GIS MODELLING OF LAND DEGRADATION IN NORTHERN-JORDAN USING LANDSAT IMAGERY

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ABSTRACT:

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. 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), and TM (28. 8. 1992). Mapping of vegetation cover was carried out by applying TM-Linear Mixture Modeling 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 predicts 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.

The study is not intended to present detailed or semi-detailed results, with the use of Landsat 30-meters spatial resolution images covering an area of 600 km^2, the model defines endangered areas, further detailed studies needs to be conducted for specific areas.

1. INTRODUCTION

Jordan is situated in the dry region of the eastern Mediterranean Sea. Its area approximates 89, 000 sq. kilometres. Of which 91% is classified as arid land, where the annual average rainfall rarely exceeds 200 mm/y. Its dry climate prevents the expansion of its agricultural land to new areas resulting in more pressure on the exiting agricultural land. Many factors contribute to the increase in this pressure, Inter alia, land fragmentation, urbanization, intensive irrigation, and absence of land use policy.

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.

The use of remote sensing and GIS technologies has proved successful in many fields of natural resources management. Its synoptism and large area extent as well as the ability of GIS to collect store and manipulate various types of data in a unique spatial database, helps performing various kinds of analysis and thus, extracting information about spatially distributed phenomena.

The Revised Universal Soil Loss Equation (RUSLE) was used to build a raster GIS-based model of soil loss by water in the study area. Input factors were calculated separately and stored as raster layers in the GIS. They were then combined in the GIS model to calculate the soil loss for each cell in the study area for the years 1972 and 1992. The predicted soil losses were checked against field observations made at the end of the 1998/99 wet season. An increase of the amount of soil losses between 1972 and 1992 is demonstrated, an evaluation of the accuracy and limitations of the model are presented in this paper.

2. STUDY AREA

The study area (shown on Fig.1) 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. A shift in lifestyle from a traditional nomadic to a more settled population practicing irrigated agriculture is being occurred in this area since the late sixties. Land is cleared of basalt boulders and stones, and then is used for irrigated agriculture. This increases soil aggregate breakdown, leads to surface sealing, and increases sheet wash by both wind and water erosion resulting in the reduction of topsoil fertility and loss of land productivity (Kirk, 1998a).

Rainfall pattern in the study area is illustrated by data analysis from the rainfall stations at Umm al-Quttayn (in operation since 1947) and Dayr al-Kahf and al-Aritayn (in operation since 1963). Most precipitation there falls between October and May. 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. 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. Consequently, 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).

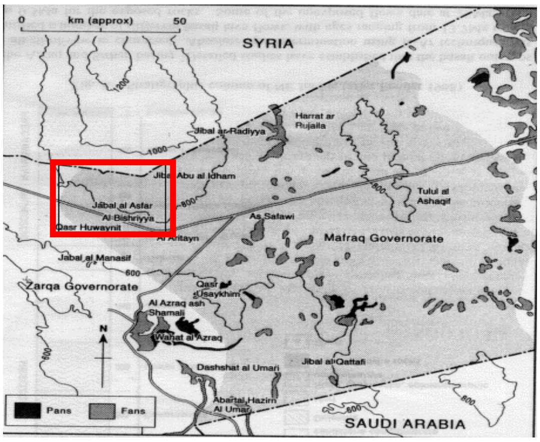

Figure 1: The location of the study area is shown in red.

Finally, soils of northern *Badia* are almost entirely formed as a result of basalt weathering (e.g. Alhomoud *et al*., 1996). Although, Kirk (1998a) suggests that the fabric of the soil is dominated by parent materials of aeolian origin.

3. GIS-BASED MODEL OF SOIL LOSS

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. 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} (Nearing *et al*., 1994).

This paper uses the RUSLE (Revised Universal Soil Loss Equation) predictive empirical model, to predict annual soil loss from agricultural lands (Wischmeier, 1978; Weischmeier and Smith, 1978; Renard *et al.,* 1994).

The **RUSLE** can be expressed as follows:

$$\mathbf{A = R\ K\ L\ S\ C\ P} \qquad \mathbf{(1)}$$

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

3.1 Calculation of the RUSLE Factors

3.1.1 Rainfall Erosivity Factor (R): As none of the three rainfall stations in the study area records rainfall intensity, Fournier's index, p^2/P, developed by Arnoldus 1977 -which uses only average monthly (p) and annual precipitation (P), was used instead. The relationship (in metric units) was:

$$R = 1.735*10(1.50 \log \sum p^2/P - 0.8188) \qquad (2)$$

Summed for each of the 12 months of each year.

The estimated R factor values for the three stations were calculated using formula (2) and were found to be equal to 22 (Umm al-Quttayn), 20 (Dayr al-Kahf), and 16 (al-Aritayn).

3.1.2 Soil Erodibility Factor (K): The K factor defines the resistance of the soil to both detachment and transport. 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 erodibility nomograph (Wischmeier, 1978), was used to determine the K-values (Table 1)

Soil Unit	K-value
BIS(Bishriya)	0.35
FAR(Mafarid)	0.34
SAB(Sabha)	0.31
THA(Ramtha)	0.32
WAY(Huwaylat)	0.39
ZUM(Zumaylat)	0.40

Table 1: The K factor values for soil units in the study area.

3.1.3 Topographic factor (LS):

Four 1:50,000 topographic map sheets were digitized. A DEM was generated using TIN and GRID Modules. The resulting layer was exported to ERDAS Imagine to generate a slope layer. The slope image was classified into six classes using Model Maker. Slope length was calculated by combining the slope angle thematic layer with a hydrological layer containing the wadi network for the study area.

The LS factor was calculated using the tables produced by Renard et al. (1994) for the RUSLE in conjunction with the thematic slope layer. The results of these operations are presented in Table 2.

Slope class (%)	0-3	3.1-6	6.1-10	10.1-15	15.1-25	>25.1
Mean L (m)	177.16	71.62	50.01	51.67	56.75	59.03
Mean LS, rangeland	0.29	0.78	1.28	2.39	4.39	10.00
Mean LS, cropland	0.37	0.93	1.48	2.69	5.04	11.86

Table 2: The estimation of LS values for each class present in the study area, for each type of land use.

3.1.4 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 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.

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 3.

Type of land use	≤ 20%	≤ 40%	≤ 60%	≤ 80%	≤ 100%
Irrigated fields	0.48	0.37	0.22	0.12	0.04
Rangeland	0.35	0.20	0.12	0.062	0.027

Table 3: Estimation of C values for vegetated fields and rangelands by vegetation cover percentage classes.

A close inspection of the NDVI statistics revealed that for the dry season 1972 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 1972 image, and this value was used in the soil loss model (Wischmeier 1978).

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.

3.2 Maps of Soil Losses

The GIS input layers discussed are listed in Table 4. 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.

Layer number	Description
1	Rainfall erosivity layer (R).
2	Soil erodibility layer (K).
3	Topographic layer (LS_C) for cropland.
4	Topographic layer (LS_R) for rangeland.
5	Vegetation cover layer (C_{92}) for bare fields, for 1992.
6	Vegetation cover layer (C_{92}) for vegetated fields, for 1992.
7	Vegetation cover layer (C_{92}) for rangeland, for 1992.
8	Vegetation cover layer (C_{72}) for bare fields and rangeland, for 1972.

Table 4: Thematic input layers to the GIS-based erosion model.

Change in vegetation cover proportions 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 the years (1972 and 1992). These runs were based on the following combinations of GIS layers (layers refer to Table 4):

Soil loss maps for 1972:
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

The results of the model runs, as soil loss maps for each year are shown in Figures 2 and 3. These maps were classified using Model Maker, and 11 soil loss classes were produced.

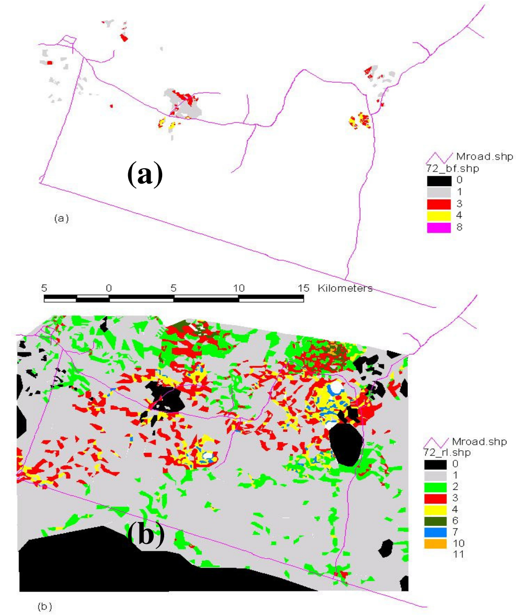

Figure 2: (**a**) Predicted soil losses from rain-fed fields for 1972. Black areas are masked out areas of basalt, built-up areas and rangeland areas. (**b**) Predicted soil losses from rangeland for the same year. Black areas are masked out built-up, basalt and cultivated areas.

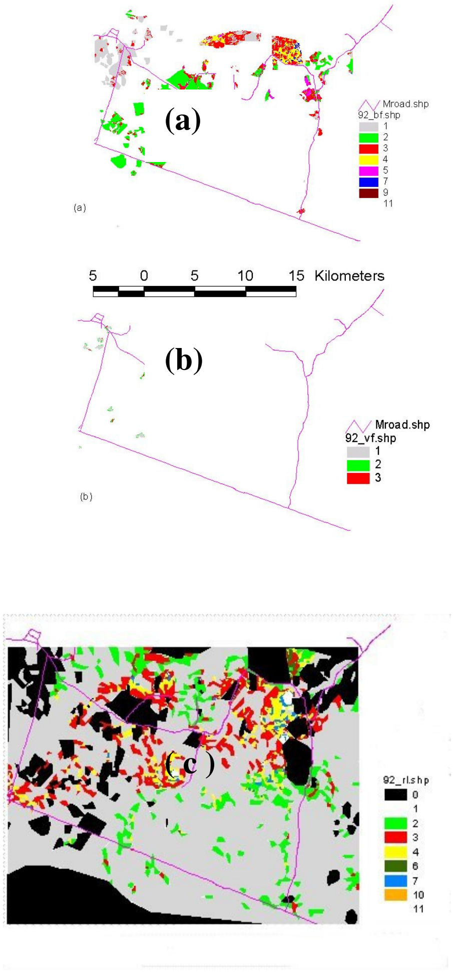

Figure 3: (**a**) Predicted soil losses from rain-fed fields for 1992. Black areas are masked out areas of basalt, built-up areas, rangelands and irrigated cropland. (**b**) Predicted soil losses from irrigated cropland in 1992. Black areas are masked out areas of basalt, built-up areas, rangelands and rain-fed fields. (**c**) Predicted soil losses from rangeland for the same year. Black areas are masked out built-up, basalt and cultivated areas.

3.3 Verification of the Soil Loss Maps

3.3.1 The Verification Data Set: It was not possible to validate the predicted soil loss maps for 1972 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 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.

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 (Plates 1, 2, 3 and 4). Furthermore, it has been found that the least ambiguous evidence of soil erosion by water in the fields was rilling (Plate 1). Therefore, most of the subsequent model verification relies on rilling as a surrogate for 'observed soil loss'.

Plate 1: Rills formation by the coalescence of two plough furrows.

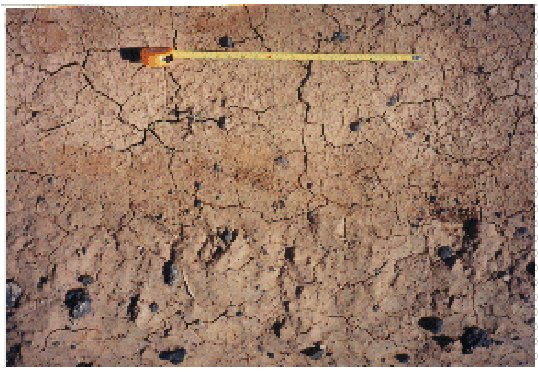

Plate 2: A trail of eroded sediment across a cracked silt-rich surface.

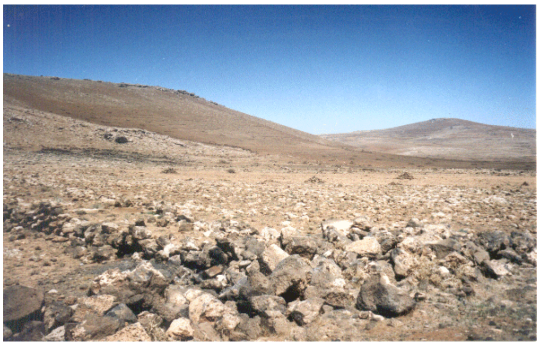

Plate 3: The fields on this hill, which is located in the mountainous area just to the south of the Syrian border, were the steepest surveyed in the verification exercise. The steepest slope angle was 6.1^{o}. These fields probably represent the steepest in the entire study area, and have only been brought into cultivation in the last 3-4 years.

Plate 1: 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.

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. A Chi-squared analysis was applied to contingency tables of predicted soil losses for categories of individual fields and evidence of rilling. Chi-square test was run on the above contingency table after combining the categories. 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. 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.

3.3.2 Quality Assessment:

R factor. The rainfall station density in the study area (1 station per 200 km^2), though low, meets the WMO (World Meteorological Organization) standard of 1 station per 250 km^2 (Shaw, 1983). 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.

K factor. The soil association maps were published by the Ministry of Agriculture of Jordan in 1994 at 1:250.000. They were produced in digital form by the same ministry in cooperation with the Royal Jordanian Geographic Center.

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.

C factor. For mapping the land cover in the 1970's, Landsat Multi-spectral Scanner (MSS) data (56×79 m^2) were available. However, land cover mapping for the 1990 year was carried out by the processing of finer resolution Landsat Thematic Mapper (TM) data (30×30 m^2). 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.

4. CONCLUSION

A visual analysis of the series of maps of soil losses 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. It is likely that these numbers lie within the likely error margin of the modeling.

Verification of the model was attempted by comparing predicted soil losses with quantitative and qualitative data obtained from 47 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: 1) time lag between the prediction of soil losses (1992) and the field measurements (1999), 2) positioning errors surrounding the geographical locations of the fields and the pixels in the raster GIS, 3) potential mismatches between field sizes and pixel size, 4) 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.

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