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Gully hydrology and related soil properties in Lesotho

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ABSTRACT Gully erosion is a serious problem in Lesotho. The runoff events recorded during the wet season of 1979/1980 in the Maama gully near Roma, Lesotho, are described together with a number of soil properties which are thought to influence gully runoff and erosion. Runoff events are of very short duration and constitute only a small percentage of the total basin precipitation. Most rainfall was easily retained by the catchment soils. Relationships between rainfall and runoff events are described and discussed. It is concluded that most runoff is generated close to the gully on the motorable trackways and that during the period of study more material was eroded from the gully headcuts than left the gully at the gauging station. The evacuation of sediment must be the result of runoff events more extreme than those observed. Attention is drawn to differences between the Maama gully and many of the other gullies in Lesotho where piping is important.

INTRODUCTION

The lowland soils and recent sediments of western Lesotho in southern Africa have been and are being seriously damaged by gully erosion. This erosion is being investigated in two ways; firstly by studying the physical and chemical properties of the soils in which gullies occur (Seithleko, in preparation), and secondly by investigating gully hydrology. This paper, reporting part of the second study, examines runoff events recorded in the Maama gully near Roma, Lesotho (Fig.1), and the relationship of these to soil hydraulic properties. Whilst an understanding of the hydrology of the gullies in Lesotho is of great practical significance with respect to erosion control, no quantitative information is available.

The gullies or "dongas" of Lesotho would appear to date from the last 100-150 years and did not exist when the first missionaries visited Lesotho (Stockley, 1947, p. 92). Serious concern was expressed about gully erosion in the 1930's in a Government Report (Pim, 1935) and more recently in a number of land resource and soil surveys (Bawden & Carroll, 1968; Binnie & Partners, 1972; the Ministry of Agriculture, 1977). The general problem of soil erosion in Lesotho has recently been reviewed by Chakela (1981) in a study of

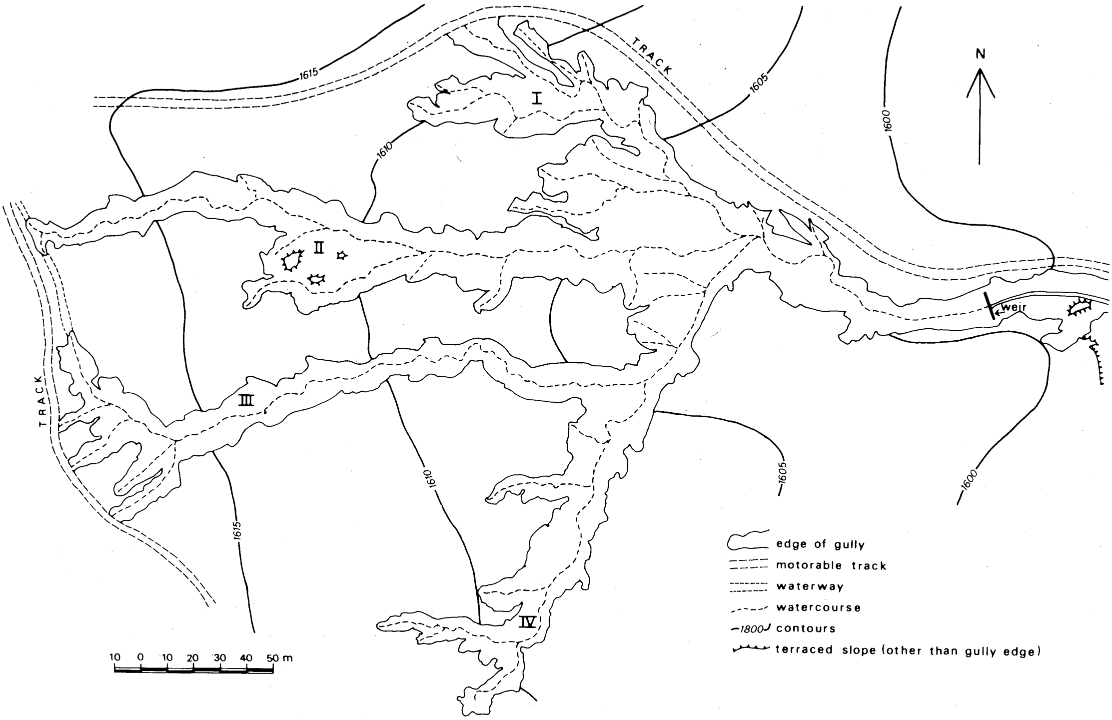

FIG.1 The Maama gully system near Roma, Lesotho.

reservoir sedimentation. Gully erosion is most severe in the extensive "duplex" or claypan soils found in the western lowlands. These soils, occupying lower valley slope and pediment positions, are characterized by a relatively coarse textured A horizon, abruptly overlying a compact, much less permeable clayey B horizon. They are described in detail by the Ministry of Agriculture Report (1977).

The field area

The Maama gully system (Fig.1) has developed in relatively recent pedisediments which overlie the interbedded sandstones and shales of the Red Beds or Elliot Formation. It ranges in elevation from 1613 m at the headcuts to 1591 m at the gauging station. The gully has a dendritic pattern but only two of the four major channels increased in length during the period of study. Upstream of their confluence the channel floors are less than 1 m wide and are cut into a mudstone overlain by pedisediments. Below the confluence the gully is cut into alluvial deposits and the sand bed channel is 2-3 m wide. The gully is generally about 4 m deep along its entire length. The soil profiles exposed along the gully channel are described by Molapo (1981) as belonging to the Maseru series (Typic Albaqualfs); erosion has generally truncated the soils to the A21 horizon. Nearly all of the Maama drainage basin is cultivated and under row crops, particularly maize and sorghum. Cattle range on the stubble during the winter. A number of conservation terraces have been constructed to control sheet erosion. Runoff from the gully is ephemeral, occurring about 12 times a year.

The climate is strongly seasonal (Table 1). Seventy-eight per cent of the mean annual precipitation falls in the summer months (October-March) and only 5.6% in the three driest winter months (June-August). Runoff producing rainfall events are usually associated with high intensity summer thunderstorms of short duration (0.25-0.5 h). Although frontal rainfall is of long duration, both in the winter and in the summer, it is of low intensity and runoff is seldom generated in the gullies. Class "A" pan evaporation data for Roma, 5 km from the Maama gully are included in Table 1.

TABLE 1 Mean monthly rainfall (mm) and potential evaporation (mm) at Roma

	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
Rainfall	*119*	*115*	*114*	*70*	*38*	*14*	*15.1*	*17.6*	*26*	*82*	*100*	*109*
Evaporation	*280*	*206*	*121*	*90*	*81*	*66*	*84*	*102*	*132*	*214*	*159*	*223*

The runoff events described below are for the period 20 November 1979 to 10 March 1980 when both the rain recorder and water level recorder at the V-notch weir were operational and not vandalized. Soil properties determined included saturated hydraulic conductivity, sorptivity, soil moisture characteristics, the volumetric shrinkage ratio and aggregate stability. A number of water samples was analysed for cation and suspended solids concentrations.

RESULTS

Rainfall-runoff events

During the period of observation nine rainfall events in excess of 10 mm were recorded (Table 2). A few additional rainfall events were lost due to interference with the rain recorder. For rain days with less than 4 h of rainfall, the maximum 1 h precipitation accounts for between 40 and 82% of the daily total, and the 2 h maximum for between 82.5 and 99%. This illustrates the showery nature of the rainfall. The measured rainfall intensities listed in Table 2 are low compared to those estimated for Maseru 40 km to the west (Binnie & Partners, 1972). The runoff hydrographs recorded at the gauging station are shown in Fig.2 and Table 3. Runoff at the weir is always of short duration and the rises appear to be almost instantaneous. Runoff usually comprises <1% of the total basin precipitation. Regression equations obtained by plotting maximum discharge (Q_{max}; l s^{-1}) and runoff volume (VQ; m^3) against the daily precipitation (P_{day}; mm) and 2 h maximum precipitation (P_{2h}; mm) are shown in Table 4 for all discharge events recorded and for discharge

TABLE 2   Rainfall events > 10 mm at the Maama gully

Date	*P (mm)*	*P 1 h max. (mm)*	*P 2 h max. (mm)*	*P max. 15 min* $(mm\ min^{-1})$	*P max. 30 min* $(mm\ min^{-1})$	*Ponding*
23.11.79	*24.6*	*5.9*	*10.3*	*0.68*	*0.34*	*possible*
12.12.79	*18.0*	*14.7*	*15.7*	*1.05*	*0.52*	*possible*
19.12.79	*14.7*	*11.5*	*13.2*	*0.88*	*0.44*	*unlikely*
23.12.79	*20.6*	*14.6*	*17.0*	*1.13*	*0.57*	*possible*
25.12.79	*13.5*	*2.8*	*3.8*	*0.25*	*0.13*	*unlikely*
6. 1.80	*16.2*	*11.0*	*16.1*	*1.07*	*0.54*	*unlikely*
22. 1.80	*14.6*	*6.1*	*9.3*	*0.62*	*0.31*	*unlikely*
6. 2.80	*29.7*	*14.5*	*24.5*	*1.63*	*0.82*	*probable*
28. 2.80	*10.6*	*3.6*	*4.2*	*0.28*	*0.14*	*unlikely*

events in excess of 0.25 m^3. Also shown are values of P for Q = 0, indicating the minimum precipitation required to generate runoff. It would seem that at least 10 mm of precipitation are required for runoff to be generated. Similar relationships have been reported by Osborn & Renard (1970) for areas up to 0.5 km^2.

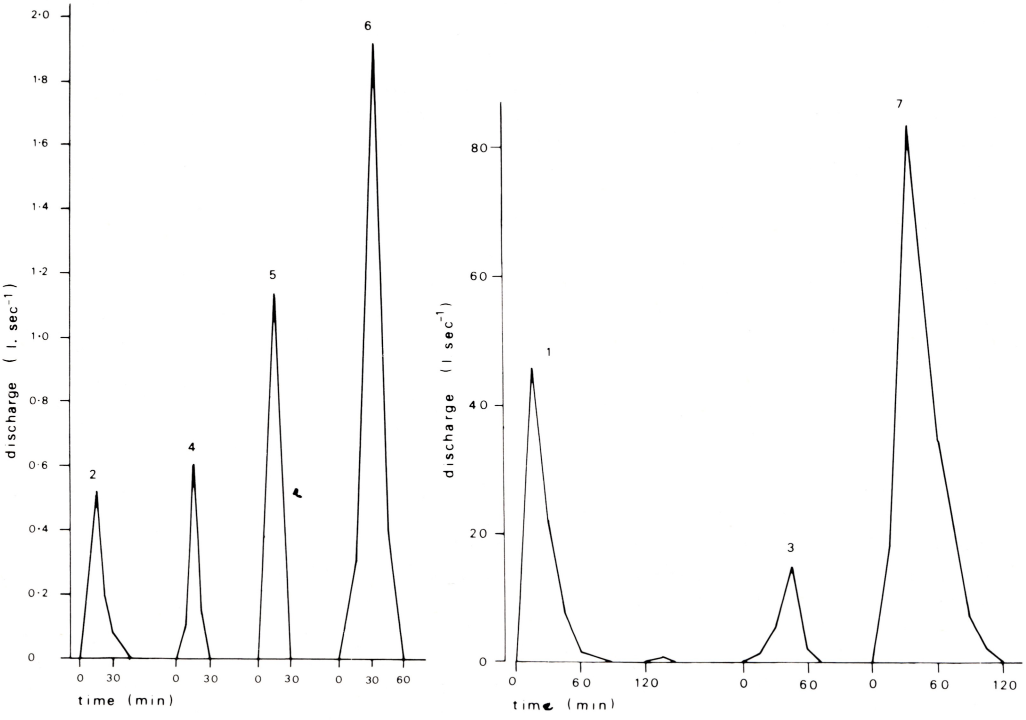

FIG.2   Discharge hydrographs recorded at the Maama gauging station: 1 (12.12.79); 2 (25.12.79); 3 (6.1.80); 4 (20.1.80); 5 (21.1.80); 6 (22.1.80) and 7 (6.2.80).

TABLE 3 Runoff events at the Maama gully

Date	Q_{max} ($l\ s^{-1}$)	VQ (m^3)	Loss, I (l)	Date	Q_{max} ($l\ s^{-1}$)	VQ (m^3)	Transmission loss, I (l)
12.12.79	45.9	72.8	7715	21.1.80	1.14	1.03	385
25.12.79	0.52	0.47	299	22.1.80	2.03	2.4	849
6. 1.80	14.8	20.3	3329	6.2.80	93.5	208	16255
20. 1.80	0.6	0.33	193				

TABLE 4 Simple regression relationships between runoff and rainfall parameters

$Q_{max} = 4.1\ P_{day} - 39$ ($Q = 0$ for P_{day} 9.6 mm)

$VQ = 8.88\ P_{day} - 90.4$ ($Q = 0$ for P_{day} 10.2 mm)

$VQ = 7.37\ P_{2\ h} - 42.4$ ($VQ = 0$ for $P_{2\ h}$ 5.8 mm)

Since the runoff hydrographs were recorded on an 8 day recorder, details with a duration < 15 min cannot be seen. In general the traces resemble those reported by Schick (1970) for Nahal Yael (Israel), where the water in the channel is described as advancing as a true "wall of water". That this might be the case in Lesotho is indicated by Chakela (1981) who has observed, during heavy thunderstorms, water advancing in ephemeral gullies in a broad front 6-30 cm high. In the Maama basin it would appear that runoff producing rain is of short duration. This situation was also encountered by Osborn & Renard (1970) in Arizona who found that runoff producing rain with an intensity > 1.27 cm h^{-1} seldom lasted for more than 30 min at any point. An important difference however is that in Arizona runoff was found to average as much as 20-25% of storm rainfall.

Soil conditions influencing runoff

Most of the soil properties measured revealed expected differences between the A2 and B2 soil horizons. The volumetric soil moisture content (θ) was determined for different pF values. At low suctions values of θ were fairly uniform in both A and B horizons but at higher values of pF, as might be expected, the B horizons retained more water. Also determined for the soils were the shrinkage limit (SL) and the volumetric shrinkage ratio (VS) (Singh, 1967). These last values were determined because it had been found that some soils of the Maseru series in the neighbourhood of pipes had B horizons with a low SL and a high VS, indicating that large volume changes could occur during wetting and drying cycles. However, at the Maama gully, where in fact piping is only observed at a few locations, the volumetric change, occurring between the saturation water content and the shrinkage limit, is zero. In the laboratory shrinkage is observed in the B horizon at water contents which would not seem to occur in the field. From values of sorptivity (s) and saturated hydraulic conductivity (k_s) it is possible to calculate infiltration envelopes which indicate the amount of rain required to produce ponding (R_p) at different intensities of rainfall. A useful equation was found to be a relationship described by Smith & Parlange (1978). In Table 5 values of R_p are shown for different rainfall intensities. To obtain these values, average values of s were used, representative of dry antecedent conditions and obtained by field measurements with a double ring infiltrometer.

TABLE 5 Calculated amounts of rainfall (R_p, mm) required to pond the soil at different intensities

		Rainfall intensity (cm h^{-1}):								
k_s	*s*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
0.3	*0.31*	*33*	*15*	*10*	*7*	*5.8*	*4.8*	*4 1*	*3.6*	*3.2*
0.3	*0.25*	*22*	*10*	*6.5*	*4.9*	*3.9*	*3.2*	*2.7*	*2.4*	*2.1*
0.3	*0.2*	*14*	*6.5*	*4.2*	*3.1*	*2.5*	*2.0*	*1.7*	*1.5*	*1.4*

Average values of k_s are indicated in Table 6 for both vertically and horizontally extracted ring samples. The values were determined in the laboratory using a falling head permeameter. With the exception of two determinations for the A22 horizon, the horizontal values of k_s are highest.

From the field and laboratory measurements it would seem that the 30-40 cm thick A soil horizons could retain between 7.5 and 10 cm of precipitation between pF 4.2 and 2 (Table 7). The development of a perched water table above the B21 and B22 horizons would seem extremely likely during wet weather in view of the low values of k_s. With dry antecedent conditions all of the rainfall events indicated in Table 2 would be retained in the soil if the ponding point is not reached. However, based on a comparison between the estimated 15 min rainfall intensity and the infiltration envelope, it would seem that one of the rainfall events in Table 2 would certainly produce

TABLE 6 Values of saturated hydraulic conductivity (k_s, cm day^{-1}) at sites along the Maama gully

Soil horizon	*Gully head:* *Vertical*	*Horizontal*	*Gully site I:* *Vertical*	*Horizontal*	*Gully site II:* *Vertical*	*Horizontal*
A21	*2.05*	*2.98*	*8.0*	*11.3*	*7.6*	*8.8*
A22	*1.75*	*1.3*	*4.2*	*1.7*	*0.4*	*0.7*
IIB21tg	*0.28*	*0.34*	*0.35*	*1.45*	*0.13*	*0.17*
IIB22tg	*0.002*	*-*	*0.012*	*0.018*	*0.03*	*0.04*

TABLE 7 The shrinkage ratio (SR), shrinkage limit (SL) and volumetric soil moisture contents (θ) at pF 0, 2 and 4.2

Soil horizon	*SR*	*SL*	*pF 0 (θ)*	*pF 2 (θ)*	*pF 4.2 (θ)*
A21	*2.13*	*19*	*23.6*	*17.4*	*7.3*
A22	*2.25*	*21.1*	*23.3*	*18.0*	*6.6*
IIB21tg	*2.28*	*26.8*	*20.4*	*18.2*	*11.4*
IIB22tg	*2.16*	*21.5*	*23.3*	*18.6*	*8.6*

ponding, three events possibly, while for the other events ponding with dry antecedent conditions would appear extremely unlikely.

DISCUSSION

The above results show that runoff in the gully is equivalent to only a very small percentage of the total catchment precipitation, the vast bulk of which is retained in the soil. From field observation it appears that most runoff is derived from only two of the tributary gullies (I and II, Fig.1), the other sites probably being deprived of their major contributing area (the motorable road) by the growth of gully II. At their point of confluence, sediment has been deposited and the gully channel takes on a meandering form. Since the heads of the gullies contributing runoff are located at different distances from the point of confluence (230 m for I and 135 m for II), an explanation is required for the single discharge peaks observed. A possibility is that storage is available in the channel sediment at the start of runoff; once this is full, runoff is generated which reaches the weir. This runoff is then governed by characteristics of the storage and not of the inflow.

This implies that the recession of the overflow from the storage can be treated as outflow from a linear reservoir. However, since transmission losses occur at and downstream of the point of confluence, the usual outflow formula:

$$Qt = Q_O K_r{}^t \qquad (1)$$

was modified to account for this. Infiltration into the bed is assumed to be proportional to the head (h) of water in the gully, which itself is proportioned to $Q^{0.6}$.

Introducing a permeability factor α we obtain

$$Qt = (Q_O K_r{}^t) - Qt^{0.6}\alpha \qquad (2)$$

When recession limbs of the hydrographs were simulated, good results were obtained with a value of $\alpha = 0.3$ and a value of K_r between 0.99 and 0.85 (Fig.3). A variable value of K_r is not unusual (cf. Viessman, 1965). For the three largest discharge events a value of K_r was most appropriate which decreased with time.

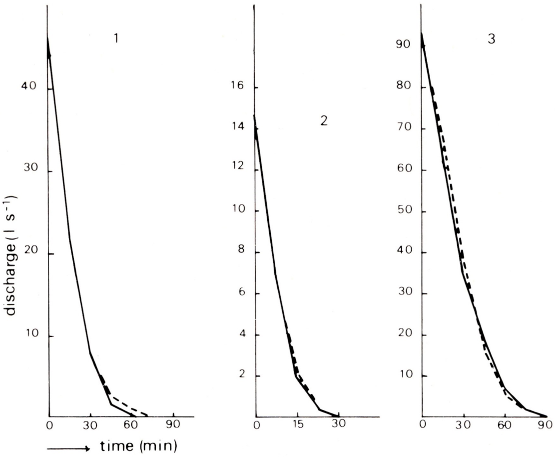

FIG.3 Actual and predicted (broken line) hydrograph recessions: 1 (12.12.79); 2 (6.1.80) and 3 (6.2.80).

On the basis of the assumptions made above, the loss of water through infiltration into the gully bed (I) is proportional to the average discharge ($\bar{Q}$) of the flood event and can be calculated from

$$I = \bar{Q}^{0.6}T\alpha$$

where T is the duration of the discharge event. These losses are indicated in Table 3 and in terms of the volume of runoff are lower for the larger discharge events.

Similar sharp hydrograph rises have been explained elsewhere as the result of water infiltrating into the channel bed (Osborn & Renard, 1970; Schick, 1970). In addition, in the Maama gully, another factor is the small area contributing runoff and its location close to and in the gully. Even for the largest storm recorded, the contributing area would amount to only 70 000 m^2, or, if allowance is made for transmission losses, to 110 000 m^2. As the total area of the basin is of the order of 10^6 m^2 it is clear that only a very small area supplies runoff and that as soon as precipitation ends, the discharge starts to recede.

The large potential for storage in the drainage basin soils has been mentioned. For the A21 and A22 horizons this is far higher than the maximum 2 h rainfall. Nevertheless, occasionally when rainfall events occur close together, large areas of the level to gently sloping slopes close to the gully become ponded. The evaporation of the ponded water is very rapid (Table 1) and on the occasions when ponding was observed, the surface detention of the roughly ploughed surface beneath the row crops was capable of retaining the rainfall.

With overland flow velocities reported from the literature (0.03-0.06 m s^{-1}, Emmett, 1978; 0.003-0.14 m s^{-1}, Dunne, 1978) a rough estimate of the maximum distance travelled by water contributing to the peak can be made. For an effective rainfall duration of 20 min water from a maximum distance of 150 m from the gully head could contribute to runoff.

Low runoff coefficients for Lesotho have been reported for the Little Caledon River at Masianokeng (945 km^2) of which the Maama River is a tributary. With an average of 11% for a mean annual precipitation of 785 mm, values ranged from 5% during the dry year of 1971 (679 mm rain) to 44% in 1976 (1238 mm rain).

Erosion in the Maama gully

During the period of observation, the Maama gully increased in size by about 180 m^3. About half of the eroded material was evacuated from the headcut area and either left the catchment or was deposited in the gully downslope of the confluence.

Unfortunately insufficient data were collected to enable the output of sediment from the gully to be calculated. The few samples collected point to sediment concentrations at the gauging station varying between 17 and 23.6 g l^{-1}. These appear to be largely independent of discharge, although this still needs to be established. Assuming an average concentration of 20 g l^{-1}, the 334 m^3 of runoff recorded (estimated as about 80% of the total discharge for the year) would only have transported 664 kg of material from the gully. It is clear that much sediment must have been deposited in the lower channel reach and that the discharge events observed were probably not extreme enough to be important with respect to gully erosion. For this reason the programme needs to be extended. There is also a need to investigate why the measured sediment concentrations are higher than those reported by Chakela (1981) by a factor of 10. Water chemistry data indicate that sodium ions form a very high percentage of the cations, that the electrical conductivity is low and that the clay almost certainly dispersed. Under these conditions high suspended solids concentrations could be expected (Imeson & Verstraten, 1981).

Since runoff to the Maama gully is comprised entirely of quickflow supplied from relatively impermeable areas close to the gully channel, the gully differs from many of those in Lesotho where pipe flow is very important. Runoff processes in these two types of gully and the resulting sediment transport are likely to be very different. This is an important consideration to be borne in mind when planning soil conservation measures, since whereas conservation terraces are likely to be effective in the case of preventing water entering gullies such as the Maama gully, in the other gullies of Lesotho where tunnel erosion is important, these may encourage rather than ameliorate gully growth. In the Maama gully, soil properties and cultivation techniques favour water retention and runoff is produced largely on cattle tracks and roads. Once runoff is produced it is the erodibility of the soils and sediments found in the B and C horizons which make gullying possible.

It might be possible to restrict gully development by channelling the runoff along water courses where the erodibility of the soils and sediments is decreased by adding Ca or Mg ions at regular intervals to the runoff.

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