would allow collection of the missing data on runoff. The potential map of the current study could be used as basis for selection of a rainfall-runoff experimental plot site. Effects such as clearing of stones from the e.g. flint covered slope could be studied. Maybe there is nowadays open access to runoff data collected at the *Mihassa* test site. These measurements could then be used for the validation of simulation modeling of a water harvesting system. Cohen et al. (1997) developed a simple water balance model with few parameters for small scale water harvesting systems such as contour strips. Input parameters include initial soil moisture content, threshold runoff function dependent on soil type and crop water requirements. The measured and simulated rainfall-runoff relationships will be the basis for the design of water harvesting systems in the project area since they will allow to calculate runoff coefficients.

Runoff coefficient - one of the design criteria for water harvesting systems

The runoff coefficient is an important factor for design of water harvesting systems. Table 5.16 shows runoff coefficients measured at sites within semi-arid regions. It was also differentiated on experimental (runoff simulation) and observed data. Some of these sites are integrated within rainwater harvesting systems (Eger 1986, Abu - Awad & Shatanawi 1997, Sharma 1986, Soumi & Abdul Aal 1999). The runoff coefficient varies normally between 0.1 to 0.5 according to Critchley & Siegert (1991), greater coefficients are observed on barren rocks or treated surfaces. A lot of research was done on ameliorating the runoff coefficient within catchment systems by spraying the soil cover with impermeable material such as bitumen or wax (Frasier et al. 1979). These measures are very costly especially for large areas and often cause environmental problems.

Table 5.16 *Runoff coefficients calculated for runoff events in semi-arid regions (observed=x, simulated=-)*

Site	Runoff coefficient r_c	Rainfall intensity [$mm \cdot h^{-1}$]	Obs./ Sim.	Reference
Loamy sand, sand and gravel deposits in Yemen	0.11 - 0.5	>5	x	Eger 1986
Flat terrain on aridisoils at Muwaqquar (Jordan)	0.03 - 0.5		x	Abu - Awad & Shatanawi 1997
Semi-arid catchment in Southern Spain	0.4 - 0.85		-	Nicolau et al. 1996
Semi-arid catchment in *Negev* (*Avdat* Farm)	0.15 - 0.66		x	Evenari et al. 1982
Contour strips at *Mihassa* (Syria), slope 5-7%	0.15 - 0.5	2 - 6	x	Soumi & Abdul Aal 1999
Microcatchments on sandy loams in Indian Arid zone	0.2 - 0.36 (uncrusted) 0.5 (crusted)		x	Sharma 1986

The other factors are the design rainfall, the crop water requirements and the efficiency factor. These allow calculation of the required ratio of catchment area to cultivated area.

$$\frac{Q_{cp} - P_D}{P_D \times r_c \times f_e} = \frac{C}{CA} \qquad [5.2]$$

Q_{cp} = Crop water requirement
P_D = Design rainfall
r_c = Runoff coefficient
f_e = Efficiency factor
C = Catchment area
CA = Cultivated area

The design rainfall is the amount of rainfall which is sufficient to meet the crop water requirements. The efficiency factor takes into account losses of water due to evaporation or uneven distribution of runoff on the catchment area. The efficiency factor is usually between 0.5 and 0.75 (Critchley & Siegert 1991).

Crop water requirements comprise "the depth of water needed to meet the water loss through evapotranspiration (Et_{crop}) of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment" (Doorenbos & Pruitt 1984). The crop water requirements are related to the reference evapotranspiration by the crop coefficient k_c. One calculation procedure splits k_c (= dual crop coefficient) into two separate coefficients, one for crop transpiration, i.e., the basal crop coefficient (K_{cb}), and one for soil evaporation (k_e) (Allen et al. 1998).

There are several programmes on the market allowing calculation of irrigation requirements for plants. The programme of FAO, CROPWAT was used for the current work . The longterm climatic data of *Tadmor* distributed within the CLIMWAT directory were used to calculate crop water requirements. Crop water requirements of barley resulted in 135 mm over the period of four months, assuming a planting date at the beginning of November.

Considering pasture, crop water requirements are around 1800 mm. With an effective rainfall of 70 mm the irrigation requirement would be 1760 mm. The crop water requirements are calculated according to the equation (Doorenbos & Pruitt 1984):

$$CWR = k_c \times ETO \times a_{pl} \quad [5.3]$$

k_c = crop coefficient
ETO = evapotranspiration
a_{pl} = planted area

CROPWAT (Smith et al. 1998) assumes that the rainfall occurs in 6 separate rainstorm separated by 5 days . Table 5.16 shows the results of calculations based on climatic data of the *Tadmor* station (FAO 1996).

The results show that none of the crops could be grown under the climatic condition without supplementary irrigation. The irrigation demand for barley, wheat, pulses, tomato and cotton is calculated up to harvesting time. Optimum growth of the plants is assumed. Tomato was included in the calculation since planting at *Al Kum* was observed during field visits. The irrigation demand for tomatoes is double the demand of barley. Perennial pastures have a high irrigation demand. Perennial pastures adapted to the local dry conditions such as indigenous vegetation in the region (e.g. *Artemisia spp.*) require much less water. The old man saltbush (*Atriplex nummularia*) which could be used as fodder shows a very low transpiration rate of less than 0.3 mm day^{-1} (Slavich et al. 1999) in the semi-arid salt-affected land of south-east Australia.

Table 5.17 *Crop water requirements for some crops (Source: FAO 1996)*

Crop	ETO [mm/period]	Growing period [days]	CWR [mm]	Rainfall [mm]	Effective rain [mm]	Net irrigation demand [mm]
Barley	207	120	136	53	51	85
Wheat	1237	240	1110	70	67	1062
Pulses	184	110	133	53	51	82
Tomato	293	145	258	53	51	207
Cotton	605	195	517	73	71	447
Date palm[1]	1988	365	1866	73	71	1796
Olives[2]	1851	270	1275	20	20	1255
Gras/legume[1]	1988	365	1948	73	71	1885
Pasture, perennial[1]	1988	365	1835	73	71	1764

[1] Planting date: November 15
[2] Planting date: March 15

Boers (1994) showed that for a microcatchment system the survival and minimum growth of *Neem* trees is guaranteed on plots of 8 m² and runoff from 16 to 40 m² (with 200 to 400 mm of rainfall under dry condition). He also concluded that a greater storage capacity is needed for *Neem* trees in the Negev since they are dormant during the rainy period. The growth period is during the rainy season. In the active period they then need more water. This is also the case for olive trees: olive trees mainly need supplementary irrigation in August and September during the stone hardening and fruit swelling which is a critical period. This would also require supplementary irrigation from small reservoirs for the growth of olive trees. They should be grown on areas with loamy soils which have a high soil moisture amount. At least they also need supplementary irrigation from groundwater near *wadi* channels. Other drought resistant trees are e.g. the pistacchio tree This develops a 1 m deep root system but is slow in growth. Moisture below 1 m is lost to percolation. Boers (1994) recommended deep-rooting and drought resistant trees for microcatchment systems in arid regions. Perennial range plants which include e.g. medics (e.g. *Medicago rotata*), Syrian vetch or subterranean clover (*Trifolium subterraneum*), bulbous barley (*Hordeum bulbosum*). Some of these plants showed a good performance on plots on the *Avdat* runoff irrigation farm in the *Negev* (Evenari et al. 1982).

Boers (1994) used two sites in an arid and in an extremely arid area for water balance calculations. Boers (1994) investigated the water balance of microcatchments by using *SWATRE*. He based his calculations on two climatic zones in the Negev (*Sede Boquer* : extremely arid and *Beersheva*, two soil types and a catchment area of 125 m² (runoff area: 116 m² and basin area: 9 m²). He found out that the extremely arid area is not suitable for microcatchment construction, especially cultivated with trees. A larger catchment area would be needed, consequently enhancing the component of soil evaporation. Also a good water holding capacity is needed to have enough water in the season where the deep root water uptake takes place. A larger basin area is also needed allowing more storage capacity in the root zone. The transpiration and root zone losses are higher for arid areas within average rainfall of 124 mm and larger runoff areas. He recommended an area of 40 m² with a runoff area of 40 to 80 m². He emphasizes at this point that the design of microcatchments is extremely dependent on rooting depth of a tree, because storage in depth increases. For extremely arid condition (below 70 mm annually), Boers (1994) calculated that even a catchment area of 250 m² would not bring the needed transpiration. Therefore Boers concluded that in extremely arid conditions rainwater harvesting from microcatchment on natural surfaces is not the appropriate technology. This is probably true for tree plantation, but for plantations of drought resistant forage shrubs or perennial pastures it might be different.

To find out more about the specific rainfall runoff relations on the study site experimental plots are needed for rainfall-runoff simulation.

5.3.3 Introduction of further criteria into the AHP process

The introduction of further criteria allows refining of the differentiation process such that even a differentiation of potential areas for specific water harvesting techniques is possible. The vicinity to local construction material e.g. allows identification of suitable areas for stone bunds. Areas with high soil surfaces covered with a high amount of stones could be cleared and the stones could be used for construction. Classification of the area by determination of soil depth allows differentiation of areas suitable for tree plantation or fodder cultivation. Most of the soils within the project area especially in the depressions are at least 1 to 1.50 m deep. The soils are very shallow on the slopes of the mountains. South of *Tadmor* the soil depth is very variable as seen on natural soil profiles near ephemeral streams. More measurements are needed to derive at a GIS layer on soil depth .

The proximity to tourist sites permits assumption of a higher economic revenue for water harvesting and therefore makes methods that are costly more suitable, such as covered tanks or *hafirs*.

The method also allows to introduce new information layers, such as socio-economic constraints. On the other hand economic cost benefit prediction could probably be also introduced into the system. Rodriguez (1997) made a cost-benefit analysis for the study site of water harvesting at *Mihassa* for the season 1995/96. He pointed out that the water harvesting structure for cultivation of barley paid off with a net benefit compared to the control sites on barley cultivation in depressions. This analysis is based on 105 mm annual rainfall. Additionally, the water harvesting structures at *Mihassa* comprise large floodwater spreading systems with cost intensive control measures. Contour lines or microcatchment might be more cost-effective per unit hectare of land. However he assumed that better simulation models on the soil-water balance of the cultivated and phenological development throughout the season allow better prediction of water yield. The cost benefit analysis also depends on the land tenure system. If access to land is unlimited the crop yield could only be assessed on an actual planted area. Cohen et al. (1995) developed a risk assessment model using stochastic climatological input. Physical and financial risks can be quantified using the above mentioned water balance model and income variability due to uncertainty of yield. This model might be transferred to the conditions of a rangeland management system that is needed within the project area.

Patrick (1997) presented a framework for assessing water harvesting suitability including the delineation of homogeneous land units and social response units. The first component comprises the natural prerequisites for water harvesting structures, which also formed topic of the current research. The social response units include components such as tenure arrangements, gender considerations or the availability of labor and capital. These socioeconomic factors should also include participatory rural appraisal. The “fencing off” policy to protect rangeland has not led the local population to appraise the control measures since it deprives them of essential livestock reserves. Many rangeland users also believe that the degradation of vegetation in the rangeland is only due to the poor rainfall. They often ignore the connection to heavy grazing pressure. It seems that the idea of plantations of new fodder shrubs such as *Salsola spp*. is more appreciated than grazing control measures (Tutwiler et al. 1997). Therefore there is a good chance that the local population will support shrub plantations irrigated through water harvesting systems. But the support of the population is more guaranteed involving them into the planning and construction of water harvesting sites. Further studies on this participation process have to be done using modern socio-economic tools such as participatory appraisal.

The socio-economic factors also involve the training of the local population and range extension workers in the new techniques. The new techniques should only comprise simple handmade structures which can be constructed by the local population. This training would involve e.g. simple leveling devices such as a line level to construct contour bunds. Since some water harvesting also has a high maintenance demand, people have to be trained in maintenance of water harvesting structures. Table 5-18 provides a short overview of socio-economic criteria of some water harvesting techniques.

The presented method linking GIS and remote sensing in combination with the analytical hierarchical process is transferable to other semi-arid regions. Depending on the local constraints, such as data availability, some of the decision criteria could be given a lower importance weight or other decision criteria could be introduced. Within the socio-economic factors also the impact of grazing management plants could be studied by using the AHP process.

Table 5.18 *Socioeconomic criteria for some water harvesting techniques (after Oweis & Prinz 1998) capital requirement: low: < 25/ha, medium: 25-100/ha, high : > 100/ha; labor requirement: low: < 5 man-day/ha, medium: 5-20 man-day/ha, high: > 20 man-day/ha)*

Water Harvesting Technique	Capital requirement	Labor requirement	Skill requirement
MIC			
Contour ridges	Low	Medium	Training needed
Semi-circular bunds	Low	High	No training needed
Negarim	Low	High	Training needed
Runoff strips	Low	Low	No training needed
MAC			
Small dams	High	High	Expert
Tanks (Hafir)	Medium to high	Medium	Expert
Water spreading	Medium	Medium	Expert

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Table A-1 *Minimum, maximum temperature and average temperatures [°C] at stations within the study area (Analysis according to data from Meteorological Department of Syria from the period of 1975 - 1992)(temp. – temperature, Av. – average, max. – maximum, min – minimum, abs. – absolute)*

	Av. air temp	Av. air temp in winter	Av. air temp in summer	Av. max. temp.	Av. max. temp. in winter	Av. max. temp. in summer	Abs. max. temp. (month)	Av. min temp	Av min temp in winter	Av min temp in summer	Abs. min temp (month)
Homs	16.8	10.6	20.1	22.9	16.5	29.2	42.5 (Aug)	10.8	5.7	15.8	-10.0 (Jan)
Hama	16.3	11.2	19.1	25.3	18.4	23.4	45.3 (Aug)	11.9	7.5	16.2	-9.2 (Feb)
Ethriyah	17.7	13.0	24.4	23.8	15.8	31.6	45.5 (Aug)	12.7	6.7	17.7	-6.6 (Jan)
Salamiyah	16.7	10.4	22.9	24.0	16.7	31.3	45.3 (Aug)	9.4	4.6	14.2	-9.3 (Feb)
Ukeirabat	16.3	10.4	22.2	22.7	15.4	29.7	42.1 (Aug)	12.7	6.7	17.7	-6.6 (Jan)
Fruklos	15.8	9.5	22.2	22.4	15.7	29.2	44 .0 (Aug)	9.4	4.6	14.2	-9.3 (Feb)
Quaryatain	15.8	9.8	21.9	22.8	1.60	29.6	43.6 (July)	10.6	7.0	14.8	-10.5 (Jan)
T4	17.3	11.1	23.3	24.3	17.0	31.6	44.5 (July)	9.2	3.9	14.5	-13.0 (Jan)
Khnaifess	16.7	10.2	23.3	23.8	15.4	32.1	41.4 (Aug)	90	39.0	14.0	-12.0 (Dec)
Tadmor	18.6	11.7	25.5	25.8	18.1	33.4	46.5 (Aug)	10.4	5.7	15.2	-9.0 (Feb)
T3	18.8	111	25.1	26.5	18.6	34.4	47.5 (July)	11.1	5.5	16.8	-7.20 (Feb)

Table A-2 *Average annual precipitation according to datasets from the period 1978 – 1996 (Source: Meteorological Department, S.A.R. 1996)*

Station	Average annual precipitation (mm)	Number of analysed years	Period of available data
Ainbah	108.25	13	1978 - 1990
Beer Shamah	79.35	19	1978 - 1996
Dayr Atiyah	97.73	15	1978 - 1992
Fruklos	172.94	15	1978 - 1992
Hama	312.88	19	1978 - 1996
Homs	385.74	19	1978 - 1996
Huwaisess	145.68	14	1978 - 1991
Jehar	143.02	9	1978 - 1986
Khnaifess	117.74	13	1978 - 1990
El Kum	110.56	7	1978 - 1982, 1984-1985
Nabk	165.45	19	1978 - 1996
Quaryatain	119.81	16	1978 - 1993
Qutaifah	164.53	17	1978 - 1994
Sa'an	222.69	19	1978 - 1996
Saba Biar	96.15	10	1978 - 1986, 1989
Sadad	126.75	19	1978 - 1996
Sadd Jebab Shaqra	110.22	18	1978 - 1995
Sadd Quaryatain	123.58	19	1978 - 1996
Sadd Sleem	114.02	19	1978 - 1996
Sadd Zkakiyah	105.61	19	1978 - 1996
Salamiyah	291.66	19	1978 - 1996
Al Suknah	128.26	17	1978 - 1994
T3	120.47	19	1978 - 1996
T4	88.40	16	1978 - 1993
Tadmor	119.75	19	1978 - 1996
Ukeirabat	229.12	18	1978 - 1995

Table A-3: *Characteristics of rainfall events in the project area (Period of data set for the different station see Table A-2) (Source: Meteorological Department, S.A.R. 1996)*

Station	Average number of rainfall events	Average annual rainfall	Average number of events exceeding 2 mm d^{-1}	Avg. cumulative rainfall events exceeding 2 mm d^{-1}	Average percentage of cumulative rainfall events exceeding 2 mm d^{-1}	Number of rainfall events exceeding 5 mm d^{-1}	Average cumulative rainfall exceeding 5 mmd^{-1}	Average percentage of cumulative rainfall events exceed. 5 mm d^{-1}
Ainbeh	15	108.25	12	104.50	96.53	6	88.13	81.41
Beer Shameh	19	79.35	13	75.29	94.89	6	53.35	67.23
Deir Atiyeh	21	97.73	19	128.76	96.34	9	96.92	99.17
Fruklos	38	172.94	33	137.90	79.74	29	68.95	39.87
Hama	69	312.88	35	288.72	92.28	20	241.17	77.08
Homs	73	385.74	41	354.69	91.95	25	308.04	79.86
Huwaisess	21	145.68	17	142.10	97.54	10	118.98	81.67
Jehar	21	143.02	17	136.58	95.49	11	118.21	82.65
Khnaifess	26	117.74	25	110.10	93.51	25	86.55	73.51
El Kum	16	110.56	11	105.49	95.41	6	89.11	80.60
Nabk	41	165.45	17	149.09	90.12	9	122.05	73.77
Quaryatain	27	119.81	7	109.19	91.14	16	82.18	68.59
Qutaifeh	25	164.53	17	157.69	95.85	10	135.50	82.36
Sa'an	41	222.69	30	211.53	94.98	15	165.06	74.12
Saba Biar	34	96.15	11	69.19	71.96	6	58.74	61.09
Sadad	23	126.75	17	120.68	95.22	8	93.56	73.82
Sadd Jebab Shaara	24	110.22	16	99.94	90.68	7	72.85	66.10
Sadd Quaryatain	28	123.58	17	112.52	91.05	8	82.00	66.35
Sadd Sleem	14	114.02	12	112.94	99.06	8	100.84	88.44
Sadd Zkakiyeh	12	105.61	12	102.17	96.75	8	92.09	87.21
Salamiyeh	63	291.66	36	269.48	92.40	19	215.78	73.98
El Sukhneh	29	128.26	17	119.36	9307	7	89.17	69.52
T3	23	120.47	11	75.81	6293	5	57.84	48.01
T4	25	66.30	15	77.33	85.89	8	55.29	83.40
Tadmor	9	119.75	16	101.61	84.85	7	70.88	59.19
Ukeirabat	39	229.12	30	219.36	95.74	15	174.04	7596

Table A-4 *Probability of maximum daily rainfall events (parameters estimated according to momentum method or Maximum Likelyhood-Analysis (MLH = Maximum Likelyhood) *Number of maximum rainfall events considered within analysis, normally one maximum per year (Source: Meteorological Department, S.A.R. 1996)*

Station	Probability density function	2-year return period [$mm \cdot d^{-1}$]	5-year return period [$mm \cdot d^{-1}$]	10-year return period [$mm \cdot d^{-1}$]	Number of maximum rainfall events *
Dayr Atiyah	Log Weibull 3	21.5	32.3	31	19
El Sukhneh	Log Gumbel	25.9	39.7	53.8	17
Fruqlos	Gumbel	24	34.8	42	15
Hama	Log-Normal	113.5	143.6	160.2	19
Homs	Weibull	34.7	49.1	58.2	19
Nabk	Log-Normal	29.4	55.5	78.5	19
Quaryatain	Log-Gumbel	18.1	27.3	35.9	13
Sa'an	Gumbel	21.9	27.3	31.1	19
Saba Biar	Log-Gumbel	23.1	35	46.9	19
Sadad	Gumbel MLH	15.8	25.2	31.3	19
Sadd Quaryatain	Weibull	21.6	32.6	38.4	19
Sadd Sleem	Gamma	53.8	36.3	45.2	18
Sadd Zkakiyah	Weibull	20.6	33.6	46.4	19
Salamiyah	Weibull	37.1	51.6	59.3	19
Tadmor	Gamma	20.1	22.7	28.2	19
T3	Normal	24.1	37.9	49.2	19
T4	Gumbel	22.3	31	31.5	22
Ukeirabat	Log Gumbel	30.4	42.9	54	20

Table A-5 *Average monthly evapotranspiration (mm·month^{-1}) according to Thornthwaite within the project area (Source: Meteorological Department, S.A.R. 1996)*

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Sum
Fruqlos	7.99	12.78	28.91	58.88	97.42	131.57	152.23	202.02	107.41	66.07	25.57	11.00	901.87
Hama	18.26	20.08	36.35	53.37	77.33	93.06	106.24	102.88	79.14	57.28	32.95	21.24	698.19
Khnaifess	8.00	12.17	28.16	61.61	106.99	147.58	165.95	154.79	116.26	66.42	28.66	12.18	908.76
Quaryatain	27.09	29.87	42.57	62.43	92.21	115.44	129.85	121.05	95.53	67.08	40.18	29.33	852.63
Salamiyah	8.85	12.76	29.51	57.15	102.92	144.23	167.13	155.98	116.22	70.78	28.30	11.50	905.32
T4	9.37	13.92	31.87	62.72	110.41	151.32	170.94	157.75	113.82	71.33	31.14	12.06	936.64
Tadmor	7.81	13.68	33.44	72.90	128.75	175.84	208.62	186.31	132.80	75.19	25.33	10.41	1071.07
Ukeirabat	8.42	12.63	29.20	56.86	101.42	137.83	157.23	147.70	109.59	71.62	34.82	12.96	880.28

Table A-6 *Average monthly evaporation (mm·month^{-1}) according to Blaney-Criddle calculated with monthly average temperature (Source: Meteorological Department, S.A.R. 1996)*

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Sum
Fruqlos	74.50	81.23	107.66	133.50	166.44	182.41	193.98	190.91	154.22	126.48	90.68	76.27	1578
Hama	77.02	79.71	103.07	119.38	144.35	153.60	163.43	155.90	131.44	112.55	87.48	77.60	1405
Khnaifess	76.19	82.19	109.27	137.43	173.58	190.97	200.62	188.02	158.80	128.08	94.29	79.57	1619
Quaryatain	92.13	93.80	116.08	132.40	158.22	168.14	177.42	168.41	146.57	128.66	102.93	93.68	1578
Salamiyah	76.82	82.80	109.95	134.20	170.42	189.04	200.80	188.72	159.16	130.94	94.66	78.57	1616
T4	78.98	85.02	113.68	139.25	175.38	192.30	202.26	189.37	158.29	132.04	97.87	80.44	1644
Tadmor	80.28	88.23	118.59	147.67	185.01	201.36	214.18	198.63	166.09	136.07	96.46	81.68	1714
Ukeirabat	75.40	81.37	108.57	132.90	168.82	185.57	196.18	184.71	155.35	130.41	98.09	79.21	1596

Table A-7 *Average reference crop evapotranspiration (mm d^{-1}) at different stations within the project area, calculated according to the Penman-Monteith model (FAO 1991,1998) (source of data of Mihassa, (IDRC 1997)*

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Hama	1.20	1.70	2.80	4.40	5.90	8.10	8.70	7.70	5.60	3.50	1.90	1.20
Homs	1.10	1.70	2.50	3.80	5.20	7.00	7.10	6.80	5.60	3.50	2.00	1.20
Ethriyah	0.98	1.79	2.84	4.58	6.03	7.76	8.15	8.45	6.26	3.42	1.82	1.12
Ukeirabat	1.04	1.60	2.60	4.05	5.62	7.37	7.50	7.78	5.77	3.21	1.90	1.12
Salamiyah	1.00	1.50	2.40	3.80	5.40	7.10	7.30	7.60	5.70	3.30	1.90	1.10
Quaryatain	1.65	2.36	3.72	5.13	6.83	8.14	8.14	7.32	5.92	4.18	2.83	1.96
Nabk	1.40	1.90	3.10	4.20	5.50	7.10	7.50	6.90	5.20	3.60	2.40	1.70
Khnaifess	1.26	1.93	3.12	5.20	8.06	9.82	9.44	8.76	6.83	4.11	2.07	1.22
T4	1.37	2.11	3.56	5.25	7.20	9.21	10.01	9.03	6.80	4.42	2.39	1.36
Tadmor	1.40	2.10	3.60	5.40	7.20	9.50	10.40	9.60	7.20	4.60	2.60	1.50
T3	1.40	2.25	3.85	5.76	7.84	10.21	11.29	10.24	7.57	4.78	2.45	1.40
Mihassa*	1.20	1.50	2.90	4.10	6.90	8.70	9.80	9.40	6.50	4.50	2.50	1.30

* only data over two years available

Table A-8 *Average monthly reference crop evapotranspiration at different stations within the area, calculated according to the Penman-Monteith model (FAO 1991,1998) (source of data of Mihassa, (Soumi & Abdul Aal 1999)*

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Sum
Hama	37.20	49.30	86.80	132.00	182.90	243.00	269.70	238.70	168.00	108.50	57.00	37.20	1610
Homs	34.10	49.30	77.50	114.00	161.20	210.00	220.10	210.80	168.00	108.50	60.00	37.20	1450
Ethriyah	30.38	51.91	88.04	137.40	186.93	232.80	252.65	261.95	187.80	106.02	54.60	34.72	1625
Ukeirabat	32.24	46.40	80.60	121.50	174.22	221.10	232.50	241.18	173.10	99.51	57.00	34.72	1514
Salamiyah	31.00	43.50	74.40	114.00	167.40	213.00	226.30	235.60	171.00	102.30	57.00	34.10	1469
Quaryatain	51.15	68.44	115.32	153.90	211.73	244.20	252.34	226.92	177.60	129.58	84.90	60.76	1776
Nabk	43.40	55.10	96.10	126.00	170.50	213.00	232.50	213.90	156.00	111.60	72.00	52.70	1542
Khnaifess	39.06	55.97	96.72	156.00	249.86	294.60	292.64	271.56	204.90	127.41	62.10	37.82	1888
T4	42.47	61.19	110.36	157.50	223.20	276.30	310.31	279.93	204.00	137.02	71.70	42.16	1916
Tadmor	43.40	60.90	111.60	162.00	223.20	285.00	322.40	297.60	216.00	142.60	78.00	46.50	1989
T3	43.40	65.25	119.35	172.80	243.04	306.30	349.99	317.44	227.10	148.18	73.50	43.40	2109
Mihassa	37.20	43.50	89.90	123.00	213.90	261.00	303.80	291.40	195.00	139.50	75.00	40.30	1813

Table A-9 *Different aquifers in the Northern Palmyrides and the Ad-Dauw Artesian basin (Lengiprodhoz 1987*

A. Northern Palmyrides

Aquifer	**Lithological unit**	**Thickness [m]**
Quaternary proluvial aquifer	pebble-bed loams, sandy loams	7 - 12
Pliocene aquifer	limestone and marls	1.5 - 45
Middle and upper Eocene aquatic system	limestone, marls, sandstones,	1 - 63
Palaeocene-lower Eocene impervious locally	clayey limestones and marls (7 - 12 m)	0.8 - 16.5
Waterbearing systems in weathering zone in Maestrichian Danian deposits	Marls and clayey limestones (19 m)	2 - 108
Cenomanian-Turonian-Coniacian aquifer system	Limestones, dolomites, marls, sandstones	29.5 -136
Jurassic aquifer system	dolomites (51 m)	416

B. Artesian AdDauw Basin

Aquifer	**Lithological unit**	**Thickness [m]**
Quaternary alluvial and proluvial aquifer	sand gravel deposits, pebble beds, sands, conglomerates, loams	10 -18
Pliocene aquifer system	conglomerates, sandstones, limestones, marls	2.5 to 51 m
Middle Micocene aquifer system	Gypsum, limestones, marls, limestones with sand and sandstone beds	13 to 19 m
Lower Miocene aquifer system	sandstones, conglomerates and sands	15 to 20 m

C. Southern Palmyrides

Aquifer	**Lithological Unit**	**Thickness [m]**
Quaternary proluvial aquifer	Sand gravel deposits, pebble beds and loams	9 - 21
Pliocene aquifer system	Conglomerates, sandstones, limestones, marls	6 - 35
Middle and *Upper Eocene* aquifer system	Limestones, marls and sandstones	3 -102
Palaocene-lower Eocene impervious locally waterbearing system	clayey limestones and marls	10 - 90
Weathering zone in *Maestrichtianian* deposits	Marls and clayey limestones	3 -130
Cantonian-Campanian sporadic GW	Clayey limestones,flints, marls	21 - 82
Cenomanian-Turonian,Coniacian aquifer system	limestones, dolomites, marls, sandstones	30 - 106
Jurassic aquifer system	dolomites, limestones, sandstones, and gypsum (5 -27 m)	60 - 315

Table A-10 *Soil texture of soils in the research area. Location see Fig. 4.13*

Sample Location	Soilscape Unit	Clay (%)	Silt (%)	Sand (%)	Texture class name
203	***A11e***	25.6	53.9	20.5	Silt loam
205	***A11d***	23.6	44.5	31.9	Loam
209	***A31b***	37.0	45.0	18.0	Silty clay loam
211	***A11c***	20.9	36.7	42.4	Loam
214	***A11e***	28.8	41.9	29.3	Clay loam
227	***A11a***	15.5	31.1	53.4	Sandy loam
238	***A12d***	43.5	32.6	23.9	Clay
244	***A31b***	39.5	31.6	28.9	Clay loam
246	***E51c***	13.0	25.9	61.1	Sandy loam
251	***E51c***	20.9	41.8	37.3	Loam
252	***A11e***	18.2	33.7	48.1	Loam
254	***A11e***	20.9	39.3	39.8	Loam
258	***E51b***	21.7	36.8	41.5	Loam
259	***A31b***	23.2	25.6	51.2	Sandy clay loam
260	***A51a***	10.9	19.0	70.1	Sandy loam
228	***E51c***	22.5	34.7	42.8	Loam
230	***A11c***	22.9	37.5	39.6	Loam

Table A-11 *Chemical analysis of soil samples within the research area*

No.	USDA	Organic matter [%]	Olsen-P [ppm]	CaCO3 [%]	pH	EC [mS··cm^{-1}]	Extractable P eq/100g	Kjeldal-N [ppm]
203	A11e	1.1	11.0	42.2	8.4	0.44	16.0	665
205	A11d	1.7	20.7	41.1	8.7	0.25	25.1	1124
209	A31b	0.5	7.8	41.1	8.7	0.42	21.0	380
211	A11c	1.3	21.1	38.5	8.7	0.33	14.3	817
214	A11e	1.5	10.4	47.5	8.7	0.91	8.7	867
227	A11a	2.1	12.3	49.0	8.6	0.21	6.4	1326
238	A12d	0.4	4.0	41.9	8.1	11.00	2.9	315
244	A31b	0.6	6.6	44.2	8.2	6.93	7.7	463
246	E51c	0.9	10.9	49.0	8.7	0.19	7.2	554
251	E51c	1.0	6.2	49.0	8.8	0.23	10.2	643
252	A11e	1.2	10.0	50.0	8.7	0.27	8.7	817
254	A11e	1.1	14.4	47.4	8.6	0.38	12.3	637
258	E51b	0.9	8.8	45.3	8.4	0.78	16.0	611
259	A31b	0.8	7.5	50.5	8.2	2.97	9.7	627
260	A51a	1.1	9.4	41.1	8.1	96.60	10.2	218
228	E51c	0.5	6.4	52.5	8.7	0.31	7.6	630
230	A11c	0.8	4.2	40.5	8.7	0.43	6.5	467

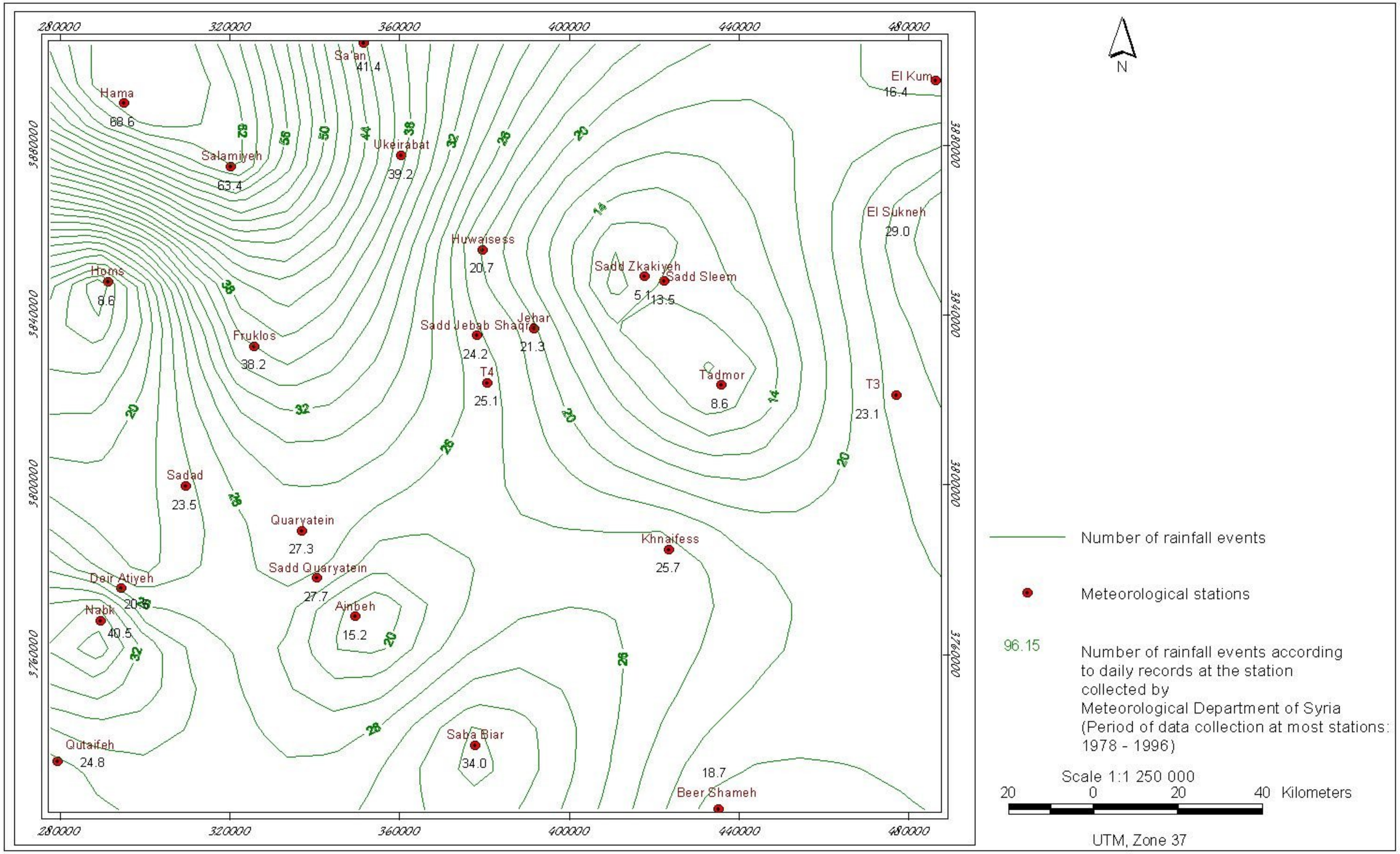

Fig. A-1 *Number of rainfall events (Source: Meteorological Department. S.A.R. 1996)*

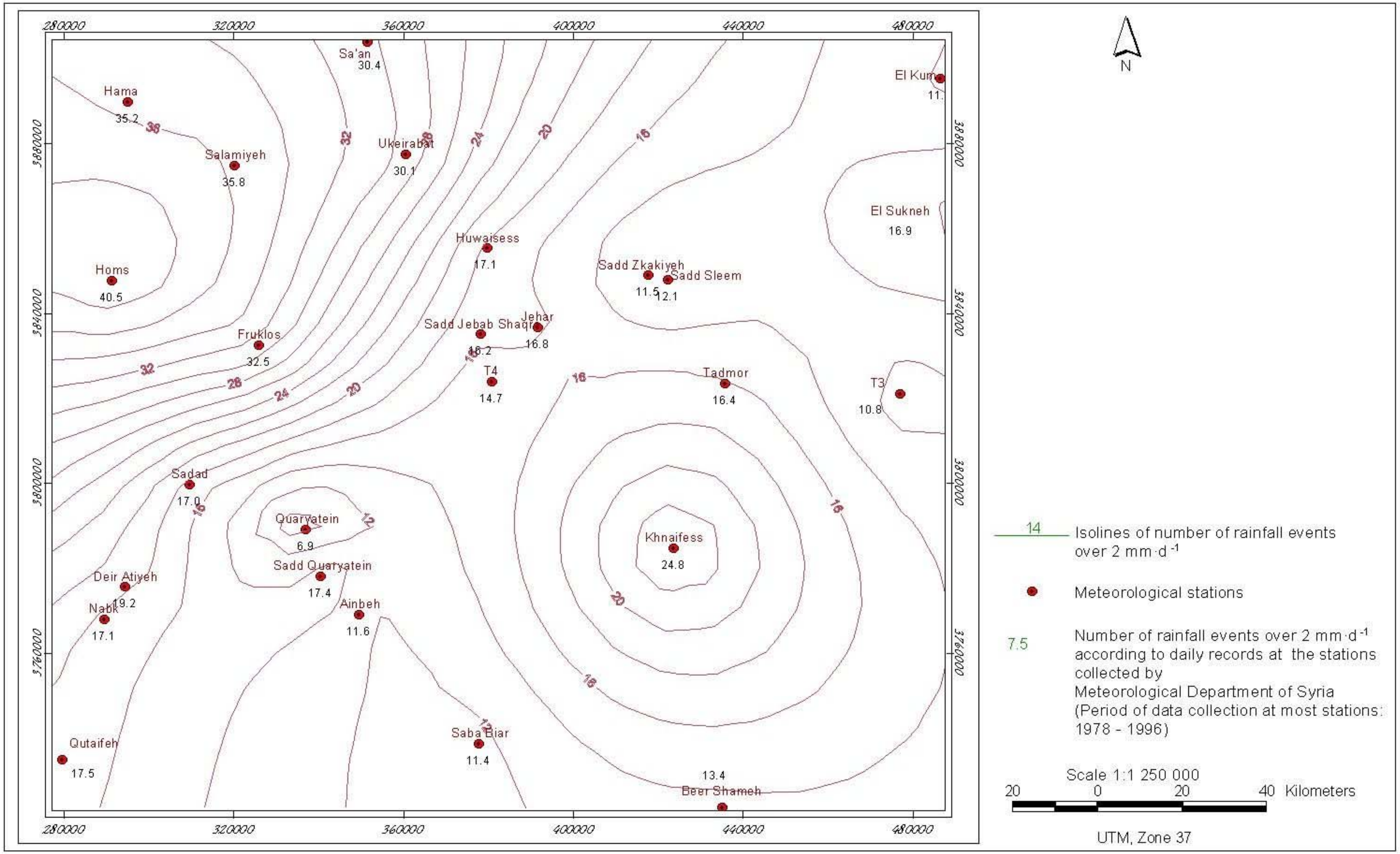

Fig. A-2 *Number of rainfall events exceeding 2 $mm \cdot d^{-1}$ (Source: Meteorological Department. S.A.R. 1996)*

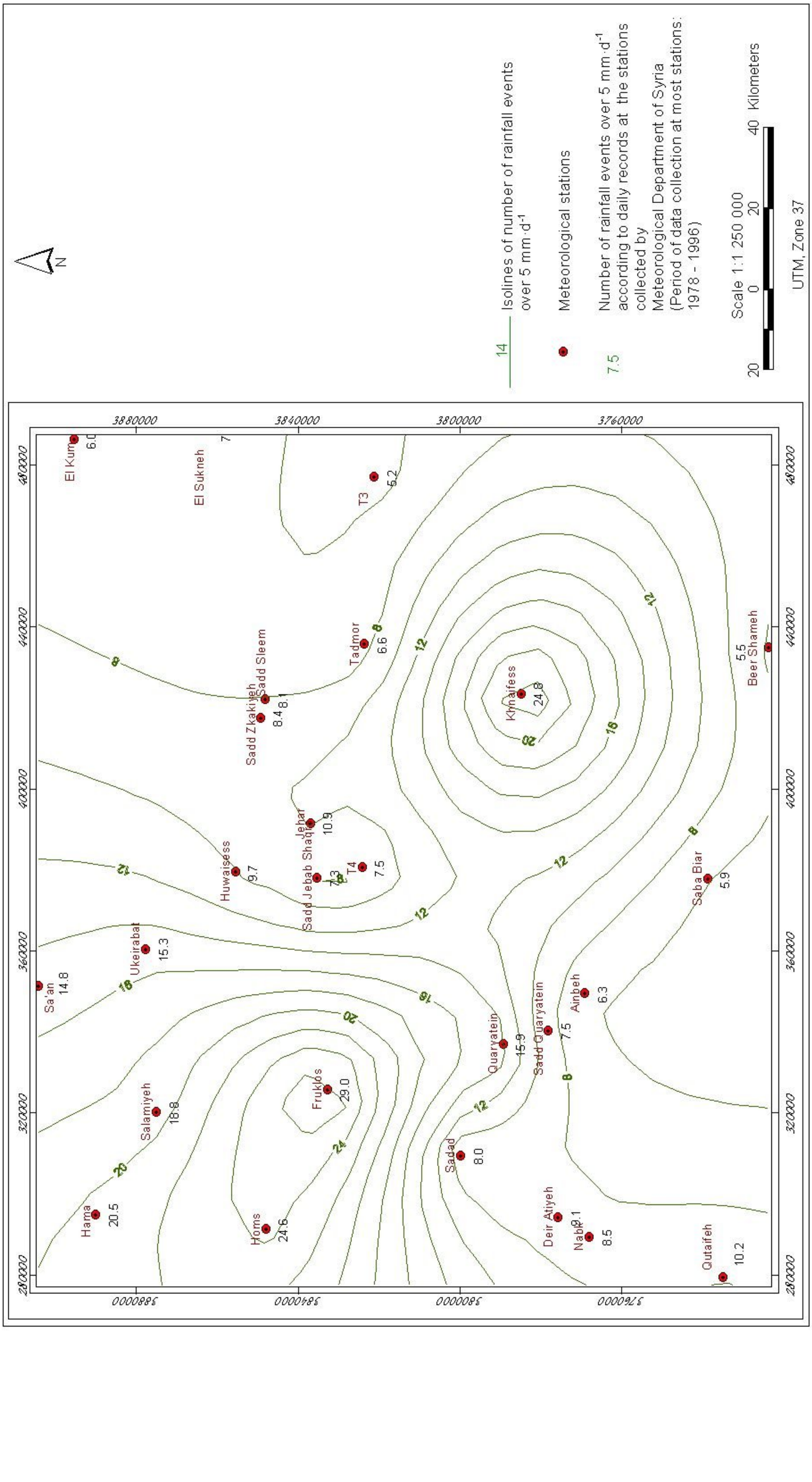

Fig. A-3 *Number of rainfall events exceeding mm·d^{-1} (Source: Meteorological Department. S.A.R. 1996)*

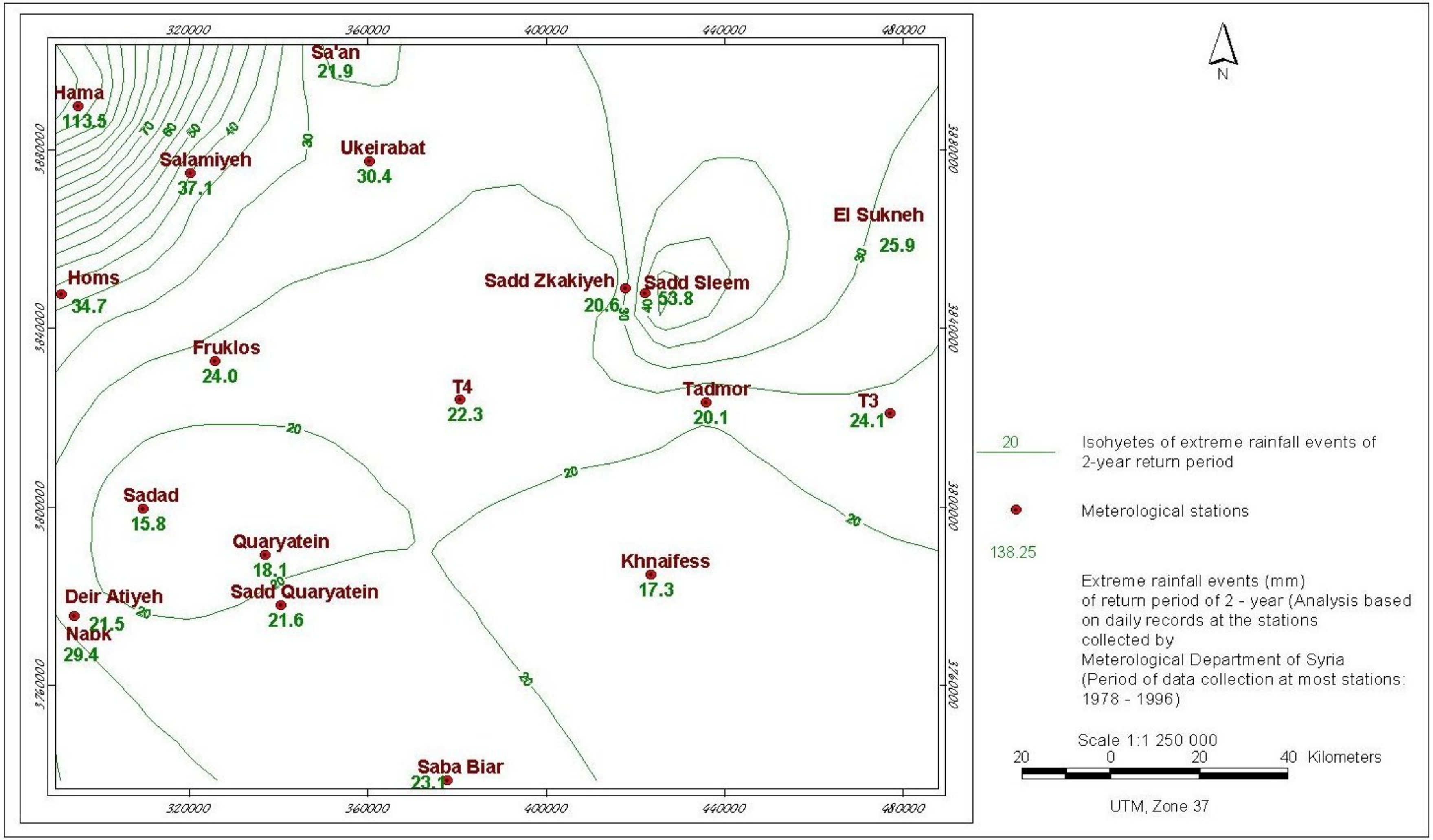

Fig. A-4 *Extreme rainfall events of 2-year return period (Source: Meteorological Department. S.A.R. 1996)*

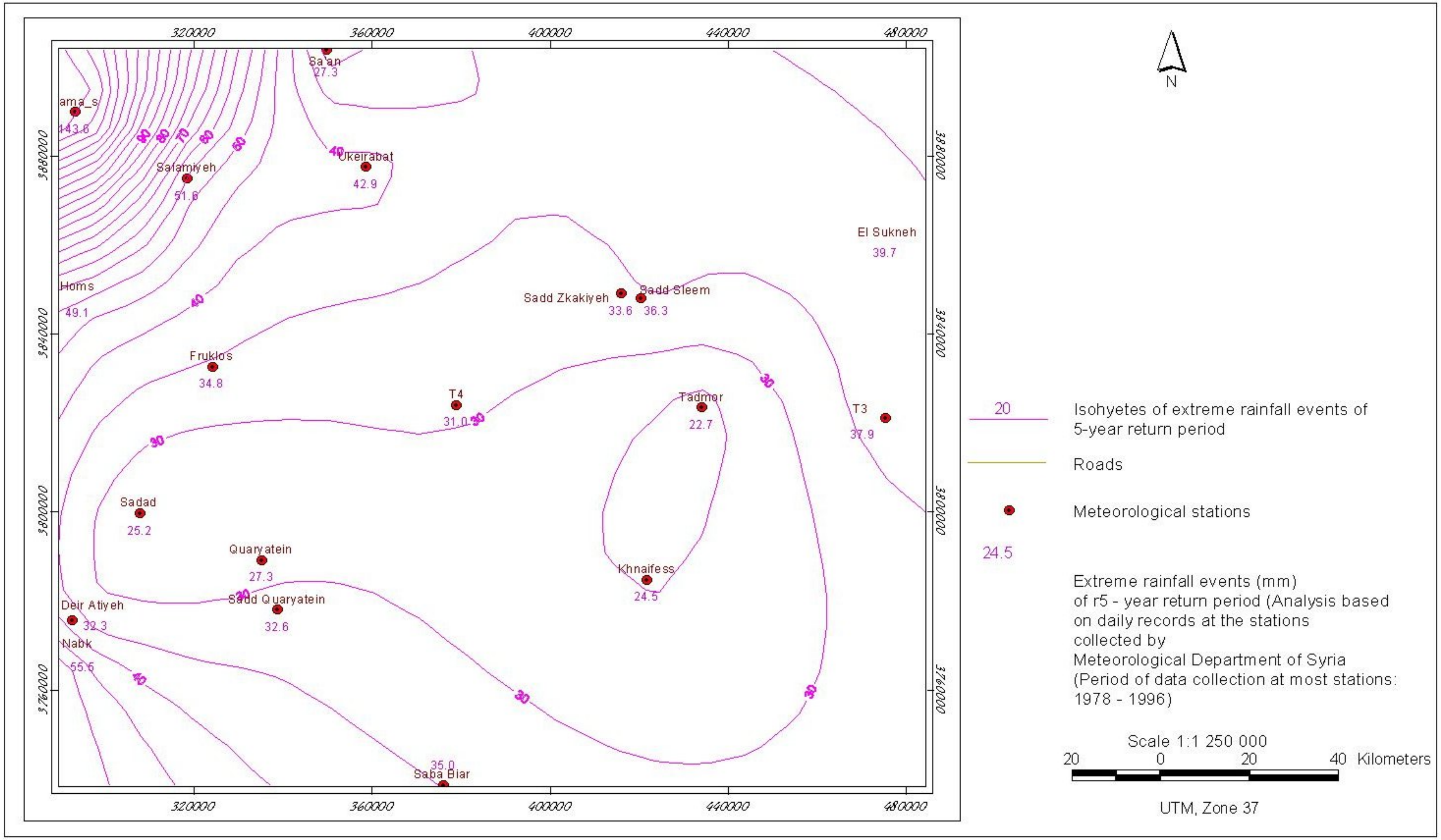

Fig. A-5 *Extreme rainfall events of 5-year return period (Source: Meteorological Department. S.A.R. 1996)*

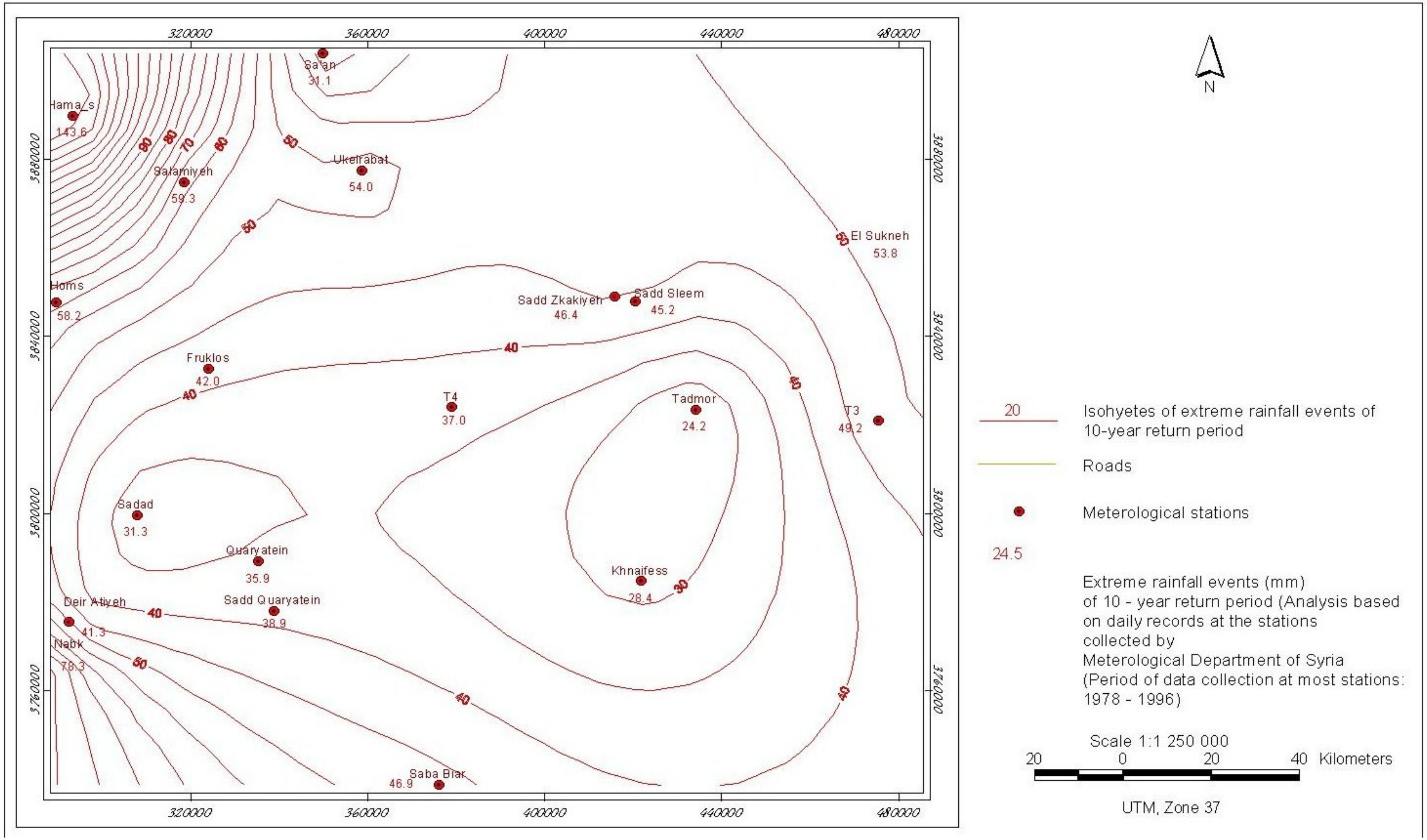

Fig. A-6 *Extreme rainfall events of 10-year return period (Source: Meteorological Department. S.A.R. 1996)*

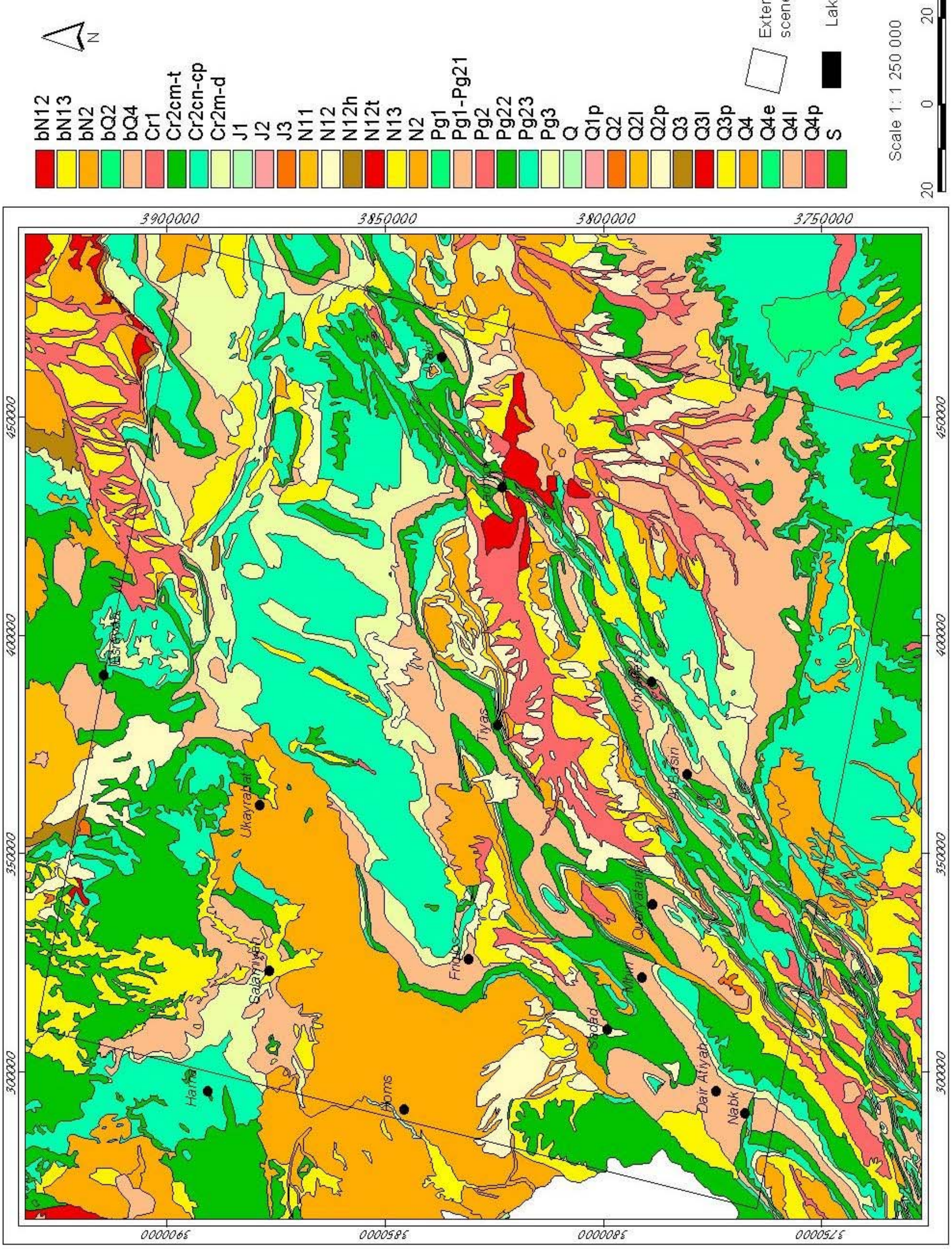

Fig. A-7 *Geological map of the project area (Ponikarov et al. 1987)*

Table A-12 *Geological units according to geological map of project area (Ponikarov et al. 1987) (Fig. A-7)*

Geological unit	Geological period	Type of deposit
Q	*Quaternary (undivided)*	Conglomerates, pebble beds, sands, loams, clays, mrls
Q4	*Holocene*	Flood plain and 1st terrace deposits-sands(above floodplain), pebble beds, loams, clays, sandy loeams,; alluvial fan and cone deposits-loams, pebble beds;eolian sands;marine calcareous sandstones, sands, pebble beds(1st raised beach)
bQ4	*Holocene*	Basalts
Q3	*Pleistocene, upper series*	The second terrace, alluvial pebblebeds and conglomerates: alluvial-proluvial and proluvial pebble beds,conglomerates, sandy loams, pebble beds; lacustrine clays and marls; marine calcareous sandstones, conglomerates (the second raised beach)
Q2	*Pleistocene, middle series*	The third terraces alluvial conglomerates and pebble beds; alluvial-proluvial and proluvial conglomerates and pebblebeds; marine calcareous sandstones, conglomerates (the third raised beach), lacustrine gypsum and loams
bQ2	*Pleistocene, middle series*	Basalts
N2	*Pliocene*	Continental conglomerates, sandstones, limestones, clays, marls;marine clays, tuff-breccia
bN2	*Pliocene*	Basalts
N13	*Upper Miocene*	NW Syria:Gypsum, marls,limestones.Al-Furat basin: clays, sandstones, marls, siltstones, gypsum (Upper Fars formation)
bN13	*Upper Miocene*	Basalts
N11	*Lower Miocene*	Northwestern Syria: marine limestones, marls, clays, conglomerates, sandstones. Anti-lebanon-Palmyrides: continental quartz sands
bN12	*Middle Miocene*	Basalts
N12t	*Tortonian*	NW-Syria: limestones, marls, conglomerates, sandstones. Al-Furat basin: gypsum, limestones, marls, clays, sandstones, rock salt (Lower Fars formation)
N12h	*Helvetian*	Organogeneous-detrital limestones (pelcypodal, gastropodal and algal varieties. Eastern slope of Kurd-Dagh: conglomerates, limestones, sandstones, marls
N11	*Lower Miocene*	Northwestern Syria: marine limestones, marls, clays, conglomerates, sandstones. Anti-lebanon-Palmyrides: continental quartz sands
Pg3	*Oligocene*	Limestones, sandstones

Geological unit	Geological period	Type of deposit
Pg2	*Eocene*	Limestones
Pg23	*Upper Eocene*	Chalky limestones, marls
Pg22	*Middle Eocene*	Soft chalky and hard nummulitic limestones, marls
Pg1-Pg21	*Lower Eocene-Palaeocene*	Chalky/nummulitic limestones with flint interbeds;marls, clays
Pg1	*Palaeocene*	Limestones and marls
Cr2m-d	*Maestrichtian-Danian*	Chalky limestones, marls
Cr2cn-cp	*Coniacian-Campanian*	Chalky and organeous-detrital limestones, interbedded with flints
Cr2cm-t	*Cenomanian-Campanian*	Dolomites, limestones, clays
Cr1	*Lower Cretaceous*	Sandstones, limestones, clays with basalts at the base
J3	*Jura/Upper series*	Limestones, marls
J2	*Jura/Middle series*	Western Syria: limestones, dolomites with spilites in Eastern and northeastern Syria: dolomites, marls, anhydrites, gypsum
J1	*Jura/Lower series*	Western Syria: limestones; Central and Northeastern Syria: Limestones, dolomites, anhydrites
Q4p	*Holocene*	Proluvial, alluvial-proluvial pebble beds, conglomerates, loams, clays, sandy loams
Q3p	*Pleistocene*	Proluvial, alluvial-proluvial pebble beds, conglomerates, loams, sandy loams
Q2p	*Pleistocene*	Proluvial, alluvial-proluvial
Q1p	*Pleistocene*	Alluvial-proluvial and proluvial conglomerates
Q4e	*Holocene*	Eolian sands
Q4l	*Holocene*	Lacustrine
Q3l	*Pleistocene*	Lacustrine
Q2l	*Pleistocene*	Lacustrine gypsum and loams
S		Lake, River

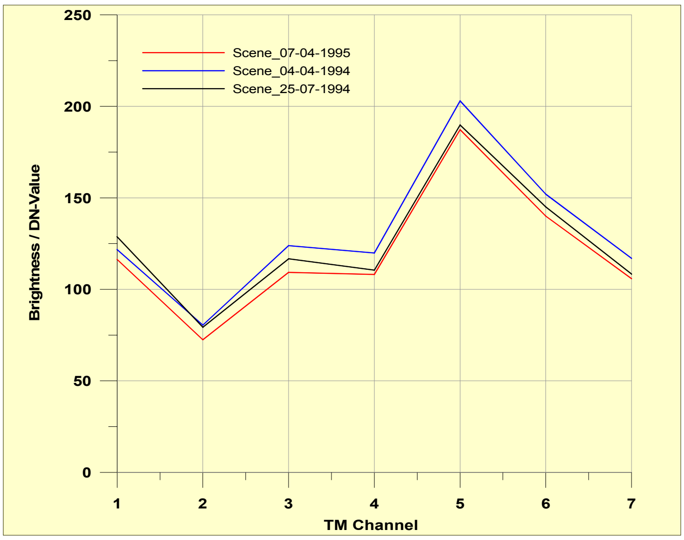

Fig. B-1 *Spectral reflectance curve of the class "Rocks and Scree slopes", showing mean values of about 10 sample sites of the scenes of 4/07/1995 ,4/04/1994 and 7/25/1994*

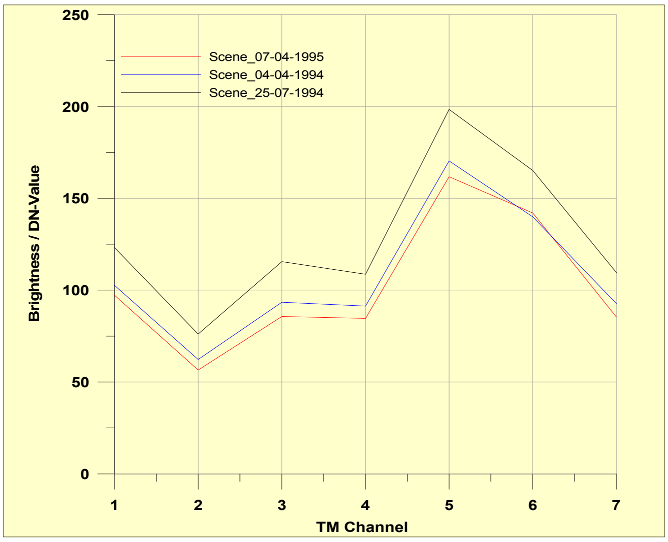

Fig. B-2 *Spectral reflectance curve of the class "Soil surfaces covered with flintstones",showing mean values of about 10 sample sites of the scenes of 4/07/1995 ,4/04/1994 and 7/25/1994*

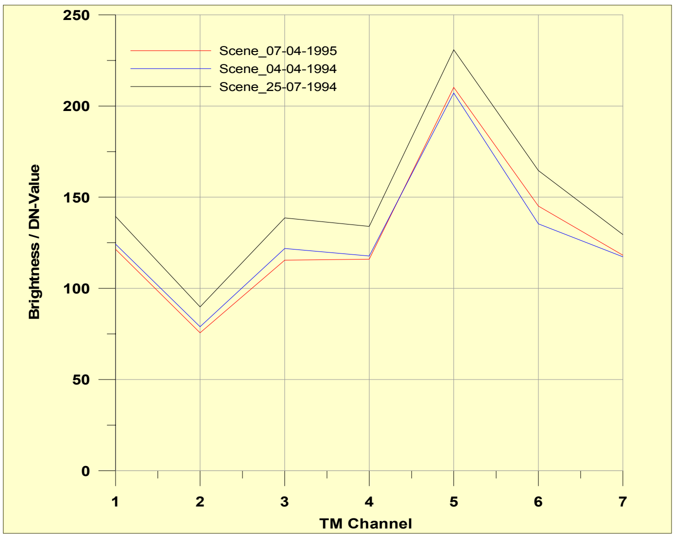

Fig. B-3 *Spectral reflectance curve of the class "Loamy soils",showing mean values of about 10 sample sites of the scenes of 4/07/1995, 4/04/1994 and 7/25/1994*

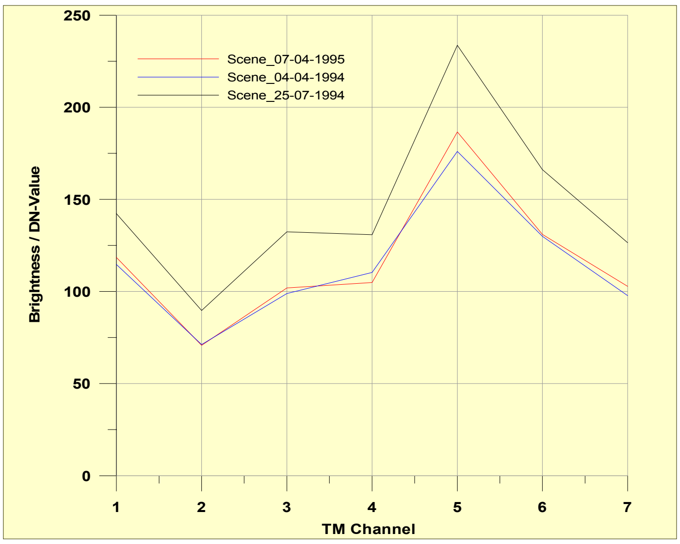

Fig. B-4 *Spectral reflectance curve of the class "Sparse vegetation",showing mean values of about 10 sample sites of the scenes of 4/07/1995 ,4/04/1995 and 7/25/1994*

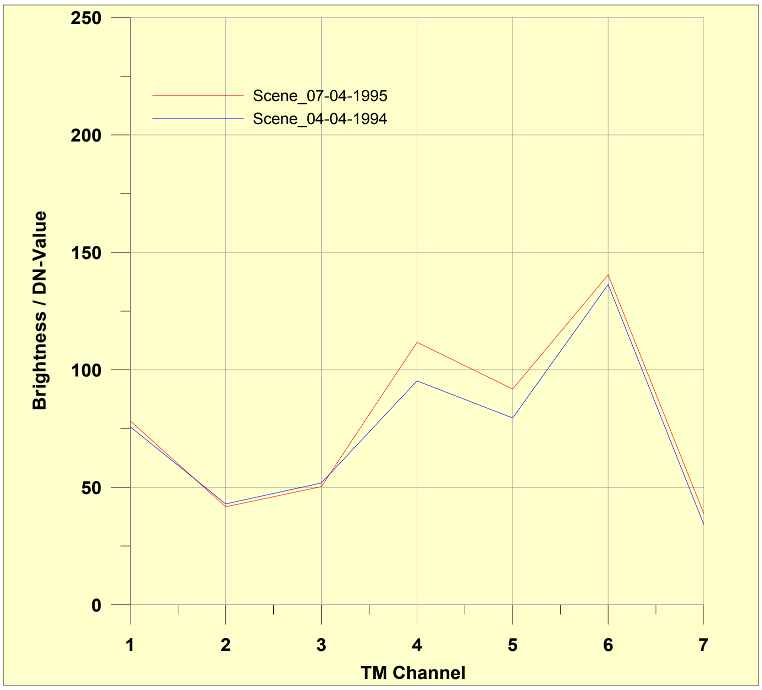

Fig. B-5 *Spectral reflectance curve of the class "Dense vegetation in flood-plains",showing mean values of about 10 sample sites of the scenes of 4/04/1994 and 4/07/1995*

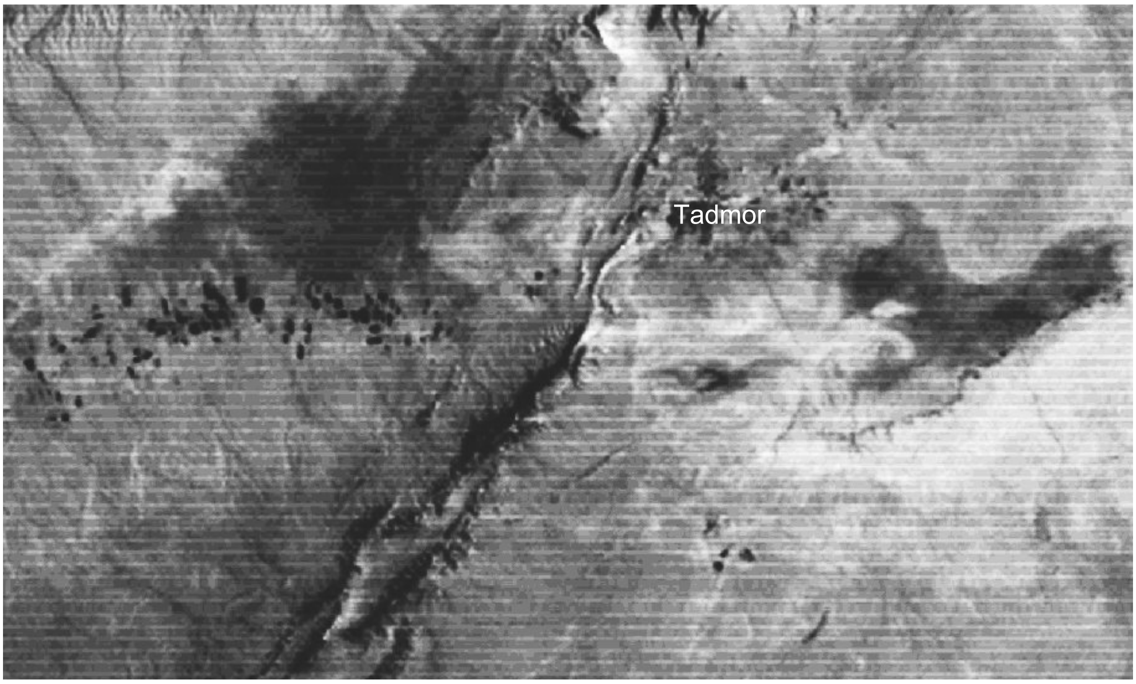

Fig. B-6 *TIR-channel (Landsat TM5 173/36, Band 6) of the image of July 25, 1994 shows cooler regions in darker grayscale, such as the irrigated fields east of the oasis Tadmor (stripes: data errors)*

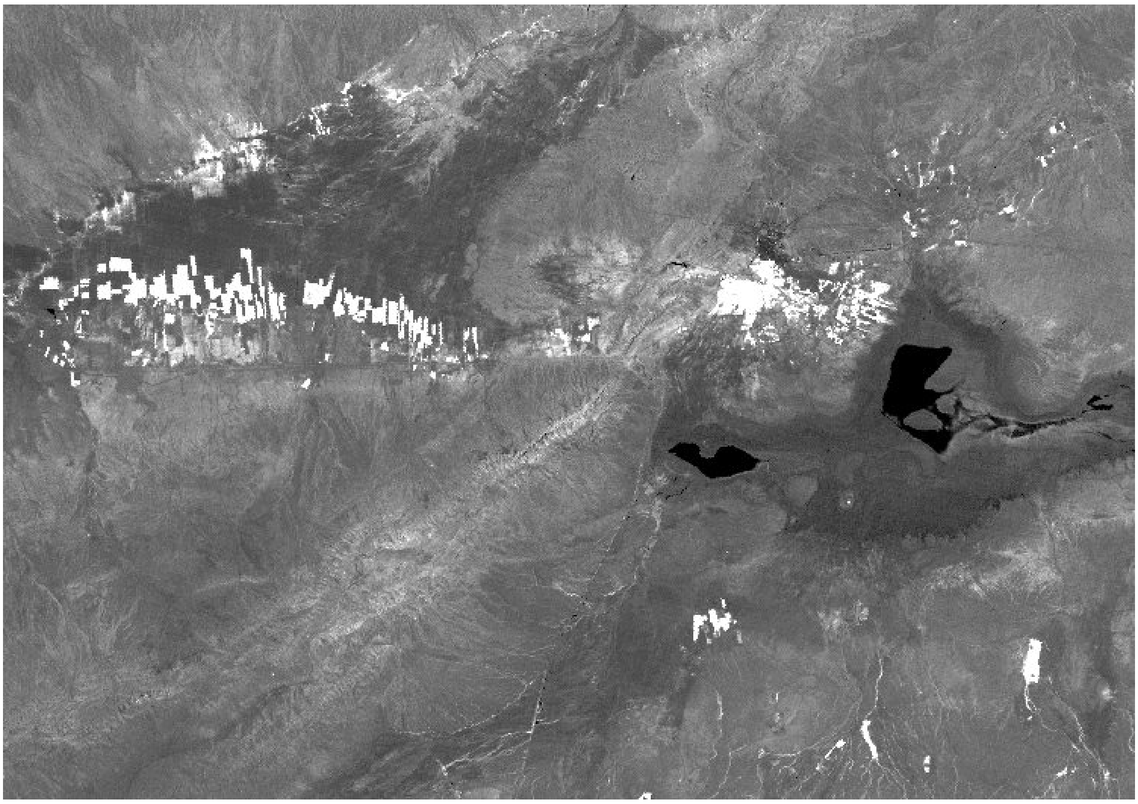

Fig. B-7 *NDVI-image of subset of TM Landsat 5 scene (04/04/1994) showing area around Tadmor*

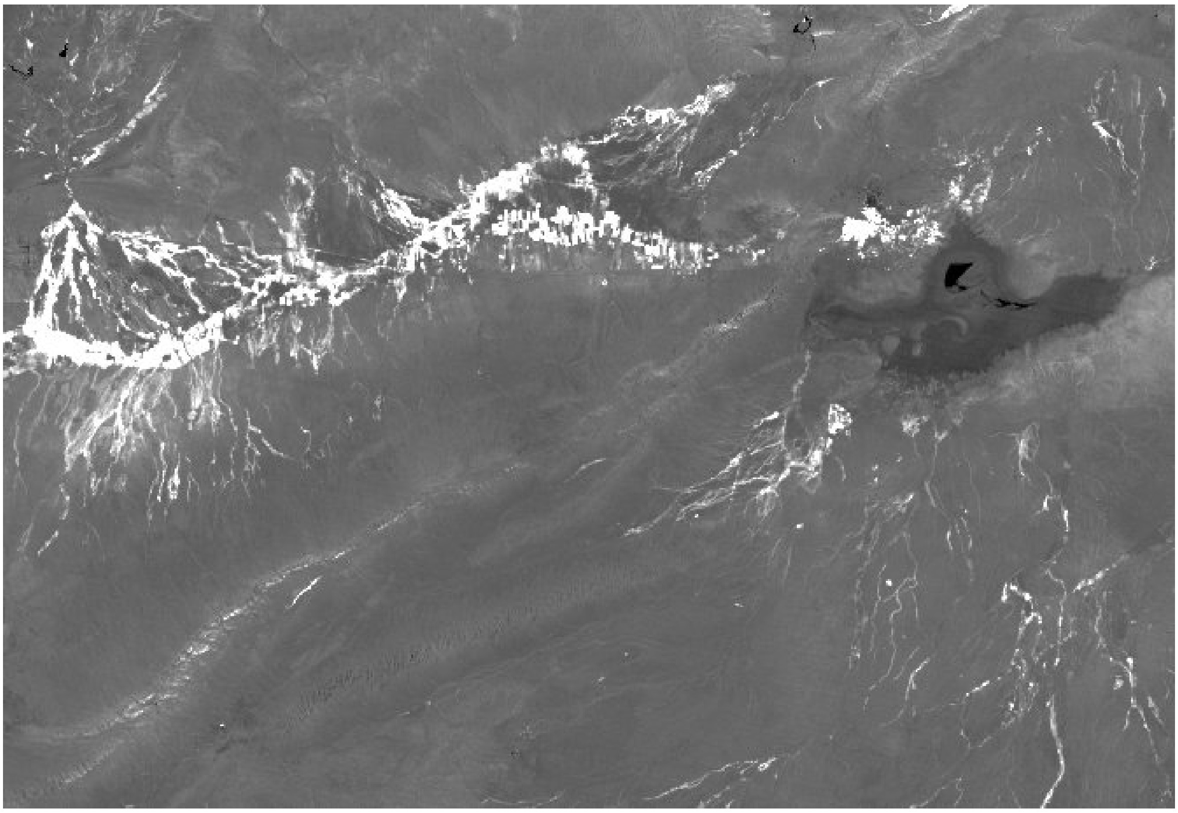

Fig. B-8: *PVI-image of subset TM Landsat 5 scene (07.04.1995) showing area around Tadmor*

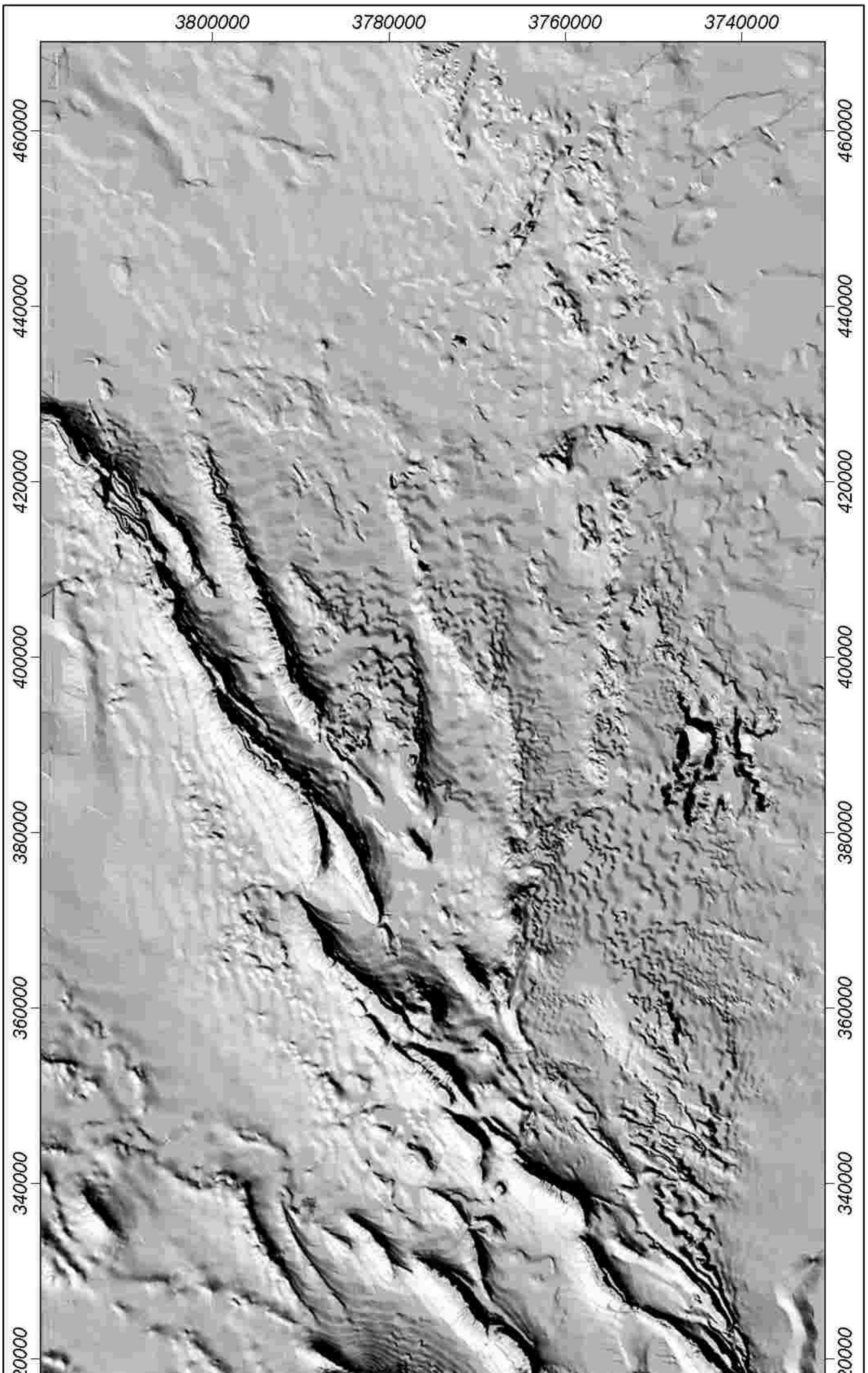

Fig. B-9 *Shaded relief of the Digital Terrain Model, based on maps of 1:100 000 scale (Source: Cartographic Department, S.A.R. 1976)*

Table B-1 *Ground control points used for geometrical correction of Landsat TM 5 subsets (research area) of scene 173/36*

Ground Control Point	X-Coordinate	Y-Coordinate	Description
GCP #1	433212	3823177	Turn W to North of road in direction of *Dayr Ez Zaur*, at the entrance to the soil column of *Tadmors*' historic site
GCP #2	429427	3820549	Road crossing west of *Tadmor*, road *Homs-Tadmor* and *Tadmor-Damascus*
GCP #3	432817	3824470	At the race course at *Tadmor* near the stables, sand course easy to be recognised on the image
GCP #4	411561	3792150	Road crossing northeast of *Khnaifess*
GCP #5	372152	3780889	Road crossing east of *Al Basiri*
GCP #6	357729	3808809	Road crossing *Homs-Tadmor* and *Homs-Al-Suknah*
GCP #7	460132	3831744	Turn to *Al Arak* on road *Tadmor-Dayr-Ez-Zaur*
GCP #8	428460	3835726	At the reservoir north west of *Tadmor*, on the western end of bridge of the retaining wall
GCP #9	394762	3823869	Road crossing *Homs-Tadmor/As-Salamiyah-Tadmor*
GCP #10	331642	3827559	Road crossing east of *Fruqlos Homs/Tadmor*-old road *Homs-Tadmor*
GCP #11	340912	3793074	Road crossing *Homs-Alsukhnah-Damascus/Homs-AlMihin-Dumayr*
GCP #12	306114	3758339	Crossing road *Quaryatain-Qutaifah* and small railway, about 40 km south of *Quaryatain*
GCP #13	289629	3765052	Turning for *Nabk* on the highway *Homs-Damascus* south of *Nabk*
GCP #14	294060	3776731	Turning for monument on the highway *Aleppo-Damascus* west of *Dayr Atiyah*
GCP #15	294067	3799261	Split of lanes of highway *Aleppo-Damascus* about 45 km south of *Homs*
GCP #16	290910	3839821	Turning for *Fruqlos* and *Tadmor* on the highway *Aleppo-Damascus* south of *Homs*
GCP #17	313177	3807159	Crossing road *Mhin/Sadad, Homs-Sadad*
GCP #18	338040	3780309	Western end of retaining wall of reservoir south of *Quaryatain*
GCP #19	328807	3779979	Turning for test area of *Mihassa* on the road *Quaryatain - Quataifah*, about 10 km south of *Quaryatain*

Ground Control Point	**X-Coordinate**	**Y-Coordinate**	**Description**
GCP #20	374085	3798684	Western side of bridge on the road *Fruqlos-Al Basiri*
GCP #21	456547	3820599	Turn of earth dam around the the wildlife reserve *Al Taliba* east of *Tadmo*r
GCP #22	358899	3775814	Escarpment of volcanic rocks west of road *Tadmor-Damascus*
GCP #23	424162	3803424	Turning for irrigated orchards on the road *Tadmor-Damascus*
GCP #24	344336	3810219	Northern end of badland area near an old phosphate mine
GCP #25	406492	3763239	Old construction with volcanic rocks, probably stable for sheep

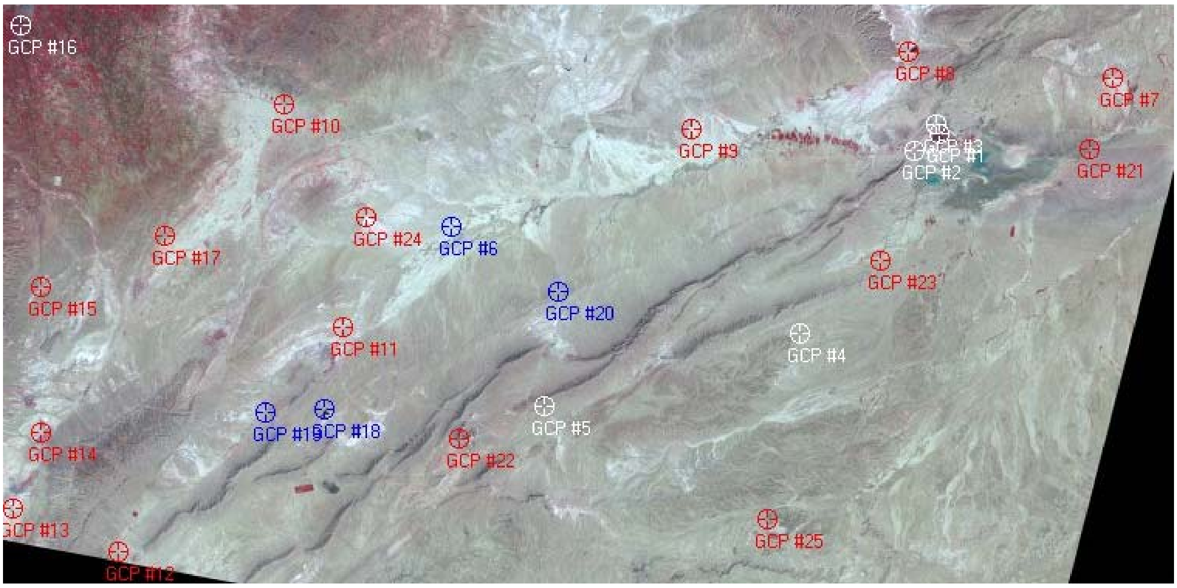

Fig. B-10 *Ground control points used during the geometrical correction process*

Table B-2 *Confusion table for classification of Landsat TM image (path 173/row 36) of 04/04/1994 (Fig..4.19), MLH classifier*

Land use / land cover	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Cl. 13	Total
Saline soils within the Sabkha cover with saltcrust (Class 1)	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	520
Gypsiferous salty soils, covered with salty crusts(Class 2)	0.00	99.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	407
Bare ground (Class 3)	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	674
Soil surface covered by flintstones (Class 4)	0.00	0.49	0.00	99.81	0.00	0.00	0.22	0.00	0.00	0.07	0.00	0.00	0.00	528
Scree slopes, degraded area (vegetation cover < 5%) (Class 5)	0.00	0.00	0.00	0.00	99.56	1.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	234
Sparse vegetation within the steppe area (Class 6)	0.00	0.00	0.00	0.00	0.44	98.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	373
Dense vegetation within the wadis (Class 7)	0.00	0.00	0.00	0.19	0.00	0.00	99.78	0.00	0.00	0.00	0.00	0.00	0.49	460
Limestones, basaltic rocks (Class 8)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.28	0.00	0.00	444
Brown clay enriched soils within the flooded area (Cl 9)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	429
Agricultural brown soils (Class 10)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.44	0.00	0.00	0.00	1409
Reservoirs (Class 11)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.72	0.00	0.00	351
Orchards of datepalms, olive trees (Class 12)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	99.23	0.00	129
Irrigated agricultural areas within rangeland (Class 13)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.77	99.60	741

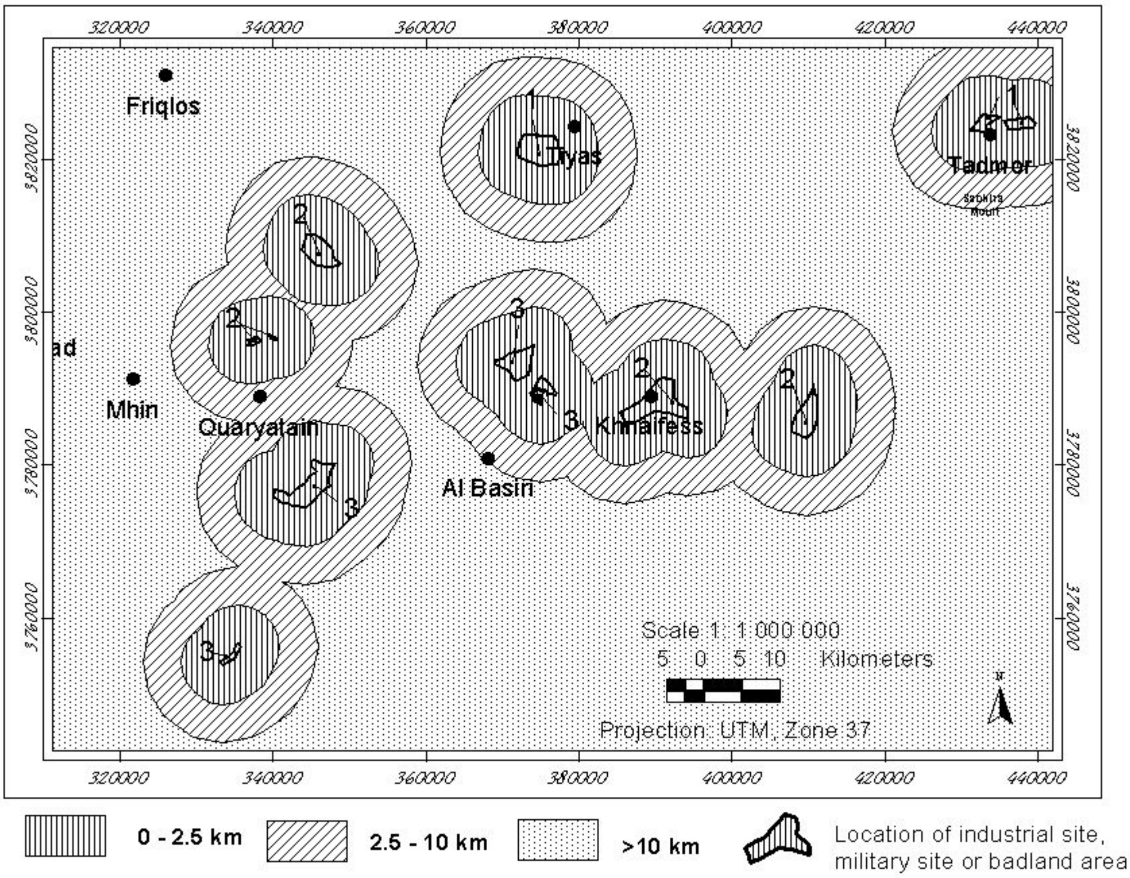

Fig. B-11 *Proximity to military (1), industrial sites (2) and badlands (3) (Criteria used in AHP process)*

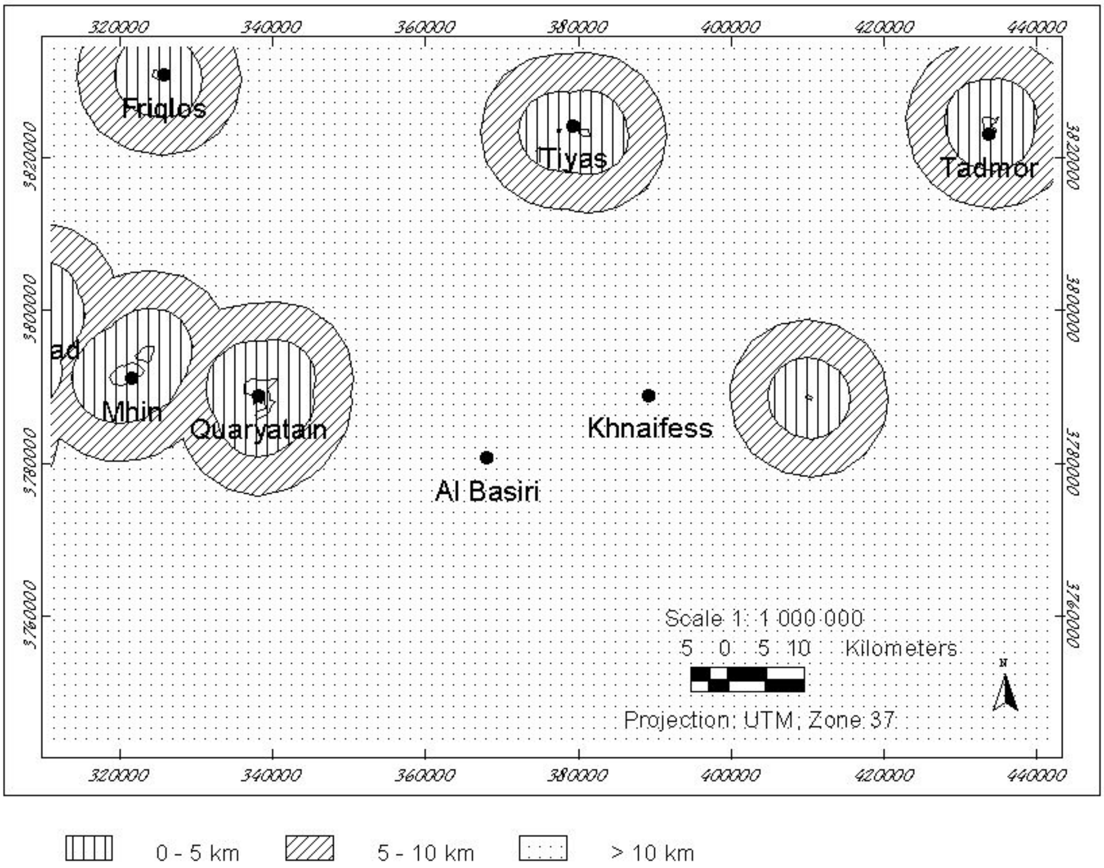

Fig. B-12 *Proximity to settlement areas (Criteria used in AHP process)*

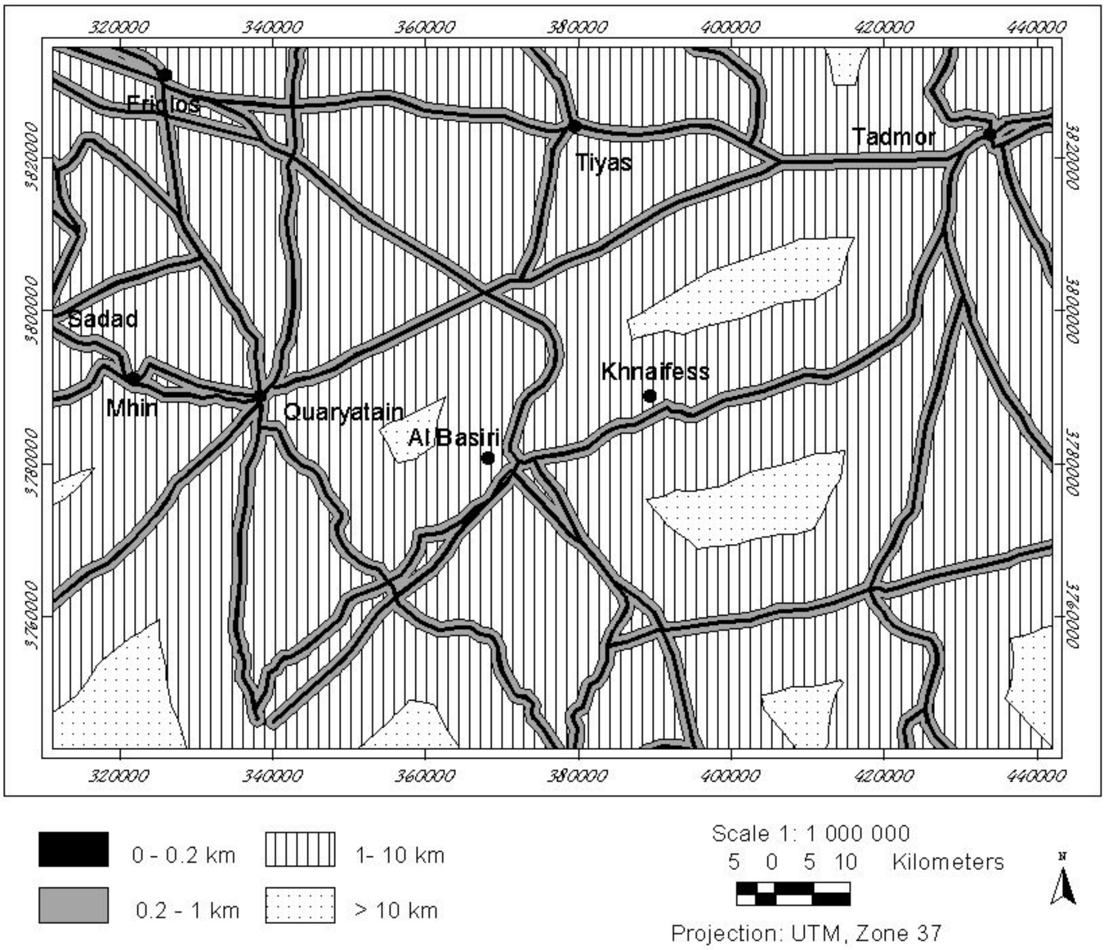

Fig. B-13 *Proximity to road (Criteria used in AHP process)*

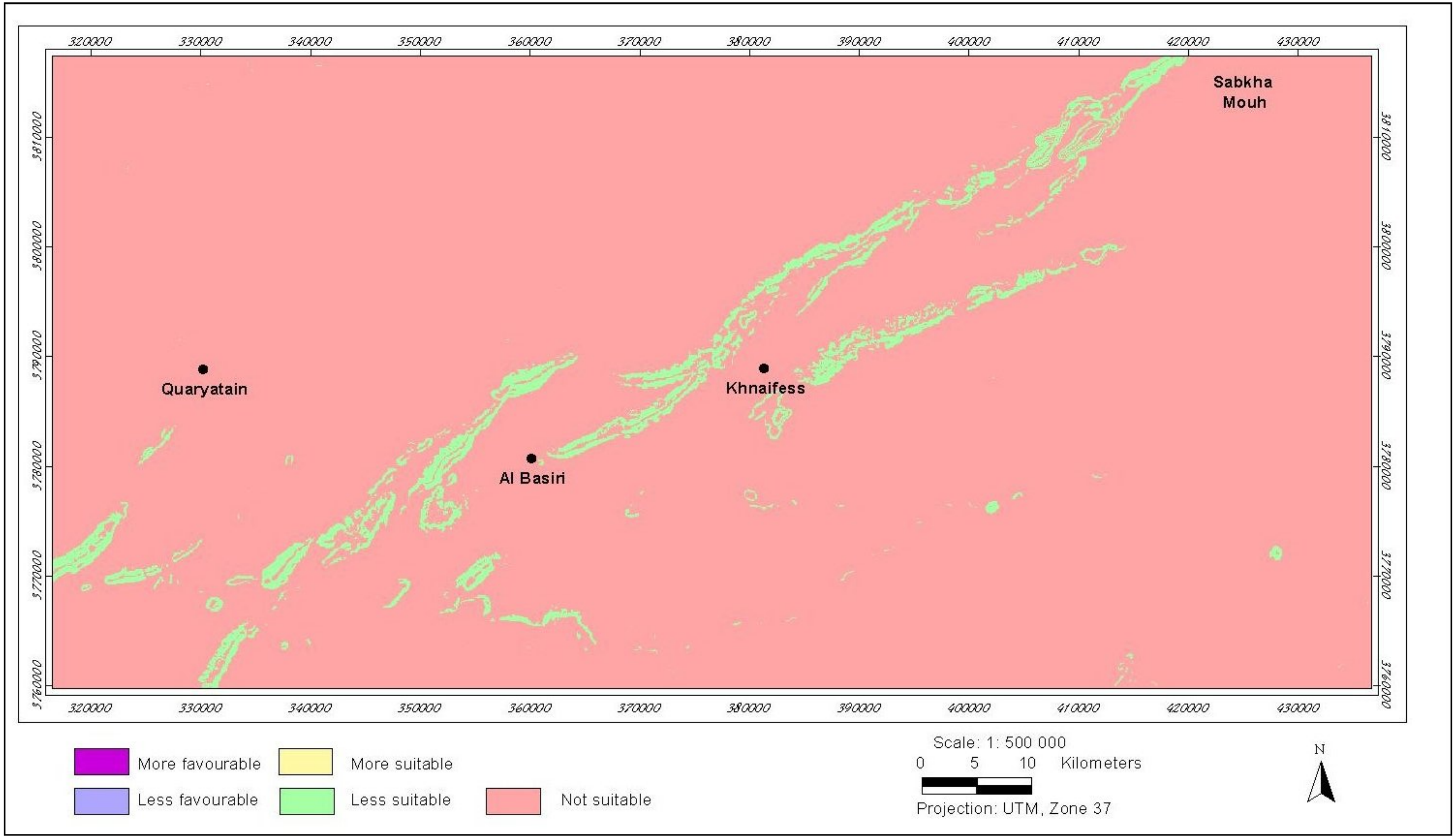

Fig. B-14 *Potential areas for floodwater harvesting systems, Scenario 2 B (calculated with runoff potential resulting from indexing method including layer flowlength)*

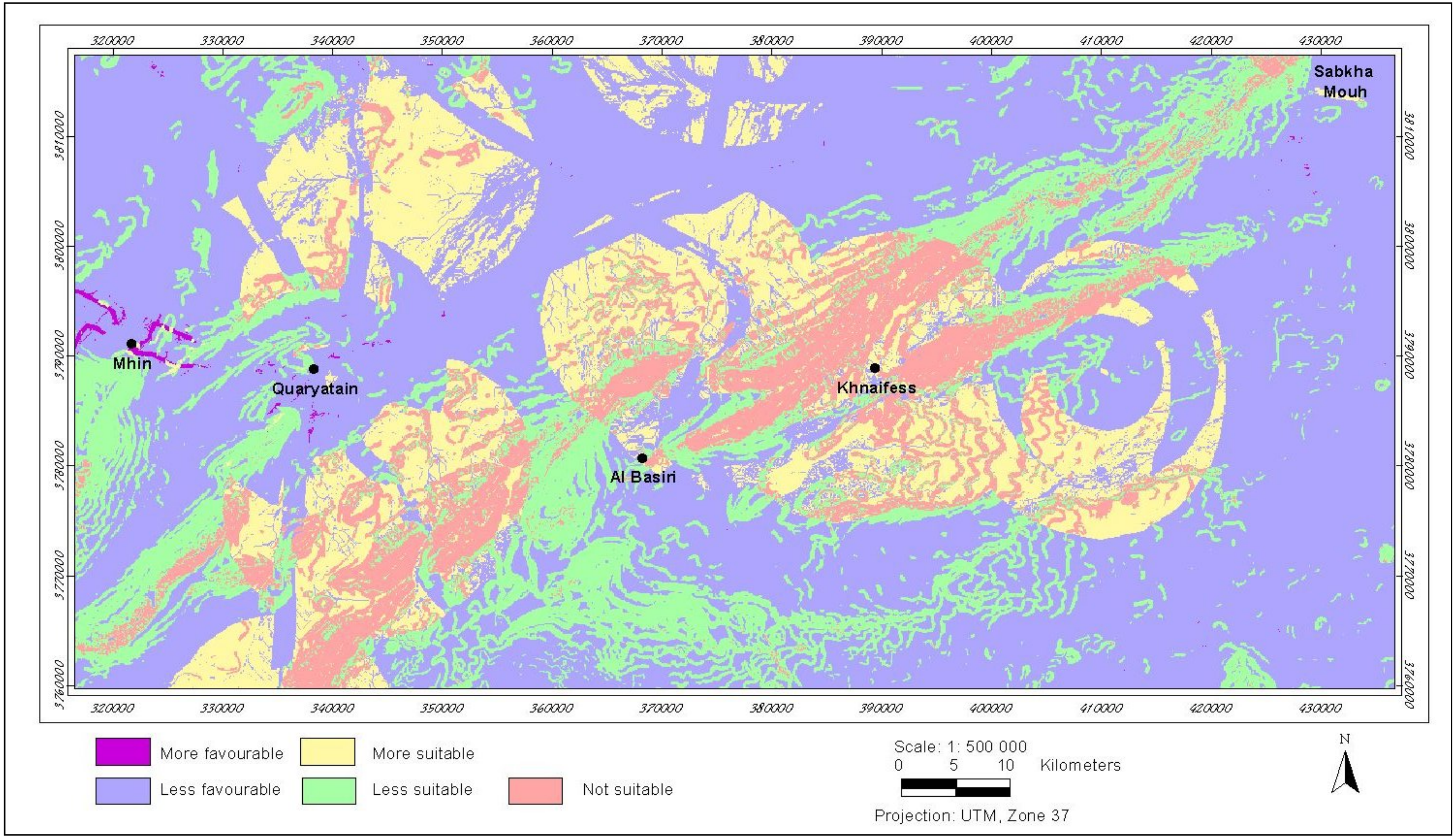

Fig. B-15 *Potential areas for microcatchment systems, Scenario 2 B (calculated with runoff potential resulting from indexing method including layer flowlength)*

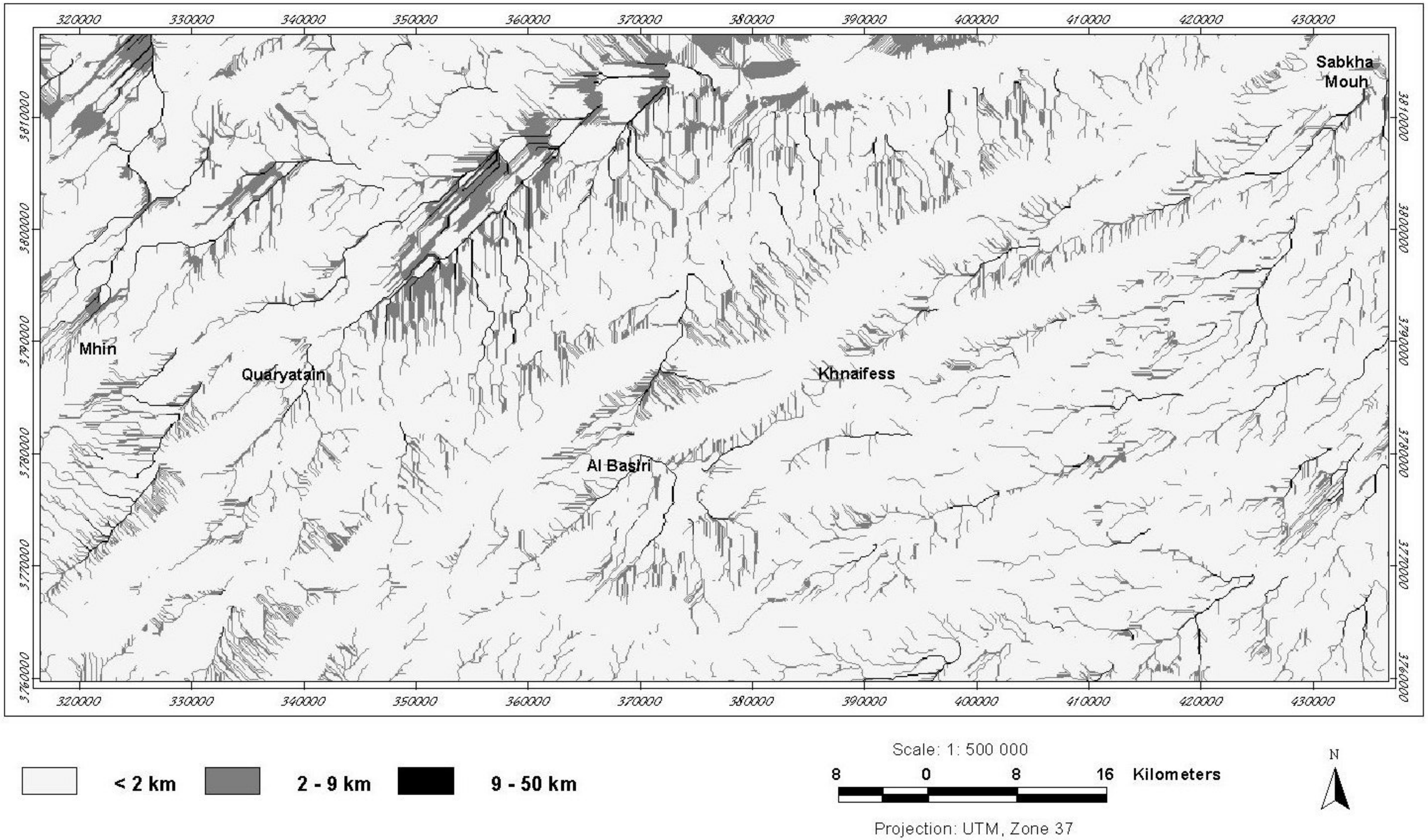

Fig. B-16 *Flowlength (Source: Landsat TM scene, path 173, row 36, 4/4/1994 (ESA 1994a), 4/7/1995 (ESA 1995)*

Fig. C-1 *Flood irrigated fields, in the background traditional houses near the road Homs-Tadmor*

Fig. C-2 *Former Barley field in the steppe area near Quasr al Hir*

Fig.C-3 *Reservoir near Quarayatain*

Fig. C-4 *Soil covered with flintstones.*

Fig.C-5 *Reforested area in the Northern Palmyrides*

Fig.C-6 *Rangeland south of Tadmor*

Fig. C-7 *Broad wadi south of Quaryatain*

Fig. C-8 *Replanted rangeland*

Fig. C-9 *Dam at Al Baridah, constructed during Roman times*

Fig. C-10 *Soil profile in a wadi near Mihinn*

Table D-1 *Sites in the rangeland of Walnut Creek, Arizona (Paige et al. 2001)*

Site	Ground Cover	Canopy cover	Soil Texture
A1: Chihuahuan desert brush	40	18	gravelly sandy loam
B1: Great Basin shrub	67	17	gravelly fine sandy loam
G1: Salt desert shrub	42	11	silty clay
K1: Sagebrush	82	20	gravelly sandy loam
A2: Chihuahuan desert grass	40	18	gravelly sandy loam
D1: Tall grass prairie	90	64	loam
D2: Tall grass prairie	90	53	very fine sandy loam
H2: Mixed grass prairie	80	20	clay
P1 & P2: Short grass prairie			clay loam

Table D-2 *Different Vegetation Indices (modified from Gorte 2000, Bastiannsen 1998, Richardson & Everitt 1992)*

Index	Strength	Source
Intrinsic Indices		
DVI: Difference vegetation index $DVI = NIR - R$	Vegetative cover	Ray 1994
RVI : Ratio vegetation Index $RVI = \frac{NIR}{R}$	Vegetative cover	Ray 1994
NDVI: Normalized Difference Vegetation Index $NDVI = \frac{NIR - R}{NIR + R}$	Vegetative cover	Tucker 1979
NDWI: Normalized Difference Wetness Index $NDWI = \frac{SWIR - MIR}{SWIR + MIR}$	Soil wetness and salinity conditions	Nageswara Rao & Mohankumar 1994
GVI: Green Vegetation Index $GVI = \frac{NIR + SWIR}{R + MIR}$	Biomass assessment	Nageswara Rao & Mohankumar 1994
Soil-line Related Indices		
Perpendicular VI: PVI Equation 4.9, Chapter 4.5.4	Vegetative cover	Richardson & Wiegand 1977
WDVI: Weighted Difference VI $WDVI = NIR - \frac{NIR_{soil}}{R_{soil}} R$	Insensitive to soil background, suited for LAI	Clevers 1988

Index	**Strength**	**Source**
SAVI: Soil Adjusted Vegetation Index $SAVI = \frac{(1+L)(NIR-R)}{NIR+R+0.5}$	Insensitive to soil background	Huete 1988
TSAVI: Transformed Soil Adjusted VI: Equation 2.10, Chapter 2.5.3	Insensitive to soil background	Baret & Guyot 1991
MSAVI: Modified Soil Adjusted vegetation index $MSAVI = \frac{a(NIR-aR-b)}{NIR+R+L}$ L=1-2a.NDVI.WDVI	Insensitive to soil background	Qi et al. 1994
OSAVI: Optimized soil-adjusted VI $OSAVI = \frac{(NIR-R)}{NIR+R+0.16}$	Insensitive to soil background	Rondeaux et al. 1996
Atmospherically corrected Indices		
ARVI: Atmospherically resistant VI $ARVI = \frac{NIR-RB}{NIR+RB}$ $RB = R-(B-R)\gamma$ [1]	Insensitive to atmospheric influences	Kaufman & Tanre 1992
GEMI: Global Environment Monitoring Index $GEMI = \eta(1-0.25\eta)\frac{R-0.125}{1-R}$ $\eta = \frac{2(NIR^2-R^2)+1.5NIR+0.5R}{NIR+R+0.5}$	Insensitive to atmospheric influences	Pinty & Verstraete 1992

[1] depends on aerosol

Lebenslauf

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