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A GIS-based Methodology for Soil Degradation Evaluation

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ABSTRACT

This paper reports on an attempt to delineate soil degradation areas in Aarsal, a dryland zone in Lebanon. The study area covers 360 km^2, including highlands and steppes. With limited data which included soil map, contours map, and land cover map, we have created soil degradation assessment maps based on three approaches: drainage density, drainage texture, and factorial scoring of the main soil degradation agents: slope, grazing, and land use. The three methods classified the project area predominantly in the low and very low soil degradation categories. There was little overlap between the three maps due to the use of different data sets, indicating different soil degradation mechanisms. A combined soil degradation assessment map, joining the data from the three assessments, was produced and successfully field checked. The approach adopted in this paper, which consists in combining different data sets, requires limited field measurements, and can provide reliable indicators of soil degradation risk. It appears, therefore, to be appropriate for regions of similar environmental and economic characteristics, especially that it may be adapted to include site-specific parameters.

INTRODUCTION

Poor agricultural practices, overgrazing and deforestation over the past three millennia have resulted in widespread degradation of the land resources of the Middle East (Dregne, 1992, Lowdermilk, 1953). Current global and regional economic changes are inducing further pressure on the land. There is a pressing need for action to mitigate land degradation.

Land degradation results from the interaction of human activity, such as agriculture, with the biophysical and socio-economic characters of a specific ecosystem. When studying large areas, it is necessary to identify zones where urgent intervention is required from those which are stable under the current land use. Achieving this complex task requires 1) the selection of land quality indicators appropriate to the natural and socio-economic environment, 2) the use of a flexible methodology that easily allows a number of permutations and "what-if" scenarios, and 3) replicability and moderate cost.

Geographic Information Systems (GIS) are ideal for this endeavor, as they offer the speed, flexibility and the power to integrate large quantities of data. They have been used in a number of similar endeavors related to natural resource management (Theocharopoulos et al., 1995; Davidson, 1992). However, the accuracy and relevance of the information produced by GIS is only as good as the data sets available. In developing countries, especially in remote, marginal, and poor areas, data is often inexistent.

This paper reports on an attempt to develop a GIS-based methodology for the evaluation of the intensity of the soil degradation on land resources in an arid, marginal environment, in the locale of Aarsal, situated in the Eastern mountain range of Lebanon.

The specific objectives of this study are to:

1. Develop two generalized erosion hazard assessment maps based on drainage density and drainage texture.
2. Develop a soil degradation risk map based on the factorial scoring of the dominant risk factors.
3. Integrate the maps to produce a generalized soil degradation assessment map.

MATERIALS AND METHODS

Study location

Aarsal is a large highland village (pop. 36,000) on the western slopes of the Anti-Lebanon mountains (mean annual rainfall 250 mm). The total village land area covers 36,000 ha, and is divided into four agroecological zones:

1) <u>The High Jurd</u> lands which used to be marginally cultivated with cereals and pulses and summer grazed, are being massively converted to stone fruit orchards with an estimated 2 million trees planted in the past 20 years.
2) <u>The Low Jurd</u> lands that used to be cultivated with cereals and grazed by flocks of small ruminants (predominantly sheep).
3) <u>The Valleys</u>, mostly planted with grape vines. The rainfall and snowmelt from the highlands, especially the Low Jurd, feed into the Valleys as seasonal streams.

<u>The Sahl Lands</u> (plain) surrounding the village are the wintering site for flocks of small ruminants (predominantly sheep) maintained on crop residues and feed concentrates.

Soil variability in Aarsal is limited due to the relatively homogeneous parent rock formation (Cenomano-Turonian hard limestone). The soils of the highlands are predominantly xeralfs, while those of the steppe are predominantly haplocambids.

Geographic Information System

The GIS used in this study is the PC Arc Info platform (ESRI), running on a Pentium II, 200 MHz, 32 Mb RAM computer, with support from the Arc Info platform running on a SUN microstation for complex data treatment.

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Thematic coverages

The following coverages were used:

The contour Map and slope classes Map

The contour map (50 m intervals) was manually digitized from the 1:100,000 maps developed by the Department of Geographic Affairs of the Lebanese Army (DGA) in 1962. The slope map was derived from the contour map of Aarsal using ArcTIN and DTM, by generating a TIN from which a grid was derived. The grid was then converted to slope polygon coverages with the desired slope classes in Arc View format.

The Land Cover Map

The land cover map was derived from Spot Multispectral Satellite image (20 m x 20 m resolution) that was taken in August, 1992. This image was then processed using the ERDAS Imagine software. Ground truthing was carried out in all accessible areas. Five land cover classes were identified based on the purpose of the project. These are: Annuals, Grazing/Old Fallow, Fruit Trees, Grapes, & Not Agriculture.

The Grazing Map

The grazing map of Aarsal was derived by monitoring and surveying the grazing patterns of sheep and goat flocks. The map includes information about the stocking rate and the grazing season.

The Rivers and Streams map

This map was manually digitized from the 1: 100,000 scale maps of the Lebanese Army and includes two waterways classifications: Main and Temporary. These streams were reclassified into three hydrologic classes (secondaries, tertiaries, and mains) and were coded accordingly.

Procedure application

Factorial soil degradation risk map

The approach is adapted from the procedure for land evaluation in arid grazing ecosystems of the Food and Agriculture Organization of the United Nation (FAO) (Breimer *et al.*, 1986). It is a stepwise approach in which 1) the relevant land use types (LUTs) are determined, 2) the land characters of relevance to the LUTs are defined, 3) a subrating system is developed for each land character, 4) a final evaluation is obtained by the summation of the different subratings.

The approach was adapted to the data sets available in this study and to the specific environmental conditions of the project area. Rainfall and soil characteristics were not considered as rainfall data was only available for one location over the whole project area, and the level of detail in the available reconnaissance soil map did not show significant variation in soil types. Thus, the coverages that were used in the production of the factorial soil degradation analysis map were the slope, the grazing pattern and intensity, and the land use. These represent the dominant biophysical soil degradation factors in Aarsal.

This approach of classification of areas at risk with 3 parameters representing the resource base, cropping and livestock systems appears to have been successfully used in degradation assessment in drylands (Mati et al., 1998).

Development of the rating scheme

Sub-rating schemes were developed for land use types, grazing patterns and slope classes. Ratings ranged from the lowest hazard (0) to the highest (10) and were allocated based on measurable parameters (see Table 1), literature reports and expert knowledge.

Rating soil degradation intensity associated with specific land use classes

Farmer practices were surveyed in order to produce a comparative assessment of the soil degradation level they will pose on the land resources. The approach we adopted is similar to that of Mellerowicz et al. (1994) who used information about cropping support practices to determine the CP (crop/practices) factors in the USLE (Universal Soil Loss Equation).

The most critical determinants of soil degradation in the different LUTs of Aarsal were found to be associated with agricultural practices related to land preparation. Tillage practices are most intensive in fruit tree orchards, followed by grape vine fields, then annual field cropping and finally fallow. Details can be found in Table 1.

These inferences were confirmed by erosion measurements in 100 m^2 plots using the pin method, in which 300 mm iron pins are driven into the soil so that the top of the pins can give a datum from which changes in the soil surface levels can be measured (Hudson, 1993). The pins were installed to a 2 m^2 grid and replicated twice in each land use type in 3 ecozones. Results from one year do not constitute conclusive evidence (Table 1), but showed that our ranking was adequate.

Table 1. Degradation risk associated with different land uses in Aarsal.

Land use	Risk factors	Absolute Risk level	Rating
Fruit trees	2-3 tillage operations per year, 20-25 cm deep, mostly mechanized, and up and down the slopes. No weeds or other surface cover. Trees are deciduous. Estimated erosion rate: 2.6 t/ha/yr.	Moderate	5
Grape vines	2 tillage operations per year, shallow to protect roots. Very little protection provided by the vines due to local pruning method. Estimated erosion rate: 1.8 t/ha/yr.	Moderate-low	4
Annual field crops	2 tillage operations per year, mostly animal driven. Good soil cover during winter. Estimated erosion rate: 0.9 t/ha/yr.	Low	3
Old fallow	No agricultural activity. Estimated erosion rate: 0.7 t/ha/yr.	Very low	1

Table 2. Subrating grazing pressure and slope characteristics

Stocking rate (head of small ruminant/ha)	Degree slope	Rating
<0.5	0-1	1
	1-2	2
0.5 - 1.5	2-4	3
	4-6	4
	6-10	5
	10-16	6
	16-21	7
1.5 -<5	21-25	8
≥ 5	>25	10

Rating the grazing activity

Recent research has shown that the maximal stocking rate that can be allowed in Aarsal for sustainable management is around 1 head of goat of sheep per ha (Hamadeh, 1999). Subratings were developed accordingly (Table 2).

Rating the slope characteristics

The slope intervals were selected after reviewing a number of sources summarized in Morgan (1986). The subratings appear in Table 2.

<u>Factorial analysis</u>

The three themes were overlaid and their scores were added up to form a final score map coverage. The resulting map classified the polygons created by the overlay into five categories of soil degradation: Very High, High, Moderate, Low, and Very Low.

Drainage density

Drainage density is the length of primary streams per unit area and is a commonly used index of erosion intensity in generalized erosion hazard assessment (Morgan, 1986). A field survey showed that the number of first order streams could be estimated by multiplying the number of secondary streams by a factor of 2.5, which is the mean bifurcation ratio. This value is the mean of 31 direct measurements in locations throughout Aarsal's ecozones.

The following procedure was used to generate the drainage density map:

A grid coverage (1 km^2 grids) was generated and clipped based on the base map. The waterway map was overlaid on the grid coverage. Finally, statistics were performed to calculate the sum of secondary streams per unit area (m/m^2).

Based on Mikhailov (1972) and Iana (1972), arbitrary values of $0.001 mm^{-2}$ and $0.006\ mm^{-2}$ (based on secondaries) were selected to represent "Low" and "Very High" erosion risk. The grid cells were classified into the same risk categories as the factorial map.

Drainage texture

Drainage texture, the number of first order streams per unit area, is another commonly used index of erosion intensity in generalized erosion hazard assessment (Morgan, 1986). The procedure is essentially the same as for drainage density except that statistics are performed to calculate the total number rather than the length-sum of the secondaries per unit area. An arbitrary value of 10 was taken to separate areas of "High" and "Moderate" erosion risk.

Matching the three assessment methodologies

The factorial-scoring map (FS) was matched with the drainage density map (DD) and the drainage texture map (DT) in order to determine whether the two approaches will identify the same high hazard/soil degradation areas. Fraser et al. (1995) use a similar method for comparing land cover classifications from different remote sensing sources.

The GIS procedures adopted were based on class selective matching. The proportion of each soil degradation class in a selected map that is matched by the same class in another map calculated by selecting each soil degradation class from the two maps, intersecting the resulting coverages and calculating the area of the overlap.

Combined soil degradation evaluation map

The factorial soil degradation assessment map, the drainage density map and the drainage texture maps were combined in order to provide a complete picture of soil degradation in the project area. In the combination procedure, the highest soil degradation rating of overlapping polygons was considered to be the actual soil degradation rating of the resulting land polygon (precautionary principle).

Validation by ground truthing

The outcome of the combined soil degradation assessment map was validated by ground truthing in 5 quadrants. The 1 km^2 quadrants were randomly selected from a grid applied onto the map. Their location in the field was identified using a Global Positioning System. They were then field surveyed and land degradation was described in the various landforms and LUTs of the quadrants areas using the FAO soil degradation-mapping framework (Breimer *et al.*, 1986).

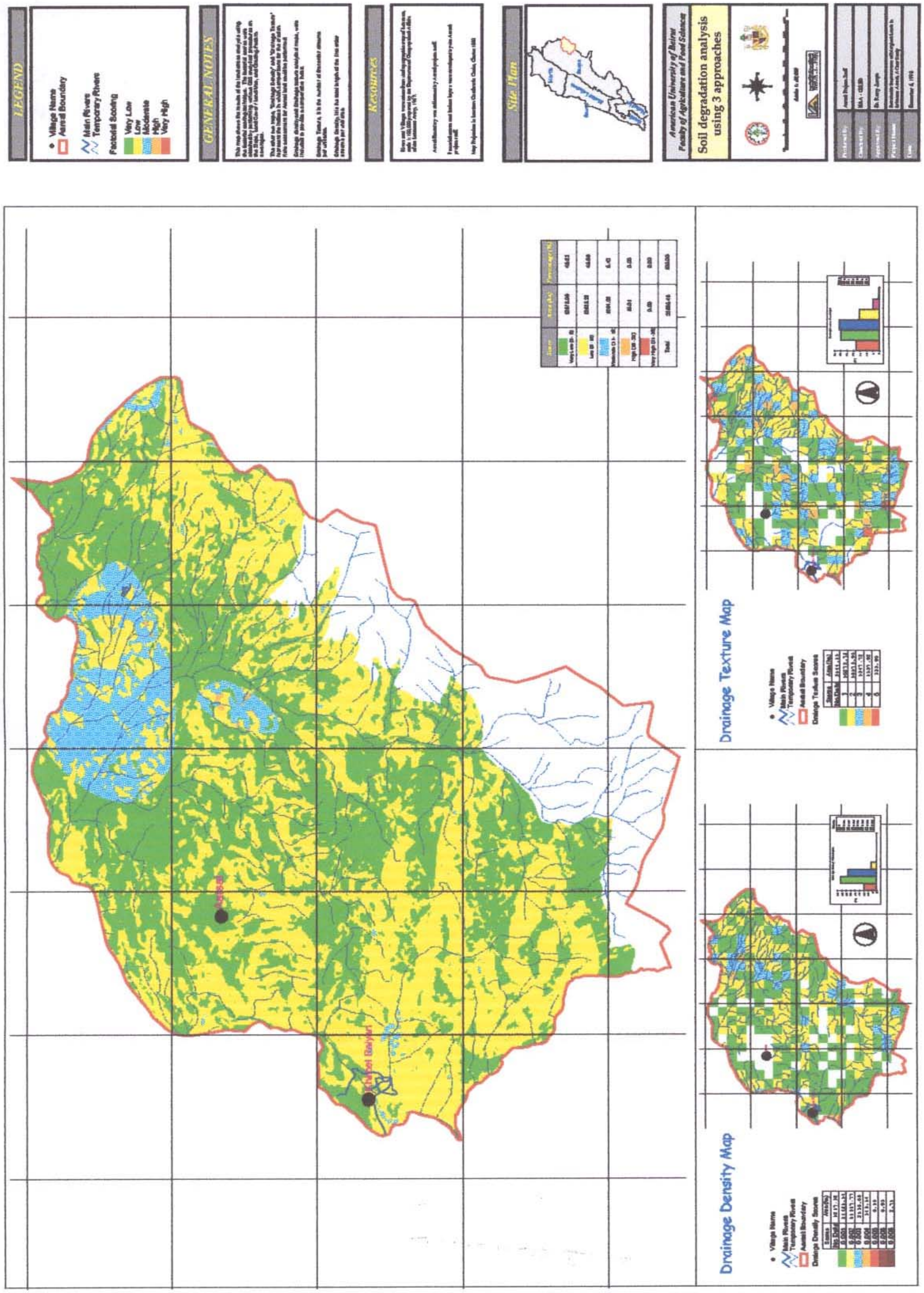
RESULTS AND DISCUSSION

The summary of the results of the assessment using the three methods appears in Table 3 and in Map 1. The factorial soil degradation assessment resulted in the classification of over 90% of the area in the low and very

Table 3. Summary of land degradation risk assessment using 3 methodologies and their combination, in percent of the total project area (29,000 ha)

Stress class	Factorial scoring	Drainage density	Drainage texture	Combined
Very high	0	0	1	1
High	0	0	5	6
Moderate	6	7	15	25
Low	47	33	24	50
Very low	47	60	50	18
Total	100	100	100	

Map 1. Soil degradation analysis using three approaches (drainage density, drainage texture, and factorial scoring) in the locality of Aarsal, Lebanon.



low soil degradation categories. Although this may seem counter intuitive, considering the desert-like aspect of the land, this is explained by the fact that due to the “low-input” agricultural practices, overgrazing is the main soil degradation agent on the land.

The main soil erosion risk in the mountainous areas of Aarsal would, in theory, be high rainfall intensity on steep slopes. However, annual rainfall is very limited, and, although data from various ecozones is unavailable, local knowledge indicates that it is similar over the whole area, except in the high elevation where precipitation is mostly as snow. This would have little additional effect on soil erosion, thereby limiting the effect of the slope. This assumption is probably correct except in two situations:

- In the case of severe, short duration storm events, which produce severe rill and gully erosion. There is no data available on the intensity and duration of these storms, which appear to have a recurrence period of 10 years. From local reports and observed erosion pattern, it appears that these events can be very damaging, which explain the severe gullying observed in the mountains, and the size of the streams that cut across the otherwise desert-like Eastern Zone.
- Where mechanical disturbance, such as keeping herds for prolonged periods on a limited area. This is, however, accounted for in the grazing patterns coverage analysis.

These remarks are confirmed by the findings that the moderate and high soil degradation level areas are those where the stocking rate is highest, independently of the slope and the land use

Our survey revealed, however, that grazing has become geographically very limited, as herd movement is declining due to the availability of hand feeding. Moreover, as herd size has been declining (from 90,000 to 60,000 over the past 40 years) (Hamadeh, 1999), this would results in further alleviation of the impact of overgrazing. It is to be noted, however, that this situation may be only temporary. Indeed, stone fruit production in the orchards is starting to shift towards a higher-input system. This will lead to the change in the land degradation risks imposed by this land use. The methodology used in this study can, however, readily accommodate this change and a new factorial map may be produced.

In order to account for the effects of storms, an indirect approach was selected. The impact of storm events on a specific area in indicated by the marks they leave on the land. The study of drainage density (the total length of streams per unit area), and of drainage texture (the density of streams per unit area) allows us to obtain an indication of this effect.

The map of drainage density classified over 90 % of the project area in the low and very low risk categories. The drainage texture assessment resulted in 80% of the area classified in the low and very low risk categories, while a significant proportion (15%) was classified in the moderate risk class. The match in risk zoning between the different approaches was limited (Table 4). Lack of correlation between the drainage texture and the drainage density was reported by Morgan (1976) in generalized assessment studies in Peninsular Malaysia. Drainage density indicates transport of runoff from moderate, regular rainfall, while drainage texture indicates the response to seasonal rainfall regime with rainfall of greater intensity (gully density). The latter is closer to the rainfall regimes in Aarsal. Moreover, the factorial scoring map delineates areas which are currently under soil degradation, mostly from anthropic origin, while the drainage maps indicate the combined effect of slope, rainfall regime and soil.

The combination of all three assessments, each representing a different soil degradation mechanism, is therefore expected to produce the most “realistic” results (see map 2 and Table 3), with nearly half the area in the “moderate” to “very high” classifications. The combination of the three maps allows, therefore, a holistic perspective on the soil degradation on Aarsal. The drainage maps offer an insight on what has happened (past effects) while the factorial analysis map addresses the current status of the land. Moreover, as the different maps use different data sets, it is possible to combine them without producing any redundancy.

Validation by ground truthing in 5 randomly selected locations indicated that the delineation was close to the actual field situation. Table 5 shows the results of the field investigation. The heaviest soil degradation was observed to take place on the rocky summits, where grazing is the dominant form of land use, and in the poor pastures of the Eastern ecozones (Tahoun el Hawa and Khirbet Daoud quadrants). The other land uses show some signs of soil degradation, but this is generally moderate of low on most of low soil the quadrant’s area. Although the number of quadrants is small and its statistical representability may be

Table 4. Matching factorial scoring map (FS) with drainage density map (DD) and drainage texture map (DT)

Stress class	Total area FS	Total area DD	Total area DT	FS/DD Match (%)	FS/DT match (%)	DD/DT match (%)
Very Low	13578.08	16855.95	14493.18	55.73	49.21	67.91
Low	13538.28	9666.36	8501.96	32.56	31.51	36.13
Moderate	1864.08	2123.36	4426.90	10.13	8.78	13.76
High	16.01	346.54	1318.29	3.75	0.00	0.00
Very High	0.00	4.21	256.06	0.00	0.00	0.00
Total	28996.45	28996.42	28996.40	41.95	38.32	52.53

Table 5. Results of the field investigation of soil degradation levels in 5 quadrants in Aarsal

Landform	Quadrant area (%)	Land use/land cover	Soil degradation*
Quadrant 1: Bdeirieh			
Rocky hill top	20	Small shrubs, grazing	Moderate Wt, f, g
Terraced fields	40	Stone fruits	SH
Catchment floor	30	Stone fruits	SA
Quadrant 2: Wadi el Hosn			
Rocky hill top	25	Sparse vegetation	Wt-Wd, f, g
Hillside field	45	Old fallow	Moderate Wt, f, a
Cuvette (wadi floor)	20	Grapes	SA
Quadrant 3: Tahoun el Hawa			
Alluvial plain	30	Barley, vines, grapes fields	SA, Cn
Alluvial plain	50	Steppe-pastures	Pc, Et, f, g
Hillside	10	Grazing	Wt, f, g
Flood route	10	Road	Extreme Wd
Quadrant 4: Khirbet Daoud			
Alluvial plain	70	Grazing	Mild Wt, Pc
Hillside	30	Grazing	Wt + gullies, f, g
Quadrant 5: Rahweh			
Plain/large cuvette	60	Stone fruits	SA
Hillside	25	Stone fruits	Mild Wt, a
Rocky hilltop	15	Grazing	Wt, g, f

******Water erosion:* **Wt= loss of topsoil, Wd= terrain deformation.** ***Wind erosion:*** **Et=loss of topsoil. Stable terrain: SA: under agriculture, SN: under natural conditions, SH: stabilized by human intervention.** ***Chemical deterioration:*** **Cn=loss of nutrients and organic matter.** ***Physical deterioration:*** **Pc=compaction/crusting.** ***Causative factors:*** **f=deforestation and removal of natural vegetation, g=overgrazing, a=agricultural activities.**

argued, it conveys, however, sufficient information to confirm the output of the analytical procedure adopted for mapping soil degradation on the whole territory of Aarsal.

CONCLUSION

It may be deduced, therefore, that the Northern part of the Eastern Ecozone is the "problem zone" of Aarsal, as both drainage density and soil degradation analysis tend to demonstrate. In addition, the drainage maps show the location of the areas where flash storms will be most damaging, and where structural interventions may be needed. Orchard expansion must be avoided in these areas.
The current soil degradation levels/erosion risks appear to be less extreme than the landscape would indicate, with overgrazing in overwintering sites (i.e. practicing a poor land use on a vulnerable site) as the biggest problem. The methodologies adopted herein complement each other, and their combination provides an assessment of reasonable accuracy. While the shortcomings of the factorial methodology are full acknowledged (it is arbitrary, not interactive, and there is no weighting of the different factors) we believe that it is a workable, practical approach, especially in view of the complexity and unreliability of land degradation measurement techniques (Barrow, 1991).

It appears that it is technically possible to carry out generalized and semi-generalized land degradation hazard assessment with limited georeferenced data sets. However, the adoption of a GIS based procedure requires a significant capital investment in material and human resources. Our initial investment of nearly $20,000 was barely sufficient to set up a PC-based system and provide training to the personnel. At least 6 months in addition to the training provided by the ESRI agent upon purchase of the system were required for developing data entry and analysis skills. Similar limitations were also reported by Theocharopoulos et al. (1995) for soil surveys using GIS, and by Harris et al. (1997) who compared manual and GIS-based systems for riparian restoration projects. However, the digital data that was produced is now available for other usages and is currently being used to develop the agroecological zoning of the area in collaboration with a number of international donors and research agencies. Thus, even though the initial cost is relatively large, we believe it is a sound investment as the digital data may have multiple users, which increases the return on the initial investment.

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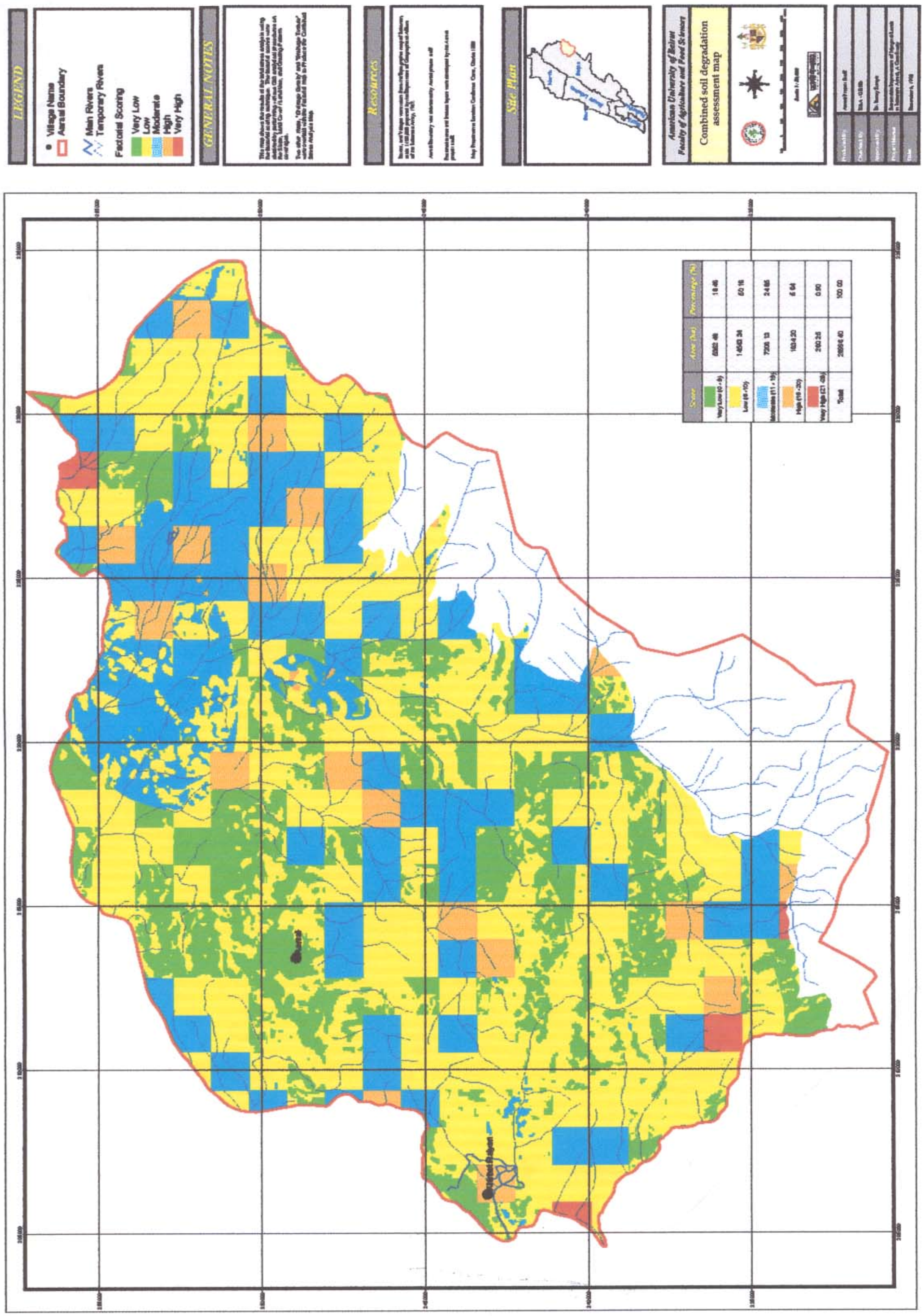
Map 2. Combination of the three-soil degradation analysis approaches into one combined soil degradation assessment map.



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