Application of a pedogeomorphic approach to sediment management strategies in the High Atlas mountains, southern Morocco

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Abstract In a study of the 97 km^2 Askaouen sub-basin in the High Atlas Mountains, it is shown that a pedogeomorphic approach based on characteristic soil toposequences can provide a framework for understanding the spatial and temporal character of erosion processes. It provides information on the pedogeomorphic units which are dominant in determining sediment yields at each point in the basin and at a scale which is more suited to the formulation and implementation of soil conservation strategies.

INTRODUCTION

Since the development of the *Politique des barrages* programme in 1967, the sedimentation of reservoirs has been a priority environmental problem for the Moroccan government. While sediment yield figures for the High Atlas region are lower than those for northern Morocco (Heusch & Milliès-Lacroix, 1971; Probst & Amiotte Suchet, 1992) they are still a considerable cause for concern both in terms of the loss of reservoir capacity and reductions in land productivity. This paper focuses on the Aoulouz basin project in which a 103 million m^3 reservoir was created at the mouth of a 4446 km^2 drainage basin in the head waters of the Oued Souss in 1991 (see Fig. 1). Sedimentation rates in the Aoulouz reservoir have been estimated at 2 154 441 t year^{-1} by the *Direction Régionale de l'hydraulique d'Agadir.* However, less is known about the actual erosion rates occurring throughout the drainage basin itself.

This paper concentrates on two sites within the 97 km^2 Askaouen sub-basin (shown in Fig. 2) where sediment yields were monitored and discusses the value of a pedogeomorphic approach in the development of strategies for sediment management.

PEDOGEOMORPHOLOGY

Pedogeomorphology is essentially the study of the interaction between pedological and geomorphic properties and processes. It is concerned with contemporary processes of soil and water movement relevant to soil erosion and the reflection of

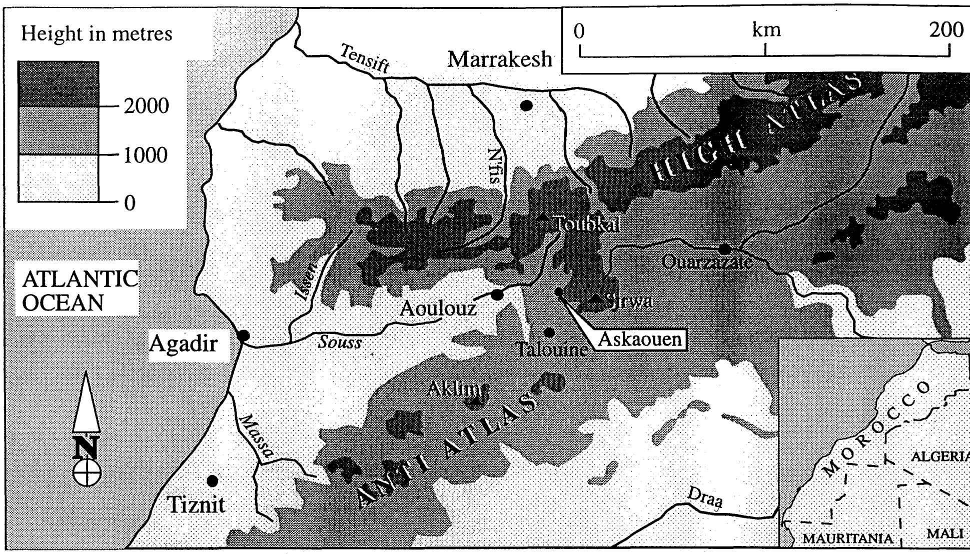


Fig. 1 Location of Aoulouz and Askaouen in southern Morocco.

these processes in features within the soil and at the surface (Conacher & Dalrymple, 1977).

Through the establishment of characteristic pedogeomorphic unit sequences, at any particular point within a drainage basin, it is possible to assess the propensity of a land surface to both generate runoff and provide sediment to the water course at its base (Newell Price, 1996). It is also possible to establish relationships between certain lithologies and the typical catenary sequences that are produced from them in different stream order positions and under certain bioclimatic conditions (Watson, 1964; Mapa & Pathmarajah, 1995). Indeed, the true characteristics of the drainage basin can be defined by the sequences of land units that occur at various points within the catchment. However, in terms of runoff generation and erosion mechanisms it is not simply the systematic variation of soil properties or the sequence of land surface units that is important, but the relative dominance and function of certain units within the drainage basin. This paper illustrates how, within the Askaouen sub-basin, the effective control of such units is crucial to the overall success of soil conservation strategies.

THE STUDY AREA

Situated in a mountainous area, between 1600 and 2800 m, the Askaouen sub-basin has a sub-humid to semiarid climate with hot dry summers and cool humid winters. Mean annual precipitation between 1972 and 1994 was 281 mm (Berkaoui, personal communication). The eastern part of the sub-basin is dominated by the micaceous ash and trachytic tuffs of the Sirwa volcanic shield. To the west, a further complex of volcanic and volcano-sedimentary rocks gives way to large areas underlain by Askaouen granite.

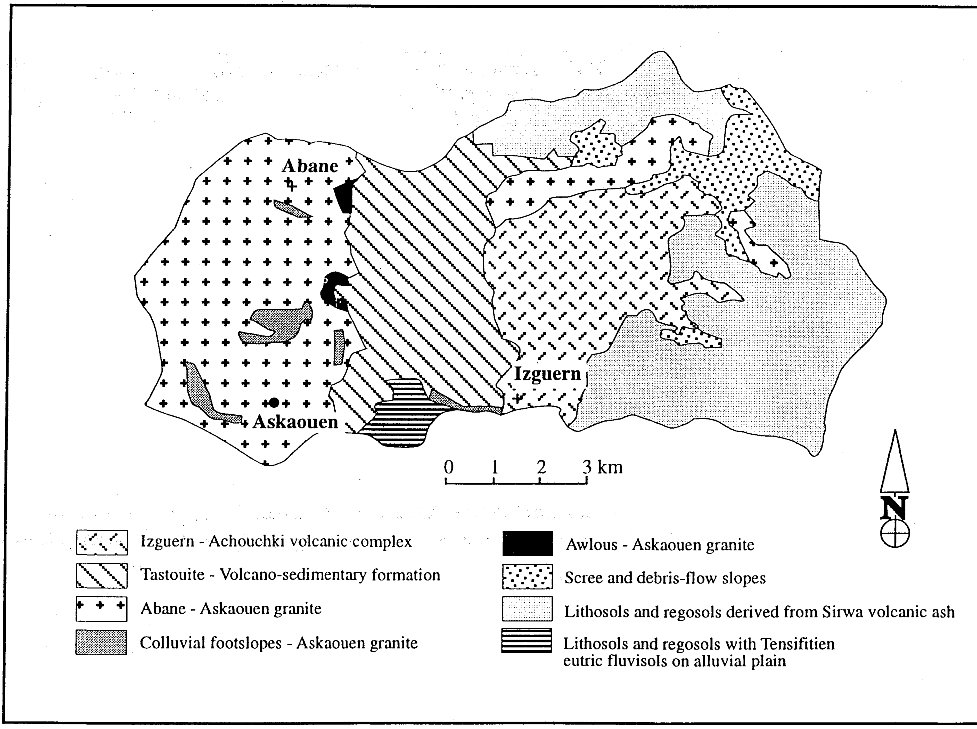


Fig. 2 Land surface types and monitoring sites within the Askaouen sub-basin.

Steeper slopes in the eastern half of the sub-basin, along with shallow and skeletal soils restrict land use to degraded rangeland. Soils throughout the sub-basin are characterised by a high stone content, thick surface crusts, low organic matter contents and large angular blocky structure. As a result, agriculture is concentrated in irrigated, terraced fields adjacent to the principal streams. Wheat and barley are intercropped with turnips, potatoes, broad beans, carrots, or alfalfa. Apple, walnut and almond trees are grown in plantations and on agroforestry plots with intercropped barley and vegetables. Barley is also sown on rain-fed land, most of which is found on the light textured soils and gentler slopes of the Askaouen granite.

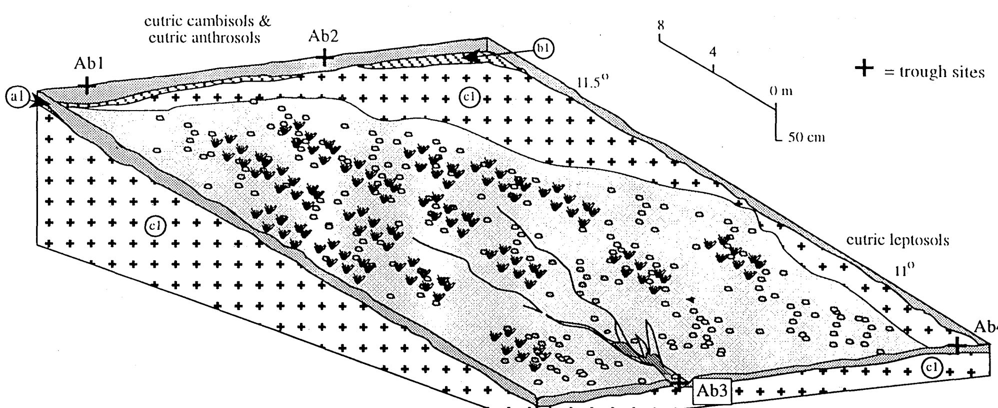
METHODOLOGY

This paper concentrates on two rangeland sites, Abane and Izguern, where contrasts in pedogeomorphic unit sequences have given rise to contrasting erosional response and, as a result, contrasting requirements in terms of soil conservation management. Abane is the site of a gully microcatchment on the weathered granite at 1950 m, while Izguern at 2200 m is a non-gullied hillslope underlain by andesitic tuff and andesite. The physical characteristics of the two sites are summarized in Table 1, while Figs 3 and 4 illustrate the three-dimensional arrangement of the various soil horizons at each site.

Table 1 Land surface characteristics for the land surface units at Abane and Izguern.

Land surface type	Parent materials	Land surface unit	Soil types	Mean rock fragment cover (%)	Mean vegetation cover (%)	Mean rill density (rills $100m^{-1}$)
Abane	Weathered granite	11.5° rilled upper slope	eutric anthrosols eutric cambisols	37.2	6.7	22 (1993-1994) 8 (1994-1995)
Abane	Weathered granite	10.5° rilled lower slope	eutric cambisols eutric leptosols	26.9	4.0	8
Izguern	Andesitic tuff	7.5° upper slope	eutric leptosols eutric cambisols	77.0	6.0	16
Izguern	Andesitic tuff	9.5° lower slope	eutric leptosols eutric cambisols	75.5	5.4	18

Sediment yields were measured using Gerlach troughs. Troughs were arranged in pairs at the base of each principal land surface unit so as to be representative of sites of flow convergence. In addition, at Abane, at the mouth of the gully micro-catchment, a granite and concrete dam was constructed on 4 December 1993, in order to trap sediment derived from the gully network and from the 5° to 19° slopes within the 4.43 ha micro-catchment. Measurement of the amount of sediment trapped by the dam permitted comparison of hillslope sediment yield with gully sediment yield.



a1 | Ao 10YR4/3 brown | Loamy Sand; fine sub-angular blocky; friable; rare medium pores; frequent interped pores provided by abundant fine roots; abundant fine gravel and occasional rocks; distinct boundary with BwCw.

b1 | BwCw 5YR4/4 reddish brown | Loamy Sand with clay; large 16 to 20cm diameter angular blocky with occasional cutans; firm friable; occasional non-continuous tubular pores; angular interped pores; frequent fine roots and occasional large roots; distinct boundary with Cw.

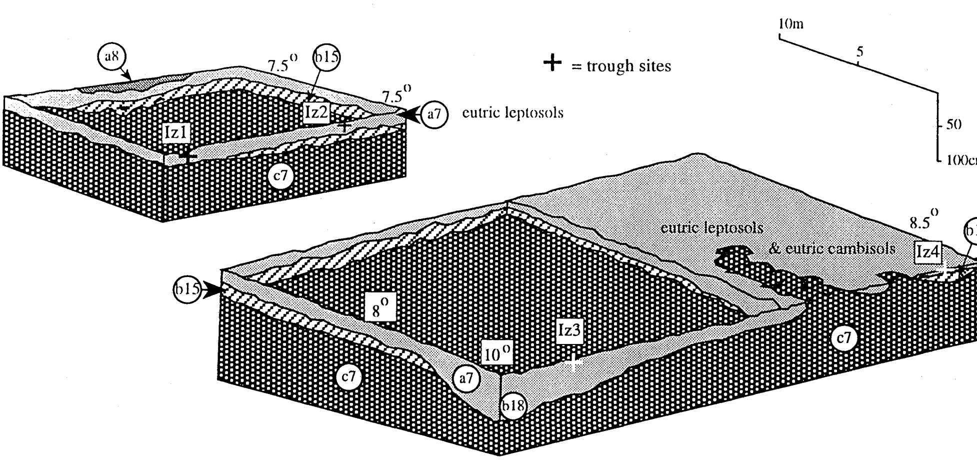
c1 | Cw 2.5YR4/2 dusky red | Loamy Sand; structureless; friable; original crystal arrangement; textural porosity and root pores; rare medium to large roots.

Fig. 3 Soil horizonation and land surface configuration at Abane.

SOIL CONSERVATION STRATEGIES

As stated earlier in this paper, the soil properties and catenary position of certain pedogeomorphic units can have a dominant effect on the sediment budget of the whole slope. A pedogeomorphic approach enables such units to be identified and appropriate conservation measures to be implemented in these priority areas.

At Abane, the present catenary relationship is a function of both the characteristic pedogeomorphic sequences developed on granite materials and the effect of past land use practices. On the 10.5° lower slope, cohesionless lenses of coarse sand material have been deposited through both rill and interrill erosion from upslope and the winnowing effect of flow (Fig. 3). Sand content is a positive component of soil susceptibility to rill erosion, especially when organic matter contents are low (Poesen & Govers 1990). This is witnessed by the fact that 8-12 cm deep rills have developed on the lower slope. Once rill incision has occurred, the low cohesion of rill walls facilitates mass movements and an increase in rill cross-sectional area. The colluvial footslopes on the weathered granite are therefore particularly susceptible to rill erosion on account of their catenary position and the material from which they have been derived. A further factor which enhances the erodibility of these lower slopes is the shallowness of the soil. Weathered granite lies



a8	Ao 5YR3/3 dark reddish brown	Clay-enriched Loamy Sand; fine angular granular; friable dry; slightly sticky wet; abundant fine pores; occasional gravel; common stones;frequent medium roots; distinct boundary with BwCw.
a7	Ao 5YR3/3 dark reddish brown	Clay-enriched Sandy loam skeletal; fine to medium sub-angular blocky; fine granular; firm friable; abundant gravel provides frequent fine pores; occasional clay on interped pores; common to frequent fine to medium roots, intra- and interped; distinct boundary with BwCw.
b15	BwCw 2.5YR3/4 dusky red	Clay-enriched Loamy Sand skeletal; large angular blocky to massive; firm friable; frequent medium to large pores; large planar interped pores; occasional medium to large roots; abundant fine roots; abundant stones and rocks. abundant unweathered minerals; frequent stone-sized weathered rock; abrupt boundary with parent rock.
c7	Cw 2.5YR4/2 dusky red	Very gravelly with clay; fractured; secondary clay minerals *in situ*; occasional fine roots.

Fig. 4 Soil horizonation and land surface configuration at Izguern.

within 15 cm of the surface, such that even during relatively low magnitude precipitation events infiltration rates are limited by the low hydraulic conductivity of the weathered granite. Both infiltration excess and saturation overland flow are therefore generated and transmitted more rapidly on these lower slopes than on slopes where soils are deeper and rapid infiltration rates are sustained for longer.

One such slope that has deeper soils is the 11.5° upper slope at Abane (see Fig. 3). The erosion susceptibility of this slope is again a function of the soil material and the steep slope, but also the position of bench terraces and the fact that they have not been well maintained. As on the lower slopes, sand contents are high and organic matter contents low. The surface is therefore inherently susceptible to rill erosion. The situation has, however, been exacerbated through lack of terrace wall maintenance and the pedogeomorphic position of the unit. The abandoned terraces are positioned 30-45 m downslope of a ridged interfluve. This is sufficient distance for overland flow to be generated and sustained on the abandoned terraces. The collapse of the terrace walls, on the other hand, has allowed the concentration of flow between cobble-sized granite fragments and increased the chances of vortex erosion and rill incision. Rills have therefore developed on the upper slope, resulting in the routing of surface runoff down slope. However, microtopography on the upper slope was only significantly transformed during an intense 36 mm storm on 1 September 1994. Rills up to 20 cm across and 4 cm deep were transformed into rills up to 50 cm across and 8 cm deep. This change in rill geometry resulted in a subsequent significant increase in sediment yields from 1.2-6.5 kg km^{-2} mm^{-1} in 1993/1994 to 10.8-457.3 kg km^{-2} mm^{-1} in 1994/1995. This emphasises the particular importance of maintaining soil conservation structures on those units susceptible to rill erosion. On granite-derived soils, these units tend to be colluvial footslopes on account of their pedogeomorphic position. The spatial pattern of erosion at Abane also illustrates how the effectiveness of bench terraces on a mid- or lower slope unit can be compromised if surface runoff from upslope is not controlled.

The susceptibility to rill incision of the colluvial footslope at Abane relative to the slopes at Izguern resulted in sediment yields being significantly higher at Abane than at Izguern for dry season erosive rainfall events. By contrast, after winter snows, there was no consistent difference in sediment yield between the two sites. This temporal and spatial pattern can be explained in terms of the contrast in the type of pedogeomorphic units present at each site. At Abane, the interfluve consists of a ridge of rhyolite, whereas at Izguern the interfluve is more extensive and able to hold and shed snow meltwater. So, whereas at Abane it is the specific nature of the colluvial footslope which is the dominant pedogeomorphic unit in determining hillslope sediment yields, at Izguern it is the interfluve and seepage slopes. The upper slopes at Izguern are occasionally covered with snow during winter months. They therefore provide lateral subsurface flow onto the lower slope, maintain the soil at or near saturation and thereby reduce the threshold amount of rainfall required to activate surface runoff and cause erosion. This has implications for the type of soil conservation strategies required at each site.

At Izguern, soil erosion can be reduced through the control of surface runoff. When saturated overland flow is generated, it is not possible to increase infiltration rates and so erosive flow can only be reduced through the diversion and dissipation of surface runoff to safe discharge areas on the colluvial and alluvial footslopes. This could be achieved through the creation of graded diversion furrows above the boundary between the 9.0° rilled lower slope and the 7.5° upper slope. The furrows could be filled with cobble sized andesite fragments or a hardy cover grass, such as a frost tolerant species of *Agropyron* or *Elymus*, in order to increase hydraulic roughness and protect the soil surface from the shear forces of flow.

At Abane soil conservation measures should concentrate on increasing infiltration, encouraging the divergence of flow and preventing rill incision. In southern Tunisia, Floret & Le Floch (1984) observed that mulching with barley straw and twigs of *Artemisia campestris* and *Aristidia pungens* drastically reduced erosion. Cold and drought tolerant *Agropyron* and *Armeria* species could also be planted along the contour with permeable debris and stone barriers to reduce flow rates and trap sediment (United States National Research Council, 1993). However, care should be taken to prevent the development of sediment fans within strips, since this can result in concentration of flowing water and the development of very bad rill erosion (Loch, personal communication): as has already been observed on the rilled upper slope at Abane.

At Abane, although the control of erosion on the hillslopes is vital for the comprehensive management of sediment redistribution, results of erosion monitoring showed that gully sediment yields were two orders of magnitude higher than hillslope sediment yields. The first priority at Abane is therefore the stabilization of gullies. Gully stabilisation could follow the strategy developed by the INRF in gullies at Souagui, in Algeria (Roose, 1991) incorporating specifications detailed by Hudson (1995). In particular, the establishment of live dams which thrive and grow with sediment accumulation would be of great value to the local agricultural communities. Dams reinforced by poplar (*Populus alba x glandulosa*) poles which regenerate in a similar way to apicormic shoots could provide timber in future years.

Whatever plant materials and structures are used, it should be ensured that gullies and riverbanks are stabilized before the installation of diguettes or terraces is begun. Soil conservation work should, therefore, begin in the gullies operating from the reaches to the gully mouth and then proceed progressively to the management of the whole basin, always proceeding from the upper slope units, the sources of surface runoff, to the lower slope units. Such an approach is acceptable where slopes are stable and subsurface erosion is not a problem, but it should be borne in mind that on less stable slopes or soils with vertic properties and/or an argillic horizon, any measure attempting to increase the rate of infiltration will at the same time increase the risks of mass movement or soil piping and the development of tunnel erosion. Only through a whole landscape, pedogeomorphic approach is it possible to take all such considerations into account, target the priority units for soil conservation and ensure that plant materials are suitably matched to the land surface properties of each unit.

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