GIS MODELLING OF LAND DEGRADATION IN NORTHERN JORDAN USING SATELLITE IMAGERY

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by

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GIS MODELLING OF LAND DEGRADATION IN NORTHERN JORDAN USING SATELLITE IMAGERY

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ABSTRACT

Northern Jordan has undergone tremendous land cover change during the last three decades. This study tried to answer the following question: How have population growth and socio-economic influences affected soil quality in northern Jordan? The underlying factors that have led to the changes in land use and land cover are poorly documented, but efforts in this area started to be effective with the creation of the Badia Research and Development Programme. However, there has been little efforts to spatially correlate the land cover changes with soil quality. An empirical model based on high resolution spatial and temporal remotely sensed data offers the ability to assess the degradation impacts of changes in land cover in a spatial context. In an attempt to assess the impacts of changing land cover on soil, a GIS-based erosion model has been developed to predict annual soil loss by water in northern Jordan. This model uses the Revised Universal Soil Loss Equation (RUSLE).

Spatially distributed static (topographic and soil) parameters for this model are extracted from a regional GIS developed specifically for the Badia Programme area. The dynamic (vegetation cover) parameter is estimated from the land cover maps, derived by digital processing of multi-resolution, multi-temporal Landsat MSS (14. 9. 1972, 16. 7. 1985) and TM (28. 8. 1992). Mapping of vegetation cover was carried out by applying TM-Linear Mixture Modelling and NDVI, while mapping of fallow lands was carried out by both on-screen digitizing and sketch mapping in the field. The image difference technique was used in the change detection analysis.

The erosion model predict an increase in the amount of soil loss in the study area from 1972 to 1992, as a result of land cover changes. It was concluded that the degradation of the soil in the study area, observed during the last two decades, was caused by effects of these land cover changes.
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<tr>
<td>ATSR</td>
<td>Along Track scanning Radiometer</td>
</tr>
<tr>
<td>AVHRR</td>
<td>Advanced Very High resolution Radiometer</td>
</tr>
<tr>
<td>BRDP</td>
<td>(Jordan) Badia Research and Development Programme</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information Systems</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HCST</td>
<td>(Jordan) Higher Council for Science and Technology</td>
</tr>
<tr>
<td>LSMM</td>
<td>Linear Spectral Mixing Model</td>
</tr>
<tr>
<td>MSS</td>
<td>Multi-Spectral Scanner</td>
</tr>
<tr>
<td>NASA</td>
<td>(USA) National Aeronautics and Space Agency</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalised Difference Vegetation Index</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infra Red</td>
</tr>
<tr>
<td>RJGC</td>
<td>Royal Jordanian Geographic Center</td>
</tr>
<tr>
<td>RUSLE</td>
<td>Revised Universal Soil Loss Equation</td>
</tr>
<tr>
<td>SAVI</td>
<td>Soil-adjusted Vegetation Index</td>
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<tr>
<td>TM</td>
<td>Thematic Mapper</td>
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<td>TSAVI</td>
<td>Transformed Soil-adjusted Vegetation Index</td>
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CHAPTER 1: INTRODUCTION

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   1.1.3 Erosion processes in drylands

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1.8 Structure of the thesis
CHAPTER 1: INTRODUCTION

The last three decades have seen an increase in the use of remote sensing as a basic technique for collecting various types of information that is pertinent to land use and cover change (LUCC) and land degradation. Because of the nature of the information on land use and cover change offered by these data, remote sensing has become central to many natural resource planning programmes that utilize geographical information systems (GIS). Moreover, with the use of ancillary field data and the calibration of remote sensing inputs, data integration within a GIS can enhance the extraction of information from satellite imagery and improve the accuracy of a variety of outputs (Janseen et al., 1990; Suga et al., 1994). This has led to a synergistic approach in spatial data handling (Mulders and Girard, 1993).

Understanding of land use and cover changes, and the assessment of land degradation, are increasingly important from both ecological and economical points-of-view of the environment (Janseen et al., 1990). Indeed, from the early stages of the operationalization of remote sensing, applications were made to map and monitor land resources. Many of these studies were undertaken in drylands.

1.1 Drylands

1.1.1 Defining drylands

Aridity results from various influences which prevent moisture-bearing weather systems reaching certain areas of the land surface. Such influences are climatic, topographic and oceanographic (Cooke et al., 1993; Thomas, 1989, Thompson, 1975). Botanical, climatic, geomorphological and pedological definitions of drylands are widely reported in the literature. They have been summarised by Agnew and Anderson (1992). In his review of the literature definitions, Heathcote (1983) lists a number of words and phrases used to describe these environments, e.g. 'unvegetated', 'barren', 'devoid of water'. However, the most widely used definitions are based on scientific criteria and, of these, the most important are the climatic definitions. They all involve a
consideration of moisture availability (usually through a precipitation-evapotranspiration relationship). Generally, drylands can be defined as those areas that experience regular water shortage on a seasonal or longer-term basis (Beaumont, 1989). This general definition of arid conditions is based on the work of Meigs (1953) who produced a moisture index based on Thornthwaite’s (1948) index of moisture availability ($Im$):

$$ Im = \frac{(100S - 60D)}{PE} $$

where $PE$ is potential evapotranspiration, $S$ moisture surplus, and $D$ moisture deficit. It is aggregated on an annual basis from monthly data and takes soil moisture storage into account.

The UNESCO map of aridity (1979), which is based on UNESCO (1977) aridity indices, as well as on considerations of soils, relief and vegetation data, delimits four zones of aridity:

(a) hyper-arid $(P/ETP < 0.03)$
(b) arid $(0.03 < P/ETP < 0.20)$
(c) semi-arid $(0.20 < P/ETP < 0.50)$
(d) subhumid $(0.50 < P/ETP < 0.75)$

where $P$ is mean annual precipitation, and $ETP$ is the potential evapotranspiration calculated using the Penman formula. Figure 1.1 illustrates the spatial extent of the four zones of aridity as mapped by UNEP (1992).

The different equations used to delimit drylands result in different numerical definitions of boundaries in the drylands and, therefore, different geographical locations of the transition zones on maps (see for example, Agnew and Anderson, 1992: p. 16-18).

1.1.2 Physical environment

In drylands, precipitation is the dominant input to the hydrological cycle. This is usually in the form of rain; but in colder areas, e.g. northern Jordan, snow, dew and frost can be significant inputs during the winter. Precipitation is spatially and
temporally variable (Agnew and Anderson, 1992; Cooke et. al., 1993, Jones, 1981; Thomas, 1989a) and the few days on which it occurs are often limited to relatively a short season (the rainfall analysis from northern Jordan illustrates this, cf. Chapter 3) (Beaumont, 1989).

Evaporation and evapotranspiration form the major water losses from the land surface: atmosphere interface in drylands. This is because of the:
high temperatures registered in deserts during the day time;
lack of vegetation cover; and
relatively high wind speeds.

The combination of low precipitation inputs and high evaporation (and evapotranspiration) rates leads to a strong seasonality in drylands. Dry seasons are characterized by high evaporative demand and little input from precipitation, and the wet seasons have a higher input from precipitation and a lower evaporative demand. On an annual basis the water balance is negative and, of course, is strongly negative during the dry season. The relationship of this seasonality to temperature is variable and depends on the macroscale climatological situation. For example in West Africa, the rains fall during the warmest time of the year. This is related to the annual progression of the ITCZ. In northern Jordan, precipitation occurs in the coldest months. In this case it is related to cyclone tracks entering the region from the Mediterranean Basin in winter, and the blocking effect of the continental tropical air mass over the Arabian Peninsula in summer.

Most desert soils exhibit weak horizon development, have low clay contents and are often relatively shallow. Soil development is usually much slower than the rates of erosion, thus distinctive horizons can evolve only on very gentle slopes where there is net accumulation (i.e. deposition of eroded material). Such areas also often exhibit soluble salt accumulation. In the driest regions sodium salts dominate, whilst calcium carbonate dominates semi-arid areas; gypsum is intermediate between the sodium and calcium carbonate zones. The accumulation of these salts in the upper horizons of soils
Fig. 1.1: The spatial extent of the four aridity zones that describe the World’s drylands (UNEP, 1992)
can be attributed to the upward water movement in the soil profile through capillary action. This is driven by the high rates of evaporation and the low rates of leaching. The resulting low moisture contents imply limited biological activity which, combined with high summer temperatures, results in low organic matter contents (Beaumont, 1989).

Like soil, vegetation also reflects the climate of drylands. This is particularly so in the: physiological adaptations of plants; the overall vegetation cover and amount of biomass; the spatial distribution of vegetation; and its temporal dynamics.

Vegetation is much more clumped and patchy than in humid climates, and the cover and biomass amounts are low. This is primarily a response to water availability and the spatial patterns of nutrient availability, but also to fire and exploitation patterns (Cooke et al., 1993; Beaumont, 1989). The limited vegetation cover in drylands has a considerable influence on earth surface processes (Thomas, 1989a). For example, the low density of vegetation exposes a large proportion of the ground surface directly to the action of wind and water (as both rainfall and runoff) thereby potentially accelerating the processes of wind and water erosion.

1.1.3 Erosion processes in drylands

A feature of many dryland soils is their naturally high susceptibility to erosion by both wind and water (Beaumont, 1989). Low vegetation cover is one of the main factors leading to high rates of erosion. But even these rates are accelerated when the vegetation cover is completely or partially removed. Disturbance of the soil surface through agricultural activities such as animal trampling or ploughing loosens the soil aggregates or breaks down surface crusts. Both processes leave the soils more susceptible to wind and water erosion. These processes, though, are far from simple. In the case of wind erosion, the very same agricultural activities that loosen soil (e.g. ploughing) also increase soil roughness, thereby increasing frictional drag, decreasing
wind velocity and reducing the ability of the wind to detach and entrain soil particles. A net result of ploughing could therefore be a decrease in soil erosion by wind!

Water is a major agent responsible for soil erosion, initially through aggregate breakdown by rain splash, soil particle transport by overland flow and in more severe cases by rill and gully erosion (Cooke et al., 1993). These processes will be discussed in detail in Chapter 5 as water erosion of soils will be the focus of the land degradation modelling aspect in this research.

1.2 Scope of the research

The population of Jordan has grown rapidly during the last three decades, with an average annual growth rate of approximately 4.5% (Maani et al., 1998). This has been partially due to political instability and the military conflicts in the Middle East which, since 1948, has fostered several waves of immigration into Jordan; the last one being in 1990-1991 as a result of the Iraqi invasion of Kuwait (the Gulf War). However, the natural growth rate of the population is high. Jordan has the second highest birth rate in the world with 6.6 live births per woman (Maani et al., 1998; Jaber et al., 1997). The implications of this high rate of population growth can be seen clearly in northern Jordan. The area to the south of the Syrian border, to the east of the city of Mafraq, has undergone significant land use changes during the last three decades, because of population growth as well as changes in lifestyle. Population growth and its implications for land use and cover change in northern Jordan will be examined in detail in Chapter 2. The combination of high population growth rates and land use change in northern Jordan makes it an ideal location in which to study the relationships between population growth, changing economic activities and lifestyles, and their effects on the ecologically fragile and economically marginal environment of this part of the country. Specifically, this research will focus on part of the Badia Research and Development Programme [BRDP] (cf. Section 1.4). This area is also the current active frontier of settlement and land conversion in northern Jordan.
1.3 Aim and objectives

The overall aim of the research is to develop a GIS-based spatial model to evaluate the impacts of land cover change on land degradation in northern Jordan.

A number of specific objectives have been defined to meet this aim (number of the chapters in which these objectives are specifically discussed are indicated):

Development of a digital terrain model, and climatological and pedological databases of the study area, (Chapter 6).


Verification of the land cover change maps through field mapping and interviews with farmers (Chapters 2 and 3).

Modelling land degradation in a GIS environment for 1972, 1985 and 1992. The approach adopted for this objective is based on coupling a parametric model of soil degradation (the Revised Universal Soil Loss Equation – RUSLE) with a GIS of the study area, (Chapters 5 and 6).

Verification of the outputs of the land degradation model for 1992 (Chapter 6).

This aim and these objectives enable the following hypotheses to be tested:
Land cover changes in the study area are caused by land use changes that have been triggered by national-scale and regional-scale socio-economic factors since the 1970s (Chapter 2).

The land cover changes that have occurred since 1972 have led to increased soil losses over the study area (Chapter 6).
1.4 The Badia Research and Development Programme (BRDP)

The badia (defined as the desert-like part of Jordan) forms a significant part of the country and it includes both the arid and hyper-arid areas. However, a more traditional definition of badia in Jordan is the arid/semi-arid transitional zone. It covers an area of approximately 72,000 km², which constitutes about 80% of the total area (89,329 km²) of Jordan (Fig. 1.2).

The Jordan Badia Research and Development Programme (BRDP) is a collaborative venture between Jordan’s Higher Council for Science and Technology (HCST) and the Royal Geographical Society with the Institute of British Geographers (RGS-IBG) of the United Kingdom. Its general objective, as stated in the original BRDP Framework Document (RGS, 1992) is:

The sustainable development of the desertified Badia environment and the improvement of the standard of living of the inhabitants.

The BRDP area covers 11,210 km² between 31°30' and 32°45' N and 36°30' and 38°10' E and represents 12.5% of the total land area of Jordan (Fig. 1.2). Despite the overall objective stated above, surveying the natural resource base of the area has been the focus of most BRDP studies. The BRDP has a field centre based at Safawi (Fig. 1.2).

The aims of the BRDP (Dutton et al., 1998) can be summarized as follows:

Make the population of Jordan more aware of badia issues and more sympathetic to them.

Emphasizing and revealing the degree to which the environment and the development potential for local people have suffered, as a consequence of the local population growth as well as of the demands on the natural resources by the local population and outsiders.

Providing relevant and accurate information, and focus as strongly on human factors as on technical factors.
Involving the local population and the external decision makers, as far as possible, in the research-process stage particularly to agree the important issues, and at the stages of translating findings into conclusions, and conclusions into recommendations.

Fig. 1.2: The BRDP area. It covers 11,210 km² and represents 12.5% of the total land area of the country.

1.5 The Study Area

The study area forms the north western part of the BRDP (Fig. 1.3) and lies close to the Syrian border. It includes both the eastern limit of irrigated agriculture and the, more-or-less, settled population. The history of this area testifies to both the nomadic
and the sedentary lifestyles of the people who live there. Their livelihoods have been and are still, to a large extent, based upon opportunistic farming and herding.

Fig. 1. 3: The location of the study area within the BRDP. The rectangular shape indicates the study area. The BRDP area is shown in darker shading.

However, during the last 30 years there has been a regular but consistent change towards more intensive rain-fed and irrigated agriculture (cf. Chapter 2). This has occurred because local people have found it increasingly difficult to earn a living from grazing sheep and goats on the rangeland. This is, in part, due to the impacts of overgrazing on land productivity, but also because of the restrictions of living so close to the border and shifts in government agricultural policies. Government loans to drill private wells have accelerated and reinforced the trend toward settled agriculture. Land is cleared of basalt boulders and stones, and then is used for irrigated agriculture. New settlers have moved further eastwards to a degree that more than 70 km east of Mafrak city there are signs of basalt boulder removal for field formation. The removal of the
basalt boulders can, in some cases, lead to surface sealing thereby reducing infiltration and encouraging the erosion of fine material by the wind (Kirk, 1998a). In other areas the removal of the ‘stone mulch’ offered by basalt stones can increase soil aggregate breakdown, lead to surface sealing, and increase sheet wash by both wind and water erosion. In either case, a consequence is reduced topsoil fertility and loss of land productivity.

1.5.1 Geology

Tertiary-Quaternary continental basalt flows and tuffs cover the majority of the BRDP area (Fig. 1.4). The basalts are alkali-olivine in character and are part of the major North Arabian volcanic province. They have been classified as the Harrat Ash Shaam basaltic supergroup, and are subdivided into five major groups: Bishriyya, Rimah, Asfar, Safawi and Wisad. The age of a number of different lava flows has been determined, and they range from 13.7 Ma to <0.5 Ma for the exposed rocks (Alhomoud et al., 1996). In addition there are pockets of sediments along wadi courses. In some cases rise sedimentary fills form intermittently inundated, mudflats known locally qa’a. Sediment textures range from fine to coarse, and most of the sediments are consolidated.

1.5.2 Geomorphology

The overall slope of the land is from the north-west to the south-east. The maximum elevation near the Syrian border is about 1150 m.a.s.l and it is less than 700 m.a.s.l at the southern extremity of the study area. The area is covered by extensive lava flows which exhibit varying degrees of exposure and weathering. They have southward direction from their source on the Jabal al-Arab (to the north, in Syria). In addition, there are a number of cones of volcanic tuffs on the undulating basalt surface.

The terrain is largely undulating and is weakly to moderately dissected by near radial drainage flowing from the Jabal al-Arab. Slopes are generally <15 %. However, on the
Fig. 1. 4: The major geological divisions of the BRDP

volcanic cones, slopes of up to 45% exist and the relative relief can reach 150 m (National Soil and Land Use Project, 1994).

Most of the basalt surfaces are boulder-strewn, unless the stones have been removed to make fields. The size of individual clasts shows considerable variation. The size distribution is principally controlled by the ground surface geology and slope position. Towards the north-west the basalt boulders become increasingly covered by lichen, probably indicating increased precipitation and moisture availability. The underlying sediment is fine grained and brown to orange in colour. The origins of this sediment are disputed, but it is probably a mixture of basalt weathering products and fine-grained aeolian deposits (Alhmoud et al., 1996).

1.5.3 Climate

The climate in the study area is characterized by two well-defined seasons: a hot, dry summer and wet, cold winter. Table 1.1 provides long-term mean monthly climatological data for Safawi from 1967 to 1995. The data for this climatological
station have been used because it is the closest climatological station to the study area (it is about 20 km to the east of the study area). Data for three other stations within the study area will be discussed in the next section. However, these stations do not have the full range of observations that are made at Safawi. As there is so little variation between the observations at climatological stations in the badia, it has been stated that almost any station could be used to represent the study area (Rakad Ta‘ani, Ministry of Water and Irrigation, personal communication, 1998). This assertion is questionable as the data will show. The mean annual rainfall amount for Safawi is 89.1 mm. The mean annual minimum and maximum temperatures are 11.6°C and 26.6°C respectively. The mean relative humidity varies from 49.9% to 63% in summer, and 56% to 82% in winter.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. temperature (°C)</td>
<td>29.6</td>
<td>22.0</td>
<td>16.3</td>
<td>14.7</td>
<td>17.4</td>
<td>20.8</td>
<td>27.0</td>
<td>31.6</td>
<td>35.1</td>
<td>34.1</td>
<td>36.3</td>
<td>34.6</td>
</tr>
<tr>
<td>Min. temperature (°C)</td>
<td>13.9</td>
<td>7.9</td>
<td>3.8</td>
<td>2.9</td>
<td>4.4</td>
<td>7.4</td>
<td>11.4</td>
<td>15.3</td>
<td>16.8</td>
<td>19.1</td>
<td>19.1</td>
<td>17.6</td>
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<tr>
<td>Mean temperature (°C)</td>
<td>21.9</td>
<td>15.0</td>
<td>9.9</td>
<td>8.6</td>
<td>10.9</td>
<td>13.8</td>
<td>19.4</td>
<td>23.5</td>
<td>26.5</td>
<td>27.8</td>
<td>27.6</td>
<td>26.1</td>
</tr>
<tr>
<td>Wind speed (ms⁻¹)</td>
<td>2.7</td>
<td>2.3</td>
<td>2.0</td>
<td>2.1</td>
<td>2.7</td>
<td>3.3</td>
<td>3.3</td>
<td>3.4</td>
<td>3.9</td>
<td>4.8</td>
<td>4.6</td>
<td>3.7</td>
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<tr>
<td>Sunshine duration (hr d⁻¹)</td>
<td>8.7</td>
<td>7.4</td>
<td>5.8</td>
<td>5.9</td>
<td>6.8</td>
<td>7.5</td>
<td>8.3</td>
<td>10.1</td>
<td>11.9</td>
<td>11.9</td>
<td>11.4</td>
<td>10.2</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>61.3</td>
<td>69.2</td>
<td>78.3</td>
<td>81.6</td>
<td>74.7</td>
<td>67.6</td>
<td>56.4</td>
<td>49.9</td>
<td>51.3</td>
<td>55.7</td>
<td>60.3</td>
<td>63.0</td>
</tr>
<tr>
<td>Rainfall (mm)</td>
<td>5.1</td>
<td>11.6</td>
<td>15.5</td>
<td>19.8</td>
<td>14.0</td>
<td>15.5</td>
<td>6.3</td>
<td>1.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Potential evaporation (mm d⁻¹)</td>
<td>7.8</td>
<td>4.3</td>
<td>3.1</td>
<td>3.0</td>
<td>5.2</td>
<td>8.1</td>
<td>6.3</td>
<td>15.2</td>
<td>17.9</td>
<td>18.1</td>
<td>15.5</td>
<td>12.2</td>
</tr>
<tr>
<td>Class A Pan evaporation (mm d⁻¹)</td>
<td>4.9</td>
<td>3.1</td>
<td>2.2</td>
<td>2.5</td>
<td>3.5</td>
<td>5.3</td>
<td>7.9</td>
<td>9.7</td>
<td>10.7</td>
<td>9.9</td>
<td>8.6</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Table 1.1: Monthly climatic means for Safawi: 1967-1995 (Source: Government of Jordan, Water Authority Records)
The prevailing wind direction is north-westerly in summer, shifting to the south-easterly in the winter. Easterly and south-westerly winds also occur. Winds are cold and dry in winter, but hot and dry, and consequently more harmful to the vegetation, in summer. The mean annual wind speed is 11.6 km hr⁻¹. This ranges between 10 and 18 km hr⁻¹ in summer and 7 and 12 km hr⁻¹ in winter. The mean annual evaporation observed from a class A pan is 6.5 mm d⁻¹. It varies from 7 to 11 mm d⁻¹ in summer and 2 to 8 mm d⁻¹ in winter.

1.5.4 Rainfall

Scarcity of water is probably the most limiting factor for sustainable development in the Jordanian badia, where most surface water comes from the erratic rainfall which falls over this arid area. More than 80% of Jordan is classified as arid (cf. section 1.1.1). Most of this land is located in the eastern part of the country, where the BRDP area lies. The aridity of the study area has already been highlighted by the data from Safawi (Table 1.1). However, the study area receives slightly more precipitation than Safawi. This is illustrated by data from the rainfall stations at Umm al-Quttayn (in operation since 1947) and Dayr al-Kahf and al-Aritayn (in operation since 1963) (Table 1.2). Umm al-Quttayn, in the north west of the study area, is situated at elevation of 986 m.a.s.l. It has lower mean temperatures and higher precipitation than the other stations in the study area, and is representative of the higher terrain found in the north west of the study area. Rainfall occurs between October and May and the mean annual rainfall is about 155 mm. Dayr al-Kahf, in the east of the study area, is situated at elevation of 1025 m.a.s.l and has a mean annual rainfall of about 114 mm. Most precipitation there also falls between October and May.

<table>
<thead>
<tr>
<th>Station code</th>
<th>Name</th>
<th>Altitude (m.a.s.l)</th>
<th>Type</th>
<th>Mean annual rainfall (1967-95), (mm)</th>
<th>Period of record</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Umm al-Quttayn</td>
<td>986</td>
<td>Daily</td>
<td>153.2</td>
<td>1947-95</td>
</tr>
<tr>
<td>F4</td>
<td>Dayr al-Kahf</td>
<td>1025</td>
<td>Daily</td>
<td>113.2</td>
<td>1963-95</td>
</tr>
<tr>
<td>F6</td>
<td>al-Aritayn</td>
<td>800</td>
<td>Daily</td>
<td>95.4</td>
<td>1963-95</td>
</tr>
</tbody>
</table>

Table 1.2: Rainfall Stations in the Study Area
Precipitation related to thunderstorms forms a large proportion of the total rainfall in the study area. Therefore, most rainfall is probably characterized by high, but irregular intensity and short duration. Orographic rainfall is important in the northern part of the study area, because of the proximity of Jabal al-Arab. Statistical data analysis of the rainfall stations has been performed and the following observations can be made.

The average number of rain days for the study area is 23. The number of days ranges from 29.4 at Umm al-Quttayn to 18 days at al-Aritayn (Fig. 1.5).

The wettest month varies between stations. At Umm al-Quttayn it is February (30.3 mm), whereas at Dayr al-Khaf and al-Aritayn it is January (24.4 and 21.5 mm respectively (Fig. 1.6).

The highest mean monthly rainfall is 30.3. The mean annual rainfall in a wet year varies between 180 and 292 mm, and between 40 to 70 mm in a dry year (Table 1.3). The coefficient of variation of rainfall varies across the study area from 0.35 at Umm al-Quttayn (the wettest station), to 0.55 at Dayr al-Kahf. This means that rainfall in the Umm al-Quttayn region (north west of the study area) is less variable than at Dayr al-Kahf region (in the east) (Table 1.3)

<table>
<thead>
<tr>
<th>Rainfall station</th>
<th>Umm al-Quttayn</th>
<th>Dayr al-Kahf</th>
<th>al-Aritayn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Annual Rainfall (mm)</td>
<td>255.2</td>
<td>292</td>
<td>180</td>
</tr>
<tr>
<td>Minimum Annual Rainfall (mm)</td>
<td>70.5</td>
<td>53</td>
<td>40</td>
</tr>
<tr>
<td>Mean Annual Rainfall (mm)</td>
<td>138</td>
<td>114</td>
<td>92</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>45.8</td>
<td>62.7</td>
<td>40.3</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>0.35</td>
<td>0.55</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Table 1.3: Maximum, minimum, mean rainfall, standard deviation and variation coefficient, extracted from daily rainfall data records covering a 22 year period, (1975 - 1997).
Fig. 1.5: Mean number of rain days for the stations in the study area

Fig. 1.6: Mean monthly rainfall (in mm) for the stations in the study area
1.5.5 Soils

Although some researchers postulate that the soils of northern badia are almost entirely formed as a result of basalt weathering (e.g. Alhomoud et al., 1996), Kirk (1998a) suggests that the fabric of the soil is dominated by parent materials of aeolian origin. The composition of the sediment is similar to that of contemporary dust carried by the Khamaseen which originates in the Arabian Peninsula during the early and late summer (Kirk, 1998). It appears likely that the basalt has been buried by material of aeolian and fluvial origin which masks weathered material.

The onset of drier conditions around 9000 B.P. would have reversed the soil-forming processes. Conditions of active chemical weathering and soluble salt removal would have been replaced by conditions which would have favoured much slower rates of chemical weathering and an increased rates of mechanical weathering. The conditions at this time would also have favoured the accumulation of soluble salts rather than leaching (National Soil Map and Land Use Project, 1994).

Xeric and Xerochreptic subgroups constitute 80% of the soils in the study area, with Xerochreptic Calciorthids being the dominant subgroup (28% of the study area). The Calciorthids mainly occur on the middle and upper slopes of the interfluves. Xerochreptic Palethiorthids comprise 17% of the area and are the second most common subgroup. They occupy similar topographic positions to the Calciorthids. Lithic subgroups together make up 27% of the area. They occur on crests, in craters, on valley sides and on the steep upper slopes of cones and higher interfluves. The other major subgroup is the Xerochreptic Camborthids, these soils occupy 10% of the area. They occur on lower slopes, in basins and valleys.

The clay content of the soils generally increases with depth and is, in part, a consequence of weathering. The CEC/Clay% ratio averages 0.5-0.6. This indicates that the clay has been subject to weathering. In many places calcium carbonate occurs at depth below soil horizons, but overlaying partially weathered basalt containing large 'core-stone' boulders. The organic matter contents are generally low and the C/N
ratios high. Under natural conditions, the soils have low to moderate salt contents (e.g. surface ECE is usually <5 mS cm$^{-1}$).

In the GIS, the soils of the study area are presented as polygons of soil units extracted and digitised from the maps of the National Soil Map and Land Use Project, produced by the Ministry of Agriculture of Jordan (1994). This project has recently completed soil mapping at various scales for the entire country. In the study area six soil units have been recognized. The soil units are mainly defined on the basis of physiography and the soil classification generally does not go beyond the level of a subgroup. Nonetheless, a few subgroups are sub-divided to the level of the soil series on the basis of soil mapping in similar areas in Jordan. The physical and chemical properties of the soil units in the study area are shown in Table 1.4.

1.6 Socio-economic background

1.6.1 Population

The population in the north-west part of the badia has exploded with five-and-a-half times as many people living in the BRDP villages in 1994 as in 1976 (Maani et al., 1998). Badia dwellers were originally pastoralists and traders, who had limited dependence on material goods and technologies. However, the last 30 years have seen a progressive switch in their lifestyle from being dominately nomadic pastoralists to village dwellers with a diverse range of economic activities.

This change in lifestyle has undoubtedly had an impact on the relationship between the population living the study area and its physical environment. This change has evolved under the influence of a wide range of factors, the origin of which have, for the most part, been outside the study area. Such changes have allowed people from outside the study area to exploit local resources for their own or shared advantages. Most notably water resources and land have, and are being, used by outsiders. Dutton (1998) has postulated that a consequence of this will be that the environment will suffer as the population, and its demands on the scarce natural resources, grows. People of the badia have become less dependent on their environment and more dependent on
<table>
<thead>
<tr>
<th>Soil Unit</th>
<th>BIS(bishriya)</th>
<th>FAR(mafarid)</th>
<th>SAB(sabha)</th>
<th>THA(ramtha)</th>
<th>WAY(huwaylat)</th>
<th>ZUM(zumaylat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay %</td>
<td>25.9</td>
<td>27.3</td>
<td>28.7</td>
<td>29.1</td>
<td>27.8</td>
<td>26.7</td>
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<tr>
<td>Silt %</td>
<td>50</td>
<td>44</td>
<td>50</td>
<td>50.9</td>
<td>50.2</td>
<td>50</td>
</tr>
<tr>
<td>Sand %</td>
<td>24.1</td>
<td>28.7</td>
<td>21.3</td>
<td>20</td>
<td>22</td>
<td>23.3</td>
</tr>
<tr>
<td>CEC meq /kg</td>
<td>17.4</td>
<td>14.4</td>
<td>15.5</td>
<td>16.2</td>
<td>16.1</td>
<td>16.5</td>
</tr>
<tr>
<td>CEC/Clay %</td>
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<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>CaCO₃ %</td>
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<td>35.4</td>
<td>33.4</td>
<td>32.2</td>
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<td>31.6</td>
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<tr>
<td>CaSO₄ %</td>
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<td>2.5</td>
<td>2.7</td>
<td>2.8</td>
<td>2.5</td>
<td>2.4</td>
</tr>
<tr>
<td>ECE mS/cm</td>
<td>7.5</td>
<td>8.6</td>
<td>9.0</td>
<td>7.5</td>
<td>8.2</td>
<td>7.6</td>
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<tr>
<td>ESP %</td>
<td>9.0</td>
<td>8.3</td>
<td>11.9</td>
<td>13.4</td>
<td>10.0</td>
<td>9.4</td>
</tr>
<tr>
<td>OM %</td>
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<td>1.21</td>
<td>1.22</td>
<td>1.22</td>
<td>1.21</td>
<td>1.22</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Mixed</td>
<td>mixed</td>
<td>mixed</td>
<td>Mixed</td>
<td>mixed</td>
<td>mixed</td>
</tr>
<tr>
<td>Depth</td>
<td>Shallow</td>
<td>shallow</td>
<td>intermediate</td>
<td>deep</td>
<td>Intermediate</td>
<td>deep</td>
</tr>
<tr>
<td>Texture</td>
<td>Silt Loam</td>
<td>Silt Loam</td>
<td>Silt Clay</td>
<td>Silt Clay Loam</td>
<td>Silt Clay Loam</td>
<td>Silt Clay</td>
</tr>
<tr>
<td>Soil</td>
<td>Thermic</td>
<td>Thermic</td>
<td>Thermic</td>
<td>Thermic</td>
<td>Thermic</td>
<td>Thermic</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Moisture Regime</td>
<td>Xeric-Aridic</td>
<td>Xeric-Aridic</td>
<td>Xeric-Aridic</td>
<td>Xeric-Aridic</td>
<td>Xeric-Aridic</td>
<td>Xeric-Aridic</td>
</tr>
<tr>
<td>Rock</td>
<td>10</td>
<td>15</td>
<td>10</td>
<td>00</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Outcrop %</td>
<td>Strong</td>
<td>Strong</td>
<td>Strong</td>
<td>strong brown</td>
<td>strong brown</td>
<td>strong brown</td>
</tr>
<tr>
<td>Colour</td>
<td>brown to brown</td>
<td>brown to brown</td>
<td>brown to red</td>
<td>to reddish to brown</td>
<td>yellowish red</td>
<td>yellowish red</td>
</tr>
</tbody>
</table>

Table 1.4: Physical and chemical properties of the Soil Units found in the study area (adapted from: National Soil Map and Land Use Project. The Soils of Jordan, Ministry of Agriculture, 1994).
opportunities outside the study area e.g. employment in the civil service and military, trading, employment in the Gulf States. Consequently, in some cases they have lost the resource management responsibilities they previously held.

1.6.2 Agriculture

The study area is located within a transitional zone between the Mediterranean climate regime to the west and the arid regime to the east and to the south. The history of this land testifies that this land has been populated by a mixture of both nomadic and settled people. Their livelihoods have been based upon pastoralism and opportunistic small-scale farming. However, during the last three decades there has been progressive change towards intensive and extensive agriculture.

Currently, the majority of farming in the study area is small-scale rain-fed barley and wheat cultivation, with declining numbers of sheep and goats. In the north, close to the Syrian border, there is enough precipitation for an occasional grain harvest whilst further south the yields of rain-fed farming decrease. In years when grain cannot be harvested, the entire cereal crop is grazed by the owner’s sheep and goats or it is rented out to other farmers. When barley is harvested it is fed to sheep, but wheat is always used for bread; the straw is always used for livestock. In many villages nomadic pastoralism has died out - but this is not so in all villages. Some villages combine seasonal pastoralism with rain-fed cereal cultivation, whilst in other villages there is no pastoralism and sheep and goats are kept at the owner’s houses. However, in the last two decades, irrigated agriculture has been encouraged by loans from the government to drill private wells. As the population has settled, land is cleared of basalt and brought under cultivation (Kirk, 1998a; Waddingham, 1998).

The local settled population relies on groundwater for domestic supplies, livestock and irrigation. This creates a dilemma. This is to provide sufficient water for local needs without aggravating the problems of over-abstraction from the Azraq Basin which has already created a negative water balance (Waddingham, 1998). It is equally important to monitor the growth of intensive agriculture in the study area and identify possible
detrimental effects it could be having upon the fragile physical resource base, especially the soil.

1.6.3 Development Strategies

Many development issues pertaining to Jordan’s *badia* are currently under discussion. Most emphasis is placed on the area’s basic natural resources and their sustainable development. Although it is postulated that population growth in the study area is the generator of all aspects of natural resources depletion, there is evidence of much influence from outside the study area. The *badia* is an exporter of water to the wetter, but more densely populated, parts of Jordan (Dottridge and Abu Jaber, 1999). However, for sustainable supplies it is essential to avoid over-abstraction. This is because over-exploitation of groundwater beyond the safe yield of aquifers is causing depletion and this should be stopped before permanent and irreversible damage occurs (HCST, 1993). Nonetheless, available sources of additional water may be possible through the harvesting and storage of surface wadi flows down Jabal al-Arab in the north of the *badia*. This is certainly one of the BRDP’s main tasks. The second major natural resource in the *badia*, the soil, is prone to many types of land degradation processes. Indeed, the removal of natural vegetation cover, as well as basalt-strewn boulders which provide natural protection of the topsoil, is exposing the topsoil to erosion and other types of land degradation (Kirk, 1998a).

1.7 Spatial data and GIS data base

1.7.1 The role of remote sensing and GIS

Land degradation is undoubtedly one of the most important threats facing dryland environments. The mapping and monitoring of land degradation can enhance the scope for rational approaches to natural resources management, as well as characterizing land use and vegetation cover (Burrough, 1986). Rational management of the natural resource base is key to the implementation of sustainable development strategies in the BRDP area because it has been the subject of the uncontrolled forces of economic change, especially during the last two decades. This has mainly come about through unplanned settlement, village formation, the creation of a network of paved roads
(Dutton, 1998), and the introduction of irrigation without (until recently) regard to sustainable yields (Dotteridge and Abu Jaber, 1999).

One of the key roles of remote sensing in this research is to generate a series of thematic maps of the study area to provide information pertinent to land degradation, to parameterise a soil erosion model, and to analyse the results in a spatial context. The use of multi-date imagery in this research will allow changes in land cover to be studied and related to the social, economic and political forces that drive these changes, and how they have impacted on the environment over time.

GIS can integrate thematic layers generated from remotely sensed data with other information of various sources. The data are geo-referenced in a common map projection to create a spatial database for spatial modelling and for spatially-explicit extrapolation of point models (Tripathy et al., 1996; Millington et al., 1994). GIS will be used in this research to spatially model land degradation in the study area using a comprehensive geo-referenced dataset combining both, satellite data and digital environmental data.

1.7.2 GIS data base

1.7.2.1 Layer structure

The structure of the data base developed in this research is based on the production of thematic layers covering the study area, which is defined by four corner co-ordinates (Table 1.5). The Jordan Transverse Mercator (JTM) projection was used to build the data base. This is the system used by the Royal Jordanian Geographic Center, the national institution responsible for mapping and surveying activities in Jordan. The thematic layers used in degradation GIS model are listed in Table 1.6.
<table>
<thead>
<tr>
<th>Point</th>
<th>Northing</th>
<th>Easting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom Left hand corner</td>
<td>32°10'</td>
<td>36°30'</td>
</tr>
<tr>
<td>Bottom Right hand corner</td>
<td>32°10'</td>
<td>37°00'</td>
</tr>
<tr>
<td>Top Right hand corner</td>
<td>32°25'</td>
<td>37°00'</td>
</tr>
<tr>
<td>Top Left hand corner</td>
<td>32°25'</td>
<td>36°30'</td>
</tr>
</tbody>
</table>

Table 1. 5: Corner coordinates for GIS layers used in this research

1.7.2.2 Image data coverage

Remote sensing image data used in the present research were acquired by Landsat MSS and TM imagery. The MSS data were acquired on September 14th 1972, March 26th 1985, and July 16th 1985. The TM data were acquired on April 1st 1987 and August 28th 1992. All data were provided by the NASA Pathfinder Programme. All digital image processing and GIS modelling were performed in Erdas Imagine Version 8.3.

<table>
<thead>
<tr>
<th>Layer name</th>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil units</td>
<td>Polygons of soil units mapped from the National Soil and Land Use Map: soils of Jordan, using ARC/INFO.</td>
<td></td>
</tr>
<tr>
<td>Rainfall</td>
<td>Polygons of rainfall erosivity estimated from mean annual Polygon precipitation of rainfall stations in the study area.</td>
<td></td>
</tr>
<tr>
<td>Vegetation</td>
<td>Vegetation cover percentages derived from Landsat TM+MSS Polygon imagery using Linear Mixture Modelling and NDVI.</td>
<td></td>
</tr>
<tr>
<td>DEM</td>
<td>A grid of 'Z' values derived from contour lines (1:50,000 topo. Point maps), using TIN and LATICE Modules in ARC/INFO.</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>A grid of slope angles derived from the DEM, using Polygon Topographic Analysis Slope Function in ERDAS IMAGINE.</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. 6: GIS data layers used in this research.
1.8 Structure of the thesis

Chapter 2 of the thesis analyses the population dynamics in the study area in the context of changes in the agricultural systems and in land cover. The wider literature on land colonization in drylands is briefly reviewed in Section 2.1. Sections 2.2 and 2.3 specifically focus on population growth and land colonization in the study area. Sections 2.4 and 2.5 address changes in agricultural land use and land cover in the study area. Finally section 2.6 links land colonization and land cover change in northern Jordan.

Chapter 3 covers remote sensing and GIS monitoring and mapping of land cover change in drylands including a case study for northern Jordan. Section 3.2 is a review of the wider literature on the use of remote sensing and GIS for environmental studies, especially for monitoring land cover changes and land degradation in drylands. The acquisition of Landsat data for the case study and the necessary atmospheric and geometric correction methods, are addressed in Section 3.3. Section 3.4 describes the methods used for mapping cultivated areas in the study area. The last section (3.5) applies change detection analysis to cultivated areas in the study areas.

Chapter 4 explains the methods used to provide vegetation cover inputs for the erosion model from TM and MSS imagery. Section 4.2 reviews the application of linear mixture modelling. The steps followed in the application of linear mixture modelling to TM data in the study area to estimate the vegetation cover percentage is given in Section 4.3. Section 4.4 focuses on vegetation cover proportion estimates for Landsat MSS data from 1985 and 1972.

Chapter 5 emphasises the issue of land degradation modelling. Sections 5.2 addresses the potential land degradation processes in the study area. An estimation of the risk of wind erosion and salinization in the study area is given. The theory of water erosion is considered in section 5.3 along with the Revised Universal Soil Loss Equation (RUSLE). Section 5.4 addresses the issue of spatial and temporal variability of land degradation.
Chapter 6 outlines the development and structure of the soil loss model (RUSLE) used in the study area. The calculation of the individual factors of the RUSLE for northern Jordan is given in section 6.2. The soil loss maps and statistics for 1972, 1985 and 1992 are described and analysed in section 6.3. The verification procedures for the application of the RUSLE are described in section 6.4. Section 6.5 discusses the issue of quality assessment of the soil loss maps.

Chapter 7, section 7.1 re-iterates the key findings of the research with specific reference to the aims and objectives. Whilst section 7.2 discusses some critical issues which have emerged during the course of this study.

To help the reader, the original research carried out during the course of this research project can be found in the following sections: (2.2-2.6); (3.3-3.5); (4.3-4.4); (5.2.1.2); (5.2.3-5.2.4); and (6.1-6.5).
CHAPTER 2: POPULATION DYNAMICS AND AGRICULTURAL EXPANSION IN NORTHERN JORDAN

2.1 Land colonisation at the Arid/Semi-Arid frontier

2.2 Land colonisation at the arid/semi-arid frontier in northern Jordan

2.3 Population growth and village establishment in northern Jordan
   2.3.1 The study area

2.4 Typology of field types

2.5 Field dynamics
   2.5.1 Large irrigated fields
   2.5.2 Large rain-fed fields
   2.5.3 Intra-urban fields
   2.5.4 Relationships between rangeland and cultivation areas

2.6 Population dynamics, policy shifts and land colonisation
   2.6.1 Policy and demographic influences
      2.6.1.1 Water policy
      2.6.1.2 Markets for agricultural produce
      2.6.1.3 Demographic factors
   2.6.2 Household factors
      2.6.2.1 Access to capital
      2.6.2.2 Political influence
      2.6.2.3 Land tenure and land availability
      2.6.2.4 Relationships between economic activities in households
   2.6.3 Environmental factors
      2.6.3.1 Water table depth
      2.6.3.2 Precipitation regime

2.7 Summary
CHAPTER 2: POPULATION DYNAMICS AND AGRICULTURAL EXPANSION IN NORTHERN JORDAN

Note: The substantive part of this chapter has been published and a copy of the paper is appended to this thesis

2.1 Land Colonisation at the Arid/Semi-Arid Frontier

Land colonisation at the semi-arid/arid frontier is a widely reported phenomena (Bernard et al., 1989; Campbell, 1981; Glantz, 1994; Goudie, 1993; Heathcote, 1980; Lofchie, 1990; Meinig, 1962; Swearingen, 1994; Warren and Khogali, 1992). The prevailing view is that people migrate from areas with a relatively high cultivation potential to marginal semi-arid/arid frontiers for three main reasons: social differentiation, political factors or environmental constraints (Table 2.1). The migrants then cultivate previously uncultivated, low potential land (which has previously often been rangeland) using rain-fed or irrigated methods. This process can be considered economic and ecological marginalisation. A combination of unfavourable environmental factors and inappropriate farming methods often leads to land degradation and declining productivity. This situation is exemplified by the Dust Bowl of the 1930s in the USA (Worster, 1979; Glantz, 1994) but there are more recent examples of population movements, land colonisation and environmental degradation (e.g. the Virgin Lands Scheme in the USSR - Zonn et al., 1994). This is a strongly neo-Malthusian construct of land degradation (Barrow, 1991), suggesting that the land being colonised has some finite limit on the population it can sustain, i.e. its carrying capacity. Three lines of arguments exist that question this construct. First, ideas that confirm farming techniques will adjust to increased population density. Boserup (1965) has hypothesised that as cultivation density intensifies farming technologies adjust and, therefore, the probability of increased land degradation diminishes (Tiffen and Mortimore, 1994; Tiffen et al., 1994). Second, the concept of carrying capacity relies on relatively constant environmental conditions over the area under consideration, but at the semi-arid/arid frontier environmental conditions show
Push factors

Demographic and migration
- Rapid population growth leads to pressure on natural resources*
- Preferred re-location – rural-to-rural rather than rural-to-urban*

Socio-economic change
- Land alienation due to requirements of cash cropping, irrigation schemes and increased food production, subsistence farmers replaced by commercial farms

Land degradation
- Declining soil fertility of rain-fed agriculture, land cannot support its population
- Declining precipitation levels in rain-fed agriculture
- Unproductive irrigation schemes (salinization and waterlogging)

Pull factors

Government policy
- Various policies and incentives to attract cultivators to rangelands
- Sedenterisation schemes*

Land factors
- Land availability*
- Land prices*

Environmental
- Wet epochs attract farmers to a region
- Availability of groundwater*

Technological
- Technology will provide for drought-mitigation or drought-proofing of farming systems

Factors which play major roles in Jordan are marked with an asterisk (for a discussion of these factors see Section 2.6).

Table 2.1: Factors influencing the movement of cultivators to the semi-arid/arid frontier.

Strong inter-annual variability which question the concept of a ‘static’ carrying capacity. Third, there is a significant body of evidence that indicates that depopulation is a significant cause of land degradation in drylands (Faus-Pujol and Higueras, 1998; Vogel 1987; Millington et al., 1989).

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2.2 Land colonisation at the arid/semi-arid frontier in northern Jordan

The research reported here provides evidence to evaluate the first two of the three arguments outlined in Section 2.1 in northern Jordan. The evidence is based on insights gained from lengthy semi-structured interviews with 30 farmers in 28 villages between Mafraq and Safawi in northern Jordan (Fig. 2.1). However, the analysis in this chapter will be restricted to the villages in the BRDP area. In addition to the socio-economic and political aspects of land cover change that were obtained from the interviews, cultivated areas were mapped from multi-date remotely sensed imagery. This latter aspect of the research is reported on Chapter 3.

The research findings concerning the relationships between population growth and shifts in socio-economic policies, and land colonisation therefore take into account evidence presented in Chapter 3; though the findings themselves will be presented at the end of this chapter in Section 2.6. These findings will be discussed in the context of the area’s demography, and national and regional shifts in economic policy.

2.3 Population growth and village establishment in northern Jordan

Northern Jordan has seen a dramatic expansion in the amount of land cultivated since the late 1960s. This expansion continues at the present time, moving ever eastwards into increasingly drier landscapes. The area has witnessed high levels of population growth as villages have been established and in-migration has occurred because of population relocation. Some in-migrants are temporary, whilst others are permanent. During the period of settlement there has been a switch from farming systems dominated by nomadic pastoralism to those comprising cultivation and stock rearing. The last two decades have witnessed a marked decline in stock rearing and a concomitant increase in rain-fed and irrigated cultivation. This transition in farming systems has occurred in parallel with migration, settlement and village expansion. The time frame for settlement in this region extends from the early Mandate period to the present day (Bocco and Tell, 1995; Tell, 1994). The corresponding spatial framework is the progressive eastward march of settlement in northern Jordan.
Fig. 2.1: Northern Jordan, villages and main road network

These complementary spatial and temporal frameworks provide an ideal geographical setting in which to study the determinants of land colonisation at the semi-arid/arid frontier and its effects on the environment. However, investigating the links between population growth and land colonisation at the arid/semi-arid frontier in this region has more than a local-scale focus. This is because it is played out against the backdrop of Middle Eastern politics and changing economic and environmental policies in Jordan, and therefore it also has to be seen in the context of social, economic, political and environmental issues at national and regional scales.

2.3.1 The study area

The wider study area extends along the Syria-Jordan border eastwards from Mafraq for approximately 80 km (Fig. 2.1). This area is more-or-less bounded to the south by the villages along the Mafraq-Safawi road, which joins the Amman-Baghdad highway to the east. The main roads were paved before 1972 but the minor roads that link the villages in the area have been paved in the last two decades. The eastern part of the area forms part of the BRDP area (BRDP, 1994) and it is this area that comprises the focus of the research carried out in this thesis. Demographic surveys were carried out in the villages of the BRDP area in January 1993, and population data is also available from 1976, 1979, 1987 and 1994. The total population of the villages reported on in
this paper, that are also in the BRDP area, increased from 4,193 in 1976 to 14,941 in 1994 (Maani et al., 1998). Growth rates of individual villages in the west of the area studied display some tentative spatial trends (Fig. 2.2). The four small villages in the extreme north-east of the study area (Mathnat Rajil, al-Jad’a, as-Suwaylimiyya and Dayr al-Qinn) form a cluster with low growth rates. The four villages in the extreme north-west of the BRDP area (Umm al-Quattayn, al-Mukayfitah, Nayifa and Rahbat Rakad) all show high growth rates. The villages between these two clusters show a wide range of growth rates that reflect both the very high natural population growth that characterises Jordan and the dynamics of migration.

Settlement around Mafraq dates from the early Mandate period when pastoralists first acquired land and began to settle (Jaradat et al., 1993, Tell, 1994). Further east, settlement began later and, prior to the late 1960s, there was little permanent settlement. This is because most people were nomadic pastoralists who migrated through a large area or dirah which included northern Jordan as well as parts of Iraq, Saudi Arabia and Syria. When they settled they evoked tribal rights to particular locations that have subsequently become villages. Traditional economic activities in the area at this time were nomadic pastoralism and trading; in addition many males joined the armed forces (Tell, 1994). Since settlement, the agricultural base of many of the region’s villages has been a mix of cultivation and grazing. Most of the population is now sedentary and transhumance is practised rather than nomadic pastoralism sensu stricto. The number of households with large flocks practising transhumance is now low, and all the households that were interviewed in respect of this thesis in 1998 and 1999 also had rain-fed fields. A more common situation regarding stock rearing is for families to keep a few sheep and goats at home, feed them grain, and then graze them on harvested fields. Nonetheless, agricultural activities in some of the smaller villages in the east are still dominated by livestock. Cultivation mainly comprises rain-fed barley and wheat in winter, irrigated vegetables and forage crops in summer, and irrigated olives and fruit trees. Irrigated agriculture in the region is a more recent phenomenon than rain-fed cultivation. People from outside the area have been influential in the expansion of irrigated agriculture, but not exclusively so. The majority of cultivated land in the region is still rain-fed, and it is the long-term residents of the area who have cleared and still cultivate these fields.
and, as the area has developed, employment opportunities in other local government sectors have increased.

2.4 Typology of field types

Five types of fields have been identified based on their size and the type of cultivation practised in them (Table 2.2). The typology of fields in the study area has been developed based on the maps of cultivated areas derived from the image data and ground surveys carried out in 1998. The methods used to identify and map cultivated areas will be presented in detail in Chapter 3.

<table>
<thead>
<tr>
<th>Population size, 1994</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 200</td>
</tr>
<tr>
<td>201 - 799</td>
</tr>
<tr>
<td>800 - 2499</td>
</tr>
<tr>
<td>Over 2500</td>
</tr>
</tbody>
</table>

Fig. 2.2: Villages in BRDP area: sizes and growth rates

<table>
<thead>
<tr>
<th>Rain-fed cultivation</th>
<th>Irrigated cultivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>Large, permanent</td>
</tr>
<tr>
<td>Small (intra-urban fields)</td>
<td>Small (intra-urban fields)</td>
</tr>
</tbody>
</table>

Table 2.2: Typology of field types in northern Jordan

33
Irrigated fields fall into two distinct size classes, those greater than \( \geq 10 \) ha in the area and those which are generally \(<1\) ha. The latter are found in most of the villages in the study area and comprise fields between buildings that are irrigated by water from the piped ‘domestic’ water supplies. In some villages (e.g. al-Ashrafiyya) there are small fields which draw their irrigation water from recently drilled wells and grow vegetables for the commercial market. However, in most villages (e.g. al-Bishriyya) these small, irrigated plots comprise olive groves and orchards and are mainly for household consumption.

The large irrigated fields fall into two categories – permanent irrigation and temporary irrigation. They are all located around wells drilled into the Upper Aquifer of the Azraq Basin (Dotteridge, 1998). Some farms use water from wells drilled by wealthy local landowners (e.g. the farms between Umm al-Quttayn and Rahbat Rakad), whilst others have been established by absentee landowners who generally live in cities in western Jordan. They have invested in irrigation in this region because of their ability to obtain permits to drill wells and the relatively cheap land prices. They grow either a rotation which includes tomatoes, melons and other vegetables with rain-fed cereals in winter, or olives and fruit trees (Fig. 2.3). They are labour intensive, with much of the labour coming from other countries, e.g. Egypt. Temporary irrigation fields are also located around wells drilled into the Upper Aquifer of the Azraq Basin. However, the location of the individual fields varies from one year to another. Temporary irrigated fields are cultivated by seasonally-migrant farmers who live in the vicinity of the farms from March until November. All of the seasonally-migrant farmers interviewed come from the areas around Mafraq and Irbid. Although the tenure relationships between the landowners and seasonally migrant farmers interviewed exhibited subtle intricacies, they can be divided into two general groups:

- Rental agreements, in which the migrant farmers rent land each year to grow a summer crop. They retain the profits from the harvested crops and then sell the crop residues or the rights to graze residues left in the fields.
- Sharecropping agreements, in which the migrant farmers clear the land and grow a summer crop. The profits from these crops are split between the landowner and the migrant farmer.
Temporary irrigation also occurs in the BRDP area, though in any one year the amount of land under temporary irrigation is less than that under permanent irrigation in the BRDP area. This is in contrast to the area between Mafraq and Umm al-Quttayn where there is more land under temporary, rather than permanent, irrigation.

Rain-fed fields form a continuum of sizes ranging from about ≥5 ha to <0.5 ha and because of this it is more difficult to divide them into the large and small categories. The smaller rain-fed fields are concentrated within villages and are another type of intra-urban field. Intra-urban rain-fed fields are found on slopes and interfluves and are used for wheat and barley cultivation. Some are found in wadis and in these situations soil moisture is derived from precipitation, runoff and seepage from adjacent slopes and, after severe storms, wadi flow. The larger rain-fed fields are generally found in the north of the study area within 5 km of the Syrian border; barley and wheat are the only crops cultivated. This distribution probably reflects the slightly higher rainfall received in this area and the lower temperatures which increase the probability of snowfall and reduce evaporation.

2.5 Field dynamics

2.5.1 Large irrigated fields

The eastward expansion of large irrigated fields in the BRDP area is clear from maps of cultivated areas for 1972, 1985, and 1992 derived from the image data (Fig. 3.7). In the 1972 there were no large irrigated fields in the study area. However, 13 years later
### Agricultural calendar: Mixed rain-fed arable and grazing system at Khasha't al-Qinn

<table>
<thead>
<tr>
<th>Month</th>
<th>Rain-fed Arable Cultivation</th>
<th>Stock rearing</th>
<th>Months with bare fields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Field prep</td>
<td>Sowing</td>
<td>Judging</td>
</tr>
<tr>
<td>Sept</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Feb</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Mar</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Jul</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Key**
- Extent of task in wet years
- Extent of task in dry years
- Indoor task
- Range grzg: Grazing on rangeland in area or to east
- Stubble grzg: Grazing of rain-fed fields after grain harvest
- Crop grzg: Grazing on standing crops in rain-fed fields
- Breeding: During this time people keep sheep away from rain-fed fields, most families breed sheep indoors in village, but some migrate into the desert to the east

### Agricultural calendar: Permanently irrigated farm to south of al-Manara

<table>
<thead>
<tr>
<th>Watermelon</th>
<th>Vegetables</th>
<th>Barley</th>
<th>Months with bare fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting</td>
<td>Harvest</td>
<td>Sowing</td>
<td>Harvest</td>
</tr>
<tr>
<td>Sept</td>
<td>(m-fed fids)</td>
<td></td>
<td>(m-fed fids)</td>
</tr>
<tr>
<td>Oct</td>
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<tr>
<td>Nov</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
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</tr>
</tbody>
</table>

**Key**
- Outdoor tasks in wet years
- Outdoor tasks in dry years in polytunnels
- Stubble grzg: Grazing of rain-fed fields after grain harvest
- Crop grzg: Grazing on standing crops in rain-fed fields
- Watermelons and vegetables (tomato, cabbage and corn) grown under irrigation
- Barley grown under rain-fed conditions

**Fig. 2.3:** Crop calendar showing the rotation of agricultural activities practised in the study area
in 1985, the area between Mafraq and Wadi al-Aqeb (22 km east of Mafraq) had a relatively high density of irrigated fields. These were mainly found in an area which extended north from the Mafraq-Safawi road for about 6-9 km and stopped about 6 km from the Syrian border. A cluster of irrigated fields was also found in an area immediately west of Wadi al-Aqeb to the south of the main road. A few scattered fields can be seen to the east of Wadi al-Aqeb, the most easterly of these being at Rahbat Rakad. By 1992 large irrigated fields were found in the BRDP area (Fig. 3.7c). In particular, a cluster around Umm al-Quttayn was noticeable and the most easterly fields were found south of Qasim and Abu al-Farth (36°44.7'E), some 48 km east of Mafraq. In the seven years between 1985 and 1992 the main areas of expansion of large irrigated fields were:

- north of the Safawi-Mafraq road to the east of Wadi al-Aqeb;
- to the south of the main road between Mafraq and Wadi al-Aqeb; and
- a general northward extension toward the Syrian border throughout the area.

Field surveys conducted in 1999 indicated that the eastern limit of irrigation in 1992 (36°44.7'E) was still the frontier of irrigation seven years later, and only limited infilling with irrigated fields between 36°44.7'E and Umm al-Quttayn had taken place.

2.5.2 Large rain-fed fields

The dynamics of rain-fed cultivation have been quite different to that of large irrigated fields. In 1972 the main areas of rain-fed cultivation were found in the villages closest to the Syrian border. All of the villages which form an arc between Mathnat Rajil and Hay Huaijah had extensive areas of rain-fed cultivation between them. Few rain-fed fields can be identified from the imagery to the south of these villages (south of 32°15.7'N). The spatial distribution of fields in 1985 was similar to that in 1972, except that to the west of Wadi al-Aqeb large irrigated fields were interspersed between rain-fed fields in the areas adjacent to the Syrian border. By 1992 irrigated fields had encroached further into the border area all the way from Sabha to Umm al-Quttayn. Although the overall geographical area of the main concentration of rain-fed fields (a zone that extends about 6 km southward from the Syrian border) had not changed much in the 20 years between 1972 and 1992, the density of rain-fed fields increased during these two decades. This was because more rangeland was cleared
and brought into cultivation. Interviews conducted in 1998 indicated that the conversion of rangeland to rain-fed cultivation is still occurring in this area wherever suitable land is available and accessible. Acting as a counterweight to the increase in rain-fed cultivation has been the encroachment of irrigated agriculture into the main area of rain-fed cultivation. Although most of the irrigation that has encroached onto rain-fed land has been of a temporary (rotational) nature, the overall density of irrigated cultivation has increased. Two trends are evident. The first is that the area of rain-fed cultivation has increased. The second is the incremental loss of rain-fed cultivation to irrigation.

It is possible that there were areas of rain-fed cultivation to the south of the main arc of rain-fed cultivation in 1972, 1985 and 1992. However, such areas are very difficult to map from the imagery as the rangelands and cleared fields exhibit significant overlap in their spectral characteristics. Evidence from the interviews carried out in 1998 and 1999 indicate that this area has mostly been rangeland in the past, and although some fields have been cultivated in this area they have been a minor component of the agricultural landscape.

2.5.3 Intra-urban fields

Intra-urban fields have expanded in number as the region’s villages have grown in size. All of the villages in the study area had intra-urban fields in 1972 and continue to do so in 1992. However, fieldwork conducted in 1998 indicates that as villages expand, land prices rise (particularly adjacent to the main roads) and some intra-urban fields are now being sold for infill construction. As yet, not all land in villages is used for construction and small olive groves, orchards and cereal fields are still widespread. On the basis of these observations an inductive generalised model has been developed (Fig. 2.4) which combines population growth and intra-urban field dynamics. This suggests that as population grows the mean size of the intra-urban fields will decrease and they will become more fragmented. The decrease in field sizes being related to encroachment of buildings onto fields, and the increased fragmentation occurring because construction takes place in an unplanned manner and fields are often broken up in the process.
2.5.4 Relationships between rangeland and cultivated areas

The relationships between rain-fed and irrigated cultivation and stock rearing are crucial to understanding the dynamics of fields in the region. Permanently irrigated farms may replace land that was formerly under rain-fed cultivation, e.g. between Umm al-Quttayn and Rahbat Rakad since 1991. In other areas permanently irrigated farms have been established on former rangeland areas, e.g. south of al-Manara. A more dynamic relationship exists between rain-fed fields and the temporary irrigation rotation cycle. Temporary irrigation fields are cultivated for one summer and revert to rain-fed cultivation in the following winter. In succeeding years the areas revert to rangeland or are used again for rain-fed cereal cultivation. The different rotation pathways lead to a dynamic spatial distribution of rain-fed cultivation and rangeland in the winter, and temporary irrigation and rangeland in the summer throughout the study area. The only static elements in this dynamic agrarian landscape being the areas of permanent irrigation.
2.6 Population dynamics, policy shifts and land colonisation

It is clear from the expansion of cultivated areas that the overall cultivation density in the study area has increased as nomads have settled and the villages have grown. The frontier of irrigated cultivation has moved progressively eastwards since 1972, though observations made in 1998 suggest it has been more-or-less static since 1992. The geographical area in which rain-fed cultivation is concentrated has remained much the same during the last 20 years and each year more land is brought into cultivation. Nonetheless there has been a loss of rain-fed land to irrigated cultivation; this has been greater in the west of the study area than in the east. In the east, some villages located beyond the frontier of irrigation continue to extend their rain-fed land holdings. Intra-urban fields have grown in number as villages have expanded, but visual evidence indicates that they are now beginning to be used as construction plots for infill housing in some villages. This summary of land colonisation is the result of a complex mélange of processes that are not just related to population growth but also to changes in socio-economic factors, political influences and environmental trends that have affected the region. Interviews conducted in 1998 have enabled the key factors in land colonisation to be identified (Table 2.3). The elements of this table are discussed below.

2.6.1 Policy and demographic influences

2.6.1.1 Water policy

The growth of irrigated agriculture in the region is clearly related to the ability of farmers to drill wells down to the Upper Aquifer of the Azraq Basin and, in the case of irrigated intra-urban fields, the provision of a piped ‘domestic’ water supply.

The provision of piped domestic water has enabled some intra-urban fields to be irrigated, although many are still rain-fed. Waddingham (1998) noted that 56.8% of the ‘domestic’ water supply in the villages in the BRDP area was unaccounted for by household use and can be attributed to irrigation and leakages. These fields, though
individually small in area, are placing an increasing demand on the water supply because as:

- precipitation in the region decreases, shortfalls in water requirements will be made up from ‘domestic’ piped supplies;
- the trees planted during the last 20 years mature, water demand will increase; and
- the villages have expanded, the total cultivated area has expanded as well.

In the absence of any controls on the use of the domestic piped supply there appears to be no limitation on the use of domestic piped water for irrigation. Water supply is therefore not a constraint on the expansion of irrigated intra-urban fields, although other factors may ultimately limit their growth.

Water policy has had a strong, direct impact on the expansion of large irrigated fields. The ability to acquire government abstraction licences to operate wells and then to obtain loans to carry out the work, has enabled relatively rich people to exploit the groundwater and cultivate large areas under irrigated agriculture, both on a permanent and temporary basis. Many other factors have aided the expansion of irrigation, and these will be discussed below. The importance of government water policy can be emphasised in two ways. First, between 1992 and 1995 abstraction licences were stopped by the government because of concerns over reduced spring flows at the Azraq Oasis which has been declared a RAMSAR site (Dotteridge and Gibbs, 1998). This has been very effective in stopping both the eastward expansion of irrigation and the drilling of more wells between Mafraq city and longitude 36°44.7'E. The only wells currently being drilled are those where permission was granted before 1995 and these are very few in number. The general view expressed in interviews with temporary irrigation farmers is that the only obstacle to their moving eastward is the moratorium on well drilling. Secondly, farmers to the west of 36°44.7'E, who had hoped for wells to be drilled on their village lands, continue to expand the areas of rain-fed cultivation once they have moved out of large scale stock rearing as an alternative to irrigated cultivation. It was made clear in interviews that they would have moved into irrigated agriculture if they had secured licences to abstract water.
2.6.1.2 Markets for agricultural produce

As irrigated farms are the only form of cultivation geared toward commercial cultivation in the study area, access to markets for their produce has clearly been a major factor in their establishment. The cities to the west of the area (e.g. Amman, Zarqa, Mafraq and Irbid) have grown significantly since the late 1960s. This is, in part, due to the high natural growth rates of the Jordanian population because of two waves of immigration. First, after the 1967 Arab-Israeli War when many Jordanians of Palestinian origin settled in Jordan, and after 1991 when many Jordanians returned from the Gulf States and Saudi Arabia. Urban growth, which has been accompanied by a loss of agricultural land in the western highlands as cities have expanded, has led to a huge increase in demand for fresh produce. A proportion of this increased demand is being met from farms to the east of Mafraq. An additional factor has been the establishment of a tomato processing plant at al-Sa’ediyyah, 1993 (just west of the BRDP area) which has also had a significant influence on the decisions of many farmers to move into irrigated farming, and to grow tomatoes as a main crop.

2.6.1.3 Demographic factors

Whilst there are parallels between population growth and the amount of land cultivated in the study area, the importance of demographic factors in promoting the expansion of cultivation varies between different types of cultivation systems and has probably varied in its significance over the last 30 years. The relationship between population growth and expansion of the cultivated area is probably strongest for intra-urban fields. It can be postulated that the expansion of intra-urban fields, and their subsequent decline, is closely related to the growth of villages. The processes outlined in the theoretical model (Fig. 2.4) can be seen in operation at the present time. For example, the third-most easterly settlement along the Mafraq-Safawi road – al-Hashmiyyah – expanded from three to 35 houses between 1997 and 1999. As the existing villagers encouraged people to settle in the area, they insisted that as a condition of the purchase of a plot for house construction an area of (range)land adjacent to the house was brought into rain-fed cultivation. The expansion of large
<table>
<thead>
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<th>Large rain-fed</th>
<th>Intra-urban</th>
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<td>♦</td>
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<td>Markets for agricultural produce</td>
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<tr>
<td>Status of expatriate Jordanians</td>
<td>◊</td>
<td>◊</td>
<td>♦</td>
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<tr>
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<td>+</td>
<td>++</td>
<td>+++/---</td>
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<tr>
<td>Access to capital</td>
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<td>-</td>
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<tr>
<td>Political influence</td>
<td>++</td>
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<tr>
<td>Relationship between economic activities in household</td>
<td>♦</td>
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</tr>
<tr>
<td>Land tenure and availability</td>
<td>+</td>
<td>+</td>
<td>+/-</td>
</tr>
<tr>
<td>Availability of cheap land to purchase</td>
<td>++</td>
<td>-</td>
<td>♦</td>
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<tr>
<td>Water table depth</td>
<td>+++</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Precipitation regime</td>
<td>(+)</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

**Key to symbols**

+ Positive causal relationship (strength indicated by number of +)
- Negative causal relationship (strength indicated by number of -)
• No significant effect
♦ Strong effect of variable influence (positive and/or negative)
◊ Weak effect of variable influence (positive and/or negative)

Table 2.3: Factors influencing land colonisation by field type in northern Jordan
rain-fed fields has been influenced by village growth. As the nomadic tribes settled in the area and villages were established, rangeland adjacent to the villages was converted into rain-fed fields for barley and wheat cultivation. In small villages with low population growth rates (e.g. al Mansoura and Mathnat Rajil) most of the rain-fed fields that were being cultivated when surveyed in 1998 had been brought into cultivation in the late 1960s and 1970s; little, if any, land is currently being cleared in these villages. However, in some villages with higher population growth rates rangeland was still being cleared and brought into cultivation in 1998 (e.g. al-Ma’azula, ath-Thilaj, Qasim and Tall al-Rimah). All of these villages had access to rangeland that had not been cleared, though in some villages (e.g. ath-Thilaj) the amount of land that is available to be cleared is limited and very stony (i.e. it is of poor quality).

2.6.2 Household factors

The decision to farm in a particular way is ultimately a household and/or personal decision, though many of the influences outlined in Table 2.5 also bear upon household decision-making. The interviews conducted in 1998 suggest four main factors concerning individuals and the households they belong to have had the greatest influences on the expansion of cultivated areas (Table 2.5).

2.6.2.1 Access to capital

Access to capital, whether in the form of liquid assets to purchase land, hire contractors to clear land or pay farm labourers has been an important influence on the expansion of large, permanent irrigated farms. It has also enabled wells to be drilled to establish rotations of temporary irrigated fields elsewhere. Access to capital also takes the form of security for bank loans for agricultural purposes. In either case, the access has enabled wealthy local landowners to move into permanent irrigated cropping. Furthermore, it has also allowed people who have accumulated wealth elsewhere to move into the study area and establish farms. Conversely, lack of access to capital has probably restricted some ‘poor’ villages in the north of the area from drilling wells and practising irrigation (this was a reason cited both at Mathnat Rajil and al-
Mansoura); though other factors, discussed below, have also worked against the expansion of irrigation in these villages.

2.6.2.2. Political influence

The role of political influence is difficult to gauge. Interviews with farmers in 1998 and 1999 indicated that it is likely that people with political influence have found it easier to obtain permissions to drill wells for themselves or their villages, and that villages with little political influence have found it much harder. Conversely, in some villages the lack of political influence may have resulted in the expansion of rain-fed agriculture.

2.6.2.3 Land tenure and land availability

Ownership of extensive land holdings by tribes and families has promoted the expansion of cultivation in the area. A number of examples serve to illustrate this. Farmers with surplus rain-fed fields around Umm al-Quttayn were able to sell land to capitalise the conversion of other land to permanent irrigated farms in the early 1990s. In villages that control large areas of rangelands (e.g. Abu Farth and Sa’dah) the availability of large quantities of land has enabled migrant farmers to build up relationships with the village and to return each year to practice rotational temporary irrigation farming. Villages that control surplus rangeland on the Syrian border (e.g. al-Maa’zula) are still able to bring new land into cultivation as their villages grow. Large land owners within villages are able to sell intra-urban fields to build houses, thereby decreasing the number of intra-urban fields, or facilitate village expansion by selling land (e.g. al-Hashmiyyah). The availability of surplus land has led to the expansion of large irrigated and intra-urban fields. The ability to purchase land at relatively cheap prices has attracted people from outside the area to buy large land holdings (>50 ha) and begin irrigated farming in the area. It is doubtful if the availability of cheap land has had any effects on the expansion of rain-fed cultivation.

2.6.2.4 Relationships between economic activities in households

The economic status of different activities in a household clearly has some bearing on cultivation practices. The switch from stock rearing to cultivation, a household
decision informed by government policies, has clearly promoted both rain-fed and irrigated cultivation in the region. This switch has been occurring since the late 1960s and continues at the present time. The recent withdrawal by the government of the sheep feed subsidy is already having an effect on the relationship between grazing and cultivation. In poorer villages to the east (e.g. al-Mansoura) the reduction in the profitability of sheep rearing that this policy shift has led to is already causing farmers to sell off sheep. The only alternative agricultural strategy for such households will be to cultivate more rain-fed crops. However, as a major proportion of the harvest from rain-fed fields is geared toward stock rearing, such an expansion may not be viable. In the irrigated areas to the west the withdrawal of the sheep-feed subsidy will have little effect as sheep rearing is now only a minor component of household economies. Perhaps the greatest impact would be at the current eastern frontier of irrigation where households could move into irrigated farming, this would however require further expansion of markets for produce, and for the government to begin to issue abstraction licences again.

2.6.3 Environmental factors

2.6.3.1 Water table depth

The depth to the Upper Aquifer of the Azraq Basin decreases southward throughout the study area. In financial terms this means that drilling wells is more expensive in the north of the study area than in the south. This has had a strong influence on the spatial distribution of irrigated fields. Between 1972 and 1985 the expansion of irrigation between Mafraq and Wadi al-Aqeb (to the west of the BRDP area) was concentrated just north of the main road and avoided the area to the north of this. Villages in the north have a higher proportion of rain-fed fields and this is, in part, due to the high costs of drilling deep wells. This pattern has continued as the irrigated frontier has moved eastward. The owner of one permanently irrigated farm that was interviewed in 1998 (who had moved into the region) made a conscious decision to locate his farm to the south of the main road because it was cheaper to drill a well there, than farther north, because the depth to the water table was less. People with
existing land holdings in the region cannot exercise such flexibility in choosing where to farm.

2.6.3.2 Precipitation regime

Low precipitation totals may have some influence on the amount of land in cultivation but the evidence is circumstantial and sometimes contradictory. Rain-fed fields are concentrated in the north of the region, where precipitation totals are higher than they are to the south. However, there is no trend in the density of rain-fed cultivation along the west to east component of the rainfall gradient in the area. This suggests that although precipitation is a very important influence on rain-fed cultivation it is overridden by other influences. These influences may be environmental, e.g. the occurrence of snow and lower evaporation rates at higher elevations, but equally important are the household and policy factors discussed earlier. Some farmers that were interviewed indicated that runs of dry years lead to farmers preparing less land for rain-fed cultivation than during runs of wet years. More interesting would be a link between runs of years with low rainfall totals and the switch from rain-fed to irrigated cultivation.

2.7. Summary

One of the arguments recognised in the beginning of this chapter was that farming methods will adjust to increase population (and cultivation) densities. It is clear that within the BRDP area that as people have settled and as villages have grown farming methods have, and are still, adjusting in the following ways:

- Increased amounts of rain-fed land have been brought into cultivation. In villages without access to wells this process is still occurring at the present-time.

- In areas served by wells, irrigated farming is taking over from rain-fed farming. However this is a complex situation with, in some cases, permanent irrigation farming being the route taken, whilst in other areas irrigation is temporary and rotates with rain-fed cultivation and grazing.
Animal rearing has also undergone change, the most notable feature of which has been a progressive reduction in flock sizes and the development of a synergy between livestock and cultivation systems, with harvested fields being used for grazing and crops being sold for fodder.

A second argument referred to in Section 2.1 was that the concept of carrying capacity is redundant in highly variable environments such as that found in northern Jordan. This chapter has presented evidence that supports this. For example, the inter-annual variability of rainfall in rain-fed cultivation means that wheat and barley cultivation for grain is a risky enterprise, with grain crops often failing and the failed crop being used for grazing. In wet years the area’s ‘carrying capacity’ for grain-based agriculture is high, but in other years it does not exist at all. ‘Carrying capacity’ clearly cannot be used in development planning based on rain-fed cultivation, but neither can it be relied on in stock rearing nor, because of declining water levels (and, possibly, water quality), can it be when considering irrigated agriculture. The farmers recognise that agriculture is risk-ridden in this area, and for many it represents only one of number of income-generating activities at the household level. Clearly, environmental instability is a factor which should be taken into account in development planning in the region.

Links between population dynamics and land colonisation have been difficult to entangle in the current study because it has only focussed on the BRDP villages. An analysis including all the villages in northern Jordan is required to draw any strong conclusions. This research is in progress but it is not the subject of this thesis. For instance, some of the villages with high rates of growth in the BRDP area (e.g. Umm al-Quttayn) (Maani et al., 1998) will have the highest pressures on land for cultivation, yet land colonisation is still occurring around such villages at the present time. In other villages the links between population growth and land colonisation confirm what might be expected, e.g. Mathnat Rajil, which has very low growth rates, has surplus land for rain-fed cultivation but the area under cultivation has remained more-or-less the same over the past two decades. It appears that village-level factors, other than demography, need to be taken into consideration when linking population dynamics and land colonisation in the region. Nonetheless, it can be generally
concluded that strong demographic growth of the indigenous population is probably the main factor driving the need to increase the cultivated area.

Consequently the spatial pattern and temporal dynamics of fields in the region suggest that land colonisation is a complicated process with no one factor or group of factors being entirely responsible. The main push factors (Table 2.1) that are in operation in the region are:

- land alienation; and
- rural-to-rural migration.

with the former being most important. Strangely, it appears that pull factors are equally, if not more important, in stimulating land colonisation in the study area. The main pull factors being:

- the availability of cheap land (especially in the easternmost parts of the study area);
- the availability of good quality groundwater resources,
- land availability; and
- for some, the ability to obtain licences to abstract groundwater.

Consequently, external demographic influences on land colonisation in northern Jordan are relatively minor. However, external influences through policy shifts and the regional political situation are potentially much more significant. The Government of Jordan, through its shifts in water policy over the last three decades (Dotteridge and Gibbs, 1998) and policies on stock feed subsidies have directly and indirectly encouraged (and discouraged) the conversion of rangeland to areas under arable cultivation. These policy shifts have also affected the decision by some farmers to switch from rain-fed cultivation to irrigated cultivation.

On the broader regional stage, Jordan’s acceptance of Palestinian refugees in 1967 led to an expansion of cities in the western highlands and created a demand for food that could be met from the areas to the east. Remittances from Jordanians working in the
Gulf States in the 1970s and 1980s supported the Jordanian economy to such an extent that it has had a strong trickle down effect in stimulating the economy of northern Jordan. Finally, migrant workers returning to the region after the 1991 Gulf Crisis swelled the population in the area but also brought investment to the region.

Northern Jordan then provides an example of a vigorous rural economy that is as much subject to regional and national influences as it is local factors such as migration and settlement. The resulting dynamic agrarian landscape has a frontier that is moving ever eastward into increasingly ecologically- and economically-marginal environments. To the west, behind the frontier, land switching between grazing, rain-fed cultivation and irrigated cultivation occurs annually in response to a wide ranging set of factors - the only static element in this dynamic agrarian landscape being the permanently irrigated fields.
CHAPTER 3: MAPPING AND MONITORING LAND COVER DYNAMICS

3.1 Introduction

3.2 Mapping and monitoring land cover dynamics in drylands using satellite imagery.

   3.2.1 The feasibility of the use of satellite imagery for mapping and monitoring land cover dynamics in arid and semi-arid lands.
   3.2.2 Change detection and multi-temporal image analysis in arid and semi-arid environments.

3.3 Image data

   3.3.1 Image geo-rectification
   3.2.3 Atmospheric calibration

3.4 Mapping cultivated areas

   3.4.1 Spectral properties of agricultural fields
   3.4.2 Verification of land cover maps

3.5 Image difference analysis

   3.5.1 Introduction
   3.5.2 Application of the technique in northern Jordan
   3.5.3 Image difference analysis

3.6 Summary
CHAPTER 3: MAPPING AND MONITORING LAND COVER DYNAMICS

3.1 Introduction

Inter-annual variability of climate and on-going land use conversion due to human activities are the main reasons behind the dynamic behavior of land cover in drylands (Millington et al., 1994). Monitoring land cover dynamics is crucial for the conservation and effective management of these lands, because the over-exploitation and mis-management of land in these areas often results in significant changes in land use and, therefore, land cover. This affects land quality and is often thought to result in land degradation.

It has been shown (cf. Chapter 2) that northern Jordan has undergone significant land use and land cover changes since the early seventies because of population growth as well as changes in lifestyle and agricultural activities. Therefore, mapping land cover changes in the north-west part of the BRDP area is essential to understanding the process of population growth and its impact on the environment, particularly through the resultant changes in, and expansion of, agricultural activities. It will be demonstrated later in this chapter that the major changes in land use and land cover in the north-west BRDP region which are, in part, due to changes in agricultural activities, can be identified from satellite image coverage of the area obtained since 1972. A Landsat MSS and TM data set were provided under the NASA Pathfinder Programme covering the whole study area. They were acquired on the following dates: 14th September 1972, 26th March 1985, 16th July 1985, 1st April 1987 and 28th August 1992. These images provide the base data for mapping land cover at different times between 1972 and 1992. The advantages of using these data are that:

- they provide a comparable method of mapping land cover over the entire area and different times and,
- if geo-corrected they provide spatially-referenced data.

However, before land cover maps can be produced the data required pre-processing. This included:

- removing striping and dropped lines
A number of change detection techniques are available for analysing land cover changes. Difference images were used to determine land cover changes in this study.

The key land cover changes in the area are the conversion of (uncultivated) rangeland to both rain-fed and irrigated fields. Mapping these cultivated areas is difficult because at any time (i.e. the wet season or dry season) they comprise both vegetated fields (either rain-fed or irrigated) and fallow areas (bare fields). The fallow areas are particularly difficult to map because they are often spectrally confused with rangelands - in fact they are often used for grazing after cultivation. Consequently, a field work campaign to verify these maps derived from the 1992 imagery was undertaken in November 1998. This included sketch mapping of these fields onto a false colour composite derived from the 1992 imagery, together with semi-structured interviews with local farmers. The results of this analysis (cf. Chapter 2) have also helped in understanding the relationships between population dynamics, agricultural practices and land cover change in the area since 1972.

3.2 Mapping and monitoring land cover dynamics in drylands using satellite imagery

3.2.1 The feasibility of the use of satellite imagery for mapping and monitoring land cover dynamics in arid and semi-arid lands

Information about land resources in arid and semi-arid lands is needed at a number of different scales for a variety of purposes. As many drylands are found in developing countries there is a particular need for synoptic overviews of land resources for development planning. The FAO was amongst the first to explore the application of Landsat MSS imagery to reconnaissance resource evaluations in arid and semi-arid areas. Three projects carried out in the mid seventies bear testament to this pioneering work:
• testing the usefulness of Landsat MSS imagery in the savanna ecosystems of Sudan (Mitchell, 1975);
• land system mapping and evaluation in Jordan (Mitchell, 1978); and
• the preparatory work for a soil degradation map of the world at a scale of 1:5,000,000 (Mitchell and Howard, 1978).

The accuracy of land cover maps produced from satellite imagery is frequently around 80 per cent (Corves and Place, 1994), increasing or decreasing with the presence or absence of ancillary data (e.g. field data and geomorphological information) and whether or not atmospheric calibration has been carried out (Mulders and Girard, 1993; Jacobberger-Jellison, 1994). Mapping land cover types in arid lands is more complicated than in many wetter areas and accuracies are often low. The two major difficulties encountered that lead to these low accuracies are that the data almost always varies as a continuum rather than a set of natural clusters (Buckland and Elston, 1994; Milne and O’Neill, 1990) and a high proportion of the reflectance is from the soil because of the low vegetation density (Jacobberger-Jellison, 1994; Mulders and Girard, 1993). In addition, many biophysical features in arid ecosystems are spatially superimposed and, as each of these features has its own pattern of spatial and temporal heterogeneity, this renders the relationship between these features and surface reflectance very difficult to model physically (Franklin, 1991). In this very heterogeneous environment it can be stated that the reflectance of a pixel is likely to be a mixture of the reflectances of the landscape elements. Given that multivariate classification techniques do not adequately address the mixtures of objects in a pixel, other approaches to land cover mapping of dryland environments need to be utilised. One such approach is spectral mixture modelling, which eliminates thematic mapping altogether, and directly estimates the proportion of each pixel covered by each soil or vegetation type (Franklin, 1991). Other techniques that could be used include fuzzy membership functions and Red-Infrared scattergrams (Foody and Cox, 1994; Bastin, 1995; Jasinski and Eagleson, 1990).
3.2.2 Change detection and multi-temporal image analysis in arid and semi-arid environments.

Monitoring land cover dynamics is crucial for the sustainable development of drylands because the (over-) exploitation and (mis-) management in these areas often leads to significant changes in land use and, therefore, land cover. Land cover changes may affect the quality of land, and are often thought to result in land degradation. Land use and land cover information is therefore a prerequisite for proper planning, monitoring and management of land resources. Change detection, using the viable source of data provided by remote sensing, is a suitable technique for efficiently and cheaply extracting up-dated land cover information (Fung and Le Drew, 1988). Furthermore, the detection of land use and land cover change, as well as other physical and biological processes, allows for the documentation of the spectral and temporal changes that are occurring within ecosystems. This provides the possibility of incorporating historical, spatial and spectral data to assess past changes in vegetation, soil properties, land use and land cover (Mouat et al., 1993; Prakash and Gupta, 1998), as well as helping to construct models to predict the impacts of future changes.

Change detection techniques are based on the assumption that a change in surface cover or surface materials will produce a corresponding change in the reflectance of the area studied (Quarmby et al., 1987). A review of the remote sensing literature reveals that there are many approaches to change detection analysis, mainly using Landsat MSS and TM imagery (Milne and O’Neill, 1990; Mouat et al., 1993; Mas, 1999). These can be divided into four broad groups:

- visual interpretation (composite transparencies. This involves producing a negative transparency of one band for date 1 and a positive transparency of the same band acquired for date 2, and overlaying them to achieve a precise registration (Crapper and Hyuson, 1983);
- linear procedures (e.g. difference and ratio images);
- classification routines (radiance vector shift, e.g. Tasseled Cap Transformation; spectral change pattern analysis which includes performing an unsupervised classification on a co-registered multi-temporal data set; post-classification image differencing or comparaison ); and
• transformed data sets (albedo difference images, PCA and selective PCA and vegetation index difference images.

The main stages in the change detection procedure of any of these groups can be summarized as follows:

1. Obtaining satellite data of a particular scene for two or more dates.
2. Registration of all the images within an accuracy of one pixel or less (Milne, 1988). At least one image should be geo-rectified to a mapping system. The other images can then be rectified to this “master” image. In arid and semi-arid areas ground control points (GCPs) are generally (relatively) permanent features such as: wadi confluences, points along sharply defined mountain fronts, roads and track junctions, bridges over wadis. Generally GCPs are less easy to locate in rangelands than in cultivated areas.
3. Calibration of the images for atmospheric effects and sensor drifts between dates, to take account of differences in solar irradiance, the prevailing atmosphere conditions and sensor defects.
4. Transformation of the DN values of the images to reflectance values. This is necessary for the techniques that deal directly with the reflectance values (e.g. difference images).
5. Applying one or more of the techniques mentioned above for the purpose of the analysis needed.

However, it should be noted that some remote sensors prefer to undertake geo-rectification (stage 2) after atmospheric and sensor calibration (stage 3) to enable the spectral integrity of the data to be retained before it is spatially distorted.

Whatever the type of change detection technique used, it should respond to the type of environmental processes being examined, the level of information needed, and the resources available in terms of labour and computer time (Mouat et al., 1993; Sunar, 1998). Indeed, the techniques used for change detection analysis must integrate temporal, spectral and spatial information to facilitate decision making. To do this, they must also be simple, easy to implement, cost-effective, and as mentioned above,
they must be suitable for the type of environment being examined as well as the levels of information needed (Mouat et al., 1993; Quarmby et al., 1987). Accuracy assessment should be applied throughout the whole procedure to ensure results are fit for the purpose of decision making (Mas, 1999; Mouat et al., 1993; Franklin, 1991; Corves and Place, 1994). Accuracy assessment usually takes place with reference to ground data. However in areas where the availability of ground information is limited, as is the case in many arid areas, an alternative is to collect data through field observations and interviews with local farmers (Pilon et al., 1988). Mas (1999), working in Mexico, compared the results of change detection using MSS data with aerial photography.

A threshold value is usually applied to the output image, before change detection analysis, to eliminate small changes that are not real (i.e. they are spectral changes but do not relate to land use changes) (Mouat et al., 1993; Milne and O’Neill, 1990; Prakash and Gupta, 1998; Quarmby et al., 1987; Fung and Le Drew, 1988). Change detection procedures have been applied in a number of dryland environments in the pursuit of increased understanding of land cover change (Alwashe and Bokhari, 1993; Pilon et al. 1998; and Quarmby et al. 1987). A full description of the application of the technique of difference images in a case study, applied to the study area is outlined and detailed later in the chapter (cf. Section 3.5).

3.3 Image data

3.3.1 Image geo-rectification

The remotely sensed data used in this study were acquired by Landsats 1, 4, and 5 and provided under the NASA Pathfinder Programme. They comprise both MSS and TM imagery. A total of five images (three MSS and two TM) were used. They cover the period from 1972 until 1992, and include imagery from both the wet and dry seasons. Two wet season images were acquired: MSS (1985) and TM (1987), and three dry season images: MSS (1972, 1985) and TM (1992). Details concerning the image data can be found in Table 3.1.
Table 3.1: Image data specifications.

Six bands of the TM images were used in the analysis. The thermal band being discarded because of its coarse spatial and poor radiometric resolutions. Some of the MSS data were also discarded because of the effects of striping and dropped lines. These were Band 1 from 14th September 1972, and 26th March 1985, Band 4 from 26th March 1985, and Band 4 from 16th July 1985. The study area, in the north-west part of the Badia Programme area (Fig. 1.3), is less than 500 km². Therefore only a small part of each Landsat scene was used for land cover mapping.

Before the multi-date imagery could be used to detect land cover changes, a series of image pre-processing tasks were undertaken. This was done, to ensure that the same spectral signature for each land cover type is recognized on each image, and that changes in boundaries between land cover types could be explained in terms of changing land uses, rather than as artifacts of spatial mis-registration. The entire TM image acquired on 28th August 1992 was geometrically corrected using ground control points (GCPs) covering the entire scene. Nineteen ground control points (GCPs) were used. These GCPs were acquired using a GARMIN GPS45 Personal Navigator in non-differential mode with spatial accuracy of 12m. The GCPs points used include: road junctions, wadi confluences, and well-defined rock outcrops. This image was then used as a ‘master image’ and the other images were registered to it using image-to-image registration techniques. The accuracy of the geo-registration ranged from 0.6-0.8 pixels.

The Landsat MSS data were resampled to 30m resolution (from their base resolution of 79 m) to provide data at the same spatial resolution as Landsat TM using nearest neighbor resampling technique. A subset from the entire TM scene comprising the
study area was made in order to decrease the size of the images to be processed. The same area was subset on the other images after they had been co-registered.

3.3.2 Atmospheric calibration

Atmospheric correction is an essential pre-processing task for change detection studies as differences in atmospheric conditions at the time of image acquisition can affect the (apparent) spectral properties of land cover types. To achieve this, ERDAS Model Maker was used to build a graphical model in which the DN values for each band were used as an input and converted, first, to radiance values, and then to reflectance values. This was done using published parameters (Chavez, 1989; Clark, 1986). The reflectance values were then atmospherically corrected using the 5s atmospheric radiative transfer computer code (Tanré et al., 1990). The characteristics of a mid-latitude summer atmosphere and a continental model of aerosol characteristics were used from the selections available for this model. An estimate for the aerosol optical depth at 550 nm of 0.2 was used (Mackay et al., 1996). Each channel was processed separately. The resulting outputs are corrected individual band data containing reflectance values for each of the channels. It is worth noting that in the case of reflectance images, since the data are real numbers, the size of the image is increased (~x4 times). Accordingly, reflectance bands were kept separated during the change detection procedure. A Min-Max Linear Stretch was applied to re-calculate the corrected DN values for each band, and a Stack function was applied to reconstruct the image with the new corrected DNs for display purposes and overlay operations (Erdas Field Guide, 1994).

3.4 Mapping cultivated areas

3.4.1 Spectral properties of agricultural fields

Cultivated areas were mapped from Landsat MSS and TM imagery after pre-processing had been undertaken (cf. Section 3.3). No single image processing technique could be used to map all the fields in the area from a single image for each year due to the following reasons. Firstly, at any one time some fields are vegetated
whilst others are fallow. In the summer, dry season irrigated fields have a high vegetation cover (of either vegetables, trees or trees under-cropped with ground crops). At this time of the year rangeland and rain-fed fields are bare (Fig. 3.1). During the late winter and early spring, rain-fed cereal fields will be vegetated (although the cover will be highly variable and dependent on soil moisture levels which vary from year to year) and the irrigated fields will have a cover of tree crops or cereals (Fig. 3.1). Vegetated and bare areas can be distinguished from each other at either of these times using the well-known differences in the spectral properties of vegetation and soil in the visible and near infra-red (NIR) wavelengths.

Secondly, bare fields are more difficult to identify than vegetated fields because their spectral properties overlap with both rangelands and the stone-strewn surfaces of lava flows. This is potentially a significant issue because the identification of bare fields is important when estimating the area under cultivation. It is not always possible to acquire imagery to map cereal fields at the optimal time (late winter), when most fields that are bare in summer will have a cereal crop, because of cloud cover constraints. The problem is further compounded by the fact that in wet winters, when cloud cover constraints are greater than drier winters, more rain-fed fields will be cultivated.

Therefore, as most cloud-free late winter images in the data archive for the area come from dry years, maps of fields derived from these images will under-estimate the areas cultivated.

A further problem affects the differentiation of bare fields from surrounding land cover types. On many lava flows there are large amounts of basalt stones. Fields can take many years to be cleared of these stones and, although many stones are cleared prior to the first cultivation, ploughing in subsequent years brings more stones to the surface. Stony fields have spectral properties that overlap with rangelands that have a moderate to low basalt stone cover. Though spectral overlap creates difficulties in bare field identification at the present time, it is potentially a greater problem on older imagery because fields were previously cleared by hand (rather than by tractor or bulldozer) and stone clearance was less complete.
Fig. 3.1: False colour composites (bands 4, 3 and 2) of the dry season 1992 TM image (a), and the wet season 1987 TM image (b). The image is 28 by 18 km, Umm al-Quttayn is the large urban area in the north west of the image. Irrigated fields are vegetated in summer whilst the rain-fed fields are bare (a). In winter the rain-fed fields are vegetated whilst the irrigated fields are bare (b). The cross hairs are of the same geographical location and show how irrigated fields can be clearly distinguished in summer from surrounding area, but less so in winter.
Fig. 3.1: False colour composites (bands 4, 3 and 2) of the dry season 1992 TM image (a), and the wet season 1987 TM image (b).
In many areas the stones cleared off the land are used to build boundary walls and, because these walls are spectrally distinct from the soil, they show up clearly on the imagery. The spatial patterns that this creates on the imagery have been exploited to map areas of cultivation. In areas with few basalt boulders, clearance of stones is not an issue and walls delimiting fields are not found. In such areas the distinction between fields and rangeland is much more difficult.

Taking into account the issues outlined above, mapping cultivated areas from the imagery relied on two methods:

- Vegetated fields were mapped from the TM and MSS imagery (1972, 1985 and 1992) using a false colour composite of Bands 1, 2 and 3 (MSS) and 2, 3 and 4 (TM). For the 1972 and 1985 images, field identifications were checked against an NDVI image which indicates areas of high vegetation cover (cf. Chapter 4). For the 1992 image, field identifications were checked against a vegetation cover proportion map derived from linear mixture modelling (cf. Chapter 4). Whichever method was used, fields were differentiated from other vegetated areas by identifying more-or-less rectangular groupings of vegetated pixels.
- Bare fields were mapped from all images by digitizing rectangular clusters of pixels which contrasted spectrally with the surrounding rangelands and lava flows, and/or which had contextual information indicating the presence of walls. In some cases the fields with bare soils that had been prepared for cultivation had higher visible and NIR absorption than the adjacent areas due to higher soil moisture contents and/or shadowing caused by ploughed fields and ridges.

The fields identified in the area have been categorised into five groups based on their size and the type of cultivation practiced (Table 2.2), (see section 2.4 for more details on the typology of field types).

All fields were digitized from the screen displays for each image and imported into ARC/INFO and ERDAS Model Maker. The overlays of cultivated areas were used to
generate statistics of cultivated areas (Table 3.2) and as an input for soil erosion modelling (cf. Chapter 6).

<table>
<thead>
<tr>
<th>Year</th>
<th>Rain-fed fields (ha)</th>
<th>Irrigated fields (vegetated) (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>816</td>
<td>1666</td>
</tr>
<tr>
<td>1985</td>
<td>1666</td>
<td>5862</td>
</tr>
<tr>
<td>1992</td>
<td>5862</td>
<td>178</td>
</tr>
</tbody>
</table>

Table 3.2: Statistics of bare and vegetated fields in the BRDP area covered by the imagery, as digitized on the screen from dry season imagery. Note that the BRDP did not exist in 1972 and 1985, but the boundary was overlain on these images for comparative purposes.

### 3.4.2 Verification of land cover maps

Verification of the ‘field patterns’ mapped from the 1992 TM image was undertaken in 1998. Cloud-free imagery acquired later than 1992 was not available at the BRDP who sponsored the project, so the gap between image acquisition and field verification was unavoidable.

Verification was done at the end of the 1998 summer growing season and in April 1999 at the end of the winter growing season. At the end of the summer growing season irrigated fields can still be recognised on the ground as crops are either still growing or being harvested. In addition, many of the rain-fed fields have been ploughed at this time in anticipation of the winter rains. Verification was achieved by identifying more than 40 locations of irrigated and bare fields from the 1992 image and then visiting these locations (Fig. 3.2). At each location the following verification procedures were undertaken:

- making sketch maps of the field patterns from high points in the landscape and then transferring these to the 1992 imagery; and
- conducting semi-structured interviews with farmers to ascertain the history of field clearance, irrigation and land use at each location.
3.5 Image difference analysis

3.5.1 Introduction

A review of change detection techniques was made in section 3.2. It is clear from the review that no one technique is capable of detecting all types of land cover changes. On the contrary, it can be stated that each technique can detect particular types of land cover change (Fung and Le Drew, 1988). Both Mas (1999) and Mouat et al. (1993) present comprehensive reviews of remote sensing techniques in change detection studies including transparency composites, image difference analysis, post-classification analysis, band ratios and principal components analysis. It is clear that the implementation of sophisticated procedures to generate transformed images should
be used only with a thorough understanding of the spectral characteristics of the land cover types in the study area. Moreover, a database of ancillary data to enable changes detected to be explained and/or verified is needed. Both of these requirements are necessary to avoid drawing false inferences about land cover change detected. The merits of such sophisticated procedures is that they may make features more evident that are not seen in the original data set. However they exhibit problems, in particular they demand much computer time and disk space and, more importantly, the interpretation of the change images produced by the more complex procedures is more difficult and requires more a priori knowledge of the scene and the application (Quambry et al., 1987; Fung and Le Drew, 1987; Sunar, 1998).

Taking into account the points raised above, image difference analysis was used in this study because of its simplicity and the fact that it requires less computer time for conducting the calculations for five different acquisition dates. Supports for the use of this technique is that it was successfully used by Quambry et al. (1987) in the semi-arid zone of south central Tunisia. In their work they concluded that there did not appear to be any advantage in choosing more complex procedures in analysing land cover changes in dryland environments. This is due to the fact that change from rangeland (which is often degraded) to cultivation results in such significant spectral shift that only simple techniques are required to identify it. Land cover changes that lead to more subtle change in reflection (e.g. progressive rangeland degradation, or declining crop productivity due to land degradation) may, however, require more complex change detection techniques. However, Mas (1999) noted that post-classification techniques were most accurate in moderately-well vegetated parts of Mexico and that enhancement techniques suffered from problems due to variations in soil moisture levels and differences in vegetation development.

Some researchers have applied image difference analysis without specifying certain bands (Quambry et al., 1987; Sunar, 1998), whilst others have found that certain bands are more useful for detecting land cover changes. For example, Fung (1990) found that TM Band 3 accurately detected rural-to-urban land conversion, and that TM Band 4 can also detect changes over cultivated areas. Fung and Le Drew (1988) found that MSS2 was suitable for detecting rural-to-urban land conversion, and that MSS4 was
good for differentiating changes in cropped areas. The bands used in the present study were TM Bands 3 and 4, and MSS Bands 2 and 3 or 4. MSS Band 3 was used as a replacement for MSS Band 4 in the images acquired on 26th March and 16th July 1985 because of the problem of striping and dropped lines.

3.5.2 Application of the technique in northern Jordan

The image difference analysis was applied to all MSS and TM images for both dry and wet seasons. Before the technique could be applied a series of image pre-processing tasks were undertaken (cf. Section 3.3).

ERDAS Model Maker version 8.3.1, was used to build a graphical model for performing image difference analysis. In image difference analysis the image for the first date (the older date) is subtracted from that for the second date (the later date) and a constant of 128 is added to ensure that the output values are positive. As the data sets were of different spectral resolutions, a decision based on the spectral overlap between TM and MSS channels, had to be taken on channels should be subtracted from each other. Table (3.3) contains the pairs of images subtracted for each season.

<table>
<thead>
<tr>
<th>Season</th>
<th>Pairs of years analysed</th>
<th>Image name</th>
<th>Pairs of bands subtracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>1992 - 1972</td>
<td>DIFF2(92-72)</td>
<td>TM3 - MSS2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIFF3(92-72)</td>
<td>TM4 - MSS3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIFF4(92-72)</td>
<td>TM4 - MSS4</td>
</tr>
<tr>
<td></td>
<td>1992 - 1985</td>
<td>DIFF2(92-85)</td>
<td>TM3 - MSS2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIFF3(92-85)</td>
<td>TM4 - MSS3</td>
</tr>
<tr>
<td></td>
<td>1985 – 1972</td>
<td>DIFF2(85-72)</td>
<td>MSS2 - MSS2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIFF3(85-72)</td>
<td>MSS3 - MSS3</td>
</tr>
<tr>
<td>Wet</td>
<td>1987 – 1985</td>
<td>DIFF2(87-85)</td>
<td>TM3 - MSS2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIFF3(87-85)</td>
<td>TM4 - MSS3</td>
</tr>
</tbody>
</table>

Table 3.3: pairs of images used in the image difference analysis for each season
3.5.3 Image difference analysis

The wet season difference images show very large increases in the visible red part of the spectral reflectance [DIFF2(87-85)] and a significant decrease in the near infra-red part of the spectral reflectance [DIFF3(87-85)] between 1985 and 1987. The visible red difference image for the wet season [DIFF2 (87-85)in Table 3.3] shows the effect that the inter-annual variability of precipitation in drylands can have on the process of land cover change detection. The image (Fig.3.3a) shows a significant increase in the visible red part of the spectral reflectance for the majority of the sub-scene. The corresponding near infra-red image [DIFF3 (87-85)] (Fig. 3.3b) shows a decrease in reflectance of similar spatial extent. Both images are from the late wet seasons of the respective years (26th March 1985 and 1st April 1987) when the vegetation cover could be representative of rainfall within the ten days or so prior to image acquisition, or of the entire wet season. These large spectral changes can therefore either be explained by the fact that the 1985 wet season was wetter than that of 1987, or that a significant rainfall event or series of rainfall events may have preceded the image acquisition in March 1985. An analysis of the rainfall data for the three stations in the area for the period preceding the acquisition dates of the two images records a storm on the 22nd March 85 immediately before the image acquisition date of the 26th March 1985. Figures 3.4-3.6 show decadal rainfall amounts for the three stations in the study area. The March 22nd storm is indicated by the relatively large rainfall for the third dekad in March 1985.

In addition, Figs. 3.4-3.6 show that the 1984-85 wet season was significantly wetter than the 1986-87 wet season. Therefore the difference that would be expected on the two dates of wet season image acquisition would be as follows:

- There would be less bare soil on March 26 1985 than on April 1st 1987 due to more abundant vegetation growth during the entire wet season; and
- The surface of the bare soil in March 26th 1985 would be moister than in April 1st 1987 due to the antecedent rainfall events in the ten days prior to image acquisition.
Fig. 3.3: 1987-1985 difference images (wet period). The image is 28 by 18 km. The road network in the BRDP area in 1992 is shown for orientation purposes. (a) DIFF2 (87-85) is the difference image between bands TM3 and MSS2. The red areas are sites with large increases in the reflectance in the visible red wavelengths between the two dates. (b) DIFF3 (87-85) is the difference image between bands TM4 and MSS3. Areas coloured blue experienced large decreases in their near infra red reflectance between the two dates. Both of these changes are due mainly to differences in soil moisture levels before image acquisition in 1985 and 1987.
Fig. 3. 3: 1987-1985 difference images (wet period).
This rendered any analysis of the differences in wet season land cover fruitless. Thus, it has been decided not to do any further work on the wet period images and to concentrate on the dry season. This is however an important point, for it shows that monitoring trajectories of land cover change in drylands using remote sensing can easily be disrupted by high magnitude - low frequency rainfall events which cause a short-term vegetative response which does not lie in with general longer-term vegetation trajectories.

Fig. 3. 4: Rainfall analysis at Umm al-Quttayn station for the years 1985 and 1987.
Fig. 3.5: Rainfall analysis at Dayr al-Kahf station for the years 1985 and 1987.
Fig. 3.6: Rainfall analysis at al-Aritayn station for the years 1985 and 1987.
Seven dry season difference images were generated (Table 3.3), two images for each of the periods 1972 to 1985 and 1985 to 1992, and three images for the period 1972 to 1992. In all of the images in (Figs. 3.7 to 3.10) a value of 128 in the output (difference) image represents a pixel for which no change (in reflectance) has occurred. A value > 128 indicates that the reflectance of the pixel in question was greater in the second image (the later date) than it was in the first, and a value < 128 indicates a decrease in reflectance from the first (the older date) to the second image. Small changes can occur between dates due to variations in atmospheric conditions (despite the fact that atmospheric calibration has taken place) or they may be due to slight image mis-registrations. Therefore a threshold value is applied to these difference images allowing those changes which are significant to be highlighted. In a study to determine the optimal threshold level for change detection images, Fung and Le Drew (1988) used threshold values of ±N standard deviations (σ). These values were iteratively selected from the mean to separate ‘change’ and ‘no-change’ pixels. A threshold value of 0.1σ was chosen for the first iteration and increased in subsequent iterations until a value of ± 2.0 σ was reached. They concluded that a value of ± 1.0 σ was the optimal threshold for change detection by image difference analysis. A threshold value of ± 1.0 σ was also used by Quambry et al. (1987) in semi-arid southern Tunisia. In the present study, the histograms of the seven difference images were examined and the mean and standard deviation values for each data set were calculated. A threshold of ±1 σ from the value of the constant (128) was chosen (Table 3.4).

In the difference images to which the threshold has been applied pixels with no change i.e. (<±1 σ) are represented by a value of ±1 σ from the constant 128 and appear on the images as light grey. Pixels with a lower reflectance in the later date, compared to the older date, are blue. Pixels that had a greater reflectance in the later date, compared to the first date, appear in red.
Table 3.4: Statistics of the difference images for the dry season.

After investigating all of the thresholded difference images (Fig. 3.8-3.10), it was evident that little information could be extracted from these images concerning the expansion of cultivation at the expense of rangeland because trends in spectral changes were not consistent, and neither were they unambiguous. Some images showed the effects of the expansion of cultivation noted in chapter 2; these were:

(a) The DIFF2 (85-72) difference image (Fig. 3.8a) where the expansion of irrigated and some moist bare fields was clear. However, this was not borne out by the corresponding near infra red image (Fig. 3.8b)

(b) The DIFF3 (92-72) difference image (Fig. 3.9b) displays an increase in the near infra red reflectance for some irrigated fields and bare soil sites over the twenty year period. In addition, the expansion of intra-urban fields along the Mafraq-Baghdad road is clear. But these changes are not evident on the visible red difference image for the same dates (Fig. 3.9a).

(c) The DIFF3 (92-85) difference image (Fig. 3.10b) shows an increase in the near infra red wavelengths for some green vegetated fields and bare soil fields south of Umm al-Quttayn. Again however, these land cover changes are not seen on the corresponding red image (Fig. 3.10a).
Fig. 3.7:
(a) is a false colour composite (bands 4, 2, 1) of Landsat MSS image acquired on 14th September 1972. The town of Umm al-Quttayn can be seen clearly in the north of the image, the volcanic cone of Abu Qu’ays forms the black area to the south west of the town. These two features can be seen clearly on Figs. 3.7 (b) and (c) as well. The lack of irrigation at this time is clear from this image as no fields indicated by red pixels can be seen in this type of composite (cf. Section 2.5.1) The image is 30 by 20 km.

(b) is a false colour composite (bands 4, 2, 1) of Landsat MSS image acquired on 16th July 1985. The spread of irrigation from Mafraq to Wadi al-Aqeb is indicated one area of fields to the west of the image (cf. Section 2.5.1) The image is 30 by 20 km.

(c) is a false colour composite (bands 4, 3, 2) of Landsat TM image acquired on 28th August 1992. The spread of irrigation into the BRDP area is clear as well as the increased density of irrigated fields to the west of the image around wadi al-Aqeb (cf. Section 2.5.1) The image is 30 by 20 km.
Fig. 3. 7: The 1972 (a), 1985 (b) and 1992 (c) dry season images:
Fig. 3.8: 1985-1972 difference images between the dry seasons. The images 30 by 20 km The road network in the BRDP area in 1992 is shown for orientation purposes.

(a) DIFF2 (85-72) is the difference image between MSS2 for 14th September 1972 and 16th July 1985. The areas coloured blue show large decreases in the visible red wavelength reflectance between 1972 and 1985. The almost rectangular areas in the west of the image are areas which were converted to irrigated cultivation between 1972 and 1985. In addition, some of the fields which show up in blue are fields which have been ploughed in 1985 in preparation for cultivation during the winter wet season. The many blue areas in the north of the image are in Syria. Nothing is known about these areas.

(b) DIFF3 (85-72) is the difference image between MSS3 for 14th September 1972 and 16th July 1985. The red coloured areas indicate a large increase in the reflectance in the near infra red wavelengths reflectance between 1972 and 1985. Strangely the irrigated fields, which would be expected to show a large increase in near infra red reflectance are not clear because other parts of the landscape also show a large increase in near infra red reflectance. The cause of this is unclear.
Fig. 3. 8: 1985-1972 difference images for the dry season.
Fig. 3. 9: 1992-1972 difference images for the dry season.
Fig. 3.10: 1992-1985 difference images in the dry season. The image is 30 by 20 km. The road network in the BRDP area in 1992 is shown for orientation purposes.

(a) DIFF2 (92-85) is the difference image between MSS2 and TM3 for 16th July 1985 and 28th August 1992. The areas coloured blue show large decreases in the visible red reflectance between 1985 and 1992. It is impossible to identify the change from rangeland to irrigated fields since 1985, because of the overall increase in red reflectance. The red area clouds on the 1992 image.

(b) DIFF3 (92-85) is the difference image between MSS3 and TM4 for 16th July 1985 and 28th August 1992. The red coloured areas indicate large increase in the near infra red wavelength reflectance between the two dates. These are mainly areas of cloud (in north-west of the image) and some green vegetated fields and bare soil sites to the south of Umm al-Quttayn.
Fig. 3.10: 1992-1985 difference images for the dry season.
3.6 Summary

Northern Jordan generally, and the north-west BRDP area in particular, has been the subject of significant land use and land cover changes during the last three decades. Using a multi-date set of Landsat MSS and TM data it has been partially possible to monitor the dynamics of land cover change in the north-west BRDP region between 1972 and 1992, though the ability of different image processing techniques to monitor land cover dynamics is variable.

A range of pre-processing tasks were applied to the image data prior to change detection analysis to increase both the accuracy and the spatial fidelity of the data. This was done to minimise the probability of falsely attributing land cover changes to land use changes rather than to factors associated with the imagery.

The easiest method of mapping irrigated fields and, to lesser extent, bare (rain-fed) fields was by on-screen digitizing of images acquired on different dates. However, mapping agricultural bare fields was most difficult than mapping irrigated (vegetated) fields because of the spectral confusion between these fields and the surrounding rangelands. Mapping cultivated areas from the imagery relied on two methods:

- Vegetated fields were mapped from the TM and MSS imagery using a false colour composite of Bands 1, 2 and 3 (MSS) and 2, 3 and 4 (TM). For the 1972 and 1985 images, field identifications were checked against an NDVI image which indicates areas of high vegetation cover. For the 1992 image, field identifications were checked against a vegetation cover proportion map derived from linear mixture modelling (cf. Chapter 4).
- Bare fields were mapped from all images by digitizing (from the screen display), rectangular clusters of pixels which contrasted spectrally with the surrounding rangelands and lava flows, and/or which had contextual information indicating the presence of walls.

Verification of the fields was undertaken in 1998 and 1999.
The change detection analysis based on red and near infra red difference images (chosen because of its simplicity, the ease with which the interpretation of the difference images is conducted, and their high potential to detect land cover change in other dryland areas) proved disappointing.

The wet period difference images showed dramatic changes within a period of two years. Analysis of rainfall data showed the great sensitivity of land cover to both seasonal differences in rainfall amounts and storms just prior to image acquisition. The resulting differences in soil moisture levels can be so dramatic as to render any changes in spectral responses due to anthropogenic land cover changes impossible to detect.

After investigating dry season difference images, the evidence proved was ambiguous. In some cases spectral changes in land cover could be attributed to anthropogenic changes (mainly the expansion of irrigation and the preparation of fields for winter rain-fed cultivation) but in no case were the trends backed up by both visible and near infra red data for the same pair of dates. It is thought that this ambiguity is due to the fact that changes in rangeland vegetation cover since 1972 would have been slight due to the fact that the range in 1972 was overgrazed. Consequently, any subsequent degradation of rangeland including conversion to fields, would be difficult to distinguish because of the very small losses of vegetation cover that would have accompanied such changes. In addition, because the spectral responses of such changes would have been very small they could easily be masked by slight differences in vegetation cover due to differences in soil moisture levels during the phenological cycle, and changes in surface soil properties due to soil erosion or deposition. Such changes have been noted by Mas (1999) in Mexico.
CHAPTER 4: VEGETATION COVER MAPPING AND DYNAMICS IN NORTHERN JORDAN

4.1 Introduction

4.2 Linear spectral mixing modelling

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4.5 Summary
4.1 Introduction

The main objective of this study is to evaluate the impacts of land cover change on land degradation in the semi-arid environment of the north-west part of the BRDP area. In Chapter 3 it was argued that traditional methods of land cover mapping, had shown that change detection analysis, produce poor results. Therefore, a different approach was taken to provide vegetation cover inputs to the erosion model. Mapping different land cover types, particularly vegetation cover, is an important element in monitoring land degradation because a reduction in, or removal of, vegetation cover accelerates rates of wind and water erosion. Although vegetation communities in semi-arid ecosystems are very sparse, they are still sensitive to changes in climate. This in turn means that monitoring the dynamics of sparse vegetation communities as an indicator of either climatic or anthropogenic change constitutes a key element in desertification research (Hill et al., 1995a).

Mapping vegetation cover in the context of the present study has a first priority over other cover types, because changes in land cover (especially natural vegetation cover) have occurred extensively in the study area (cf. Chapter 2). Furthermore, it is believed that agricultural activities have a direct link with land degradation. However, mapping vegetation cover in the study area poses a problem because of the high contribution of the soil to the background spectral properties of each pixel as a result of the low vegetation density commonly found in drylands.

Mixed pixels are very common in this environment because vegetation cover very rarely reaches 100%, making most pixels a mixture of vegetation, fine sediments (soils) and stones. Consequently mixed pixels are the main cause of classification error in drylands (Campbell, 1981; Foody, 1988, Drake, 1992) because image classification techniques assume pixels to be pure, i.e. to comprise a homogeneous area representative of one land cover class (Fisher and Pathirana, 1990). Unfortunately this is not the case in drylands where the land cover classes are
continuous rather than discrete and they inter-grade (Wood and Foody, 1989). Furthermore many classes which are commonly defined as “urban” or “bare rock” are often spectrally heterogeneous because they are a mosaic of numerous spectrally different materials, and rock outcrops exhibit topographies that lead to variations in illumination. The result of this within-class heterogeneity is that classes with high variance suffer significant levels of misclassification. Furthermore, classification approaches cannot provide objective vegetation maps because of the human intervention required in highly interactive processes such as spectral class definition. Objective monitoring is also almost excluded because of the difficulty in comparing updated maps with maps from earlier dates (Hill et al., 1995; Sommer et al., 1998).

Vegetation indices have been developed to identify the presence of green vegetation. Commonly used indices, such as the Normalized Difference Vegetation Index (NDVI) (Perry and Lautenschlager, 1984), suffer from a variety of problems; in particular their sensitivity to the atmosphere, illumination and observation geometry (Pinty and Verstraete, 1992a) and to the background reflectance of soils and parent rock.

Image enhancement procedures (linear contrast stretches, decorrelation stretches, intensity hue saturation transformation, band ratios, principal components analysis) have been used to illustrate certain features in the imagery where quantitative information is not necessary, but image enhancement only uses a small amount of the spectral information and then, like classification techniques, has its own problems (Drake, 1992; Lillesand and Kiefer, 1987; Mather, 1987; Richards, 1993).

The study area is characterised by the following:

- the study area is a transitional zone between semi arid and arid environments where land cover types are gradational rather than discrete;
- basalt boulders are strewn on the soil surface, confusing the soil spectral signature as well as the vegetation signature, which is one of the weaknesses of the vegetation indices; and
- the pixels in the imagery are heterogeneous because they are a mixture of different land cover types.
It is clear that a method for mapping vegetation is needed that: 1) uses the maximum amount of spectral information; 2) takes into account the fact that most pixels are mixtures; and 3) neutralizes the effects of the atmosphere, as well as the problems of illumination and observation geometry. Linear mixing model using the concept of the end-member spectra satisfies all of these conditions. In the following sections the assumptions behind linear mixing are discussed, and a solution to the linearity of the mixing problem is proposed. Following this, the procedure is applied to a number of TM images to generate different end-member maps of the study area. However, it will be shown that this can only be applied to Landsat TM data and, therefore, in section 4.4 vegetation cover estimation for the 1972 and 1985 dry season imagery using NDVI will be discussed.

4.2 Linear spectral mixture modelling

4.2.1 The question of linearity

Spectral mixture modelling is based on the concept of dividing each pixel, which is the smallest ground resolution element of a satellite image, into its constituent materials or components using end-members which represent the spectral characteristics of the cover types. In spectral mixing analysis, it is assumed that signatures of a subset number of surface elements can reproduce the observed spectra when mixed together in various proportions. This limited number of surface materials can be any number of land cover types that are present in the scene in sufficient concentrations and are able to form diagnostic spectra in the image, e.g. they can be vegetation, soil or shade (Smith et al., 1990). They commonly mix at the sub-pixel scale, thereby producing a spectrum of a mixed pixel. This subset of surface elements may be referred to as end-members, components or factors; but they may, in fact, be mixtures themselves (Gong et al., 1994).

Spectral mixing can be considered as linear if each photon has only interacted with one ground component on its path between the sun and the sensor (Drake, 1992). The question of linearity is therefore dependent on the size and shape of the particles and the optical path length of the materials composing these particles. Materials that are
distributed as particles smaller than their optical path length will tend to mix non-linearly as photons will be transmitted through them and they may then interact with different materials. The scale at which materials are distributed in the natural environment will therefore have a large control on the linearity of mixing in the visible and infrared. Less scattering will occur between materials of larger particle size, the albedo will be lower and mixing will tend towards linearity. In the case of boulders lying on soils (which is common in the study area), mixing will be linear for nearly all materials because the particle size of the stones is large.

Non-linear mixture models assume that canopy reflectance is a non-linear function of canopy optical and structural parameters due to the scattering between components in the mixture. However, non-linear models that realistically describe the radiative regime of plant canopies (Borel and Gerstl, 1994) present serious difficulties when it comes to inferring parameters necessary for applying the technique at small scales as with reconnaissance surveys (García-Haro et al., 1996).

Linear mixture modelling is relatively simple and has been used successfully in many fields, inter alia, geology and geomorphology (Adams et al., 1986; Drake, 1992) and land cover and vegetation studies (Foody and Cox, 1994; Smith et al., 1990). Linear spectral mixture modelling has been applied in the present study with the basic physical assumption that there is an insignificant amount of multiple scattering between surficial materials due to the simple nature of arid zone vegetation canopies. Therefore the flux received by the sensor comprises the sum of the fluxes from the end-members and that the fraction of each end-member (end-member fraction) is a function of the area it covers. Though it must be noted that non-linear mixing has been recognized in soil and vegetation systems generally (Borel and Gerstl, 1994) and desert vegetation in particular.

The linear spectral mixing model is defined by:

$$X = Mf + e$$  \hspace{1cm} (4.1)

where:

- $X$ is the \((n)\) observation vector for a pixel (the recorded reflectance in each waveband),
- $X = (x_1, x_2, \ldots, x_n)$, where $n$ corresponds to the number of spectral bands;
$f$ is the $(m)$ unknown vector of area fractions, $f = (f_1, f_2, \ldots, f_m)$, where $m$ corresponds to the number of end-members; $M$ is the $(n \times m)$ end-member matrix where all the reflectances, radiances or digital numbers are arranged; and $e$ is a noise term.

The following constraints are imposed on the term $f$:

$$0 \leq f_j \leq 1 \text{ and } \sum_{j=1}^{m} f_j = 1, \quad j = 1, 2, \ldots, m. \quad (4.2)$$

The first of these conditions means that it is impossible to have $< 0\%$ or $> 100\%$ of a pixel occupied by a certain cover type. The second that the pixel’s signal is only made up of contributions of the components under consideration.

### 4.2.2 Solution to the linear mixing model

Fractions of each end-member, i.e. $f$, can be obtained by solving (4.1). In fact, an estimate of $f$ can be obtained by minimizing the sum of squares of $e$ which means minimizing the function:

$$(X - Mf)^{\top} (X - Mf) \quad (4.3)$$

$X$ is known from the image pixel values, and $M$ can be obtained from laboratory data or can be derived from the image. It is clear that, in order to have a deterministic solution, the number of end-members should not exceed the number of spectral bands, i.e. $m \leq n$. This will allow a least squares solution for $f$.

On the assumption that the error term has statistical properties that are independent of the mixture and that the covariance matrix of $e$ is constant and equal to $C$ (Cross et al., 1991) then the vector of fractions, $f$, which describes the land cover composition of a pixel may be derived by minimizing the term:

$$(X - Mf)^{\top} C^{-1} * (X - Mf) \quad (4.4)$$

subject to the constraints:

$$0 \leq f_j \leq 1 \text{ and } \sum_{j=1}^{m} f_j = 1, \quad j = 1, 2, \ldots, m$$
Once image end-members have been identified, the entire image can be unmixed, pixel by pixel, by solving (4.4). When $f$ is obtained for each pixel, the validity of the least squares estimation of $f$ is controlled by calculating the root-mean-squared error (RMS).

$$\text{RMS} = \sqrt{\frac{1}{n} \sum (X_i - \sum r_{ij} f_j)^2} \quad (4.5)$$

Note: $i = 1, \ldots, n$  \hspace{1em}  $j = 1, \ldots, m$, and $r_{ij}$ are the elements of the matrix $M$.

With (4.4) and (4.5), one can construct $m$ end-member images and one error image (the RMS image). The average RMS error for the image provides a measure how much of the spectral variability was explained by the selected end-members. Moreover, an image of RMS error for each pixel will highlight spatial objects which could not be adequately modelled. The overall RMS error provides an important diagnostic for handling uncertainties of the mixing model and for its optimization (Hill et al., 1995).

### 4.2.3 End-member selection procedures

It has been shown in the previous section that a solution to the linear mixing model exists by solving equation (4.4). To do so, image end-members should first be identified to train the matrix, $M$, in which the columns are the signal vectors of each end-member. Different methods can be used to do this depending on the availability of ground reference data. The multivariate calibration method, which has been adopted by Pech et al. (1986), uses pixels with known estimates of the ground proportions of all the components to train the model. However, if this level of information is not available, or if shade is an important component in the image, this method cannot be adopted as it is impossible to measure the proportion of the shade in a pixel in the field. When either of these problems occur, a possible solution is to use the concept of the end-member spectra (Adams et al., 1986). The end-member spectra are the pixels that are the purest examples of each component in the image. However, if the pixels representing the end-members are not the purest example of each component in the image, then purer pixels will cause negative ranges to occur (Drake, 1992). If pure pixels do not exist in the image these spectra can still be
obtained from libraries of end-member spectra (Boardman, 1990; Sommer et al., 1998) which have either been measured in the laboratory or in the field.

The selection of the end-members necessitates the determination of the number of components in the image and the identification of the area where they are dominant. A common approach for determining the number of end-members is to perform an inspection of the principal components of the data set to find the significant principal components or eigenvectors accounting for most of the variance in the image (Smith et al., 1985; Drake, 1992). The remaining variance is equal to instrumental error or noise. If there are N significant eigenvectors, then there will be N+1 end-members in the space they span (Bateson and Curtiss, 1996). However, it has been argued by Drake (1992) that if the end-members are impure, this number must be considered a minimum.

Principal components analysis (PCA) has the advantage of reducing the dimensionality of a data set, with the resulting components being uncorrelated whilst at the same time retaining its maximum variance. A method of finding end-members in the image using PCA is described by Smith et al. (1985). They performed their analysis by producing scattergrams of pairs of principal components (e.g. PC1 and PC2). The scattergrams show a multi-dimensional feature space distribution of the data in which the end-members are represented by the purest pixels in the image. These pixels lie at the extremes of the feature space and mixture pixels will lie within the region defined by these end-members (Fig. 4.1). Drake (1992) concluded that scattergrams of the significant PCs would define all the image end-members.
Fig. 4.1: Feature space analyses of the principal components PC1 to PC4 of the 1992 TM image.

(a) is the feature space analysis of PC1 and PC2 which shows the mineral, limestone and waste water end-member pixels, (b) is the feature space analysis of PC2 and PC3 which shows the green vegetation, limestone, waste water and mineral end-member pixels, (c) is the feature space analysis of PC3 and PC4 which shows the green vegetation, mineral and limestone end-member pixels. The identification of the end-member pixels in all three diagrams is discussed in section 4.3.
The methodology used in this research to determine the number of components in the image and the location of their respective end-members was that adopted by Drake (1992). It can be summarized in the following sequence:

1) Run a PCA on all bands.
2) Determine the number of significant PCs to give the minimum number of components contained in the scene, and determine which PCs contain relevant spectral information.
3) Produce scattergrams of pairs of significant PCs and locate the end-members that lie at the extremities of these scattergrams. This is done sequentially (i.e. PC1/PC2, PC2/PC3, PC3/PC4...).

Once the identification of ‘pure’ end-members using these procedures has been accomplished, the co-ordinates of the candidate pixels for the end-members are identified. These are then subject to investigation in the field to decide on their degree of purity. However, for other less pure components which cannot form distinct extremities on the scattergrams, e.g. bare soil and basalt boulder fields, other approaches to end-member identification were adopted in this study (cf. Section 4.3).

### 4.3 Application of the linear spectral mixing model in northern Jordan

The land in the northern Jordan is characterised by basalt plains consisting of largely undulating terrain which is weakly to moderately dissected by near radial drainage flowing from the Jabal al-Arab. Slopes are generally less than 15 % and the relative relief is generally low. The area is covered by extensive lava flows. Steppe vegetation occurs mainly in areas where the rainfall ranges from 100 - 250 mm per annum. Most of the former rangelands are now cultivated (cf. Chapter 2).
Fig. 4. 2: The uppermost TM image acquired on 1st April 1987 is 15 by 10km and is a false colour composites of bands 4, 3 and 2. The city of Mafraq is clearly seen in the centre of the sub-scene. Limestone quarries can be seen to the west of Mafraq. The lowermost image of the same area was acquired on 28th August 1992 and clearly shows (by comparing the crosshairs) the extension of quarrying in the area between 1987 and 1992. The quarries are the location of limestone end-member pixels.
Construction activities are present in the area because of the expansion of existing villages, the creation of new factories and the extension of the paved road network. This has invigorated the quarrying industry to provide limestone and basalt for houses construction, and gravel and sand for road construction and building. Quarrying of limestone, for example, manifests itself on the imagery as large limestone quarries to the west of Mafraq. These quarries are very well seen on the false colour composite of 1987 and 1992 TM images as they comprise the brightest pixels of the scene (Fig. 4.2). Water is an important component of the imagery in many pixels as it is present in the form of:

(a) soil moisture, in particular in those fields that are newly ploughed and irrigated at the starting of the agricultural season;
(b) as foliar moisture in green vegetation; and
(c) as water bodies, which show up very well on the wet season image from 1987 (Fig. 4.3).

Fig. 4. 3: A TM false colour composites of bands 4, 3 and 2 covering an area of 15 by 10km. The image was acquired on 1st April 1987. The city of Mafraq is in the west-central part of the image and the air base is the large dark brown area in the centre. The water body (al-Ghadeer al-Abyad) is located in the north-west of the image.
Linear spectral mixture modelling can be applied to generate fraction images of main land cover types in any scene. Prior knowledge of the area, as well as a thorough examination of the TM colour composites and field visits to the study area, suggest that the main image components and their respective end-members are confined to the following five components:

- Basalt (both massive and in the form of boulders and loose stones)
- Limestone (both massive and in the form of loose stones)
- Bare soils (derived from basalt and limestone)
- Green vegetation
- Water (and shade).

The collusion between water and shade occurs because, like shade, increasing amounts of moisture reduce the overall reflectance and, as they both have the same effect on the spectral response of the surface, there is spectral confusion between them. Because of this Drake (1992) could only find a composite component of shade and water in southern-central Tunisia. He related this to the collusion problem manifesting itself by the fact that, when spectra of two different materials are almost identical, they form a single extremity on the scattergrams and the two materials are thus mapped as one during mixture modelling.

The main focus of linear mixture modeling in this thesis is to map green vegetation in the north-west part of the BRDP. This component will become an input to the GIS erosion model (cf. Chapter 6). Therefore, the collusion problem between water and shade does not have any significant impact on the validity of the prediction model because neither of these components is required within the scope of this research. On the contrary, it helps by eliminating the effects of these components and hence produces accurate fraction images devoid of shade.

The TM images used for linear spectral mixture modelling were acquired on April 1st 1987 and August 28th 1992. Atmospheric corrections for both images were undertaken to enable the use of laboratory spectra for those end-members that were
not pure (i.e. where pixels with 100% cover of the component could not be located on the imagery and/or in the field). This situation occurred for both the water and the basalt end-members. No pixels with 100% basalt were found in the two images and therefore this end-member cannot form an extremity in the scattergrams. The water end-member formed distinctive extremities in the scattergrams but was discarded after a field visit of the site of the ‘pure’ pixels because it was related to a waste water treatment plant (at al-Khirbat al-Samra, to the south west of Mafraq) and the water was judged to be impure because of sediment and algal growth. Therefore published data on water spectra were used (Dekker et al., 1995), while field and laboratory spectroradiometric measurements of basalt from the BRDP area were used (White, 1996). These published data were used after performing statistical analysis on the atmospherically corrected images to fit the published DN values into these images (Tables 4.1 (a) and (b)). No pure bare soil end-member could be found on the imagery, neither has it been easy to find pure sites of bare soils (devoid of stones or other materials) in the field. This is because soils in the study area are derived from a variety of sources (basalt and limestone). In addition, deposits of aeolian origin are very common and wind-blown sediments mix with sediments derived from the underlying parent material. Nonetheless, a few ‘relatively’ pure pixels (cf. Section 4.3.1) were identified in the field and were used to generate a spectral signature for bare soils Table 4.1 (c).

All pre-processing tasks were executed on ERDAS Imagine Version 8.3. All the images were exported to the PCI/Easi-Pace software to perform the unmixing procedures.

4.3.1 Selection of end-members

PCA was run on the six reflective bands of both TM images. The first four PCs contain most of the spectral information for both acquisition dates as the sum of their eigenvalues represent more than 99 percent of the total variance of each image. This indicates there are at least five end-members. Scattergrams of the four PCs revealed four well-defined end-members that were found to correspond to limestone, volcanic tuff, water and green vegetation. Examples of the three scattergrams of the following
pairs of PCs: 1/2, 2/3, 3/4 of the late summer 1992 image are shown in Fig. 4.1. However, we know from the inequality relationship (cf. Section 4.2) that there are at most five end-members. Furthermore, we know that basalt and bare soils are two end-members which will be present in the study area (cf. section 4.3). However, they do not form distinctive extremities on the scattergrams because they are not pure.

Bare soils in the study area are rarely free of basalt boulders and only small stone-free parcels are inter-dispersed between the stony areas. Furthermore, it is not easy to collect spectra from libraries that match exactly the spectra of bare soils of the study area because it is debatable whether these soils are basalt-derived, limestone-derived or deposits from aeolian material (cf. Chapter 1). For these reasons, ground-based surveys of the proportions of basalt of 'relatively' pure bare soil pixels were necessary so that a mixture model can be run using the spectra of these pixels identified in the field and reported on the image using GPS co-ordinates. Sites of 'relatively' pure pixels were selected and measurements were undertaken as described in the following steps:

- Candidate pixels were first detected on the 1992 TM image. These were areas with bright tones in bands 4, 3 and 2 and apparently devoid of any land cover.
- Field visits were undertaken to ensure that these were in fact 'bare soil' sites rather than rock, construction areas or habitations. In addition, investigations in the field were undertaken to check if these sites had been unused since the acquisition date of the imagery. This was ensured through checking the current use and by talking to local people.

Once these sites were identified, measurements were made using 1m² quadrat. In total 8 sites were identified, and an average of 30 measurements were taken for each site.

- The quadrat was thrown randomly on the ground every 10 to 15 paces, and the estimation of the ground cover percentages was made visually.
- Simple statistical analyses were performed on these measurements. The mean and standard deviations of bare soil area were determined for each site. The mean bare soil percentage on these sites was found to be 98.5% with ±1.5% standard deviation.
• Spectral measurements of the DN values from these sites were obtained from the imagery (Table 4.1c) and considered as the spectral signature for bare soil in the unmixing procedure.

Laboratory measurements of basalt stones collected in the area were used (White, 1996). He sampled five basalt formations of the Harrat Ash-Shaam super-group, along with their associated fine-grained substrate in the field. The data are simulations of the response in the six reflective bandpasses of the TM sensor and are published as reflectance values. The values adopted for this study area of the north-west part of the BRDP area are those for the weathered basalt surfaces. The values for the five weathered basalt formations were averaged and converted to DN values (Table 4.1a) to be used in the unmixing model. This procedure was applied to the laboratory-derived pure water spectra as well (Table 4.1b).

Potential sites of limestone end-members were visited in the field. These sites were active quarries with large open areas that contain groups of pure pixels to the west of Mafraq (Fig. 4.2). Thus, the purity of this end-member was ensured without ambiguity using visual assessment.

Purity of the green vegetation end-members was assessed by visiting irrigated fields of forage, tomatoes and water melons with a full, green canopy cover. The pixels from the canopies were selected to generate spectra for this end-member. Groups of very dense ephemeral vegetation pixels along wadis were selected for the 1987 wet season image as few irrigated fields were evident on the image at this time.

4.3.2 Component maps (fraction images)

After the determination of the five end-member spectra, the unmixing model was run in PCI/Easi Pace using the spectra of these end-members. A fraction image for each end-member and an error image was obtained for each of the two dates. The average error is less than 2% of the DN values in each band. Fig. 4.4 shows the end-member fraction image of green vegetation for the late summer 1992 image. It can be seen that
<table>
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(a)

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<th>Mean Reflectance values</th>
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<tr>
<td>TM3</td>
<td>0.103</td>
<td>69</td>
</tr>
<tr>
<td>TM4</td>
<td>0.030</td>
<td>22</td>
</tr>
<tr>
<td>TM5</td>
<td>0.011</td>
<td>5</td>
</tr>
<tr>
<td>TM7</td>
<td>0.010</td>
<td>5</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>TM Bandpasses</th>
<th>DN values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1992</td>
</tr>
<tr>
<td>TM1</td>
<td>163</td>
</tr>
<tr>
<td>TM2</td>
<td>118</td>
</tr>
<tr>
<td>TM3</td>
<td>150</td>
</tr>
<tr>
<td>TM4</td>
<td>134</td>
</tr>
<tr>
<td>TM5</td>
<td>206</td>
</tr>
<tr>
<td>TM7</td>
<td>130</td>
</tr>
</tbody>
</table>

(c)

Table 4.1: Simulated TM band spectral reflectance and corresponding DN values of (a) weathered basalt (from White, 1996), (b) pure water (from Dekker et al., 1995), and (c) bare soils.
vegetation in the irrigated fields has been enhanced. They appear as light grey tones, indicating a high fraction of vegetation in the pixels.

In Fig. 4.5 it can be seen that most brighter tones appear in pixels that will include a high percentage of shade due to the topographic effect due to the high relative relief on stony basalt surfaces. However the RMS image histogram (Appendices A-I and A-II) shows that the mean value never exceeds 2%. It can also be seen that the vegetated fields (to the south of Umm al-Quttayn) are very dark indicating low RMS values and, consequently, the high accuracies of pixels with high green vegetation cover proportions.

A selection of vegetated fields were visited and their vegetation covers were assessed by visual observations. In this sense the validation is limited, as the visits were not made at the times of image acquisition. These visits were made at approximately the same time of the year, but four and six years later at the beginning of summer 1996 and autumn 1998 respectively. Of course, vegetation is not only present in the irrigated fields on the vegetation fraction images. Vegetation is also present along wadies and, at much lower percentages, on the rangelands.

Fig. 4.4: Fraction image of green vegetation. The area is 28 by 18km. The area is equivalent to that in Fig. 4.5. The areas with high amounts of green vegetation are in light grey, whilst areas without vegetation are black. The bright almost rectangular areas are the irrigated vegetated fields.
4.3.3 Applying vegetation cover data from linear mixture modeling in northern Jordan to the erosion model

The DN values of the vegetation fraction images needed to be converted to percentage vegetation covers because the GIS-based erosion model, which is based on the Revised Universal Soil Loss Equation (cf. Chapters 5 and 6), uses percentage vegetation cover. To achieve this the DN values were converted to percentages using the following equation:

\[ \% VC = \frac{DN}{255} * 100 \]

where \( \% VC \) is the vegetation cover (as a percentage)

A graphical model in the Model Maker module of ERDAS Imagine was built to produce the vegetation percentage images.

DN values of the basalt component fraction image were not converted to percentage values because it was decided to mask the basalt areas in the erosion model. This is
because they are completely covered with basalt boulders and stones and are not used for cultivation, though they are used for grazing.

4.4 Vegetation cover estimation from Landsat MSS images in 1985 and 1972 using NDVI

4.4.1 Introduction

Linear spectral mixture modelling could not be used for unmixing the MSS image data because of their low spectral resolutions. The Normalized Difference Vegetation Index (NDVI) was used instead to map the vegetation cover for the 1972 and 1985. The output of the NDVI application, for the years where TM imagery cover was not available, were used in the GIS model for calculation of the amount of soil erosion by water during these years, to create a baseline for further comparison between these years to assess the impact of soil degradation due to water erosion along the period of study.

4.4.2 NDVI in drylands

Vegetation indices, in particular the Normalised Difference Vegetation Index (NDVI), has been used extensively since the early 1980’s to investigate vegetation responses in all biomes globally, significant amounts of research have been carried out in dryland environments (e.g. Pareulo and Lauenroth, 1995). Most of this research has used NDVI values derived for the NOAA-AVHRR system and this can be termed large area analysis because of the base spatial resolution of AVHRR of 1.1 km at nadir. This research has shown that AVHRR-NDVI can be correlated with above-ground green biomass in drylands (Everitt et al., 1984; Todd et al., 1998; Wellens, 1993) percent vegetation cover (Purevdorj et al., 1998) and that intra- and inter-annual variations in AVHRR-NDVI are closely correlated with vegetation phenology and the seasonality of dryland climates (Millington et al., 1994).

Despite the fact that most of these studies have been carried at spatial resolutions in excess of 1 km, these research findings can be applied to finer spatial resolution data
because the principles of plant physiology and canopy reflectance that underpin the research at coarse spatial resolutions are equally applicable at finer spatial resolutions.

4.4.3 Applying the vegetation cover data from NDVI analysis in northern Jordan to the erosion model

It must be borne in mind that, in areas where the vegetation canopy is poorly developed (as would have been the case in the study area in the dry seasons of 1972 and 1985) that much of the spectral response would have resulted from interactions of incoming visible red and near-infra red radiation with the soils and desiccated vegetation, rather than green vegetation. In such circumstances, the use of the NDVI has been questioned (Huete and Jackson, 1987) and alternative vegetation indices to the NDVI have been developed such as TSAVI (Qi et al., 1994), SAVI (Huete, 1988); though some researchers (e.g. Dymond et al., 1992; Pickup et al., 1993; Senseman et al., 1996) have been able to monitor rangeland degradation using vegetation indices. The issue of accuracy of vegetation indices using data from broad channel sensors (such as those on MSS and AVHRR) has also been questioned, but work in rangeland targets in the USA has indicated that for single dates and reconnaissance-scale assessments using reflectance data from broad channel sensors data is quite adequate (Bork et al., 1999)

Vegetation cover percentages estimation in the BRDP area using NDVI was carried out by Edwards et al., (1996). An ATSR-2 image, along track distance 164116925, dated 28th November 1995, and two AVHRR images dating from April 1995 and November 1995 were used in their analysis. They calculated the average red response and the average NIR response of the 9 pixels chosen as field sites (to include the central 1 km² sampling frame and to allow for the slight inaccuracy in geometric correction). They produced a table (Appendix B-I) giving the NDVI and percentage vegetation cover for the nine field sites considered. The results of NDVI values plotted against percentage vegetation cover for November (at the beginning of the winter season) (Appendix B-II) are low and never exceed 0.14.
NDVI was calculated for both 1972 and 1985 MSS dry season images. The study area was then subset and the range of NDVI values for both dates were determined (Table 4.2).

<table>
<thead>
<tr>
<th>Image date</th>
<th>Minimum NDVI</th>
<th>Maximum NDVI</th>
<th>Mean NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>-0.134</td>
<td>0.087</td>
<td>0.012</td>
</tr>
<tr>
<td>1985</td>
<td>-0.172</td>
<td>-0.06</td>
<td>-0.121</td>
</tr>
</tbody>
</table>

Table 4.2: NDVI date calculated from MSS images for 1972 and 1985.

A close look at the NDVI statistics for both dates shows that the NDVI values never exceed 0.087. Using the Figure produced by Edwards et al. (1996) (Appendix B-II), the values of the NDVI never exceed the threshold of 20%. This result is expected because this area of Jordan usually experiences very low levels of vegetation cover at the end of the summer season in particular, because of overgrazing and the absence of irrigated vegetated fields before 1985 in the study area (cf. Chapter 3).

4.5 Summary

The aim of this chapter was to create maps of vegetation cover percentages for the study area from the three dry season images as input to the RUSLE. A brief review of the different techniques commonly used for land cover mapping has been presented which indicates their relative merits and limitations. All of the common techniques suffer from a variety of problems many of which are related to the high levels of spectral confusion created by the sparse vegetation cover and soil background and the continuous rather than discrete nature of many land cover types.

It has been shown that linear spectral mixing modelling does not suffer from these problems. On the contrary, it has been found that the technique is well suited to dryland environments like northern Jordan where linear mixing is likely to occur because surficial materials are characterised by large basalt boulders distributed on the soil surface and simple canopy structures. In addition, changes in almost all land cover
types in this area are gradual rather than discrete, and pixels are commonly mixtures of several land cover types. However, the linear spectral mixing modelling has limitations, the most important of which are:

- the assumption of linearity,
- the condition of purity of the end-member, and
- the collusion problem created when two different types have similar spectra within the spectral resolution of the TM images.

Each one of these limitations can be addressed and their effects can be minimized; though the extent to which this is possible depends on the particular conditions in the study area.

Linear spectral mixing modelling was used in this research to map the proportions of cover types present in the study area using the following assumptions. Firstly, the spectral mixture of the components in the environment of northern Jordan is linear. Secondly, the number of image components and their respective end-members are known. Thirdly, that the locations of these end-members are known. The purity of the end-members pixels was assured by field visits wherever possible, and spectra from spectral libraries were used when the purity was contested for water and basalt.

Five component images (green vegetation, soils, basalt, limestone, water and shade) were produced together with an error image for both 1987 and 1992 TM images. The overall accuracy was judged by the value of the RMS, which was less than 2% for all bands. It was felt that this is a satisfactory result given the reconnaissance nature of this study. Vegetation cover maps were calibrated and used as inputs to the GIS-based soil loss model (cf. Chapter 6).

It was not possible to run linear spectral mixing modelling on the MSS images from the 1985 and 1972 dry seasons, NDVI maps were produced from these images and calibrated using NDVI-vegetation cover developed for Jordan by Edwards (1996).

In all three years, the vegetation cover percentages for rangeland and rain-fed field areas were < 20%. 20% is an important threshold in the RUSLE as will be shown in Chapter 6.
CHAPTER 5: MODELLING LAND DEGRADATION PROCESSES

5.1 Introduction

5.2 Soil degradation processes

5.2.1 Soil surface crusting

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5.2.1.2 Crusting in the study area

5.2.2 Soil erosion by water

5.2.2.1 Raindrop impact
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5.2.3 Soil erosion by wind
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5.3 Modelling soil erosion by water

5.3.1 Introduction
5.3.2 The Revised Universal Soil Loss Equation (RUSLE)

5.3.2.1 Introduction
5.3.2.2 Erosivity
5.3.2.3 Erodibility
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CHAPTER 5: MODELLING LAND DEGRADATION PROCESSES

5.1 Introduction

Land is synonymous with the terrestrial ecosystem that comprises soil, water, biota on the Earth’s surface and the ecological processes that operate within the system. Land degradation, therefore, refers to the degradation of the entire ecosystem. From the economic point of view, in an ecosystem that produces agricultural goods (an agroecosystem), it can be defined as the reduction in the capacity of land to produce what the associated human society expects from it (Kassas, 1995).

Soil degradation is a part of land degradation in the sense that soil is an important component of an ecosystem or agroecosystem. It is a general term comprising a number of earth surface processes such as water erosion (e.g. inter-rill, rill and gully erosion), soil sealing (or crusting), salinization and waterlogging, wind erosion, and biological, chemical and physical degradation (FAO, 1979; Barrow, 1991). Some authors refer to these processes in drylands as desertification. This is because these processes are promoted by human removal of vegetation cover and they lead to a decline in land productivity (Hill et al., 1995; Bilsborrow and Ogendo, 1992; Goudie, 1990). However, caution in the application of this term is essential, and in this thesis only the specific earth surface processes are evaluated rather than desertification in general. Two approaches to studying land degradation can be distinguished in the literature. De Jong (1994) refers to these as the agronomic and the scientific approaches. Whilst the agronomic approach is 'scientific', it looks at the effects and consequences of land degradation strictly in agricultural terms. This research project uses the agronomic approach, as the main focus of interest is to examine the consequences of land degradation in northern Jordan because of the intensification of agricultural practices in the last two to three decades, and its potential impacts on agricultural production. The specific approach adopted is that proposed by the FAO (FAO, 1979).
FAO (1979) defined land degradation as:

"A process which lowers the current and/or the potential capability of soil to produce (quantitatively and/or qualitatively) goods or services. It is not necessarily continuous. It may take place over a relatively short period between two states of ecological equilibrium". (FAO, 1979, p. 2).

They go further in distinguishing six main types of land (soil) degradation:

- Water erosion: sheet, rill and gully erosion, and mass movements (in this thesis the term sheet erosion is replaced by inter-rill erosion to accord with currently accepted usage which acknowledges the combined effects of splash and sheet erosion);
- Wind erosion;
- Excess salt accumulation (salinization and sodication);
- Soil chemical degradation (soil acidification and the build-up of chemicals to potentially toxic levels);
- Soil physical degradation; and
- Soil biological degradation.

Land degradation is not confined to arid and semi-arid areas, for it is also widespread in both humid temperate and humid tropical areas (FAO, 1979). Nonetheless, soil degradation processes have a profound impact, and cause much damage, in the semi-arid zone due to the combination of relatively low (natural) vegetation cover and relatively high rainfall intensities (Hill et al., 1995; Kok et al., 1995). It is this relationship between vegetation cover and rainfall intensity that leads to high natural rates of soil erosion in semi-arid areas. These can be exacerbated by specific soil properties and, in places, high cultivation densities which lead to further vegetation clearance.

The causes of land degradation in drylands can be grouped under two main categories: (1) the inherent ecological fragility of dryland ecosystems; and (2) excessive human pressure on the land (Kassas, 1995; Warren et al., 1996; Goudie, 1990). The inherent
fragility of dryland ecosystems relates to a number of ecological features (Kassas, 1995):

1. low rainfall and a negative annual moisture balance (cf. Chapter 1, for climatological definitions of drylands);
2. rainfall variability with recurrent incidences of drought;
3. low bio-productivity with little plant growth to protect the land against erosion; and
4. poor soil development with low organic matter contents because of rapid oxidation at the surface.

The driving forces behind the excessive human pressure are:

1. population growth;
2. increases in the demands for water and land which accompany economic development;
3. political processes that change the subsistence economy of traditional societies to a more commercially-based economy; and
4. the settlement of nomadic societies, nation building and the formation of political boundaries which restrict population migration (Kassas, 1995; Warren et al., 1996).

A worldwide effort led by the UN started to diagnose and map the distribution and trends of soil degradation in drylands, particularly after the severe droughts which afflicted Africa in the early 1970s. These efforts resulted in compilation of many important documents, such as the World Map of Desertification (UNCOD, 1977) and, ultimately, to two global conventions. The first of these, the Global Action Plan to Combat Desertification, arose from the 1977 UN Conference on Desertification, and more recently, the International Convention to Combat Desertification, which arose from the Rio Earth Summit in 1992 (Toulmin, 1997). Whereas the World Map of Desertification provided the first overview of the magnitude and extent of the problem; the conventions provided the frameworks for scientists to investigate desertification and for national and regional bodies to tackle the problem. A second major effort of the UN agencies was the joint project of FAO, UNEP and UNESCO,
which constructed regional-scale soil degradation maps for North Africa and the Middle East.

These showed the, then, current status of soil degradation (i.e. the degradation that was actually occurring) and the risks of future soil degradation (i.e. the risk that degradation will occur under certain defined, adverse conditions) (FAO, 1979).

Soil degradation by water is of particular interest for this study because it is generally acknowledged to be the most important form of soil degradation occurring in arid and semi-arid areas (Anys et al., 1994; Hill et al., 1995). This has been confirmed from field observations in the study area. I have made qualitative field observations of soil erosion by water (e.g. rills, evidence of sheet wash) and related phenomena such as crusting (Plates 5.1 and 5.2). The importance of crusting has been elucidated by Kirk (1998) in the study area. At the same time I have seen little evidence of wind erosion (even during the dry season) and no visual evidence of salinization on irrigated land. Nonetheless, these soil degradation processes (wind erosion and salinization) will be introduced in this chapter as they are potential risks in the study area. The dominance of water erosion can be explained by the fact that rainfall in the area is characterised by short but intensive periods of precipitation at the beginning of the season when the ground is essentially devoid of vegetation cover and the soil aggregates formed by cultivation are prone to raindrop impact. This is in accord with Grenon and Batisse’s (1989) observation that more than 15 tonnes ha^{-1} of soil is lost each year in at least one third of the Mediterranean basin because of the frequent violent rainstorms that follow the dry summer period, and which cause severe soil erosion of the unprotected topsoil. Furthermore, the soils in the area are generally shallow, and the soil structure and aggregate stability is weak. This makes these soils vulnerable to crust formation, sealing and aggregate breakdown (De Jong, 1994). Kirk (1998a) confirmed this by discovering through field experimentation that erosion processes pose potential problems to soil quality in the northern badia. As a consequence, this research will focus on modelling water erosion in the study area, and to evaluate the effect of changes in land use system and agricultural practices on soil degradation in the study area.
Plate 5.1: Crusting near Caum al-Rouf. The field on the left has been ploughed recently, whereas the field on the right has been exposed to rainfall during one winter growing season. The extensive surface crusting and a smoothing of the plough lines is clearly evident.

Plate 5.2: Initiation of rilling near the bottom of a ploughed field near Tell al-Rimah.
Changes in land use are often hypothesised as leading to a reduction of the quantity and diversity of natural vegetation, and in the acceleration of soil erosion in drylands (Bilsborrow and Ogendo, 1992). It is further postulated that this, in turn, will lead to a reduction in the potential productivity of the land (Sommer et al., 1998; Hill et al., 1995).

It is believed that remote sensing approaches can significantly contribute to solving the problem of extrapolating and scaling-up of earth-surface processes from a patch-scale to relatively large areas, as they have the potential to perceive, map and monitor operationally at regional scales the extension and effects of land degradation and how they might develop and evolve with time (Sommer et al., 1998). However, remote sensing is not a feasible technique for deriving information on all the parameters required to model and predict degradation, e.g. rainfall characteristics and sub-surface soil properties cannot be derived from remotely sensed data. Hence, other sources of information, as well as an integrated technology to deal with all these forms of information especially GIS technology, will always be necessary:

"The complexity of the degradation processes requires a multi-disciplinary approach and a thorough integration of several techniques, which originate from and have been developed in different disciplines" (De Jong, 1994).

5.2 Soil degradation processes

Soil erosion, considered as the most important land degradation process occurring in the study area, can be defined as a smoothing or levelling process, in which soil and rock particles are carried, rolled, or washed down-slope by the force of gravity. Water and wind are the main agents which loosen, break down and transport the particles (Hudson, 1981). Water erosion is the focus of the modelling described in this chapter. Nonetheless, other forms of degradation processes common in arid and semi-arid areas, e.g. wind erosion and salinization probably, occur in the area. However, it is assumed that water erosion is the most important land degradation process occurring in the study area. The reasons behind this assumption can be summarized as follows:

- The climate of the study area is characterized by a severe moisture deficit in mid-summer due to five-six months without rainfall and large potential and actual evapotranspiration and evaporation at this time (Ta’ani, 1996; Kirk, 1998b). This
leads to a sparse vegetation cover at the start of the wet season. Therefore, the intense autumn rainstorms (cf. Section 1.5.3) occur when the soils are exposed and the soil aggregates are highly prone to raindrop impact. High rainfall intensities lead to infiltration-excess overland flow and, as a consequence, sheet wash. Rills may also be initiated under these conditions (Plate 5.2). In both cases, fertile topsoil can be moved down-slope.

- The soil structure, particularly aggregate stability, is weak. Therefore these soils are very vulnerable to crust formation, sealing and aggregate breakdown (cf. Section 5.2.1).

- Significant changes in the land use system have occurred in the last two to three decades in the study area (cf. Chapter 2). These changes have encouraged the development of both intensive and extensive agricultural systems. The conversion from pastoralism to a mix of pastoralism and cultivation has possibly led to a decrease in vegetation cover and disturbance of the soil surface. Both of which can lead to increased water erosion.

- No salt-affected sites were found during the field visits. The reason behind this is thought to be the fact that most irrigation practices in the study area only started in the late 1980s and early 1990s (cf. Chapter 2). In addition, migrant farmers commonly practice a rotational agricultural system in the study area (cf. Chapter 2), which manifests itself in a continuous movement towards new lands and the continual clearance of basalt-covered areas. This has the role of alleviating the pressure of irrigation on the same piece of land, hence delaying the accumulation of salts in the topsoil.

- Little evidence of wind erosion has been seen during fieldwork even during the dry season. This may be explained by the relatively low mean wind speed in the study area compared to the velocity threshold in the wind erosion equation (cf: Section 5.2.3).
5.2.1 Soil surface crusting

5.2.1.1 Introduction

Soil surface crusting is a very common earth-surface process in arid and semi-arid soils, where the topsoil is characterised by low organic matter content, high silt content and weak aggregate stability (Abu-Awwad, 1997; Akasheh and Abu-Awwad, 1997). Crusting is the response of the soil surface to intense rainfall and can be described as the consolidation of surface particles (De Jong, 1994; Morgan, 1986; Farres, 1978). Generally, two types of crusts can be identified: structural crusts caused by compaction, and depositional crusts built up of several layers of sedimentation. Morgan (1986), Poesen (1986), Valentin (1985) and Valentin and Bresson (1992) have noted that crusts at the soil surface have several adverse effects:

- The infiltration capacity of the soil is reduced. This in turn induces runoff, increases erosion, and can lead to rill and gully formation.
- The water retention capacity of the topsoil is reduced.
- Soil aeration is reduced, thereby retarding root development.
- Germination of seedlings and the development of vegetation are hampered.

However, despite the negative impact of soil crusting as a process that promotes water erosion, it is worth noting the positive role that soil crusting can have in arid and semi-arid areas in protecting the underlying soils from further erosion once a crust has formed (Kirk, 1998a). In addition, since surface crusts produce high runoff rates, they foster natural water harvesting (Abu-Awwad and Shatnawi, 1997; Valentin, 1985); in such cases the low rainfall quantity, itself often insufficient to raise a crop, is collected over a large area facilitating runoff farming even in extremely dry regions.

From a review of the literature, it is clear that the process of crust formation is complex and not yet completely understood. Several studies relate crust formation to aggregate stability (Levy et al., 1993; Shainberg et al., 1992; Le Bissonais, 1990; Farres, 1987), and aggregate stability is used as a measure of the potential soil for crust formation. Organic compounds serve as stable, bonding agents for aggregates and therefore organic matter content could be used as an indicator of the potential of a
soil to crust. Furthermore, aggregate stability depends on the types of clay minerals present. For instance, aggregates form more easily in soils that contain illite and smectite. However, the open lattice structure of these minerals and the greater swelling and shrinkage which occurs upon wetting and drying, renders the aggregates less stable than those formed from kaolinite (De Jong, 1994; Levy *et al.*, 1993; Morgan, 1986).

Le Bissonais (1990), who has studied crust formation in detail, was one of the first researchers who attempted to define a conceptual model of soil surface crusting by analyzing the aggregate breakdown mechanisms and the effect of raindrops on soil surface. Different mechanisms of aggregate breakdown can be distinguished:

- total breakdown by slaking;
- micro-cracking; and
- mechanical breakdown and dispersion.

Total breakdown by slaking occurs during the initial wetting by the first rainstorms and appears to be a function of wetting kinetics, air-free pore volume and aggregate shear strength. Micro-cracking is caused by the swelling of clay minerals and/or from moderate slaking in soils with high porosity. Mechanical breakdown results from the direct impact of raindrops on aggregates, causing the inter-aggregate pores to be filled with the small detached particles. Furthermore, rainfall simulation experiments have shown that two different effects are important (Le Bissonais, 1990):

- If aggregates are saturated before rainfall, the intensity of aggregate breakdown is due to the contact between water and aggregates, and the most important processes are slaking and micro-cracking.
- If aggregates are dry before rainfall, the breakdown intensity is dependent on rainfall kinetic energy, and the most important processes are mechanical breakdown, splash erosion and surface compaction.

It is evident that surface crusting depends not only on soil or rainfall characteristics, but also on interactions between several variables (e.g. the status of the aggregates at the beginning of the storm, the wetting kinetics of the rainfall, air-free pore volume and aggregate shear strength). Some of these factors are very variable in time and space, e.g. the (initial) moisture content and the (initial) structural state of the soil.
5.2.1.2 Crusting in the study area

The mechanisms of formation of soil surface sealing and crusting have been detailed in the above paragraphs. The focus in this section will be on the existence and the extent of this kind of soil degradation processes in the study area.

Field visits to the study area at the beginning and at the end of the rainy season (November/December 1998) and (April 1997 and April 1999), showed well developed seals on the surface of most soils (Plate 5.1), especially on cleared fields with low vegetation cover. On the basis of these qualitative field observations, it was concluded that soil sealing affects all soil units in the study area to more-or-less the same degree. Thus, initially, it can be assumed that an index of crusting will probably be constant for the whole area.

The crusts are not very strongly developed. Poorly developed crusts can easily be broken up if there is an occurrence of at least ten nights of frost (Professor Tony Parsons, University of Leicester, 1998 personal communication). Such conditions are common in the badia of Jordan in most years. Tillage operations and grazing of sheep and goats also are significant in breaking up the crusts in the study area. These crusts can play some role in reducing erosion, whilst at the same time promoting surface runoff. The fact that the crusts form within 15 to 20 minutes of the start of a rainstorm (Kirk, 1998b) means that they soon provide some kind of protective cap to erodible topsoil. Nevertheless, much soil erosion can occur before crust formation, as rainfall in the badia is short, intense and generally of less than 10 minutes duration (cf. Section 1.5.4). The crusts probably play a more significant role in protecting the topsoil from wind erosion (Kirk, 1998a) and this may be the reason why so little wind erosion was observed in this area.

The method proposed by the FAO (1979) for large area assessment of crusting is to conduct a generalised assessment of the crustability of the soils of the area under investigation. The properties of the soil units (Table 1.4) were used to calculate the following index of crusting (FAO, 1979):
Crusting Index (CI) = (Zf + Zc)/C

where: Zf = % fine silt,
Zc = % coarse silt, and
C = % clay.

and, where the values of this index are:

- < 1.5: non-crusting soils
- 1.51-2.5: soils subject to weak to moderate crusting
- > 2.5: soils subject to intense crusting.

In calculating the CI for Jordan (Table 5.1), only a combined silt percentage was available. Therefore separate values Zc and Zf were not used. It should also be noted that different textural systems will mean that the coarse silt/sand boundary will differ, and as a consequence the amount of silt will vary depending on the textural systems used. Therefore, sand proportions are shown in Table 5.1 for information. However, the high proportion of silt in the soil units present in the study area means that the slight variations at this textural boundary will not have a significant effect on the crusting class.

It can be seen that the crusting index varies from a minimum value of 1.61 to a maximum of 1.93. This indicates that all the soil units are subject to crusting, but only weak to moderate crusting, i.e. the crusts can easily be broken. These values also indicate that the spatial variability of the crusting is low throughout the study area. This provides support for the earlier assumption that, in general, the crusting index (or to support the generalization – the crusting class) is more-or-less the same throughout the study area.
Table 5.1: Calculation of the crusting index for the soil units in the study area

5.2.2 Soil erosion by water

Soil erosion by water involves two phases (Meyer and Wischmeier, 1969; Lal, 1990):

- the detachment of soil particles; and
- the transportation of soil particles.

Different processes of soil particle detachment can be distinguished. The most important is detachment of particles by raindrop impact. Under continuous rainfall the soil surface is disturbed and soil aggregates are destroyed (Hudson, 1981; Morgan, 1986). Other processes are wetting and drying, freeze-thaw, biochemical processes and tillage. Two important soil transport processes can be identified. The first consists of rainsplash with a down-slope component and overland flow (i.e. inter-rill erosion). The second includes water flow in small channels (rills) or in larger, permanent channels (gullies) (Morgan, 1986; De Jong, 1994). The amount of soil eroded is determined by the quantity of material supplied by detachment and the capacity of the transport processes.

The area affected by erosion can be subdivided into: inter-rill areas, rills and gullies. Inter-rill erosion occurs along the entire slope segment, whereas gullying begins further down slope than rilling. A fourth feature, closely related to soil erosion, is soil surface
surface crusting. This is particularly so in arid and semi-arid areas where soils are very susceptible to crusting formation for inherent characteristics of soils and climate of these regions (cf. Section 5.2.1).

5.2.2.1 Raindrop impact

Water erosion usually begins when raindrops strike an unprotected soil surface. The rainfall erosivity depends on raindrop size distribution, fall velocity and total mass (Hudson, 1981; Morgan, 1986). The kinetic energy of the raindrops reaching the ground is transferred to the soil surface. Raindrop impact has two effects (Morgan, 1986). First, it provides a consolidation force, which compacts the soil and forms surface crusts. Second, it provides a disruptive force, which destroys soil aggregates and can even launch soil particles into the air causing transport of soil particles by raindrop impact. The effectiveness of splash erosion is variable and depends on the impact force of the raindrops, the direction of rainfall, soil erodibility, vegetative and other forms of ground cover (e.g. stones) and slope angle. Hence, raindrops are agents of both consolidation and dispersion.

The rate of detachment of soil particles by rainsplash has an exponential relationship with the instantaneous kinetic energy of the rain and the slope of the site under investigation (Morgan, 1986; Wischmeier and Smith, 1978). Morgan (1986) postulates that the erosivity of a rainstorm is a function of its kinetic energy (which comprises its intensity and duration) and the mass, diameter, direction and velocity of its raindrops. Morgan (1986) describes kinetic energy as the best single parameter expressing rainfall erosivity. Nevertheless, as it is difficult to measure some of the variables influencing kinetic energy, e.g. raindrop size distribution, other erosivity indices have been developed. For example, the rainfall intensity-based erosivity index developed by Wischmeier and Smith (1978) is based only on rainfall intensity. This makes it more practical and has been used in several erosion models.

The effect of raindrop impact is strongly reduced when the soil is covered by vegetation, litter or any other type of cover (Morgan, 1986; Hudson, 1981; Wischmeier and Smith, 1978). The effectiveness of a vegetative cover in reducing
erosion depends upon the continuity (and the height) of the canopy and the density of
the ground cover. Remote sensing is especially useful for assessment of vegetation
cover as well as for monitoring temporal changes of this cover, as has been shown in
previous chapters.

5.2.2.2 Overland flow

Overland flow occurs on slopes during, or directly after, rainstorms when either
surface depression storage or topsoil moisture storage of the soil is exceeded (Morgan,
1986). The transport capacity of runoff depends on runoff velocity. The transport
capacity increases as the slope angle increases, and as a consequence the flow velocity
increases with slope angle. As the flow velocity increases, the turbulence of flow
increases and surface flow concentrates in depressions. Overland flow removes the
lighter soil particles, organic matter and soluble nutrients from the land (Beasley,
1972). In other words it selectively removes certain elements of the topsoil leaving
relatively coarse topsoil deficient in organic material and clay minerals. The amount
of material transported depends upon the transporting capacity of the runoff and the
transportability of the soil (De Jong, 1994).

5.2.2.3 Rill and gully erosion

Rills are considered ephemeral features. Those formed after one storm are often
obliterated before the next storm (of sufficient intensity to create rills) occurs
(Morgan, 1986). The processes causing sheet erosion differ from processes that lead
to rill formation. However, the position of rill initiation on the slope may coincide
with critical locations on the slope (Bryan, 1987; Morgan, 1986), where:

• overland flow becomes channeled;
• standing waves occur in the overland flow; or
• the lithological properties of the soil change.

Furthermore, some of the processes cited as possible causes of gully formation (cf.
following paragraph) may also play an important role in rill development.

A gully is defined as a permanent steep-sided eroding watercourse which is subject to
periodic flash floods (Hudson, 1981). Several causes of gully formation are described
in the literature (Morgan, 1986; Beasely, 1972): they may develop from rills, they may
be initiated by removal of the vegetation cover (by deforestation, by grazing, by fire or
by overland flow); they can be initiated by collapsing subsurface pipes and tunnels; or
they can form due to headward erosion in weakly consolidated sediments over
impenetrable layers.

5.2.3 Soil erosion by wind

Wind erosion occurs in many environments, but it is more pronounced and often leads
to its most serious problems in drylands. The normally sparse vegetation cover and
low, erratic rainfall characteristic of dry areas predisposes them to the direct action of
wind. However, the increasing human pressures in the world’s semi-arid and arid
lands has promoted the acceleration of soil erosion by wind. Wind erosion
impoverishes the soil and also buries the soil and crops on surrounding land making
wind erosion more hazardous (Morgan, 1986; Middleton, 1990).

The transport of soil and sand particles by wind takes place in suspension, and by
surface creep and saltation. Suspension describes the movement of fine particles,
usually < 0.2 mm diameter, high in the air and over long distances. Surface creep is
the rolling of coarse grains along the ground surface. Saltation is the process of grain

Morgan (1986) postulated that the main factor in wind erosion is the velocity of the
moving air. Wind speeds are lowest near the ground surface because of the roughness
imparted by soil, stones, vegetation and other obstacles. From a height (Zo) above the
ground surface at which the wind velocity is zero, windspeed increases exponentially
with height. The critical velocities vary with the grain size of the material, being least
for particles of 0.1 to 0.15 mm in diameter and increasing with both increasing and
decreasing grain size (Chepil, 1945). The resistance of the larger particles results
from their size and weight. That of finer particles is due to their cohesiveness and the
protection afforded by surrounding coarser grains (Morgan, 1986). Compared with
water erosion the most detachable particles are smaller in size and the critical
velocities are much larger.
Prediction of wind erosion has been the subject of development since the late 1930s, consequent upon the research carried in the USA after the Dust Bowl of the 1930s. An equation similar to the USLE has been developed for wind erosion (Woodruff and Siddoway, 1965) taking account of soil erodibility (I); wind energy, expressed by a climatic factor (C); surface roughness (K); length of open wind blow (L); and the vegetation cover (V). The equation is:

$$WE = f(I, C, K, L, V)$$

where $WE$ is the annual wind erosion (t ha$^{-1}$), $I$ is expressed in t ha$^{-1}$ y$^{-1}$, $L$ is in m, $V$ is the quantity of vegetative cover expressed as small grain equivalent in kg ha$^{-1}$ and $C$ and $K$ are dimensionless. The equation allows for interactions between the factors. Hence, multiplying the values of the various factors together cannot solve it and the relationships between its factors are complex.

This equation has been used to conduct general assessments of the wind erosion risk in the study area. Nevertheless, the complicated procedure for its calculation on the one hand and the lack of information necessary for the detailed calculation of its factors in the other, have led to the conclusion that a rigorous and quantitative calculation of wind erosion in the study area is irrelevant for this kind of reconnaissance study. Furthermore, the mean monthly wind speed recorded at the meteorological stations (Table 1.1) in the study area never exceeds 4.84 m s$^{-1}$, which is far below the threshold velocity value (10 m s$^{-1}$) in the Wind Erosion Equation. This indicates that the potential of wind erosion is minimal in the study area, though it does not indicate that it does not occur.

Since threshold velocities are determined by the availability of loose particles at the soil surface, this velocity will be increased by the effect of non-erodible elements. Consequently, the removal of wind-stable surfaces such as stone pavements or basalt boulders, which are very common in the study area, reduces the resistance of the soil to wind erosion. Vegetation influences the nature of wind erosion in several ways. The quantity (proportion of ground surface covered) and quality (height, density, and flexibility) of vegetation governs the extent to which a surface is exposed to erosion.
and the degree by which surface roughness is decreased (Middleton, 1990). Chepil and Woodruff (1963) suggest that grass offers one of the most effective protective covers. Vegetation also stabilizes soil structure through its root systems, and vegetative decay adds organic matter to the soil. This implies that the removal of vegetation will increase the risk of wind erosion. Such removal may occur naturally during drought periods and in many instances population growth and overgrazing may also alter and destroy vegetation cover.

In conclusion, it can be postulated that human pressure in the study area, through increasing agricultural and urban use of the lands, can exacerbate these natural processes making wind erosion more hazardous. These kind of practices have a variety of motives such as: clearance of vegetation for agriculture and urbanization; land use systems may change for cropping practices; and land disturbance by ploughing, off-road vehicle use, military operations, construction, or trampling by animals (Middleton, 1990). All these factors exist and affect the resistance of the soil to wind erosion in the study area. Remotely sensed data and GIS technology should be incorporated in an integrated approach for the monitoring of this hazard. In particular, the detection of spatial and temporal land cover variations is now possible by direct imaging of the soil surface and the modelling of these hazards is made possible because of GIS.

5.2.4 Salinization

At the beginning of the research it was thought that the salinity hazard threatened large areas of irrigated lands in the study area. However, after a series of field visits no sites of active salinization were found. This is thought to be the result of various factors that can be summarized as follows:

- The irrigation systems have only been implemented in the study area since the late 1980s. Irrigation in the area, to the east and northeast of Mafraq, started in the late 1960s. It was concentrated in the villages to the west of Hay Huayjah. In the early 1980s it extended east towards the villages of Sabha and Subhyyah, but by the mid-to late 1980s it had reached areas around Umm al-Quttayn and Qassim in the
the east (cf. Chapter 2). By 1985/87 most of the land close to the Syrian border could be bought by Jordanians (these lands belonged to Syrians before the demarcation of the border line in the 1920s). This made the implementation of large irrigated plots feasible by that time.

- The rotational pattern of temporary irrigated agriculture practiced by migrant farmers promotes the clearance and preparation of new lands each year. Hence, irrigation is practiced for one year and then the land is abandoned four to five years before being cropped again. This current system of irrigated agriculture in the study area, whilst removing vegetation and boulders which protect the topsoil, minimizes salt accumulation.

5.3 Modelling soil erosion by water

5.3.1 Introduction

Soil loss is defined as the amount of soil lost in a specified time period over an area of land which has experienced net soil loss. It is expressed in units of mass per unit area, e.g. tonnes ha\(^{-1}\) y\(^{-1}\). Sediment yield is defined as the amount of sediment which leaves a specified area of land in a given time period and is expressed in units of mass per unit area (kg m\(^{-2}\)y\(^{-1}\)). Most fields have some areas that experience net soil loss over time and some areas that experience net deposition over time. The difference between the spatially integrated net soil loss and the spatially integrated net deposition is the sediment yield (Nearing \textit{et al.}, 1994; Wischmeier, 1978).

Because processes in the real world are often very complex, as many factors are involved with multiple interrelationships between variables, models are often used to simplify such complicated systems. Modelling soil erosion is the process of mathematically describing soil particle detachment, transport and deposition on land surfaces. There are at least three reasons for modelling soil erosion processes. First, erosion models can be used as predictive tools for assessing soil loss for conservation planning. Second, process-based mathematical models can predict where and when erosion is occurring, thus helping the conservation planner target efforts to reduce
erosion. Thirdly, models can be used as tools for understanding erosion processes and their interactions (Nearing et al., 1994).

In the modelling literature erosion models have developed from empirical models (e.g. USLE [Wischmeier and Smith, 1978]), towards process-based models (e.g. Eurosem [Quinton and Morgan, 1998] and WEPP [Nearing and Nicks, 1998]). Most of the models used are of empirical grey-box type. They are based on defining the most important factors and, through the use of observation, measurement, experiment and statistical techniques, relating them to soil erosion (Morgan, 1986). The Revised Universal Soil Loss Equation (RUSLE) is the empirical erosion model which has been used most widely for predicting soil erosion in agricultural situations worldwide; its primary focus is to predict average soil loss from fields. Physically-based models are intended to represent the essential mechanisms controlling erosion. This research is only concerned with predictive empirical models, such as the (RUSLE), since they are most useful for practical applications at the reconnaissance level.

The original Universal Soil Loss Equation was developed as a design tool for conservation planning (Wishmeier, 1978; Weischmeier and Smith, 1978). It was designed for areas with inter-rill and rill erosion and does not incorporate a sediment delivery ratio. It was developed to estimate long-term mean annual soil loss from small areas such as hillslopes and fields. It cannot be used to predict erosion from an individual storm. Furthermore, great care has to be taken when selecting factor values, as the selection problem can be a potential source of prediction error if the equation is applied to conditions for which the factor values have not been determined and therefore they need to be estimated by extrapolation (Wischmeier, 1978; Morgan, 1986). The U.S. Department of Agriculture (USDA) in 1985 and 1987 revised the USLE. This revision was aimed at including corrections to the USLE factors and resulted in a new handbook and technology called RUSLE - the Revised USLE – (Renard et al., 1994).

Its focus on areas of inter-rill and rill erosion; the annual time-scale for the predicted soil loss and the relative ease of parameterisation in a spatial context, along with its
reconnaissance-scale, agricultural focus, make the RUSLE the clear choice of a model in this research project.

5.3.2 The Revised Universal Soil Loss Equation (RUSLE)

5.3.2.1 Introduction

The empirical RUSLE model was chosen in this research to assess the impact of soil erosion on the newly converted cropland in the study area. The RUSLE is simple and easy to implement for predicting soil loss from agricultural fields, as well as a conservation tool (Wischmeier and Smith, 1978) to help farmers taking management practices measures to sustain the productivity of their land.

The RUSLE can be expressed as follows:

\[ A = R K L S C P \]

where:

- \( A \) is the computed soil loss per unit area, expressed in the units selected for \( K \) and the period selected for \( R \);
- \( R \) is the rainfall and runoff factor;
- \( K \) is the soil erodibility factor;
- \( L \) is the slope-length factor;
- \( S \) is the slope-steepness factor;
- \( C \) is the cover and management factor; and
- \( P \) is the support practice factor.

The techniques used in this research for the calculation of the factors in the RUSLE will be discussed in Section 6.2.1.

5.3.2.2 Erosivity

The detaching power of raindrops striking the soil surface and the transport capacity of runoff are closely related to soil loss. Rainfall intensity is thought to be the most important rainfall characteristic behind the energy of raindrops and runoff capacity to erode soils (Morgan, 1986). This is expressed as rainfall erosivity. Erosivity indices were developed to determine the part of the rainfall in the erosion process amongst
other variables (e.g. erodibility, topography, vegetation cover). The most suitable expression of the erosivity of rainfall is an index based on the kinetic energy of the rain. Thus the erosivity of a rainstorm is a function of its intensity and duration, and of the mass, diameter and velocity of the raindrops (Morgan, 1986). A suitable index developed for estimating rainfall erosivity is the R-factor developed for the USLE/RUSLE (cf. Section 6.2).

5.3.2.3 Erodibility

The susceptibility of soil to sheet wash, rill and gully formation and surface crusting is referred to as soil erodibility. Erodibility defines the resistance of the soil to both detachment and transport. At a general level, erodibility depends primarily on the structural stability of the soil and on its ability to absorb or store water. Erodibility of the soil varies with changes in soil texture, aggregate stability, shear strength, infiltration capacity, and the organic and chemical contents of the soil (Morgan, 1986). The role of soil texture is complex. Large particles are resistant to transport because of the greater force required to detach them, and then to transport them. Some fine particles are resistant to detachment because of their cohesiveness i.e. they are strongly bonded to form soil aggregates. Aggregate stability depends on organic matter and clay contents as well as the type of clay minerals present, the presence of iron and aluminum oxides, and the moisture condition of the aggregate (Farres, 1978; 1980). The shear strength of a soil is a measure of its cohesiveness and resistance to shearing forces exerted by gravity, flowing water and mechanical pressure. Infiltration capacity, defined as the maximum rate at which soil can absorb water, is influenced by pore size and stability of the topsoil, and the variations in these two properties down the soil profile. As soil properties vary with the profile depth, infiltration capacity changes with depth as well. The properties discussed above also exhibit considerable spatial and temporal variability and, as a consequence, erodibility will vary both spatially and over time.

Several attempts have been made to develop a simple index of soil erodibility. An overview of these indices is given by Morgan (1986). Most of the methods are based on one, or a limited number, of the previously discussed soil properties. One of the
most commonly used erodibility indices is the K-factor developed for the USLE by Wischmeier and Smith (1978). The computation of the K-factor is based on grain-size distribution (texture), organic matter content, soil structure and soil permeability (cf. Section 6.2.1.3).

5.3.2.4 Topography

Topography is an important variable controlling rates of soil erosion by water. Three topographical properties appear to be important with regard to soil erosion by water, they are slope steepness, slope length and slope shape (Morgan, 1986; Hudson, 1981). Erosion normally increases with increasing slope steepness and slope length as a result of a respective increase of velocity and volume of surface runoff.

The RUSLE (Wischmeier and Smith, 1978; Renard et al., 1994) considers all three topographical properties in the LS factor. Slope length, L, accounts for the effects of greater accumulation of runoff with distance down-slope. The slope steepness factor, S, accounts for the increased erosiveness of runoff and ease of sediment movement as slopes steepen. Corrections to LS factor are made based on the convexity or concavity of the slope. Remote sensing seems suitable to provide information on topographical properties. For example, two SPOT images of the same area with different viewing angles together with a suitable software are able to generate a digital elevation model (DEM). However, in areas where SPOT images cover is not available, a DEM of the ground can still be produced from previously digitized topographic maps using GIS technology. Both techniques were used in this study as will be discussed later in Chapter 6.

5.3.2.5 Vegetation cover and land management factors

Vegetation plays a very important role in erosion processes in a number of ways. The effects of a vegetative cover on erosion comprise the following:

- Interception, this accounts for the changes in volume and energy of the rainfall reaching the ground surface as a result of interception of rainfall by the plant cover. Its main effect is to decrease the amount of soil detached.
Evapotranspiration and rooting depth account for the transfer of moisture from the soil to the atmosphere through the plant cover as well as by the increase in pore spaces due to plant root growth. Its effect is a reduction of runoff by maintaining a drier soil and, therefore, greater soil moisture storage capability at the start of each storm event. In addition, the infiltration capacity is increased.

Ground cover accounts for the effect of a vegetation cover in decreasing the transport capacity of the runoff through reduction in flow velocity and the physical control of soil particle movement. Finally, the decomposition of plant material in the soil release organic materials which promote soil aggregation (Stocking, 1994; Morgan, 1986; Hudson, 1981; Wischmeier and Smith, 1978).

It is too time consuming and costly to measure interception, evapotranspiration, rooting depth and soil chemistry separately. Therefore to obtain an understanding of how vegetation reduces soil erosion rates many researchers have used compound indices. In the RUSLE the empirical crop cover factor (C) is used. It is also used in several other erosion models, e.g. the Morgan and Finney method (Morgan, 1986) and WEPP (Nearing and Nicks, 1998). The C factor is defined as the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow. The C factor accounts for the different crop stages during the growing period and for differences in land management practices.

Most estimates of C relate to agricultural crops, and there are few estimates of C for areas of natural or semi-natural vegetation. Information on the spatial variations in ground cover, can be achieved using remote sensing techniques, particularly the technique of linear spectral mixing modelling (LSMM) which can estimate the proportion of the vegetation cover in each pixel. Furthermore, this technique can provide estimates for each agricultural type for which a spectral signature can be defined. The linear spectral mixing model has been used in this study to estimate the vegetation cover proportions from Landsat TM imagery, for both cultivated and rangelands, on a pixel basis as has been shown in Chapter 4.

The USLE/RUSLE’s soil management factor (P) represents how surface conditions affect flow paths and flow hydraulics (Renard et al., 1994). For example, with
contouring, runoff flows around the slope in channels formed by tillage. P has been developed to reflect conservation practices on range and crop lands (Wischmeier, 1978).

5.4 Spatial and temporal variability

The severity of erosion varies in time and space. Regional variations in erosion can be caused by local topographic, soil and land use conditions. In addition, climatic events of different intensities can be used to explain short-term temporal variations in erosion. However, climatic characteristics, especially rainfall amount, rainfall intensity and wind speed vary regionally, whilst land use can change over time in relation to economic incentives and government policies (De Jong, 1994). In addition, long-term temporal variations in erosion may come from fluctuations in climate, such as periods of drought or exceptionally wet years, or from changes in soil properties (e.g. the loss of organic matter) (Morgan, 1986) due to the overexploitation of poor soils. Thus, the interactions of the processes which lead to spatial and temporal variations are complex.

The scale at which any investigation is conducted must also be considered. Scale influences the number of factors which need to be incorporated in the model. At macro-scale (e.g. 1:1,000,000) climate is considered as a very important factor (Morgan, 1986; FAO, 1979). However, at a micro-scale (e.g. < 1:50,000) climate can be considered as uniform for the entire study area whilst variations of soil, lithology and vegetation properties become more important.

The spatial variability of factors controlling land degradation processes is indeed very important. For example, existing choropleth maps of soils and vegetation are often used to derive specific input parameters such as the texture and vegetation cover densities necessary for erosion modelling studies. However, three major problems may arise. First, choropleth maps are by definition not accurate because they involve generalization (Trotter, 1991). Secondly, the mapping units (polygons) are considered as homogeneous areas ignoring the variance within these polygons, which is not the case. In fact, it is well known that the variance inside these polygons is generally very
large (Burrough, 1986). Thirdly, polygons imply sharp boundaries between the polygons where in reality most boundaries of natural phenomena are gradational. The quality of the information contained in these thematic maps is of great importance if the outcome of the model is to be assessed as accurate.

Monitoring and modelling of erosion processes at a regional scale requires the assessment of the spatial distribution of the critical soil parameters or at least an assessment of the spatial distribution of soil types which are associated with these soil properties. The use of remote sensing and GIS to contribute to degradation monitoring and modelling depends on their ability to handle this information in an integrated environment.

5.5 Summary

It is generally agreed that soils of the arid and semi-arid areas are prone to degradation. Water erosion is by far the most threatening form of degradation in arid and semi-arid lands because the soils are shallow, weakly developed and, in general, they have minimal protection against raindrop impacts due to the low vegetation cover. Increasing population pressure on the land available, in addition to the changes in climate conditions, can aggravate the degradation of the already fragile soils. The result is an increase in the vigor of degradation processes to such a degree that natural processes alone cannot redress the situation without corrective measures from societies.

Monitoring and modelling land degradation is a prerequisite for assessing the extent of the problem, to obtain quantitative information on degradation, and to predict future levels of degradation and to implement conservation measures. The complexity of the degradation problem needs a multi-disciplinary modelling approach.

Remote sensing is a promising technique for the capture of data concerning many of the controlling variables of the degradation processes. In particular, the spatial and temporal variability of natural features are best monitored through remote sensing techniques. However, remote sensing alone is not able to offer information about all
the controlling variables. Hence other data sources are necessary, whether field data or from the laboratory.

All the data required for modelling land degradation need to be utilized in an integrated environment. GIS not only satisfies the above condition, but at the same time it is able to use many hypothetical scenarios to run processes and predict various possible results to feed back decision makers before implementing policies.

Crusting occurs throughout the study area. The FAO crusting index was calculated. Little spatial variation in crusting between the soil units in the study area was found.

It has been shown that wind erosion is not a serious problem in the study area. This is because the threshold velocities are generally very low, and boulder and surface crusting usually provides adequate protection of the topsoil. However, human activities can loosen the soil particles providing more material to be detached by the wind, and remove the protective stone cover thereby accelerating rates of wind erosion.

Salinization is not a threat in the present time because irrigation has only recently been practiced in the study area, and the migratory nature of irrigated agriculture in the area means that same piece of land is not being irrigated every year. However, it could become an important hazard in the future.

The main focus of this chapter is on modelling water soil erosion, as it is the most important form of land degradation occurring in the study area. In particular, inter-rill and rill erosion are commonly found on agricultural fields in the study area. The RUSLE was chosen as the soil erosion model because of its applicability to agricultural situations dominated by inter-rill and rill erosion, its focus on annual soil losses, and the ease with which it can be parameterized. The methods used to parameterise the RUSLE and its application will be examined in Chapter 6.
This chapter is an introduction to the following chapter. It explains and clarifies the theoretical background of the degradation problem in the area. Chapter 6 will show how the water erosion model was built in a GIS environment.
CHAPTER 6: GIS-BASED MODELLING OF SOIL LOSS

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6.2 Modelling soil loss: Integrating GIS and remotely sensed data

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CHAPTER 6: GIS-BASED MODELLING OF SOIL LOSS

6.1 Introduction

Land degradation processes in drylands were reviewed in Chapter 5 and the Revised Universal Soil Loss Equation was introduced. Particular emphasis was placed on water erosion of soils on the grounds that this form of degradation prevails in arid and semi-arid lands in general, and in the study area in particular. The Revised Universal Soil Loss Equation (RUSLE) was chosen as the model to be used in this research. It is a parametric model of the grey-box type, i.e. it is constructed on the basis of statistical correlations between parameters known to influence soil erosion processes and rates of soil loss. It was chosen because:

- it is widely used in agricultural situations (both cultivated areas and rangeland) throughout the world;
- the parameters required are relatively straightforward to conceptualise and are easily available (and, if not obtainable, the volume of conducted research on the USLE has meant that alternative parameters have been developed);
- it has been continually updated since its introduction in the 1970s;
- it has been specifically adapted for drylands; and
- it lends itself to reconnaissance-level soil loss assessment.

However, the model has its limitations (cf. Section 5.3) and it can be argued that the factors used in the equation are more ‘universal’ than the equation itself.

In this research each of the factors in the RUSLE (erosivity, erodibility, topography, vegetation/cropping and management practices) was calculated separately and stored as a raster layer in the GIS. They were then combined in the GIS-based model to calculate the soil loss for each cell in the study area for 1972, 1985 and 1992. The specific issues addressed in calculating these factors are discussed in Section (6.2.1). The GIS model is raster-based and was built using Model Maker in ERDAS Imagine Version 8.3.1. This was found to be very practical for modelling soil losses because of its simplicity and its ability in handling both vector and raster layers. The predicted soil losses were checked against field observations made at the end of the 1998/99 wet season (Section 6.3). An evaluation of the accuracy and limitations of the model will
be presented in Section 6.4. The emphasis will be on the quality of the input data as well as the accuracy of the output data. This will enable the most important sources of errors and uncertainties to be highlighted.

6.2 Modelling soil losses: Integrating GIS and remotely sensed data

6.2.1 Calculation of the RUSLE factors

6.2.1.1 Rainfall erosivity factor (R)

The rainfall erosivity factor, the R factor in the RUSLE, is the product of the kinetic energy of a particular storm and the maximum 30-minute storm depth ($I_{30}$) of that storm summed for all the storms in a year. As none of the three rainfall stations in the study area records rainfall intensity, it was impossible to calculate the R factor using this method. Thus an alternative approach had to be adopted.

Arnoldus (1977) found that the Fournier index was an adequate substitute for the USLE R factor in dryland situations where too few data exist to calculate the rainfall erosivity factor using the method outlined above. Fournier’s index, $p^2/P$, uses only average monthly ($p$) and annual precipitation ($P$). Arnoldus conducted his experiments in Morocco using monthly rainfall data for 112 stations. He found a very high, significant correlation between $p^2/P$ and the R factor values calculated using Wischmeier’s method. The relationship (in metric units) was:

$$ R = 1.735 \times 10^{1.50 \log \sum p^2/P - 0.8188} \quad (6.1) $$

summed for each of the 12 months of each year.

The model, which was developed for Morocco, can be applied to the area under investigation in the *badia* region because it is a semi-arid environment characterised by the same type of precipitation processes and events as Morocco. Although this assumption is probably reasonable, it should be noted that the total annual mean
rainfall is slightly higher in some of the areas of Morocco studied by Arnoldus than the study area in Jordan.

The values of $\frac{\sum p^3}{P}$ for the three stations in the study area are given in Table 6.1. The estimated R factor values for the three stations were calculated using formula (6.1) and are also presented in Table 6.1.

<table>
<thead>
<tr>
<th>Station</th>
<th>$(\sum p^3/P)$</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umm al-Quttayn</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>Dayr al-Kahf</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>al-Aritayn</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 6.1: Values of Fournier’s index and R factor for the three stations in the study area.

Fig. 6.1: The rainfall erosivity in the study area. The R factor varies from 23 (the darkest grey area in the north-west) to 17 (the lightest grey area in the south-east). Each grey tone represents one increment of the R factor. Areas outside the BRDP that were not considered during modelling are in black. The area is approximately 28 by 18 km, and the 1992 BRDP road network is overlain for location purposes.
The study area was sub-divided by drawing parallel isolines between the three stations, resulting in six homogeneous zones. This formed the rainfall erosivity layer in the GIS (Fig. 6.1), with each zone being assigned an R factor value ranging from 17 to 23. This layer was generated using ERDAS Imagine software by first creating an annotation polygon layer, which was then converted to a raster layer with a pixel resolution of 30 m to make it compatible with the spatial resolution of TM data.

6.2.1.2 Soil erodibility factor (K)

The K factor defines the resistance of the soil to both detachment and transport. The properties of the soil are the most important determinants of its erodibility, although other factors play a role in determining the soil resistance to erosion such as topographic position, slope steepness and the amount of disturbance created by human activities (Morgan, 1986). The spatial variation of the K factor was determined using the soil units maps produced by the Ministry of Agriculture (National Soil Map and Land Use Project, 1994). The soil survey project, which was completed in 1994 by the Ministry of Agriculture, produced 1:250,000 soil maps with profile descriptions and ancillary information for all of Jordan. The maps and their legends were the only consistent source of data available. They were digitized and a thematic layer representing soil units was produced in ARC/INFO. This was exported to ERDAS Imagine to be used in the soil loss model after assigning a K value to each polygon to represent the erodibility of each soil unit. The soil erodibility nomograph (Wischmeier, 1978), (Appendix C) was used to determine the K-values (Table 6.2)

<table>
<thead>
<tr>
<th>Soil Unit</th>
<th>K-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIS(Bishriya)</td>
<td>0.35</td>
</tr>
<tr>
<td>FAR(Mafarid)</td>
<td>0.34</td>
</tr>
<tr>
<td>SAB(Sabha)</td>
<td>0.31</td>
</tr>
<tr>
<td>THA(Ramtha)</td>
<td>0.32</td>
</tr>
<tr>
<td>WAY(Huwaylat)</td>
<td>0.39</td>
</tr>
<tr>
<td>ZUM(Zumaylat)</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table 6.2: The K factor values for soil units in the study area.
using average data on soil texture, organic matter and permeability for the different soil mapping units. These data have been provided in Table 1.4.

It can be seen from Table 6.2 that the range of the K factor values is low. This indicates that the spatial variability in erodibility across the study area is also low. Therefore, it can be concluded that the spatial variability of water erosion will depend less on soil properties and more on the pressures exerted on these soils by external agents, e.g. disturbances created by human activities. Each of the soil unit polygons was assigned its corresponding K value. A raster GIS soil erodibility layer was prepared from these data, thereby adding the second input layer to the erosion model - the K layer (Fig. 6.2).

6.2.1.3 Topographic factor (LS)

Soil losses would normally be expected to increase with increasing slope steepness and increasing slope length, because of the resulting increases in the velocity and the volume of surface runoff. Furthermore, on sloping ground more soil is splashed down-slope than up-slope: the proportion increasing as the slope angle increases. Therefore, determination of the slope length and gradient occupies an important position in any soil loss prediction model. Digital elevation models provide an excellent data source to calculate these parameters in a GIS and to analyse their spatial variability.

The first approach used in this research was to create slope layer generated from an existing DEM that had been generated from SPOT stereogrammetric imagery produced for the BRDP by the University of Glasgow. However, this approach proved unsuccessful because the SPOT images used for the creation of the DEM only partially covered the BRDP area and, in particular, the area around Umm al-Quttayn was missing. The second approach used was to generate a DEM for the study area (of this research project) from existing topographic maps. Four 1:50,000 topographic map sheets produced by the RJGC were digitized, processed and appended using ARC/INFO software (Table 6.3). The study area was then clipped from the maps and
Fig. 6.2: Soil erodibility layer for the study area. The codes for the soil units relate to those in Section 1.5. The K factor varies from 0.31 (darkest grey polygons) to 0.40 (lightest grey polygons). Areas not considered during modelling are in black. The area is approximately 30 by 20 km, and the 1992 BRDP road network is overlain for location purposes.

A DEM was generated using TIN and GRID Modules. The resulting layer was exported as an .e00 file, and imported in ERDAS Imagine to generate a slope layer using the Topographic Analysis/Slope function (ERDAS Field Guide, 1994). The slope image produced at this stage was a raster continuous layer giving slopes angles as percentage values. For reasons of simplicity and practicability, it was deemed necessary to classify this continuous image to produce a thematic layer with defined nominal values. Hence, the slope image was classified into six classes using Model Maker and a conditional function, producing a thematic slope layer map (Fig. 6.3) with the following class values:
0% \leq \text{class 1} \leq 3%
3.1% < \text{class 2} \leq 6%
6.1% < \text{class 3} \leq 10%
10.1% < \text{class 4} \leq 15%
15.1% < \text{class 5} \leq 25%
class 6 > 25.1%

<table>
<thead>
<tr>
<th>Name</th>
<th>Source</th>
<th>Serial Number</th>
<th>Date of survey</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umm al-Quttayn</td>
<td>RJGC</td>
<td>NI 37A 2c</td>
<td>1989</td>
<td>1:50,000</td>
</tr>
<tr>
<td>Dayr al-Kahf</td>
<td>RJGC</td>
<td>NI 37A 2d</td>
<td>1989</td>
<td>1:50,000</td>
</tr>
<tr>
<td>al-Bishriya</td>
<td>RJGC</td>
<td>NI 37A 2b</td>
<td>1989</td>
<td>1:50,000</td>
</tr>
<tr>
<td>al-Hamidiya</td>
<td>RJGC</td>
<td>NI 37A 2a</td>
<td>1989</td>
<td>1:50,000</td>
</tr>
</tbody>
</table>

Table 6.3: The topographic maps used in the creation of the DEM.

The slope angle thematic layer (Fig. 6.3) was used to calculate the slope length. This was done by combining the slope angle thematic layer with a hydrological layer (Fig. 6.4) containing the wadi network for the study area. The wadi network was produced by digitizing existing 1:50,000 topographic maps. The calculation of slope lengths was carried out as follows:

- the hydrological layer was used with the slope angle layer to help identify the length of the slopes;
- a grid of 1x 1 km cells was generated and overlaid on the combined slope angle and hydrological layer;
- measurements of L were made in 77 randomly distributed 1 x 1 km cells;
- these measurements were used with the slope angles from the same cells to estimate LS values for each class present in the cell.

The LS factor was calculated using the tables produced by Renard et al. (1994) for the RUSLE (Appendices D-I and D-II) in conjunction with the thematic slope layer. One table (Table 5.2, Renard et al. 1994) was used for estimating LS for rangeland
situations, and another table (Table 5.3, Renard et al. 1994) was used for estimating LS for cultivated areas. The results of these operations are presented in Table 6.4.

Fig. 6.3: Slope angle thematic layer classified into six classes. The black areas are outside the study area and were not considered during the modelling. The slope classes are as follows: light yellow 0-3%, dark yellow 3.1-6%, purple 6.1-10%, dark blue 10.1-15%, turquoise 15.1-25%, green >25.1%. The area is approximately 30 by 20 km, and the 1992 BRDP road network is overlain for location purposes.
Fig. 6.4: Slope thematic layer with hydrological network. The classes are the same as in Figure 6.3. The wadi network (blue) is used as a background. Areas not considered during modelling are in black. The area is approximately 30 by 20 km, and the 1992 BRDP road network is overlain for location purposes.

<table>
<thead>
<tr>
<th>Slope class (%)</th>
<th>0-3</th>
<th>3.1-6</th>
<th>6.1-10</th>
<th>10.1-15</th>
<th>15.1-25</th>
<th>&gt;25.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean L (m)</td>
<td>177.16</td>
<td>71.62</td>
<td>50.01</td>
<td>51.67</td>
<td>56.75</td>
<td>59.03</td>
</tr>
<tr>
<td>Mean LS, rangeland</td>
<td>0.29</td>
<td>0.78</td>
<td>1.28</td>
<td>2.39</td>
<td>4.39</td>
<td>10.00</td>
</tr>
<tr>
<td>Mean LS, cropland</td>
<td>0.37</td>
<td>0.93</td>
<td>1.48</td>
<td>2.69</td>
<td>5.04</td>
<td>11.86</td>
</tr>
</tbody>
</table>

Table 6.4: The estimation of LS values for each class present in the study area, for each type of land use.

The distinction had to be made between rangeland and cultivated areas (cropland) because of the distinction between the ways in which LS values are calculated in the RUSLE. As a result, LS values are presented as two separate layers in the GIS-based soil loss model - one for rangeland and another for cropland – and the model had to be run separately for rangeland situations and cultivated areas.
6.2.1.4 Vegetation/Cropping and management practices factors (C and P)

The vegetation/cropping – C – factor was parameterized from remotely sensed data. The fractional vegetation cover map for the 1992 TM imagery produced by linear spectral unmixing (Section 4.3) was used to estimate the values of C for rangelands and croplands in the 1992 dry season. Calibrated NDVI images were used to estimate C from similar areas in 1972 and 1985 (Section 4.4). A geographical distinction had to be made between cropland and rangeland when calculating and mapping the C factor from these three images because, like the LS factor, the C factor is calculated separately for rangeland and cultivated land in the RUSLE.

In the context of soil loss modelling, rangelands in the study area were defined as those areas that have been cleared of basalt boulders and are used only for grazing. There are three potential difficulties with this assumption:

1. Some grazing takes place on the basalt-covered areas. However, this will have a negligible effect on the overall soil loss, because vegetation cover is very low on these surfaces and good surface protection is afforded by the basalt boulders.

2. Some of the areas cleared of basalt are used for grazing, whilst others are areas of temporary irrigated cultivation (cf. Chapter 2). However, this only applies to the 1992 image as irrigated cultivation had not reached the study area in either 1972 or 1985.

3. There is an overlap between areas of grazing and rain-fed cultivation (cf. Chapter 2). This is potentially more serious as it would have been the case in all three years for which soil loss was modelled.

Raster images of the rangeland areas were created by masking out areas of basalt (lava flows), built-up areas and cropland (cultivated areas) from the images. To do this basalt lava flows and built-up areas were digitized on the screen (using the same technique described in Chapter 3 for the delineation of bare fields). The cropland areas were masked out using the cropland raster layer described below.
Cultivated areas were digitized on-screen for all three dry season images. No irrigated, vegetated fields in the area that is now in the BRDP could be identified on the MSS images acquired in the 1972 and 1985 dry seasons. However, interviews with local farmers (cf. Chapter 2) confirmed that there were rain-fed cereals close to the Syrian border in 1972 and 1985, and that these had been there since the time of the early settlements in the region (i.e. in early 1960s). As a consequence, maps of rain-fed bare field areas were created by digitizing around rain-fed bare fields evident in the images from the dry seasons of 1972, 1985 and 1992. Maps of irrigated, vegetated fields for the dry season of 1992 were also created by digitizing on-screen (cf. Section 3.4). These two maps, combined, are the cropland area maps for 1972, 1985 and 1992 (Fig. 6.5).

Thematic layers, each representing the C values for either cropland and rangeland, were generated as follows for 1992:

1. The vegetation fraction image (cf. Section 4.3) was classified using conditional functions in Model Maker. The result is a thematic layer representing the vegetation proportion classes. These classes are defined as follows: $80.1\% < \text{class 1} \leq 100\%$; $60.1\% < \text{class 2} \leq 80\%$; $40.1\% < \text{class 3} \leq 60\%$; $20.1\% < \text{class 4} \leq 40\%$ and class 5 $\leq 20\%$

2. The areas of irrigated fields, rain-fed fields and rangeland (see above) were individually intersected with classified fractional vegetation cover map to produce maps of vegetation cover percentages classes in each of the three types of cultivation.

3. The vegetation cover classes were ranked in inverse order. This is because land cover is a protective layer against erosion. The C factor is therefore higher when the vegetation cover percentage is low, i.e. the C value for class 5 is higher than C value for class 4.
Fig. 6.5: Spatial distribution of bare (rain-fed) and vegetated (irrigated) fields in the study area for the 1972, 1985 and 1992. Areas of rain-fed cultivation are shown in grey and irrigated fields are in black. The 1992 road network is included on all three maps for locational purposes. The area of each map is approximately 30 by 20 km.
4. C values were estimated using the tables produced by Wischmeier (1978) (Appendices E-I and E-II). In these estimations three cultivation systems (rain-fed fields, irrigated fields and rangeland) were considered. It was considered that the residual plant remains (stubble) would be very low for rain-fed fields due to low yields and stubble grazing. At 30% cover of mulch the estimated C value is 0.4. For the irrigated fields and rangeland the C values are presented in Table 6.5.

<table>
<thead>
<tr>
<th>Type of land use</th>
<th>≤ 20%</th>
<th>≤ 40%</th>
<th>≤ 60%</th>
<th>≤ 80%</th>
<th>≤ 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigated fields</td>
<td>0.48</td>
<td>0.37</td>
<td>0.22</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>Rangeland</td>
<td>0.35</td>
<td>0.20</td>
<td>0.12</td>
<td>0.062</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Table 6.5: Estimation of C values for vegetated fields and rangelands by vegetation cover percentage classes.

The next step was to estimate C values for the land cover types present in the BRDP area on the 1972 and 1985 imagery, namely rangeland and rain-fed fields. The MSS-NDVI values were calculated from these image data (cf. Section 4.4) and the corresponding vegetation cover percentages were determined using published relationships between NDVI and vegetation cover proportions derived for the study area (Edwards et al., 1996).

A close inspection of the NDVI statistics (cf. section 4.4.3) revealed that for both dry season 1972 and 1985 the NDVI values never exceeded 0.087. According to the calibration data, this indicates that the vegetation cover percentages never exceeded 20% (Edwards et al. 1996). Moreover, as 20% is the lowest threshold value for the estimation of C, a constant value for C (= 0.35) was applied to the rangelands and bare fields in the 1985 and 1972 images, and this value was used in the soil loss model (Wischmeier 1978, Table 10, Appendices E-I and E-II).

The management factor (P factor) was assigned a value of one for the entire study area as no specific management measures are used for either rangelands or croplands in the study area (Appendix E-III).
6.2.2 Maps of soil losses

The GIS-based input layers discussed are listed in Table 6.6. They were combined, as described by the RUSLE, to estimate annual soil losses on a pixel-by-pixel basis. A low pass (7 × 7 Kernel) filter was applied to all input layers before running the model. This eliminated anomalies resulting from digitizing and/or masking operations. The model was built in ERDAS Imagine/Model Maker.

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rainfall erosivity layer (R).</td>
</tr>
<tr>
<td>2</td>
<td>Soil erodibility layer (K).</td>
</tr>
<tr>
<td>3</td>
<td>Topographic layer (LS_C) for cropland.</td>
</tr>
<tr>
<td>4</td>
<td>Topographic layer (LS_R) for rangeland.</td>
</tr>
<tr>
<td>5</td>
<td>Vegetation cover layer (C_92) for bare fields, for 1992.</td>
</tr>
<tr>
<td>6</td>
<td>Vegetation cover layer (C_92) for vegetated fields, for 1992.</td>
</tr>
<tr>
<td>7</td>
<td>Vegetation cover layer (C_92) for rangeland, for 1992.</td>
</tr>
<tr>
<td>8</td>
<td>Vegetation cover layer (C_85) for bare fields and rangeland, for 1985.</td>
</tr>
<tr>
<td>9</td>
<td>Vegetation cover layer (C_72) for bare fields and rangeland, for 1972.</td>
</tr>
</tbody>
</table>

Table 6.6: Thematic input layers to the GIS-based erosion model.

Change in vegetation cover proportions consequent upon land use change is the key dynamic variable in predicting soil losses over time in the study area. It was assumed that all other variables were constant over the 20 year time period of the study. To capture this change, the soil loss model was run separately for all three years (1972, 1985 and 1992). These runs were based on the following combinations of GIS layers (layers refer to Table 6.6):

Soil loss maps for 1972:

layer 1 × layer 2 × layer 3 × layer 9  
layer 1 × layer 2 × layer 4 × layer 9
Soil loss map for 1985:
layer 1 × layer 2 × layer 3 × layer 8
layer 1 × layer 2 × layer 4 × layer 8
Soil loss map for 1992:
layer 1 × layer 2 × layer 3 × layer 5
layer 1 × layer 2 × layer 3 × layer 6
layer 1 × layer 2 × layer 4 × layer 7

In each combination the layers were combined using the mathematical equation described by the RUSLE. The results of the model runs, as soil loss maps for each of the three years are shown in Figs. 6.6, 6.7 and 6.8. These maps were classified using Model Maker, using 11 soil loss classes (Table 6.7).

<table>
<thead>
<tr>
<th>Class</th>
<th>Mean annual Soil loss (tonnes ha^{-1} a^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>2</td>
<td>1.1 - 2</td>
</tr>
<tr>
<td>3</td>
<td>2.1 - 3</td>
</tr>
<tr>
<td>4</td>
<td>3.1 - 4</td>
</tr>
<tr>
<td>5</td>
<td>4.1 - 5</td>
</tr>
<tr>
<td>6</td>
<td>5.1 - 6</td>
</tr>
<tr>
<td>7</td>
<td>6.1 - 7</td>
</tr>
<tr>
<td>8</td>
<td>7.1 - 8</td>
</tr>
<tr>
<td>9</td>
<td>8.1 - 9</td>
</tr>
<tr>
<td>10</td>
<td>9.1 - 10</td>
</tr>
<tr>
<td>11</td>
<td>&gt;10.1</td>
</tr>
</tbody>
</table>

Table 6.7: Soil loss classes.
Fig. 6.6: (a) Predicted soil losses from rain-fed fields for 1972. Black areas are masked out areas of basalt, built-up areas and rangeland areas (b) Predicted soil losses from rangeland for the same year. Black areas are masked out built-up, basalt and cultivated areas.
Fig. 6.7: (a) Predicted soil losses from rain-fed fields for 1985. Black areas are masked out areas of basalt, built-up areas and rangeland areas (b) Predicted soil losses from rangeland for the same year. Black areas are masked out built-up, basalt and cultivated areas.
The expansion of rain-fed cultivation has progressively brought more land into cultivation (Fig. 6.5, 6.6a, 6.7a and 6.8a). Between 1972 and 1985 the majority of this land was in the north of the study area it mainly comprised fields with <1.0 t ha\(^{-1}\) a\(^{-1}\) soil loss, except for some fields around Dayr al-Khaf where the predicted soil losses were in the 2.1-3.0 t ha\(^{-1}\) a\(^{-1}\) range. These higher values are mainly a function of the combination of the high topographic (LS) factor to the south-west of Dayr al-Khaf (Fig. 6.4) and the high soil erodibility (K=0.40) of the Zumaylat (ZUM) soil mapping unit. The northward expansion of the rain-fed fields towards the Syrian border
dominated by the Sabha (SAB) soil mapping unit which has the lowest K factor (K=0.31) of all the units in the study area. The westerly expansion toward Umm al-Quttayn resulted in many fields in the <1 t ha\(^{-1}\) a\(^{-1}\) soil loss class. These fields are mainly in the Sabha soil mapping unit and the plains in this area leads to low LS factors. The south-westerly expansion in cultivation mainly leads to fields with soil losses between 1.1 and 2.0 t ha\(^{-1}\) a\(^{-1}\). These are also plains (with low LS factors) and appears the reason that the soil losses in the fields here are higher than those to the north-west is because they occur in the Huwaylat (WAY) soil mapping unit, which has a K factor of 0.39.

The advent of irrigated agriculture in the study area after 1985 had little impact upon the overall soil loss as would be expected. The majority of these fields are located on very gentle slopes and the soil losses are low. In most areas they do not exceed 1.0 t ha\(^{-1}\) a\(^{-1}\). This is because the LS factors are low for these fields, and the C factor is low (i.e. vegetation cover is high). The combination of these two factors, negates any variations in the K factor.

The largest areas contributing to the overall soil loss in all three years are the areas that were defined as rangelands. In all three years the majority of the rangelands contributed only small amounts to the overall soil loss on a unit area basis. The dominant erosion class on rangelands was < 1.0 t ha\(^{-1}\) a\(^{-1}\) soil loss. However, areas with soil losses exceeding 6.1 t ha\(^{-1}\) a\(^{-1}\) were found around to the west and north-west of Dayr al-Khaf and to the west of Umm Husayn in all three years. These are hilly areas with very high LS factor values. In addition the area to the west and north-west of Dayr al-Khaf occurs in the Zumaylat soil mapping unit which has a K factor of 0.4, and the area to the west of Umm Husayn occurs in the Huwaylat (WAY) soil mapping unit which has a K factor of 0.39. Rangelands with intermediate levels of soil loss were mainly found in the north of the study area, and in the south-west of the study area in all three years. Almost all of these area are found in the Zumaylat and Huwaylat soil mapping units wherever there is hilly terrain. A visual analysis of the maps (Fig. 6.6-6.8) indicates that the expansion of rain-fed cultivated areas between 1985 and 1992 has mainly been in the areas with medium to high rates of soil loss. From this analysis it is clear that the RUSLE factors which have the main influence on predicted soil loss are the topographic and soil erodibility factors.

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Huwaylat soil mapping units wherever there is hilly terrain. A visual analysis of the maps (Fig. 6.6-6.8) indicates that the expansion of rain-fed cultivated areas between 1985 and 1992 has mainly been in the areas with medium to high rates of soil loss. From this analysis it is clear that the RUSLE factors which have the main influence on predicted soil loss are the topographic and soil erodibility factors.

Table 6.8 provides a tabular analysis of the contribution of different soil loss classes (as defined in Table 6.7). There has been a 4.2% increase in overall soil loss from the study area from 1972 and 1992. There is some evidence that the rates of overall soil loss is accelerating: the increase from 1972 to 1985 was 1.0% and from 1985 to 1992 it was 3.2%. All classes have experienced an increase in soil loss from 1972 to 1992 with the exception of the 5.1-6 t ha\(^{-1}\) a\(^{-1}\) and 9.1-10 t ha\(^{-1}\) a\(^{-1}\) soil loss classes both of which showed a decline in soil loss over this time period. The largest increase was in 7.1-8.0 t ha\(^{-1}\) a\(^{-1}\) class (373.2% increase). However, this is thought to be due to errors in the masking out of volcanic tuffs and basalts. The increases from no soil loss in 1972 to relatively high amounts in the 4.1-5.0 and 8.1-9.0 t ha\(^{-1}\) a\(^{-1}\) classes is also

<table>
<thead>
<tr>
<th>Soil loss class (for values see Table 6.7)</th>
<th>Total soil loss (tones) per soil loss class for the study area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1972</td>
</tr>
<tr>
<td>Class 1</td>
<td>15623</td>
</tr>
<tr>
<td>Class 2</td>
<td>6942</td>
</tr>
<tr>
<td>Class 3</td>
<td>9974</td>
</tr>
<tr>
<td>Class 4</td>
<td>5320</td>
</tr>
<tr>
<td>Class 5</td>
<td>0</td>
</tr>
<tr>
<td>Class 6</td>
<td>1263</td>
</tr>
<tr>
<td>Class 7</td>
<td>1633</td>
</tr>
<tr>
<td>Class 8</td>
<td>26</td>
</tr>
<tr>
<td>Class 9</td>
<td>0</td>
</tr>
<tr>
<td>Class 10</td>
<td>231</td>
</tr>
<tr>
<td>Class 11</td>
<td>1471</td>
</tr>
<tr>
<td>Total annual loss</td>
<td>42483</td>
</tr>
</tbody>
</table>

Table 6.8: Total soil loss (in tones) and soil losses from each class in the study area for 1972, 1985 and 1992.
thought to be due to errors in masking. Many of the other classes show moderate increases in soil losses: a 11.6% increase in the soil loss from the 1.1-2.0 t ha\(^{-1}\) a\(^{-1}\) class; a 15.4% increase in the soil loss from the 2.1-3.0 t ha\(^{-1}\) a\(^{-1}\) class; and a 15.1% increase in the soil loss from the 6.1-7.0 t ha\(^{-1}\) a\(^{-1}\) class. The two classes with the lowest increases in soil loss between 1972 and 1992 are the 1.4% increase in the soil loss from the <1.0 t ha\(^{-1}\) a\(^{-1}\) class and a 3.2% increase in the soil loss from the 3.1-4.0 t ha\(^{-1}\) a\(^{-1}\) class.

6.3 Verification of the soil loss maps

6.3.1. The verification data set

It was not possible to validate the predicted soil loss maps for 1972, 1985 and 1992 in the years for which the data was acquired. However, an attempt to verify the soil loss model was made by comparing the soil loss predictions for 1992 with evidence of soil loss from 47 rain-fed fields (Appendix G) at the end of the 1998/1999 wet season. The presence or absence of visual evidence of soil erosion in these fields was used to determine whether erosion had occurred or not during the preceding wet season. This could not be done for rangelands because of the very high levels of ground disturbance by sheep and goats in the latter part of each wet season and, in the case of features such as rills it would not be clear whether they were created in a previous wet season. In addition, verification was not carried out on irrigated fields because they are abandoned after cropping (cf. Chapter 2) and disturbed by crop harvesting and grazing early in the wet season.

The collection of the field evidence for model verification took place at the end of the wet season, in April 1999. This time was chosen because the cumulative effects of erosion during the wet season would clearly be evident on rain-fed fields at this time as normally they will not have been disturbed by either harvesting or grazing in April. Moreover, only fields cultivated during the preceding wet season were chosen as ploughing at the end of dry season and early wet season would have destroyed evidence of crusting, inter-rill erosion and rilling from previous years. However, the 1998/99 wet season was the driest on record in the study area (i.e. in the instrumental period in northern Jordan, which goes back to 1963). According to the meteorological
data obtained from the Water Authority of the government of Jordan, the rainfall totals for the wet season were only 16 mm, 13.5 mm and 16 mm for Umm al-Quttayn, Dayr al-Kahf and al-Aritayn respectively. These figures can be compared to the mean annual rainfall for these three stations, which are 153, 114 and 92 mm respectively (cf. Chapter 1). However, the lack of rainfall in 1998/99 does give verification using field data an advantage. With such low rainfall totals, it might be expected that the rates of soil loss would be low and therefore any evidence of erosion on the fields will indicate the field most susceptible to soil erosion. The erosion evidence gathered from the 46 fields surveyed will therefore constitute a ‘minimum set’ related to low rates of soil loss. This then provides rigorous conditions for verification. However, because of the low rainfall amounts the cereal harvest failed entirely in the 1998/99 season. In many fields there was no vegetation in April, and in those with a cereal crop it was stunted and very patchy. There are two consequences of this for the verification work. First, failed crops are grazed rather than harvested (cf. Chapter 2) and in a few fields there was evidence that they had been grazed already. These fields were not sampled as the grazing animals would have disturbed the soil surface thereby destroying evidence of erosion. Furthermore, the sparse vegetation cover (Plate 6.1) means that the soils would have been less protected against raindrop impact than they would be in a wet year and, as a consequence, rates of inter-rill and rill erosion may have been higher than normal. A further assumption that was made during the verification exercise was that the fields sampled in 1998/99 correspond to fields in 1992. This is probably a reasonable assumption, because field patterns in most areas of northern Jordan are static once land is brought into cultivation because of the stone walls that are built around fields. In addition, cropping patterns have been constant in the area since settlement (cf. Chapter 2) and the slope angles and length are unlikely to have changed over a seven year period. As far as was possible the fields that were chosen were in cultivated areas in 1992, and this was verified by talking to farmers wherever possible. However, one of the parameters that was measured – the direction of ploughing – could easily have varied from 1992 to 1998/99.
Plate 6.1: A barley field at the end of the 1998/99 growing season. Note the stunted growth and the sparse, patchy cover. Many fields surveyed in April 1999 had a sparser cover than this field.

The method proposed by the FAO (1979) for the identification of soil erosion using post-erosion evidence was adopted. This method uses simple visual criteria. As this research was very much in the reconnaissance mode, a qualitative approach, such as the FAO (1979) method, was deemed appropriate to this research. Besides which, as there are not erosion plot data for the area, quantitative soil loss data for the area could not be used. Qualitative methods have the merit of achieving validation quickly and easily. The following visual evidence was looked for in the fields surveyed:

- **Rills.** When they were encountered, their maximum depth and width were measured, and their spatial relationship to fields above and below that being surveyed were noted. It was noted that rills often emanated from plough furrows when two or more furrows combined (Plate 6.2), though in some cases rills were initiated where flows depths enable detachment as well as transportation to take place (Plate 6.3).

- **Erosion pedestals beneath stones.** These were very rare, only one was noted in all of the fields surveyed.

- **Sedimentation** of soil on gentle slopes and in field bottoms (Plate 6.4).

- **Deposits of silt and debris** in rills and along ploughed furrows (Plate 6.5).

- The presence of **surface sealing/crusting**.
Plate 6.2: Rills formation by the coalescence of two plough furrows.

Plate 6.3: Rill initiation in the lower portion of a field that was surveyed. This can be attributed to the flow velocity and depth of overland flow exceeding threshold values and detaching, as well as transporting, topsoil.
Plate 6.4: Sedimentation in the lower part of a field. The buried stones show the impact of sediment accumulation. Desiccation cracking is a result of the high silt and clay content of these sediments.

Plate 6.5: A trail of eroded sediment across a cracked silt-rich surface.
Plate 6.6: The plough topography had been subdued by rainfall impact.

- *How far the plough topography had been subdued by rainfall impact.* For this a four class scheme – sharp, slightly subdued, moderately subdued and very subdued - was used (Plate 6.6).

- *Desiccation* and the resultant topsoil cracking (Plate 6.5).

- *Vegetation cover and stone cover* was measured at five randomly selected sites in each fields and recorded as percentages.

In addition other notes were made and, although gullies were considered, none were found in sites visited.

A sampling strategy for these fields was determined by factors that are known to influence rates of soil loss. First, the fields were divided into three slope angle classes: < 1.0%, 1.1-3.4%, and > 3.5%. The maximum slope recorded was 6.1° (Plate 6.7). Secondly, the fields were divided into two length classes (>80m and <less 80m). Thirdly, the fields were classified by plough direction in relation to the direction of maximum slope. The measurements of slope angles were made using an abney level along the line of steepest slope. Slope lengths were measured by pacing along the line of steepest slope and then converting these measurements by my average stride length over fields. The plough direction was measured using a prismatic compass (the bearing being taken along the furrow). The decision as to whether a field had been
ploughed across or down slope was achieved by comparing whether the plough bearing was within +/- 45° of the bearing of the steepest slope. The categories of field sampled are given in Table 6.9

<table>
<thead>
<tr>
<th>Slope angle Class</th>
<th>Long, ploughed down-slope</th>
<th>Long, ploughed across-slope</th>
<th>Short, ploughed down-slope</th>
<th>Short, ploughed across-slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1%</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>1.1-3.4%</td>
<td>6</td>
<td>None found</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>&gt; 3.5%</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6.9: The number of fields in each category used for verification of the soil loss model. Whilst the target was to survey five fields in each category, fields on very steep slopes were difficult to find and for one class no fields falling in that category were observed during seven days of fieldwork.

The least ambiguous evidence of soil erosion by water in the fields was rilling. The evidence of erosion (rilling) in fields with different combinations of slope angles, slope lengths and plough directions is summarized in Table 6.10. This is because almost all of the fields showed some evidence of sealing and crusting. This was to be expected from the earlier research into the application of the crusting index in the area which indicated little spatial variation (cf. Chapter 5). The evidence of splash pedestals was sparse. Almost all fields showed some sign of either sediment of debris movement along furrows where they were oriented downslope, and many fields showed evidence of sediment accumulation in their lower portions. Rilling was, therefore, the only type of erosion evidence that was seemed to discriminate between fields. It also has the advantage that is was easily observed and unambiguous when it was found. Therefore, most of the subsequent model verification relies on rilling as a surrogate for ‘observed soil loss’. The full details of the fields observations can be found in Appendix F.
<table>
<thead>
<tr>
<th>Field category</th>
<th>Evidence of rilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope angle class (in degrees)</td>
<td>Other characteristics</td>
</tr>
<tr>
<td>&gt;3.5°</td>
<td>Across slope ploughing</td>
</tr>
<tr>
<td></td>
<td>Down slope ploughing</td>
</tr>
<tr>
<td></td>
<td>Length &gt;80m</td>
</tr>
<tr>
<td></td>
<td>Length &lt;80m</td>
</tr>
<tr>
<td></td>
<td>All fields in slope</td>
</tr>
<tr>
<td>1.1-3.4°</td>
<td>Across slope ploughing</td>
</tr>
<tr>
<td></td>
<td>Down slope ploughing</td>
</tr>
<tr>
<td></td>
<td>Length &gt;80m</td>
</tr>
<tr>
<td></td>
<td>Length &lt;80m</td>
</tr>
<tr>
<td></td>
<td>All fields in slope</td>
</tr>
<tr>
<td>&lt;1.0°</td>
<td>Across slope ploughing</td>
</tr>
<tr>
<td></td>
<td>Down slope ploughing</td>
</tr>
<tr>
<td></td>
<td>Length &gt;80m</td>
</tr>
<tr>
<td></td>
<td>Length &lt;80m</td>
</tr>
<tr>
<td></td>
<td>All fields in slope</td>
</tr>
</tbody>
</table>

Table 6.10: Summary statistics for the proportions of fields in each category displaying evidence of rilling. The full data set can be found in Appendix F.
Plate 6.7: The fields on this hill, which is located in the mountainous area just to the south of the Syrian border, were the steepest surveyed in the verification exercise. The steepest slope angle was 6.1°. These fields probably represent the steepest in the entire study area, and have only been brought into cultivation in the last 3-4 years.

6.3.2 Verification statistics

The statistical method used to provide verification of the application of RUSLE in the study area compares predicted soil losses and evidence of rilling. The predicted soil losses were derived from the RUSLE for the geographical co-ordinates of the fields surveyed. Unfortunately only 41 of the 47 fields surveyed could be used in the statistical analyses because 6 fields fell just outside the boundary of the GIS layers.

A Chi-squared analysis was applied to contingency tables of predicted soil losses for categories of individual fields and evidence of rilling. This test is adequate for two independent samples which is the case in the present study because the first set of data is provided by modelling using data in a GIS model, this included satellite imagery, topographic maps, and thematic soil maps. The second set of data is sampled in the field. Another argument is the temporal lag of time between the two samples, indeed the satellite imageries are from 1992 while the field verification took place in 1999. A (7 x 2) contingency table of frequencies of predicted soil loss categories and observed fields with evidence of rilling categories was produced, the results are
summarized in Table 6.11. As more than 20 percent of the cells have an expected frequency of less than 5 with two of them having less than 1, categories 5, 6 and 7 have been combined to increase the expected values in these cells. Finally, as the chi-square test is insensitive to the effects of order this will give us an overall assessment only.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Frequency of predicted soil loss classes (expected values)</th>
<th>Frequency of observed rill evidences (observed values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1=</td>
<td>27</td>
<td>23</td>
</tr>
<tr>
<td>2=</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>3=</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>4=</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5=</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>6=</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>7=</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6.11: Contingency table of predicted soil loss classes frequency and frequency of fields and evidence of rilling categories.

Chi-square test was run on the above contingency table after combining the categories, the results are given in table 6.12. The value of the chi-square is 12.175, this is, just, less than the critical value of 13.28 of the chi-square with significance level 0.01. This can be interpreted in both sides as the numbers are very close together. Therefore, if we accept the null hypothesis, then we can say that no significant difference between the two data sets with 99% confidence level.

The results of the chi-square therefore provide weak support for veracity of the application of the RUSLE in the study area. However more work is required to provide convincing support.
Combining categories 5-7

<table>
<thead>
<tr>
<th>Model</th>
<th>Actual</th>
<th>Row Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>E</td>
</tr>
<tr>
<td>1</td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>5.5</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>&gt;4 (5,6,7)</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

Column 41 41 82

Totals

degrees of freedom (5-1)(2-1)=4

CHISQ= 12.17454545

Table 6.12: Summary of results of \( \chi^2 \) analysis for predicted soil loss and field measurements.

The reasons for this situation are as follows:

The predictions of soil losses are for 1992, whilst the field measurements were made in 1999. The rainfall conditions would have varied between these two years and therefore vegetation and soil losses would have been different.

There are positioning errors surrounding both the geographical locations of the fields (measured in the field) and the pixels in the raster GIS. These positioning errors relate to both the accuracy of the field locations and the correspondence between field and GIS locations.

Large fields will comprise more than one pixel, and therefore there is an issue of which value of predicted soil loss relates to the field, and small fields will be sub-pixel in size.
The field evidence used to compare with predicted soil loss was evidence of rilling. Whilst rilling is accounted for in the RUSLE, it is not the only erosion process contributing to soil loss from the fields surveyed. Evidence of inter-rill erosion could have been used as well. Though, bearing in mind the comments on field evidence made earlier, it is very doubtful whether this would have added much to the verification data set. The biggest issue here probably lies in comparing a qualitative observation with a numerical prediction.

6.4 Errors and error propagation

The resolution and level of precision required in a GIS data depends on its purpose. The issue of data quality, accuracy of the applied models and how errors in spatial data propagate through GIS operations has generally received little attention until recently (Arbia et al., 1998; Burrough, 1986; Goodchild and Gopal 1989; Heuvelink et al., 1989; Lunetta et al., 1991; Shi, 1998).

GIS-based modelling of soil losses using input data from remote sensing and ancillary sources yields several potential sources of errors. In the context of the C factor inputs from remote sensing, a ground feature does not necessarily have a characteristic reflectance in all topographic conditions and more than one feature are likely to have the same spectral response. For example, the spectral response of a particular vegetation type will differ depending on the slope aspect and gradient and more than one vegetation type may have the same reflectance in optical and near infrared wavebands. Therefore all land cover classification data has to be assessed for accuracy purposes (Curran, 1985; Harris, 1987; Buckland and Elston, 1994).

An overview of error sources using remote sensing data for input in a GIS is given by Lunetta et al., (1991). In their study, they identified potential sources of error in the data processing flow for the integration of remote sensing data into a GIS, and the consequences of error in the decision making and implementation processes. In total, 8 steps were recognized to affect the accumulation of error in a typical remote sensing information processing flow. These were:
1) Data acquisition error;
2) Data processing error;
3) Data analysis error;
4) Data conversion error;
5) Error assessment;
6) Final product presentation error;
7) Decision making; and
8) Implementation.

It is obvious that an analysis of the entire procedure of soil erosion modelling with a GIS and using input from remote sensing will result in several potential sources of errors. Beside errors mentioned above, errors also arise from the natural variation (spatial and temporal) of the input data and also by estimating parameter values (Burrough, 1986; Openshaw, 1989). Nonetheless, Burrough (1986) argues that of these errors, the more subtle, and therefore potentially damaging, errors can arise through data processing operations such as digitising and map overlay and that natural spatial variation in the original data is probably the major source of unseen errors. The resulting variation in data can contribute to unreliable results being produced by a Geographical Information System.

The dimension of the problem of errors in soil erosion modelling with a GIS goes beyond the level of identification of error sources as errors propagate throughout the whole process. Error may be transferred from one data process step to the next until it manifests in the final product, error may accumulate throughout the process in an additive or multiplicative fashion. Usually, the decision maker is provided graphic final products, statistical data, or modelling results with little or no information concerning the confidence that can be placed in the information. This limits the confidence in the implemented decision(s). It is, therefore, imperative to improve the ability to quantify the error associated with the data, and monitor the error as it propagates through the GIS application (Lunetta, 1991). However, it is agreed that one of the major problems facing the application of error propagation analysis to a model linked to a GIS is the data requirement. Detailed information on the model itself and the input data are needed to apply the error propagation analysis successfully.
An assessment of the quality of the input data as well as the estimation of the Revised Universal Soil Loss Equation Parameters is presented in the following section (cf. Section 6.5). It is shown that none of the input data layers has an estimated error or uncertainty. Furthermore, the approach adopted for the verification and validation of the model outputs, for this reconnaissance study, was qualitative. Consequently, it was not possible to conduct an error propagation analysis in the actual research, subject to further researches, in the area, in the future.

6.5 Quality assessment

The quality of the model in this study is assessed as follows:

\textbf{R factor.} The rainfall station density in the study area \((1\ \text{station per 200 km}^2)\), though low, meets the WMO (World Meteorological Organization) standard of \(1\ \text{station per 250 km}^2\) (Shaw, 1983). The creation of the rainfall erosivity layer (R layer) was achieved by creating an annotation layer and converting this layer to a raster layer using ERDAS Imagine. The locational errors in this layer will be low given that it is a simple linear extrapolation, and the accuracy of resulting layer will be determined by the accuracy of the computer and software. Given the low variability in rainfall and R factor across the study area, combined with the greater inter-annual variability of mean annual rainfall, it was assumed that any more sophisticated method of rainfall and R factor extrapolation would provide unverifiable spatial distribution which probably has a greater accuracy than the method used.

\textbf{K factor.} The soil association maps were published by the Ministry of Agriculture of Jordan in 1994 at 1:250,000 scale. They were produced in digital form by the same ministry in cooperation with the Royal Jordanian Geographic Center. Clearly there may be digitizing errors associated with these maps which are beyond the control of the current research. However, the accuracy of these digitized maps was judged ‘satisfactory’ by the Ministry of Agriculture. Soil properties are derived from a conventional soil map, the value of that soil property at a certain location is therefore, assumed to be the mean value of the observation within that unit and clearly there is the potential for large amounts of variability within each soil mapping units. The Ministry of Agriculture has no data on within-unit variability of soil parameters.
within these mapping units. The cartographic production of these maps was achieved at the Royal Jordanian Geographic Center (RJGC) using the most accurate cartographic tools available. It can be postulated that the accuracy of these maps is as good as the accuracy of the topographic maps produced at the same (RJGC). The quantification of the accuracy of these maps could not be done as it is not a routine carried out at the RJGC.

**LS factor.** The accuracy of the DEM built by interpolation from topographic maps with contours drawn at 40 m interval, is determined by the x, y and z accuracy of the topographic maps. The most common measure for the quality of a map feature is its relative and absolute positional accuracy. The topographic maps available for this study conform to the RJGC (Jordan) map accuracy standards and it was not possible to measure absolute accuracy because no other information was available. Minor positional inconsistencies were found during edge matching contour coverages digitized from individual sheets. Since the DEM of the study area was derived from the topographic maps, its accuracy could never be greater than the source data which themselves contained errors. The distortion, introduced after transforming the data from geographic (latitude/longitude) to plan coordinates, was a source of geometrical inaccuracy of the DEM. In order to measure the relative vertical accuracy, the DEM generated from topographic maps was visually compared (on the screen) with a DEM generated from SPOT images (for specific areas) and was found to be consistent.

**C factor.** The decision about the selection of imagery was made after considering several factors. Above all, the main aim of the image processing was to quantify the vegetation land cover in the study area. For mapping the land cover in the 1970’s, Landsat Multi-spectral Scanner (MSS) data (56 × 79 m²) were available. However, land cover mapping for late 1980’s and early 1990’s was carried out by the processing of finer resolution Landsat Thematic Mapper (TM) data (30 × 30 m²). For the MSS images, the data of band 1 (0.6-0.7 μm) was damaged and could not be used in image processing. However, this was not a problem as the remaining optical and near infrared wavebands supplied all the spectral information needed. The calibration of the NDVI and fractional vegetation cover images from spectral unmixing with vegetation cover data relies on ground sampling of vegetation that was not collected simultaneously with the imagery. Calibration data between remotely sensed data and biogeophysical variables have relatively low accuracies, and this will be the case in
this study. It is likely that the greatest errors like are in the C factor layers. However, as this is a reconnaissance study the C factor layers probably show the relative spatial and inter-annual variations in vegetation cover that are appropriate to the investigation.

P factor. The only error surrounding the P factor would be that some management practices for soil conservation had been omitted from the analysis. This is extremely unlikely given the prevailing farming systems.

The verification of the soil loss model outputs cannot be statistically verified by the data collected in the field, though there is some weak support for the use of the RUSLE to predict soil losses in the study area. This aspect of accuracy assessment is dealt with fully in section 6.3.2.

In conclusion, it is questionable whether the 4.2% increase in soil loss predicted by the model over the 20 years period, was caused by changes in land cover. It is probable that this number (4.2%) lies well within the likely error margin of the modeling. This aspect of errors, likely to occur during modeling, is dealt with fully in section 6.4.

6.6 Summary

The initial work in this chapter reports on the parameterization of the RUSLE. This was achieved in the following manner.

The rainfall erosivity factor (R) was calculated using Fournier’s p²/P index in the manner that Arnoldus (1977) has applied it in Morocco. The R factor in the study area ranged from 17 to 23.

The soil erodibility factor (K) was assessed using soil data for soil units mapped by the Jordanian Ministry of Agriculture. The nomograph produced by Wischmeier (1978) was used to estimate the K factors. These estimations were mainly based on the textural composition and organic matter percentages and the values K ranged from 0.31 to 0.40, indicating a low spatial variability of K across the study area.
The topographic factors (LS) were assessed using slope layer generated in ERDAS Imagine. The slope layer was derived from a DEM generated in ARC/INFO from 1:50,000 topographic maps at RJGC. The slopes were classified into six different classes, and the corresponding values of LS were determined using published data for the RUSLE. The majority of the area has slope angles less that 2-3°, though steeper slopes are found on the few volcanic cones in the area. The slope lengths are far more variable.

The vegetation cover and management practices factors (C and P) were calculated by (a) assuming a value of 1 for the management practice factor (P), as no specific management practices are present in the study area; and (b) the C values were assessed using vegetation cover percentages determined by linear unmixing of TM image data and NDVI data obtained from MSS imagery. The values of C were determined using published data for three different categories of land use: rangeland, vegetated cropland and fallow land.

Rangelands contribute most to the overall soil loss in all three years, though most rangeland areas only contribute a small amount to the overall soil loss on a unit area basis (the dominant erosion class on rangelands was < 1.0 t ha\(^{-1}\) a\(^{-1}\) soil loss). Rangelands with soil losses exceeding 6.1 t ha\(^{-1}\) a\(^{-1}\) were found around to the west and north-west of Dayr al-Khaf and to the west of Umm Husayn in hilly areas.

The RUSLE was then run for 1972, 1985 and 1992; in each occasion using different vegetation cover (C factors) for bare fields, irrigated fields and rangeland. The expansion of rain-fed cultivation has progressively brought more land into cultivation and between 1972 and 1985 the majority of this land was in the north of the study area it mainly comprised fields with <1.0 t ha\(^{-1}\) a\(^{-1}\) soil loss, except for some fields around Dayr al-Khaf where the predicted soil losses were in the 2.1-4.0 t ha\(^{-1}\) a\(^{-1}\) range, later northward expansion of rain-fed cultivation increased the proportion of fields with soil losses in the 2.1-4.0 t ha\(^{-1}\) a\(^{-1}\) soil loss range. The westward and south-westerly expansion of rain-fed fields between 1985 and 1992 had less impact on increased soil erosion rates than the corresponding northward expansion. The advent of irrigated agriculture in the study area after 1985 had little impact upon the overall
soil loss as the majority of these fields are located on very gentle slopes and the soil losses are low.

A visual analysis of this series of maps indicates that the most critical factors in the RUSLE were:

- The topographic (LS) factor; and
- The soil erodibility (K) factor.

Though in the case of irrigated agriculture the C factor is also important.

Overall there was a 4.2% increase in the predicted soil loss from the study area between 1972 and 1992. There is not enough support for the contention that rates of overall soil loss are accelerating: the increase from 1972 to 1985 was less than 1% and from 1985 to 1992 it was 3.2%. It is likely that these numbers lie within the likely error margin of the modeling. All predicted soil loss classes experienced an increase in soil loss from 1972 to 1992 with the exception of the 5.1-6 t ha\(^{-1}\) a\(^{-1}\), 9.1-10 t ha\(^{-1}\) a\(^{-1}\) and the >10.1 t ha\(^{-1}\) a\(^{-1}\) soil loss classes, all three classes showed a decline in soil loss over this time period. Some classes with large percentage increase (e.g. 7.1-8.0 t ha\(^{-1}\) a\(^{-1}\) class) are thought to be prone to digitizing errors during the masking out of volcanic tuffs and basalt. Most predicted soil loss classes show moderate increases in soil losses between 11.6 and 15.4%. The two classes with the lowest increases in soil loss between 1972 and 1992 are the <1.0 t ha\(^{-1}\) a\(^{-1}\) class (1.4%) and the 3.1-4.0 t ha\(^{-1}\) a\(^{-1}\) class (3.2%).

Verification of the model was attempted by comparing predicted soil losses with quantitative and qualitative data obtained from 41 fields in the study area. The quantitative data mainly comprised slope angle, slope length and direction of ploughing; and the main type of qualitative data used was the presence or absence of rills.

The proportion of fields with rills was compared to the mean predicted soil loss for different classes of fields using a simple chi-square test. Not enough support was found that predicted soil loss and the presence or absence of rilling might be related.
The reasons for the weak support for the application of the model are thought to be due to:

The time lag between the prediction of soil losses (1992) and the field measurements (1999).

Positioning errors surrounding the geographical locations of the fields and the pixels in the raster GIS.

The potential mis-matches between field sizes and pixel size.

The qualitative and partial nature of the field evidence used to compare with predicted soil loss. The biggest issue here probably lies in comparing a qualitative observation with a numerical prediction.
CHAPTER 7: CONCLUSION

7.1 Introduction

7.2 Specific objectives

7.3 Evaluation of hypotheses

7.3.1 Land use and land cover change
7.3.2 Land cover change and soil losses

7.4 Further considerations

7.5 Suggestions for future work in northern Jordan
CHAPTER 7: CONCLUSIONS

7.1 Introduction

The overall aim of the research reported on in this thesis was to develop a GIS-based spatial model to evaluate the impacts of land cover change on land degradation in northern Jordan to enable two hypotheses to be tested. These are that:

Land cover changes in the study area are caused by land use changes that have been triggered by national-scale and regional-scale socio-economic factors since the 1970s. The land cover changes that have occurred since 1972 have led to a small amount of increased soil losses over the study area. It is thought that this increase is probably within the error margin of the modeling.

In the course of achieving this aim and evaluating these hypotheses, a number of specific objectives (which were outlined in Section 1.3) were addressed. These are:

1. The development of a digital terrain model, and climatological and pedological databases of the study area.
3. Verification of the land cover change maps through field mapping and interviews with farmers

These five specific objectives are reported on in Section 7.2. These are followed by an evaluation of the two hypotheses (Sections 7.3.1 and 7.3.2). Several key issues which emerged during the research are summarized in Section 7.4, and the prospects for further improvement of this type of work in Jordanian drylands are outlined in Section 7.5.
7.2 Specific objectives

**Objective 1.** The digital terrain model and climatological and pedological databases produced were used to parameterize the RUSLE in the following manner.

The rainfall erosivity factor (R) was calculated using Fournier’s $p^2/P$ index in the manner that Arnoldus (1977) has applied it in Morocco. The R factor in the study area ranged from 17 to 23.

The soil erodibility factor (K) was assessed using soil data for soil units mapped by the Jordanian Ministry of Agriculture. The nomograph produced by Wischmeier (1978) was used to estimate the K factors. These estimations were mainly based on the textural composition and organic matter percentages and the values of K ranged from 0.31 to 0.40, indicating a low spatial variability of K across the study area.

The topographic factor (LS) was assessed using a slope layer generated in ERDAS Imagine. The slope layer was derived from a DEM generated from 1:50,000 topographic maps at RJGC. The slopes were classified into six different classes, and the corresponding values of LS were determined using published data for the RUSLE. The majority of the area has slope angles less that 2-3°, though steeper slopes are found on the few volcanic cones in the area. The slope lengths are far more variable.

**Objective 2.** Providing spatial distributions of vegetation cover for 1972, 1985 and 1992 was critical to the soil loss modelling because vegetation cover was the only variable that was likely to have changed significantly in the 20 year period considered in the study. Consequently the temporal variations in the spatial distribution of the C factor were the only dynamic elements in the soil loss modelling.

Change detection analysis based on red and near infra red difference images was undertaken because of its simplicity, the ease with which the interpretation of the difference images can be conducted, and the fact that the technique has been successful in other dryland areas. The results were ambiguous. In general, changes in vegetation cover caused by the conversion of rangeland to rain-fed and/or irrigated fields were clear in one of the pair of difference images (e.g. the visible red image)
but were not supported in the other images (e.g. the near infra red image). It is argued that this occurred for two reasons:

1. The rangeland was very degraded in 1972 and subsequent conversion to rain-fed fields (which would be bare in the dry season when the imagery was acquired) would have had little effect on the spectral response in the reflective visible and near infra red parts of the electromagnetic spectrum. The conversion to irrigated fields would have led to a far greater spectral change.

2. With small amounts of above-ground biomass, responses to variations in antecedent soil moisture conditions and changes in the spectral properties of surficial materials consequent upon erosion and deposition could mask out spectral changes due to the vegetation cover degradation caused by human activities.

As a consequence, inputs into the RUSLE based on change detection were not considered further, and attention was focused on providing calibrated vegetation cover percentage data from remotely sensed imagery to enable C factor estimates to be calculated.

Linear spectral mixing modelling was used to map the proportions of cover types present in the study area from Landsat TM data acquired in the 1992 dry season. The following assumptions were met: the spectral mixture of the components in the environment of northern Jordan is linear, the number of image components and their respective end-members are known, the locations of these end-members are known, and the purity of the end-members pixels was assured by field visits or spectra from spectral libraries were used when the purity was contested. Five component images were produced together with an error image for the 1992 TM image. The overall accuracy was judged high, as the RMS values for all bands were <2%. The fractional vegetation cover image was converted to percentage cover values and used with tabular data to provide C factor values for the study area for 1992.

It was not possible to run linear spectral mixing modelling on the MSS imagery from 1985 and 1972. As a consequence, NDVI images were used to produce vegetation cover maps for these dates and these were then converted to percentage cover values.
using a calibration diagramme developed for the study area by another researcher at the University of Leicester. All vegetated fields were visited and their vegetation covers were assessed by visual observations.

The vegetation cover data was used in the RUSLE alongside maps of different types of cultivated areas. These were irrigated and rain-fed fields, and rangelands (i.e. uncultivated areas). Maps of irrigated and rain-fed fields were created through on-screen digitizing of images acquired in 1972, 1985 and 1992. Mapping the rain-fed fields that were bare was difficult because of the spectral confusion between these fields and the surrounding rangelands. In summary, mapping cultivated areas from the imagery relied on two methods:

- Vegetated fields were mapped from the TM and MSS imagery using a false colour composite of Bands 1, 2 and 3 (MSS) and 2, 3 and 4 (TM). For the 1972 and 1985 images, field identifications were checked against NDVI images which indicated areas of high vegetation cover. For the 1992 image, field identifications were checked against a vegetation cover proportion map derived from linear mixture modelling.

- Bare fields were mapped from all images by digitizing (from the screen display), rectangular clusters of pixels which contrasted spectrally with the surrounding rangelands and lava flows, and/or which had contextual information indicating the presence of walls between fields.

Objective 3. Verification of the fields was undertaken in 1998 and 1999. This was done in two ways:

- During semi-structured interviews with farmers, in which the histories of land use on their farms were discussed; and

- By drawing sketch-maps of land use from high vantage points and comparing these to the field patterns on the 1992 dry season image.

Objective 4. The approach adopted for this objective is based on coupling a parametric model of soil degradation (the Revised Universal Soil Loss Equation – RUSLE) with a GIS of the study area. The RUSLE was chosen as the soil erosion
model because of its applicability to agricultural situations dominated by inter-rill and rill erosion, its focus on annual soil losses, and the ease with which it can be parameterized.

The RUSLE was run for bare field, irrigated field and rangeland areas for 1972, 1995 and 1992. Rangelands contribute most to the overall soil loss in all three years, though most rangeland areas only contribute a small amount to the overall soil loss on a unit area basis (the dominant erosion class on rangelands was < 1.0 t ha\(^{-1}\) a\(^{-1}\) soil loss). Rangelands with soil losses exceeding 6.1 t ha\(^{-1}\) a\(^{-1}\) were found to the west and north-west of Dayr al-Khaf and to the west of Umm Husayn in hilly areas.

The RUSLE was then run for 1972, 1985 and 1992; on each occasion using different vegetation cover (C factors) for bare fields, irrigated fields and rangeland. The expansion of rain-fed cultivation has progressively brought more land into cultivation between 1972 and 1985. The majority of this land was in the north of the study area and it mainly comprised fields with <1.0 t ha\(^{-1}\) a\(^{-1}\) soil loss, except for some fields around Dayr al-Khaf where the predicted soil losses were in the 2.1-3.0 t ha\(^{-1}\) a\(^{-1}\) range. Later, northward, expansion of rain-fed cultivation increased the proportion of fields with soil losses in the 2.1-4.0 t ha\(^{-1}\) a\(^{-1}\) soil loss range. The westward and south-westerly expansion of rain-fed fields between 1985 and 1992 had less impact on increased soil erosion rates than the corresponding northward expansion. The advent of irrigated agriculture in the study area after 1985 had little impact upon the overall soil loss as the majority of these fields are located on very gentle slopes and the soil losses are low.

A visual analysis of this series of maps indicates that the most critical factors in the RUSLE were the:

- topographic (LS) factor; and to a lesser extent
- soil erodibility (K) factor.

Though in the case of irrigated agriculture the C factor is also important.
Overall there was a 4.2% increase in the predicted soil loss from the study area between 1972 and 1992. There is not enough support for the contention that rates of overall soil loss are accelerating: the increase between 1972 and 1985 was less than 1% and between 1985 and 1992 it was 3.2%. All predicted soil loss classes experienced an increase in soil loss from 1972 to 1992 with the exception of the 5.1-6 t ha$^{-1}$ a$^{-1}$, 9.1-10 t ha$^{-1}$ a$^{-1}$ and the > 10 t ha$^{-1}$ a$^{-1}$ soil loss classes, all three classes showed a decline in soil loss over this time period. Some classes with large percentage increases (e.g. 7.1-8.0 t ha$^{-1}$ a$^{-1}$ class) are thought to be prone to digitizing errors during the masking out of volcanic tuffs and basalts. Most predicted soil loss classes show moderate increases in soil losses between 11.6 and 15.4% from 1972 to 1992. The two classes with the lowest increases in soil loss between 1972 and 1992 are the <1.0 t ha$^{-1}$ a$^{-1}$ class (1.4%) and the (3.1-4.0) t ha$^{-1}$ a$^{-1}$ class (3.2%).

**Objective 5.** Verification of the model was attempted by comparing predicted soil losses with quantitative and qualitative data obtained from 41 fields in the study area. The quantitative data mainly comprised slope angle, slope length and direction of ploughing; and the main type of qualitative data used was the presence or absence of rills.

The proportion of fields with rills was compared to the mean predicted soil loss for different classes of fields using a simple chi-square test. Not enough support was found that predicted soil losses and the presence or absence of rilling might be related.

The reasons for the weak support for the application of the model in the study area are thought to be due to:

- The time lag between the prediction of soil losses (1992) and the field measurements (1999).
- Positioning errors surrounding the geographical locations of the fields sampled and the pixels in the raster GIS.
- The potential mis-matches between field sizes and pixel size.
- The qualitative and partial nature of the field evidence used to compare with predicted soil loss. The biggest issue here probably lies in comparing a qualitative observation with a numerical prediction.
7.3 Evaluation of hypotheses

7.3.1 Land use and land cover change

It is clear from the maps of cultivated areas (Fig. 6.5) that increased amounts of rain-fed land have been brought into cultivation as nomads have settled in the region since 1972. In villages without access to wells this process is still occurring at the present-time. In areas served by wells, irrigated farming is replacing rain-fed farming. However, the situation is complex as, in some cases, permanent irrigation farming is being followed, whilst in other areas irrigation is temporary and rotates with rain-fed cultivation and grazing. Animal rearing has also undergone change, the most notable feature of which has been the progressive reduction in flock sizes and strengthening of a synergy between livestock and cultivation systems, especially with regard to harvested fields. These observations, derived from interviews with farmers, support the hypothesis first promoted by Boserup (1965) that farming methods adjust to increasing population (and cultivation) densities.

The results of this research lend support to the view that the concept of carrying capacity is redundant in highly variable environments such as that found in northern Jordan. Evidence supporting this comes from (a) the fact that farmers recognise that agriculture is risk-ridden in this area and, for many, it represents only one of number of household survival strategies, and (b) that monitoring land cover change trajectories from remotely sensed data can easily be deflected by the effects of the inter-annual variability of seasonal rainfall.

The links between population dynamics and land colonisation have been difficult to disentangle in this research project, partly because of the focus on the BRDP. Some villages in the study area have high rates of population growth (e.g. Umm al-Qutayn) and have high pressures on land for cultivation. In other villages (e.g. Mathnat Rajil) the links between population growth and land colonisation confirm that with low population growth rates the area under cultivation has remained more-or-less over the last 20 years. Whilst population growth rates are not the main causes of land colonization per se, certain push and pull factors are influential in leading to land colonization and, therefore, land use and cover change in the study area. Amongst a
range of push factor known to lead to land colonization in drylands (Table 2.1), land alienation and rural-to-rural migration are important in the study area, with the former being the most important. Interviews with farmers indicate that pull factors are equally, if not more important, in stimulating land colonisation in the study area. The main pull factors being the availability of cheap land (especially in the east of the study area); the availability of good quality groundwater, land availability; and for some people the ability to obtain licenses to abstract groundwater.

External influences through policy shifts and the regional political situation are potentially very significant in this study area and, on the basis of the interviews with farmers, this appears to be a fertile area for further research on land use and cover change. The government, through its shifts in water policy over the last three decades (Dotteridge and Gibbs, 1998) and policies on stock feed subsidies has directly and indirectly encouraged (and discouraged) the conversion of rangeland to arable cultivation. On the regional stage the influx of refugees in 1967 led to an expansion of cities in the western highlands and created a demand for food to be met from the areas to the east. Remittances from Jordanians working in the Gulf States in the 1970s and 1980s supported the national economy to such an extent that it has had a strong trickle down effect in stimulating the economy of northern Jordan. Finally, migrant workers returning to the region after the 1991 Gulf Crisis swelled the population in the area and brought investment to the region.

Northern Jordan, then, provides an example of a vigorous rural economy that is subject to regional and national influences as well as local factors. These multi-scale political and socio-economic factors have created forces that have led to land use and cover change in the agrarian landscape. The frontier of cultivation continues its eastwards march into increasingly ecologically- and economically-marginal environments. Behind the active frontier of colonisation, land switching between grazing, rain-fed cultivation and irrigated cultivation occurs on an annual basis.

7.3.2 Land cover change and land degradation

Though the focus of the research was on land degradation due to soil erosion by water other forms of land degradation were briefly evaluated. Crusting occurs throughout
the study area. The FAO crusting index was calculated, but little spatial variation in
the high levels of crusting between the soil units in the study area was found. It is
argued that wind erosion is not a serious problem in the study area. This is because
the wind velocities are generally very low, and boulder and surface crusting usually
provides adequate protection of the topsoil. However, human activities can loosen
the soil particles providing more material to be detached by the wind, and remove the
protective stone cover thereby accelerating rates of wind erosion. Salinization is not a
threat at the present time because irrigation has only recently been practiced in the
study area, and the migratory nature of irrigated agriculture in the area means that
same piece of land is not being irrigated every year. However, it could become an
important hazard in the future, as it has in some villages west of the study area.

Soil erosion by water is the most important form of land degradation occurring in the
study area. In particular, inter-rill and rill erosion are commonly found on agricultural
fields in the study area (cf. Section 6.3). However, the issue in question is whether the
changes in land use and land cover that have been stimulated by political and socio­
economic factors in the study area over the past (cf. Section 7.3.2) have led to an
increase in soil losses from rangeland and cultivated land?

To a certain extent the answer to this question is ambiguous given the results obtained
during the research. In Section 6.2 it was shown that as rain-fed fields have expanded
at the expense of rangelands at least some of them have been constructed on terrain
that will result in relatively high rates of soil loss due to topographic and soil
erodibility considerations. However, there has been a 4.2% increase in predicted soil
losses from the study area between 1972 and 1992. Given that error sources and error
propagation during modeling (cf. section 6.4), the 4.2 cannot be strongly interpreted in
terms of real increase in soil losses in the study area.

Three reasons can explain this:

1. The conversion from rangeland to rain-fed fields is a fluid concept in the area.
   In some years there are more or less rain-fed fields because of perceived ideas
   about the probability of a wet growing season. In addition, in many areas the
range is so degraded that a conversion to bare fields will not automatically lead to an increase in soil loss.

2. The conversion from rangeland to irrigated land (or rain-fed fields to irrigated land) leads to decrease in predicted soil loss (Fig. 6.8b).

3. It has been impossible to conduct error propagation analysis for reasons raised in section 6.5, and to verify the use of the RUSLE in this environment, therefore the results must be used cautiously.

7.4 Further considerations

Whilst the link between policy initiatives and socio-economic factors appears to be strongly linked to land use and cover change, linking national and household level socio-economic data to land cover changes monitored using remotely sensed data, should be conducted with caution. As has been shown in Chapter 3, monitoring land cover change in this environment using remote sensing can easily be disrupted by high magnitude-low frequency rainfall events which cause a short-term vegetative responses which do not lie with general longer-term vegetation trajectories.

Furthermore linking, land cover change to land degradation (in this study with a GIS-based erosion model - the RUSLE - to estimate soil losses) should also be done cautiously. In the case of the widely used RUSLE, some factors cannot be directly calculated due to lack of detailed data (e.g. the R factor). Whilst linear mixture modeling appears an attractive method to map vegetation cover, the results of the unmixing was contested in the basaltic areas because of the high proportions of the shade due to basalt boulders, and there is always the possibility of non-linear mixing.

Nonetheless, an empirical model or a lumped-conceptual model such as the RUSLE should provide perfectly acceptable results for this kind of reconnaissance study. However, to be convincing in this aspect the issue of model verification would need to be tackled in a different manner to the way it was attempted in this study.

7.5 Suggestions for further work in northern Jordan

Further research needs to be conducted on land use policy and agricultural activities at the semi-arid/arid frontier, and in Jordan in particular, in order to fully understand the
relationships between policy, population dynamics, land use and cover change and land degradation.

More work needs to be done in northern Jordan to assess the impact of intensive irrigation and basalt clearance on the land quality. Salinization and wind erosion are promoted by such activities and do occur in the present time to a limited extent, but they are likely to become more important in the future.

One of the major weaknesses in the model lies with the estimation of its input factors, further work is needed to assess the quality of these factors, and to be able to conduct quantified accuracy assessment analysis on the model outputs.
REFERENCES


Chepil, W. S. (1945). Dynamics of wind erosion. Soil Science, 60:


Climatological Data of Jordan (1975-1997). Meteorological Department, Jordan.


SPECIAL NOTE

THIS ITEM IS BOUND IN SUCH A MANNER AND WHILE EVERY EFFORT HAS BEEN MADE TO REPRODUCE THE CENTRES, FORCE WOULD RESULT IN DAMAGE
ERDAS Imagine File Information

File Information:
    File Name: 280892-tm-sub-geo.img
    Number of Layers: 12

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    Pixel Depth: Unsigned 8-bit
    Compression Type: None

Histogram:
    Bin Function: Direct
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    Maximum: 151
    Mean: 5.29356

Appendix A.1: Histogram of the RMS file of the unmixing model
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Number of Layers: 12

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Mode: 1.000000
Standard Deviation: 3.923940

Appendix A-II: File Information of the RMS layer in the 1992 TM image
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Appendix B-I: Table of calibrated values of the NDVI and vegetation cover percentages for selected 9 sites in the BRDP (Edwards *et al.*, 1996)
Figure 1: Percentage vegetation cover plotted against NDVI for Nov/Dec 1995

Appendix B-II: Percentage vegetation cover plotted against NDVI for NOV/Dec 1995 in the BRDP (Edwards et al., 1996)
Appendix C: The soil erodibility nomograph (after Weischmeier, 1978)

Procedure: With appropriate data, enter scale at left and proceed to points representing the soil's sand, OM, structure, and permeability, in that sequence. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: sand 20%, silt 35%, OM 2%, structure 7, permeability 4. Solution: K = 0.31.

**Figure 1** The soil erodibility nomograph. Where the silt fraction does not exceed 70 percent, the equation is 100 K = 2.1 M⁻³ (10⁻¹) (12 - a) + 325 (b - 2) + 2.5 (c - 3).

where M (percent silt), a (percent organic matter), b = structure code, and c = profile permeability class.
Table 5.2 Values for topographic factor, LS, for low ratio of rill to interrill erosion, such as for rangeland and other consolidated soil conditions with cover (applicable to thawing soil where both interrill and till erosion are significant).

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Appendix D-I: The values for the topographic factor, LS (from Renard et al., 1994) applied to rangelands.
Table 5.3 Values for topographic factor, LS, for moderate ratio of till to intertil erosion, such as for row cropped agricultural and
her moderately consolidated soil conditions with little to moderate cover (not applicable to thawing soil).

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Appendix D-II: The values for the topographic factor, LS (from Renard et al., 1994),
applied to cultivated lands.
SPECIAL NOTE

THIS ITEM IS BOUND IN SUCH A MANNER AND WHILE EVERY EFFORT HAS BEEN MADE TO REPRODUCE THE CENTRES, FORCE WOULD RESULT IN DAMAGE
soil loss ratios for conditions not evaluated in Table 5

ROWCROPS: a certainly standing; use col. 2L;
harvesting; col. 4L at times 3:15.

SML ALAN:
Table 6B:

values from lines 33-52, seedbed column.

SMAL GRAIN:
Values by selecting from Table 5 the soil loss per-
the successive croostage periods of each crop.

Table 6C:

FULL YEAR PERCENTAGES:
mix 0.25 0.5 0.75 1.0 1.25 1.5 1.75 2.0 2.25 2.5
and year 1 0 1.5 2 2.5
second-year sericed 2.0 2.5

WILLFULL NURSE CROP:
time lengths of croostage periods SB, 1, and 2 and
given for small grain seeding.

SOYBEANS is suggested

variable. Tentative values derived analytically are
in the SCS in Hawaii or the Western Technical Serv-
ces Portland, Oreg. [Reference 3].

n for corn, on the basis of expected crop residues over.

variable. Probably most nearly comparable to par-
the residue benefit.

variable from sources given for pineapples.

LOW RAINFALL AREAS, USE GRAIN OR ROW
soil loss percentage after each successive tillage
be obtained from the following tabulation by esti-
mate surface cover after that tillage and selecting
the appropriate amount of initial residue. The
real benefits of the residue much, residues mixed
litter, and the crop system residual.

COVER: Initial residue. Lbs. Al

0.0

1-12 13-14

16 17 18 19

20 22 24 25

26 28 30 32

29 32 34 35

36 38 40 42

43 46 48 50

41 44 46 48

47 50 52 54

51 54 56 58

rain-residue only

N ROW CROP (TURF) OR RESIDUES

Table 5-C.—Soil loss ratios (percent) for croostage 4
when stalks are chopped and distributed without soil

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<td>67</td>
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<tr>
<td>95</td>
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</table>

1. Part of a field surface direct covered by pieces of residue much.

2. This column applies for systems other than no-till.

3. Cover after bean harvest may include an appreciable number of
stalks carried over from the prior corn crop.

4. Grain with meadow seedings, include meadow growth in percent
cover and limit grain period 4 to 3 mo. Thereafter, classify as estab-
lished meadow.

5. N LOW-RAINFALL AREAS, USE GRAIN OR ROW
soil loss percentage after each successive tillage
be obtained from the following tabulation by esti-
mate surface cover after that tillage and selecting
the appropriate amount of initial residue. The
real benefits of the residue much, residues mixed
litter, and the crop system residual.

Table 5-D.—Factors to credit residual effects of turned

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APPENDIX E-1: The values for the crop factor, C (from Wischmeier, 1978), applied to the bare and vegetated fields.
The values of the crop factor C (from Wischmeier, 1965).
F SUPPORT PRACTICE FACTOR (P)

By definition, factor P in the USLE is the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down-slope culture. Improved tillage practices, sod-based rotations, fertility treatments, and greater quantities of crop residues left on the field contribute materially to erosion control and frequently provide the major control in a farmer's field. However, these are considered conservation crossing and management practices, and the benefits derived from them are included in C.

Contouring

Practice of ridge and planting on the contour has been effective in reducing soil erosion. Limited field studies, the practice provides complete protection against erosion by moderate to low intensity, but little or no protection against the accnivere storms that caused extensive breakovers of the contoured rows. Contouring appears to be the most effective on slopes in the 3- to 8-percent range. As land decreases, its approach to erosion resistance decreases, while the soil loss ratio approaches 1.0. As slope increases, the soil loss ratio decreases, and the soil loss ratio again approaches 1.0.

Full observations from field surveyed in northern Jordan, April 1999.

Table A: Fields with slope angles <1 degree

<table>
<thead>
<tr>
<th>Field number</th>
<th>Date</th>
<th>Slope angle</th>
<th>Slope aspect</th>
<th>Direction of ploughing (p)</th>
<th>Difference (d=a-p) [m]</th>
<th>Slope length [m]</th>
<th>Crusting class</th>
<th>Crust cover (%)</th>
<th>Crust cover (std dev)</th>
<th>Presence of pedestals (%)</th>
<th>Mean stoniness</th>
<th>Stoniness pedestals (%)</th>
<th>Vegetation cover (%)</th>
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<td>Slope length &gt; 80m</td>
<td>Down-slope ploughing</td>
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<tr>
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<td>N none</td>
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</table>
Full observations from field surveyed in northern Jordan, April 1999.

Table B: Fields with slope angles between 1.1 and 3.4 degrees

<table>
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<th>Slope aspect</th>
<th>Direction of ploughing</th>
<th>Difference</th>
<th>Slope length</th>
<th>Crusting class</th>
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</thead>
<tbody>
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<td></td>
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<td>(x)</td>
<td>(a)</td>
<td>(d=a-p) [m]</td>
<td>(l) [in m]</td>
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<td>Slope length &gt;80m Down-slope ploughing</td>
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<td>3</td>
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<td>107</td>
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</tr>
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<td>8</td>
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</tr>
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</tr>
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<td>116</td>
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<td>137.4</td>
<td>15.4</td>
<td>35.0</td>
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</tr>
</tbody>
</table>

| Slope length <80m Down-slope ploughing |
| 22           | 21/04/99 | 1.3         | 340          | 349                    | 9          | 69           | 2              |
| 2            | 20/04/99 | 1.7         | 320          | 100                    | 160        | 60           | 3              |
| 26           | 21/04/99 | 3.3         | 214          | 170                    | 44         | 39           | 2              |
| 7            | 20/04/99 | 1.5         | 283          | 252                    | 31         | 63           | 1.2            |
| 19B          | 21/04/99 | 2.5         | 284          | 284                    | 0          | 54           | 4              |
| Means        |          | 2.1         | 288.2        | 231.0                  | 48.8       | 57.0         | 2.8            |
| Std devs     |          | 0.8         | 48.1         | 97.5                   | 64.6       | 11.4         | 1.0            |

| Slope length <80m Across-slope ploughing |
| 15           | 20/04/99 | 2.3         | 282          | 186                    | 94         | 36           | 2, 3           |
| 16           | 21/04/99 | 3.0         | 223          | 280                    | 57         | 73           | 1.2            |
| 24           | 21/04/99 | 2.3         | 323          | 267                    | 56         | 23           | 2, 3           |
| 14           | 20/04/99 | 2.3         | 282          | 186                    | 94         | 14           | 2              |
| 13           | 20/04/99 | 2.3         | 282          | 188                    | 94         | 12           | 3              |
| Means        |          | 2.4         | 278.4        | 222.2                  | 79.0       | 31.4         | 2.5            |
| Std devs     |          | 0.3         | 36.7         | 47.1                   | 20.5       | 25.0         | 0.7            |

Summary statistics in presence of rills

<p>| All across-slope fields | 2 of 6 | 33% |
| All down-slope fields   | 4 of 11 | 36% |
| All &gt;80 m fields        | 3 of 7  | 43% |
| All &lt;80 m fields        | 3 of 10 | 30% |
| All fields &gt;3.5 deg     | 6 of 17 | 35% |</p>
<table>
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<tr>
<th>Crust cover (%)</th>
<th>Crust cover (std dev)</th>
<th>Presence of pedestals</th>
<th>Mean stoniness (%)</th>
<th>Stoniness (std dev)</th>
<th>Vegetation cover (%)</th>
<th>Presence of rills</th>
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<td>0.8</td>
<td>&lt;1</td>
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<tr>
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<td>N</td>
<td>4.4</td>
<td>0.9</td>
<td>0</td>
<td>0</td>
<td>Y</td>
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Other notes and observations

ttom of field
se, grazed
r and channel formation
Full observations from field surveyed in northern Jordan, April 1999.

Table C: Fields with slope angles >3.5 degrees

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Summary statistics in presence of rills

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<td>All down-slope fields</td>
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<tr>
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<td>All fields &gt;3.5 deg</td>
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Appendix F: Field observations for verification of the erosion model.
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<th>Crust cover (std dev)</th>
<th>Presence of pedestals (%)</th>
<th>Mean stoniness (std dev)</th>
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| 7.1 N               | 23.0                      | 9.1                     | <1                  | Y sedimentation and buried stones, more cru |
| 23.6 N               | 1.8                       | 2.0                     | 0                   | Y rill initiation, sediment in furrows |
| 23.3 N               | 17.0                      | 7.3                     | <1                  | N none |
| 18.0                 | 13.9                      | 6.1                     | 0.0                 | 2 of 3 |
| 7.7                  | 8.9                       | 3.0                     | 0.0                 | 66% |

| 14.1 N               | 14.2                      | 8.6                     | 0                   | N none |
| 32.1 N               | 15.5                      | 7.2                     | 0                   | N none |
| 21.9 N               | 12.0                      | 5.4                     | 0                   | Y rill from lowest furrow which gathers water |
| 22.7                 | 13.9                      | 7.1                     | 0.0                 | 1 of 3 |
| 9.0                  | 1.8                       | 1.6                     | 0.0                 | 33% |

| 2.2 N                | 14.9                      | 7.3                     | 0                   | N sediment washed from this field into one be |
| 3.5 N                | 26.0                      | 12.4                    | 0                   | Y rill initiation near top of field, sediment accu |
| 2.9                  | 20.5                      | 9.9                     | 0.0                 | 1 of 2 |
| 0.9                  | 7.8                       | 3.6                     | 0.0                 | 50% |
Other notes and observations

cumulation at base, rill initiation at base of field

sting at bottom of field because of silt accumulation

from above, extends >100m into next field, 110cm wide & 20cm deep

ear it

umulation at base
<table>
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<th>Field number</th>
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<th>Min. Predict soil loss</th>
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<th>Slope length</th>
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<th>Down slope</th>
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Appendix G: Predicted soil loss values from 47 sites visited in the field