

Desertification Hazard in a Mountainous Ecosystem in the High Atlas Region, Morocco

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Abstract: Soil erosion is a major threat to the resource soil. This is true especially in developing countries where the loss of top soil reduces soil fertility and diminishes the living conditions of the people. Objective of this 3-year study was to assess the long-term average soil loss in the Ouneine watershed in the High Atlas Mountains in Morocco using the RUSLE model. The investigation area is a remote valley of ca. 200 km² and is located appr. 100 km south of Marrakech. The altitude ranges from 832 m to 2,746 m. Average annual rainfall of ca. 300 mm is unevenly distributed with highest amount between December and March and high intensity rainstorms in spring.

A soil map was developed based on field survey, lab analyses and geology. Additionally investigations have been carried out in the field related to soil surface cover (rocks and plant residues). This information was used to derive a soil erodibility map. Precipitation was measured at nine sites in different altitudes. Rainfall erosivity was calculated from two station equipped with automatic rain gauges. Rainfall erosivity at other areas was derived corresponding to amounts of rainfall. The topography factor (LS) was obtained from an existing digital elevation model. A vegetation map was created from satellite images based on ground truth data.

In the watershed average yearly soil loss ranges between 0 and 7,000 t • ha⁻¹ depending on land use and condition, topography and rainfall with an average soil loss in the whole watershed of 33.7 t • ha⁻¹ • yr⁻¹. Soil conservation strategies are recommended to improve the conditions in the watershed.

Keywords: soil erosion, soil degradation, simulation model, RUSLE

1 Introduction

Soil erosion is a major threat to the resource soil. This is true especially in developing countries where the loss of top soil reduces soil fertility and diminishes the living conditions of the people. The trigger for accelerated erosion in arid and semi-arid countries is loss of vegetation cover. This can be caused by long-term climate change or more immediately as a result of inadequate land management like deforestation or overgrazing. Loss of vegetation cover exposes soils to wind and water erosion, loss of soils decreases the potential for vegetation production. Although the precipitation in arid and semiarid countries is not high, the erosion is largely the result of infrequent but heavy rainfall events with high intensities and high erosivity. Objective of this 3-year study was to assess long-term average soil loss in the Ouneine watershed in the High Atlas Mountains in Morocco and to develop soil conservation strategies.

2 Materials and methods

2.1 Description of the ouneine watershed

The investigation area is a remote valley of ca. 200 km² located appr. 100 km south of Marrakech

(Fig. 1). The altitude ranges from 832 m to 2,746 m. Despite the proximity of the Sahara the regional climate of the north western part of Africa is of quite Mediterranean character. Due to the relative high latitude significant cold and hot seasons occur. Average annual rainfall of ca. 300 mm is unevenly distributed with highest amount between December and March. Rain falls mostly within relatively short time with high intensities. During the rainy period floods are common. In the mountainous regions of the Atlas these heavy rainstorms cause severe erosion. A lot of rills, gullies and mega-gullies indicate the effects of these rainstorms. Snowfall is essential for the ecosystem of the Atlas region. The slowly melting snow provides infiltration to the joints and clefts of the bedrock. Therefore the mountains act like seasonal storage tanks and provide spring-water during summer.

The population of 10,000 Berber lives in 20 villages. Only a very small part of the area which is terraced and irrigated with spring water is used as cropland. The rest of the watershed is pasture and rangeland. The vegetation in these regions consists of aromatic and medical herbs, thujas, junipers and chestnut oaks with very sparse soil cover. The trees are used by the people as fire wood and for charcoal production leading to degradation of the native vegetation. This results in increased susceptibility for soil erosion by water and wind. Water requirements are met by springs and wells. Open channel systems provide the villages and agricultural used land with water. A traditional schedule for distributing the especially in summer scarce water has emerged over the centuries. Major agricultural areas can be found at the border of the central basin, where the proximity of springs allows cultivation on artificial bench terraces.

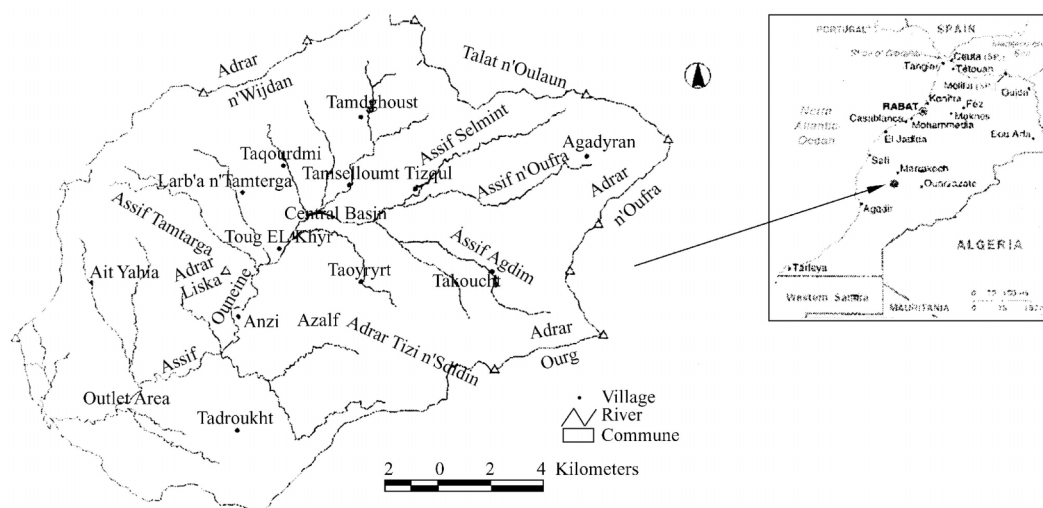


Fig. 1 Location of and situation in the Ouneine watershed

2.2 Description of the RUSLE model and used input parameters

For the assessment of spatial distributed soil erosion by water in the watershed the RUSLE model (Renard *et al.*, 1999) was used and combined with ArcView based on a 10 m × 10 m grid. This enables to analyze the spatial varying land surface (soil, slope, land use, vegetation,...) and rainfall characteristics.

2.3 R-Factor

To quantify the erosive force of the rainfall, eleven rain gauges were installed in different altitudes between 1,030 and 2,360 above sea level. Two of them were equipped with data logging systems for continuous registration (in 1 min intervals). Data from only two years were used to calculate the R-Factors. Rainfall kinetic energy (KE in $\text{MJ} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$) was calculated using following equation (Brown and Foster, 1987)

$$KE = 0.29 \{1 - 0.72 \exp(-0.05Im)\}$$

where I_m is the rainfall intensity in mm h^{-1} .

The R factor of a single rainstorm event was calculated by multiplying the kinetic energy of this rainstorm (KE) with its maximum 30 min intensity (I_{30}). When adding up all rainstorms of a year the R -factor was obtained. The calculated R -Factors of stations Ourg and Wijdan were used to derive relationships for the other stations based on annual precipitation P (in mm). Following relationship was found:

$$R = 0.13 \cdot P + 4.88 \quad (R^2 = 0.5001)$$

1999 and 2000 were extremely dry years with annual precipitation values of 370 mm and 204 mm, respectively. Calculated R -Factors in the watershed range from $23 \text{ kJ} \cdot \text{m}^{-2} \cdot \text{mm} \cdot \text{h}^{-1}$ to $57 \text{ kJ} \cdot \text{m}^{-2} \cdot \text{mm} \cdot \text{h}^{-1}$. With increasing altitude, precipitation as well as R -factors increase. Highest values are found in the northern and north-eastern part of the area.

2.4 LS-Factor

For calculation of the Topography-Factor (LS) the digital elevation model of the Ouneine watershed was used and combined with a GIS-procedure for automatically calculating the USLE LS -factor on topographically complex landscape units (Desmet and Govers, 1996). In a real 2D-application overland flow and resulting soil loss does not really depend on the distance to the watershed divide or the upslope border of the field, but on the area per unit contour length contributing runoff to that point. The chosen approach overcomes this problem by replacing the slope length by the unit contributing area. To determine the contributing area of a cell within a grid structure it is necessary to find within a moving 3×3 -submatrix, the neighbouring cell(s) to which the central cell is draining, and to determine which proportion of the total flow is transferred to each downslope neighbour.

The USLE2d software offers different algorithms to calculate the steepness factor S and the slope length exponent m in equation including originally LS equation developed by Wischmeier and Smith (1978), and equations of McCool *et al.* (1987, 1989), Govers (1991) and Nearing (1997). Mitasova *et al.* (1998) found a simpler, continuous form of equation for computation of the LS -factors for a grid cell.

When using the different algorithms different LS -values are obtained. The LS -factors calculated with Nearing vary from 0.1 in the flat areas of the valley bottom up to 3,329 for areas of flow accumulation. When using McCool's equation LS range between 0.1 and 5,787 and with Mitasovas equation between 0 and 5,787. Overall averages of the investigation area are 31.6 (Nearing), 28.6 (McCool) and 41.7 (Mitasova), respectively.

It must be considered that both the standard and modified equations can be properly applied only to areas experiencing net erosion, so the direct application of USLE/RUSLE to a complex terrain within a GIS is rather restricted. Depositional areas should be excluded from the study area because the model assumes that the transport capacity exceeds detachment capacity everywhere, whereas erosion and sediment transport is detachment capacity limited. The results can be interpreted as an extreme case with maximum spatial extent of erosion possible.

2.5 K-Factor

As the main part of the watershed is used as forest, rangeland and pasture, the change of soil condition due to farming practices is not relevant. Natural seasonal variations, mainly affected by freezing and thawing, are negligible since temperatures rarely fall under 0°C in winter. For these reasons an approach with a constant soil erodibility (K -factor) without any seasonal variations was chosen. Based on a created soil map, the erodibilities of the existing soils were calculated using the equations of Wischmeier and Smith (1978) and Schwertmann *et al.* (1987).

In the Ouneine watershed nine different soil units can be distinguished. Within each soil unit one to ten profiles were investigated. Overall, 29 profiles were selected and main physical and chemical soil parameters were determined (Table 1). For the northern, mountainous area sand content from 20 % to 56 % were determined, silt content from 24 % to 74 % and clay content from 4 % to 20 %. Content of organic matter (OM) ranged from 1.5 % to 3.3 %. In the lower regions of the central basin and in the

outlet area sand contents ranged between 15 % and 72 %, silt contents between 19 % and 52 %, clay contents between 1 % and 25 %, and OM between 0.6 % and 4.3 %.

Table 1 Sand, silt, clay and organic matter contents as well as infiltration and aggregate classes and K-factors of investigated soil units in the Ouneine watershed

Soil unit	Nr. of profiles	Sand (%) (min—max)	Silt (%) (min—max)	Clay (min—max)	Silt+vfs (min—max)	Org. matter (min—max)	Infiltration class	Aggregate class	K
1	4	34.8—72.8	19.2—42.6	8.1—23.0	24.2—48.0	0.6—3.5	4	2—3	0.29
3	4	19.9—55.6	23.9—76.3	3.8—20.5	33.0—75.6	1.5—3.3	4	3—4	0.49
4	1	53.6	46.2	0.2	51.7	1.9	5	3	0.49
5	7	32.0—60.8	18.9—56.3	3.9—23.5	31.1—59.3	0.4—2.5	5	2—4	0.42
6	10	29.7—67.6	22.5—57.7	1.2—20.5	27.8—67.6	0.1—4.3	6	3—4	0.35
7	3	15.3—59.8	31.3—60.2	8.8—24.6	15.3—59.8	1.6—3.7	6	2—3	0.33

2.6 C-Factor

From the satellite images of the investigation area 13 different vegetation classes were distinguished. Dominating species within the vegetation classes can be seen in Table 2. Based on these results the C-factor map was derived. To overlay the map with the other maps (*K*-, *LS*-, *R*-map) it was necessary to geo-reference and to resample the vegetation map.

Table 2 Dominating species within the vegetation classes

Class	Dominating species
1	<i>Quercus ilex</i> , <i>Juniperus oxicedrus</i> , <i>Thymus Saturejoides</i> , <i>Cyste ssp</i> , <i>Salvia aucherii</i>
2	<i>Artemisia herba alba</i> , <i>Thymus ssp.</i> , <i>Lavandula dentata</i>
3	<i>Tetraclinis articulata</i> , <i>Juniperus phoenicea</i> , <i>Thymus saturejoides</i> , <i>Thymus albidus</i> , <i>Pistacia lenticus</i> , <i>Cistus villosus</i>
4	<i>Pinus halepensis</i> , <i>Juniperus phoenicea</i> , <i>Pistacia lenticus</i> , <i>Thymus sturejoides</i> , <i>Cistus villosus</i> , <i>Juniperus oxycedrus</i>
5	<i>Tetraclinis articulata</i> , <i>Juniperus phoenicea</i> , <i>Thymus saturejoides</i> , <i>Lavandula ssp</i> , <i>Argania spinosa</i> , <i>Acacia gummifera</i>
6	<i>Ziziphus lotus</i> , <i>Artemisia herba alba</i> , <i>Olea europea oleaster</i> , <i>Lavandula ssp.</i>
7	<i>Chamaerops humilis</i> , <i>Lavandula dentata</i> , <i>Juniperus phoenicea</i> , <i>Thymus saturejoides</i> , <i>Stipa tenacissima</i>
8	<i>Juniperus phoenicea</i> , <i>Juniperus oxycedrus</i> , <i>Thymus saturejoides</i> , <i>Pistacia lenticus</i> , <i>Cistus villosus</i>
9	<i>Ononis atlantica</i> , <i>Burbleurum spinosum</i> , <i>Lavandula stoechas</i>
10	<i>Quercus ilex</i> , <i>Juniperus phoenicea</i> , <i>Juniperus phoenicea</i> , <i>Thymus Saturejoides</i> , <i>Cistus villosus</i> , <i>Lavandula dentata</i> , <i>Pistacia lenticus</i>
11	Agricultural used areas, settlements
12	<i>Juniperus phoenicea</i> , <i>Chamaerops humilis</i> , <i>Lavandula dentata</i> , <i>Lavandula multifida</i> , <i>Thymus saturejoides</i>
13	<i>Ononis natrix</i> , <i>Ziziphus lotus</i>

Most of the investigation area can be regarded as rangeland and pasture for which the C-factor is nearly constant throughout the year. For the croplands time varying C-factors have been calculated based on existing crop files for Morocco (Gour and Weesies, personal communication) and information of crop and rotation practices given by Crepeau (1984). A C-factor of 0.022 was computed based on a typical crop rotation (barley and corn) in the Ouneine valley.

Since every vegetation class represents a more or less homogenous distribution of different plants, the weighted average of the elaborated values for the existing plants at one site have been used to obtain

the *C*-factor for one vegetation class. Field investigations have been carried out to determine the input parameters needed for the *C*-factors calculations in RUSLE. During two field trips in October 2000 and March 2001, 21 representative sites have been chosen and sampled.

With standard sampling rings (Φ 5cm and 10 cm) soil samples of the top soil layer 4" (~10.2 cm) have been taken near the most common plants or plant societies as well as from the bare soil between them and average root mass has been obtained (Table 3). The surface roughness was measured using the chain method ($l = 100$ cm, distance of chain links of 6 mm). The chain was laid directly on the soil surface following the micro-relief and shortage of the projected length due to soil surface roughness was measured. A total flat surface results in a value of 0 while increasing random roughness leads to increasing tortuosity (Boiffin, 1984). Tortuosity is defined as

$$T = (L - L_0) / L_0$$

where L is the actual length of the profile and L_0 is the projected length of the profile. Measurements of soil surface roughness changes performed in Austria with the same chain led to following relationship between random roughness (RR in mm) and tortuosity (T):

$$RR = -29.37 T^2 + 35.79T + 0.75 \quad (R^2 = 0.9508)$$

The canopy cover and ground cover (including stones) expresses the effectiveness of vegetation canopy in reducing the kinetic energy of the rainfall striking the soil surface. The fraction of land covered by canopy and average fall heights were estimated during the field trips and verified by analyzing photographic images (Table 3). To assess the total percentage of ground cover two methods were applied: 1) measurement of percentage of cover along an one meter transect, and 2) digital analyses of photographs of the soil surface (0.5 m \times 0.5 m area) using Microsoft Photo Editor.

Table 3 Input parameters and *C*-factors for investigated vegetation classes

Veg. Class	Nr. of sites	Root mass (g m ⁻²)	Ground cover (%)	Canopy cover (%)	<i>RR</i> (mm)	Av. Fall height (m)	<i>C</i> -factor
1	1	125	41	60	5.7	0.36	0.028
2	3	22	32	15	6.2	0.17	0.128
3	2	51	45	45	8.7	0.35	0.053
4	2	25	30	17	7.0	0.19	0.128
5	2	30	28	20	2.1	0.22	0.127
6	2	37	31	23	5.7	0	0.107
7	2	48	45	30	4.9	0.15	0.065
8	1	53	32	33	n.m.	0.15	0.085
9	1	11	56	15	n.m.	0	0.075
10	2	91	32	60	4.6	0.40	0.033
12	3	53	32	33	6.0	0.25	0.085
13	1	13	35	15	5.7	0	0.125

n.m. no measurements

2.7 P-Factor

In the whole region of the Atlas mountains the traditional technique to cultivate steep slopes with poorly developed soils is terracing. Close to the villages or in between them small plots of approximately 5 m \times 10 m are created and supported by simple stone walls. The difference in elevation of the plots depends on the overall angle of the slope. Basin irrigation is applied. Irrigation water is supplied and distributed by open channels from springs or day-night reservoirs, respectively. The irrigation efficiency is low because of high evaporation and infiltration losses. Due to terracing and good canopy cover soil erosion is no major threat to cultivated land around the villages and will not dedicate in a comparable

amount to the overall erosion of the whole watershed. The P -factor for these areas as well as all other land (rangeland, pasture) was set to 1.

3 Results and conclusions

3.1 Potential soil loss

The values of potential yearly soil loss by water using the LS-algorithm of McCool range from 0 to 7,020 $t \cdot ha^{-1} \cdot yr^{-1}$ with an average soil loss in the whole watershed of 33.7 $t \cdot ha^{-1} \cdot yr^{-1}$. 16.7 % of the investigation area shows low erosion potential (0 $t \cdot ha^{-1} \cdot yr^{-1}$ —5 $t \cdot ha^{-1} \cdot yr^{-1}$) while 58.2 % of the area has average yearly soil loss of 10 $t \cdot ha^{-1}$ —50 $t \cdot ha^{-1}$. On 3.5 % of the watershed soil erosion exceeds 100 $t \cdot ha^{-1} \cdot yr^{-1}$ (Figure 2).

The erosion rates in the central basin of the Ouneine valley (experiencing mainly interrill erosion) range between 0.5 $t \cdot ha^{-1} \cdot yr^{-1}$ and 8 $t \cdot ha^{-1} \cdot yr^{-1}$.

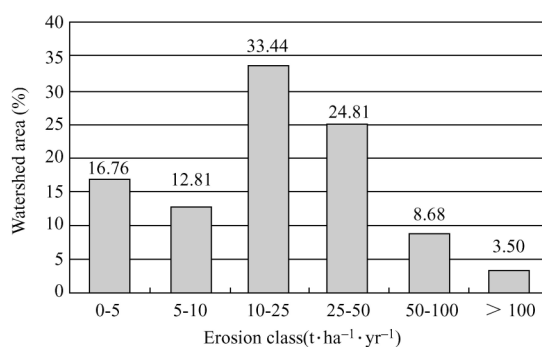


Fig. 2 Distribution of different soil erosion classes in the Ouneine watershed

The erosion in this part of the investigation area (Figure 3, Area 1) is low to moderate in relation to the rest of the watershed. Low C -values are not because of an intact vegetation but due to a high percentage of stone cover which is a result of severe erosion (and deposition) in the past. Especially in this region soil conservation measures seem to be useful as the topography provides possibilities for agricultural use.

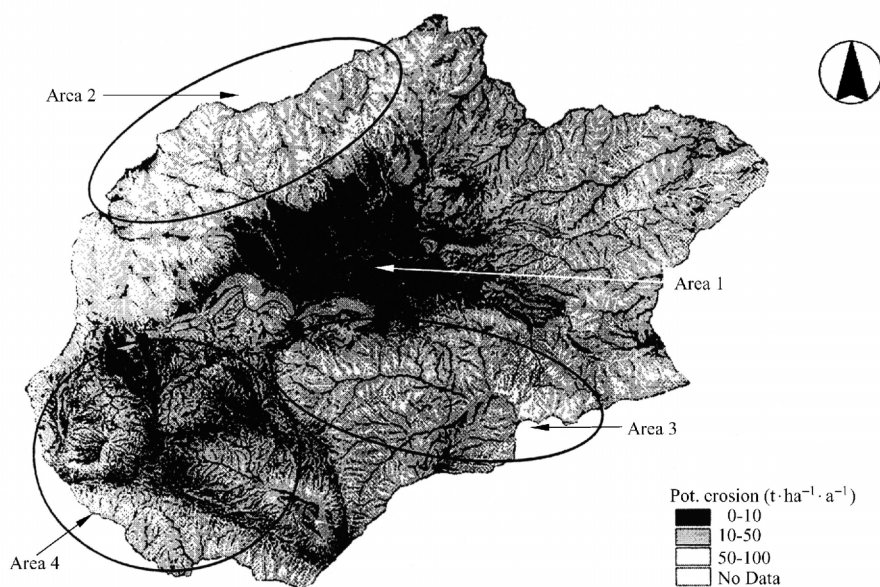


Fig.3 Spatial distribution of average yearly soil loss by water in the Ouneine watershed

The potential erosion on the slopes of Adrar n'Wijdan in the northern mountainous region with more than $25 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ is high (Fig. 3, Area 2). Because of overgrazing and production of charcoal and firewood the vegetation is degraded. Human activities concentrate on the easy accessible regions, so that in higher areas the vegetation cover is more dense than in lower regions. Therefore in an altitude between 2,000 and 2,400 m the erosion rate is lower than $25 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$. Above an altitude of 2,400 m there is a natural climatic border for higher plant societies to grow.

The south-eastern area (Fig. 3, Area 3) shows erosion rates mainly from $5 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ to $20 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ which is low for a mountainous area with high *LS*-factors. The reason for this moderate potential erosion rate is the low mean *C*-factor of in this region reflecting the good vegetation cover. The next settlements are quite far and the terrain is difficult to reach. The situation on the north side of Adrar n'Tizi Sdidine is contrary with considerable erosion rates around $30 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ and more. There the *C*-factors are higher than on the south side. This is because of intensive pasture and firewood production as the villages (Tough El Khyr and Taouryrt) are relatively near.

With respect to the relative low *LS*- and *R*-factors the potential erosion rate in the hilly area near the outlet of the watershed in the south-west is still considerable (Fig. 3, Area 4). Especially here, the calculated erosion rate does not reflect the real situation since often hardly any soil is left to erode and green schist is exposed. In the past the loss of vegetation cover led to severe erosion leaving unproductive land.

3.2 Recommendations

The results show that degradation of the land has strongly progressed over the years. Average potential soil loss in the whole watershed is calculated with 34 t per hectare and year and represents a yearly soil loss of 2.5 cm. Soil erosion cannot be controlled by a single practice but by a system, composed of a number of components. Each component performs one or several functions, including (1) reduction of the destructive impact of rainfall on the soil surface, (2) reduction of kinetic energy of surface runoff, and (3) controlled deposition of eroded material.

Reduction of destructive rainfall impact on soil surface:

- Improvement of the condition for the natural vegetation to reclaim land and to develop a dense canopy cover. Grazing should be stopped or at least reduced to a minimum in sensitive mountainous areas. The animals diminish the vegetation especially in higher region where biomass production is low and increase runoff because of compaction. Management strategies should be worked out to provide either meadows in lower, non sensitive areas of the watershed or fields reserved for fodder (hay) production.
- Ongoing deforestation for firewood and charcoal production must be stopped. The use of solar energy should be expanded to provide an alternative energy source for the inhabitants. Also an economic alternative to charcoal production should be found.
- Afforestation should be carried out only together with structural measures of the slopes. Preferable are site specific plants with a dense canopy to protect the soil from splash erosion due to rainfall (*Quercus ilex*, *Juniperus phoenicea* and *oxicedrus*, and *Tetraclinis articulata*). On the free area between the trees aromatic or medical plants like lavender, thyme and rosemary can be cultivated.

Reduction of kinetic energy of surface runoff including concentrated runoff in rills and gullies:

- Farming along the contour
- For cultivating trees and other large plants individual basins ("eyebrow" terraces) are suitable to control runoff and soil erosion on steep slopes. Often they are supported by hillside ditches or orchard terraces to control excessive runoff (Sheng, 1989).
- A general term for simple structures on the contour to reduce the kinetic energy of surface runoff is "stop-wash lines" (Hudson, 1987). On stony ground, using the stones to build rock lines serves the dual purpose of clearing them from the potential field as well as building the

stop-wash lines. A larger number of small barriers will be more effective than a small number of large structures.

- Grass strips or grass hedges: these vegetative barriers are narrow vegetative strips of stiff, erect, dense, perennial vegetation established along the general contour of slopes (Dabney *et al.*, 1993). Due to deposition processes on the upslope side of the hedge and erosion on the downslope side, some kind of terracing occurs with time.
- Construction of additional terraces in combination with afforestation is recommended especially in the strongly degraded areas of the lower parts of the valley. The area of terraces in the irrigated zones should be extended for food and fodder production.

Controlled deposition of eroded soil material:

All the above mentioned measures which reduce the transport capacity of water are able to deposit the eroded material to a certain extent.

All these proposals must be realized within an integrative watershed management including active participation of the people. As in any development region a big soil conservation issue is whether the result justifies the cost. In semi-arid areas it is complicated because of the limited alternatives and the complex interactions between ecology and human needs. In the Ouneine watershed the limiting factor for agricultural food production is water and not arable land. Necessary crop water requirement was not covered in the last years. A lot of existing terraces have not been tilled due to a series of alarming dry years. Concluding all above, soil conservation measures in this area should mainly laid out to increase crop productivity by increasing infiltration and water holding capacity of the soils while reducing soil loss at the same time.

Acknowledgements

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