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THE RELATIONSHIPS BETWEEN LAND USE AND EROSION IN THE CENTRAL NORTH ISLAND, NEW ZEALAND

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ABSTRACT

Yellow-brown pumice soils cover a large area of the central North Island of New Zealand. In the Waikato River Basin these soils occupy over 7000 km². Since land development started in the mid 1930s approximately 4000 km² have been converted from the native vegetation to exotic forests (1243 km²) and pasture (2740 km²), and a further 500 km² could be developed. Since about 1959 gully erosion has become more common and widespread. The causes of this erosion were not known, although many hypotheses attempting to account for erosion have been put forward. Research was therefore undertaken in an attempt to isolate the most important causes of erosion.

Three experiments have been completed:

(1) A study of runoff from plots placed in areas of pasture grass, ungrazed grass and scrub vegetation has been made. Climatic, soil, vegetation, and slope variables were studied, and as a result of statistical analysis it is concluded that surface water runoff is greater from developed land in pasture and less from areas covered by scrub and ungrazed grass vegetation. The major causes of runoff from pastures are very intense rainfall on a soil with low moisture content.

(2) Infiltration studies with an infiltrometer, designed and built for the purpose, reinforce the conclusions drawn from runoff studies. They also show that modifications of soil properties, especially compaction caused by animals and vehicles, decrease infiltration and hence promote runoff.

(3) Flume studies of the erodibility of pumice soils indicate that soil particles are easily entrained by running water, but that plant roots inhibit this process.

Analysis of data from the three experiments indicates that land development should be carried out so that: (a) a close vegetation cover is kept on all soils; (b) channel development is avoided; (c) vulnerable areas such as valley floors and steep valley sides are kept as water absorption areas; (d) animals and vehicles are excluded from water absorption areas to prevent soil compaction; (e) plants with strong and dense root systems are used to protect surface soils.

INTRODUCTION

Gully erosion is the most common and economically the most important type of soil erosion on the Volcanic Plateau of the central North Island. The nature of the erosion has been described by

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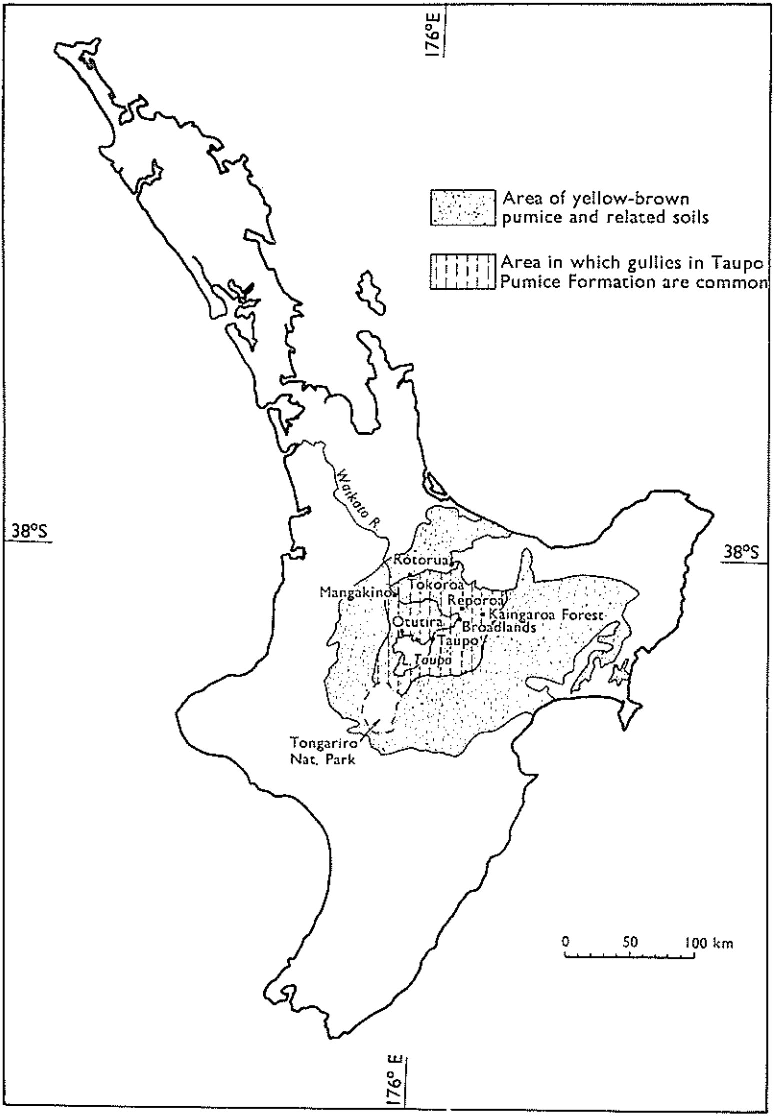

FIG. 1 — The distribution of yellow-brown pumice soils and of gully erosion in the central North Island.

Healy (1967) and by Selby (1967a). The gullies have been described by Blong (1965, 1966, 1970), Healy (1967) and Oliver (1969). The morphology of gully erosion is controlled by the geology and topography of the region. Over large areas sheets of plateau-forming ignimbrites are cut by narrow or gorge-like valleys. This landscape has been coated by a number of volcanic ash showers, the last of which are the Taupo Pumice Ash Beds erupted about A.D. 130 (Healy *et al.*, 1964). During and immediately after the Taupo eruptions many of the valleys were partly filled with thick deposits of airfall, nuée ardente, lahar and colluvial pumice. Some valleys were re-excavated soon after the A.D. 130 eruptions but others retained much of the pumice. This was gradually colonized by plants, and a yellow-brown pumice soil was formed (Taylor *et al.*, 1968).

In the pumice-filled valleys most water seeped through the porous deposits and there were few surface streams, but since land development, converting the native forest and scrub cover to pasture grass, there has been both an increased flow of surface streams and an increase in erosion of the pumice valley-infills. The first noticeable recent erosion of the infills occurred at Broadlands about 1959, but the first large-scale features were produced in 1962 when nearby Rotorua had a rainfall of 2580 mm, which is nearly twice the normal annual rainfall of 1384 mm. Erosion was also noticed in other parts of the pumice lands, especially at Reporoa and around Mangakino, at the same time (Fig. 1). In all areas it appeared to coincide with the first unusually wet season occurring after land development.

The economic significance of a relationship between gully erosion and land development may be gauged from the areas of land with yellow-brown pumice soils in the Waikato River catchment (Table 1). With nearly 3000 km^2 of land already developed and another 500 km^2 capable of development, further erosion could become a very serious regional problem.

The causes of gully erosion have been subjectively assessed but, as yet, no quantitative data have been published. Hypotheses put forward suggest that an increase in surface water flow has caused the gullies, and that the increased flow is a result of:

(1) Short-duration high-intensity rainfalls (Robertson, 1963; Blong, 1965).
(2) Resistance to wetting of dry pumice soils (Van't Woudt, 1954; Packard, 1957; Glass and Drost, 1962).
(3) Organic matter accumulation in the upper horizons of pumice soils (Dixon and Jackman, 1954; Jackman, 1964).

TABLE I — Vegetation, in the Waikato River Basin, on yellow-brown pumice soils (source: Waikato Valley Authority).

Cover type	*Present cover*		*Percentage of area physically capable of further development*	*Remarks*
	Area (km^2)	*Percentage of Waikato Basin pumice land*		
Bare rock, ice, permanent snow	184	3	0	—
Tussock	370	5	100	Mainly in gazetted National Park
Tussock/scrub associations	842	12	Probably up to 95	Current figures include 285 km^2 in East Taupo Forestry proposals
Indigenous forest, including cut-over forest	1632	23	30	Difficult country, mainly in the Kaimanawa & Hauhungaroa Ranges. Economics probably the limiting factor to development.
Pasture	2740	39	—	Already developed
Exotic forest	1243	18	—	Already developed
Total:	7011	100	—	—

(4) Soil compaction as a result of consolidation by heavy machinery and stock (Packard, 1957; Campbell, 1965).
(5) The absence of earthworms, and the build-up of a dense root mat (Bailey, 1953).
(6) High seasonal rainfall soon after land development (Healy, 1967).
(7) Lower infiltration rates into grass root mats than into soil and roots of scrub areas (Selby, 1967b).
(8) Reduction of flow-restricting vegetation (Oliver, 1969).

Many of these hypotheses overlap, but they fall into two classes: (1) those concerned with the effects of prolonged or intense rainfalls; (2) those concerned with the physical properties of the soils upon infiltration and hence upon runoff.

In addition, field work suggests that the building of roads and culverts and the diversion of drainage water on to pastures has been important in the initiation of some gullies.

EXPERIMENTS

Three experiments have been devised to test the hypotheses listed above and to give an assessment of the quantitative contribution of major variables to overland flow and to gully development. The individual experiments have been, or will be, reported in detail elsewhere by Selby (1970b, 1970c, in press) and Selby and Hosking (1971, in prep.), but as the separate experiments each contribute only a little to an understanding of the causes of erosion the main conclusions of each are presented here, their relationship to each other is demonstrated, and general conclusions are drawn.

Published hypotheses and field observations suggested that there were three main problems to be investigated: (1) the influence of soil properties on infiltration; (2) the influence of soil, vegetation and climatic variables on runoff; (3) the influence of soil and vegetation variables upon gully erosion.

Otutira Catchment

Because of the large area occupied by yellow-brown pumice soils, the widespread occurrence of gullies, the necessity to disturb the ground in order to place instruments in the soil and to remove large soil samples, and the requirement of constant experimental conditions, all of the work has been concentrated in the Otutira IHD Experimental Basin. This catchment of 299.3 ha drains into Kawakawa Bay (38° 39′ S, 175° 50′ E), Lake Taupo (Fig. 1).

The catchment has the three classes of vegetation which are widespread on the volcanic plateau – scrub, ungrazed grass and grazed pasture. In the scrub communities the dominant species are manuka (*Leptospermum scoparium*), kanuka (*Leptospermum ericoides*), bracken (*Pteridium esculentum*), five-finger (*Neopanax arboreum*), kamahi (*Weinmannia racemosa*) with *Erica lusitanica, Hebe stricta, Coprosma* sp. and kohuhu (*Pittosporum tenuifolium*). The most common grasses in the ungrazed area are cocksfoot (*Dactylis glomerata*), Yorkshire fog (*Holcus lanatus*) and ryegrass (*Lolium perenne*). In the pasture the most important plants are white clover (*Trifolium repens*), suckling clover (*T. dubium*) and ryegrass. In the experiments vegetation was represented in the analyses by its dry weight per unit area and the dry weight of root matter per unit volume of soil.

The soils of the Otutira catchment are yellow-brown pumice soils. In the analyses the following properties were used: four soil particle sizes – particles greater than 6.35 mm diameter, 0.63 to 6.35 mm, 0.063 to 0.635 mm, less than 0.063 mm; two measures of soil aggregation; two measures of soil organic matter; thickness of the root mat; bulk density; particle density; total porosity; two measures of macroporosity.

Infiltration

A rainfall-simulating infiltrometer was built and used on Otutira soils (Selby, 1970c). Six sample sites were chosen – two from each of the main classes of vegetation – and 18 undisturbed samples of soil were removed from each site. The soil samples were inclined so that in the infiltration tests six were at an angle of slope of 0°, six at 15° and six at 30°. Treatment of the samples ensured a wide range of pre-existing soil moistures.

Analysis of the experimental results (Selby and Hosking, 1971) showed that the range of infiltration rates on all yellow-brown pumice soils from Otutira is large but that there is a statistically highly significant greater mean infiltration under scrub and ungrazed grass than under grazed pasture. This shows that change of vegetation alone is not responsible for decreasing infiltration, but that it is land use practices which are most important. The soil property which pastoral farming might be expected to modify most readily is soil compaction. Soil compaction is statistically negatively correlated at a high level of significance with total soil porosity (–0.525) and macroporosity (–0.553 and –0.534), indicating that as compaction increases porosity decreases. It may be reasonably concluded therefore that the change of land use from scrub to pastoral farming has decreased infiltration rates.

The other notable conclusion from the analysis is that, in general, soils with high pre-existing soil moisture have a higher infiltration rate than dry soils. All other soil properties have a rather low level of correlation with infiltration, suggesting that many soil properties affect infiltration rates but that no measured soil property has a dominant influence.

Because of the very variable nature of infiltration into the soils beneath a uniform kind of vegetation, water running off one area is likely to infiltrate into another. This suggests that a whole catchment, or even a slope, must be considered as a series of discrete plots each with its own infiltration characteristics. This conclusion is compatible with the finding of Beckett and Webster (1971), who have shown that most soils are highly variable materials. The implication is that infiltration studies are of little value for predicting runoff from a catchment; their use is in determining the effects of soil and vegetation properties on water storage and water yield.

Runoff

Twenty runoff plots each of 4 m^2 were established at Otutira (Selby, in press). Measurements of runoff from 44 storms were taken over a two-year period. Thirty-six variables were selected to characterize each of the 20 plots for each observation period or storm. Runoff is the dependent variable for which explanation is sought, and the other variables fall into four classes: (1) precipitation; (2) temperature; (3) plot characteristics; (4) soil properties.

Precipitation variables are: total precipitation falling in the observation period; maximum precipitation in the following periods within the storm – 24 hours, 12 hours, 6 hours, 1 hour, 0.5 hour; number of storms in the observation period; total precipitation for the maximum storm; total duration of precipitation; total duration of rainless time. Five temperature variables were used to give measures of seasonality and potential evapotranspiration: mean maximum daily air temperature; maximum air temperature; mean air temperature; minimum air temperature; mean soil temperature at a depth of 10 cm. Plot characteristics measured were: dry weight of vegetation; soil compaction; angle of slope; aspect; roughness ratio. The 14 soil characteristics have already been listed.

Analysis of the runoff data has shown that six variables are particularly important in explaining runoff.

(1) *Intense precipitation*, especially that occurring as the maximum precipitation in 0.5 hour or 1 hour, gives rise to overland flow because the precipitation rate exceeds the infiltration rate only for the short periods in which rainfall is very intense. This finding is in accordance with what has already been demonstrated in other environments by numerous workers (Selby, 1970a) and was suggested by Robertson (1963) for pumice soils. In conditions of very

high rainfall in short periods the percentage of runoff is very much greater than the mean values of the 44 observation periods.

During the period 22 January 1970 to 3 February 1970, when 30.2 mm of rain fell, runoff from all pasture plots was about ten times higher than the mean runoff for the two years of observations. It reached 68 percent of precipitation on plot 9 and exceeded 10 percent on all pasture plots except plot 2, compared with a mean for pasture plots of 4.6 percent. The ungrazed grass and scrub plots had approximately five times as much runoff as their mean. The greater significance of intense rainfall in pasture areas than undeveloped areas is demonstrated by the correlation coefficients. For pasture areas the correlation of the maximum precipitation in 0.5 hour with runoff is 0.733 and for 1 hour 0.710, but for the undeveloped areas the coefficients are 0.624 for 0.5-hour rainfalls and 0.656 for 1-hour rainfalls.

(2) *The highest air temperature* in the observation period is a reflection of the rate of evapotranspiration but probably more importantly of soil moisture content before rainfall commenced. This conclusion is reinforced by the third variable, duration of rainless time.

(3) *Duration of rainless time* is also a measure of soil moisture. Positive correlations of highest air temperature and duration of rainless time indicate that runoff increases as soil moisture decreases. This finding also supports the conclusion of Van't Woudt (1954) and Packard (1957) that pumice soils exhibit a resistance to wetting once they have dried out. This phenomenon, which is widely known in other soils (Debano and Letey, 1969), has not yet been fully investigated in pumice soils.

(4) *Total precipitation* is of greatest importance in the areas of ungrazed grass and scrub. It is probable that this is because soils are less compacted and retain their moisture more readily in the undeveloped areas than in the pasture. This is indicated by the highly significant differences between penetration resistance among the three vegetation types, and by the correlation coefficients of total precipitation with runoff. From the undeveloped area the correlation coefficient is 0.501, but from the pasture area it is 0.187.

(5) *Penetration resistance* is not correlated with runoff at any but a low level (0.196 in the overall analysis), but in a multiple regression analysis it emerges as the second most important variable in the overall analysis. From this it may be concluded that the importance of many soil properties – each only slightly correlated with runoff – is subsumed in the penetration resistance.

(6) *Soil particles of 0.63–6.35 mm diameter* enter the multiple regression equation for the undeveloped area at the fourth step. This variable is negatively correlated with runoff, indicating that runoff decreases as the proportion of this coarse sand to fine gravel fraction in the soil increases. This is presumably because the presence of this fraction increases soil permeability.

(7) *Slope angle* occurs as the second most important variable in the undeveloped areas. Its correlation coefficient with runoff is 0.297, which is lower than that of several other variables, but these other variables interact and their effect is subsumed in the two major precipitation variables and in the coarse sand to fine gravel variable. Slope presumably behaves largely independently of other variables and, because slope is positively correlated with runoff, runoff increases with slope angle. In pasture areas slope is unimportant, having a correlation coefficient of only 0.042 with runoff.

Rate of Runoff

The rate of runoff was measured at only three plots – plot 17 under scrub and plots 8 and 9 under pasture. The runoff from the plots in relation to rainfall has been studied in detail for the two periods 7–10 May 1970 and 24–26 September 1969. These periods were chosen as being representative. In both periods the pattern of runoff was approximately the same. Runoff began first under the scrub, but at a very slow rate. The maximum rate of runoff on all plots approximately coincided with the most intense rainfall, although on plot 9, which has a very steep slope of 33°, the maximum runoff rate occurred earlier than on the other plots. In the May storm, runoff from the pasture plots was prolonged even when rainfall intensity had declined to a low value. In general, runoff from scrub plots is more nearly instantaneous than that from pasture, and the pattern of runoff follows that of rainfall intensity. The amounts of runoff during low-intensity precipitation on scrub are rather greater than amounts from the pasture plots. This indicates that under scrub the lower-intensity rainfalls are more important causes of runoff than under pasture where intense rainfalls are more important.

Total Runoff

The runoff plots in the pasture area yielded a mean runoff of 4.6 percent of precipitation received, and this is significantly greater than the 0.89 percent from plots beneath scrub and 0.67 percent from those beneath ungrazed grass. In individual storms the same ratio was preserved, with the important difference that from very intense storms the percentage runoff was increased by a factor of up to 10.

Stepwise multiple regression equations have been developed for runoff from the plots. For ungrazed grass and scrub plots taken together, 60.8 percent of runoff can be predicted in terms of four variables –

First step:

Predicted runoff = – 374.676 + 282.075*** (Maximum precipitation in one hour) (Where $R^2 = 0.430$)

Second step:

Predicted runoff = – 1916.866 + 282.161*** (Max. precip. in 1 h) + 94.378*** (slope angle) (Where $R^2 = 0.519$)

Third step:

Predicted runoff = – 2370.493 + 232.345*** (Max. precip. in 1 h) + 94.385*** (slope) + 15.768*** (Total precipitation) (Where $R^2 = 0.576$)

Fourth step:

Predicted runoff = 508.341 + 232.400*** (Max. precip. in 1 h) + 75.463*** (slope) + 15.769*** (Total precip.) – 109.920*** (Particle size 0.63–6.35 mm diam.) (Where $R^2 = 0.608$, F: 100.478***)

For pasture plots 62.7 percent of runoff can be explained in terms of three variables –

First step:

Predicted runoff = – 2965.118 + 1736.470*** (Max. precip. in 0.5 hour) (Where $R^2 = 0.554$)

Second step:

Predicted runoff = – 13896.941 + 1646.915*** (Max. precip. in 0.5 h) + 568.878*** (Highest temperature) (Where $R^2 = 0.612$)

Third step:

Predicted runoff = – 16596.516 + 1586.105*** (Max. precip. in 0.5 h) + 589.993*** (Highest temp.) + 7.171*** (Duration of rainless time) (Where $R^2 = 0.627$, F: 343.084***)

The rather low levels of explanation require comment. There are several interacting causes which can be separated. One obvious cause is the large number of variables which have some, albeit small, influence on runoff. Most of the soil properties are only slightly correlated with runoff – some negatively and some positively – but some of these variables will change their relationship with runoff with seasonal or other influences. The changing influence of variables greatly reduces the level of explanation when data are agglomerated. It has been shown by Soons (1970) that explanations

***: significance level 1.0 percent.

varying from 54 to 93 percent may be achieved for six plots using 15 variables. Such an approach would not, however, have given the understanding of general conditions which the Otutira study was designed to achieve. Secondly, there must be some experimental and sampling error in any study of this kind. Thirdly, the interrelationships inherent in the soil and climatic variables will have reduced the explanation achieved by the stepwise multiple regression form of analysis which was adopted.

Gully Erosion

Because of the large size of natural gullies and the irregular time intervals between periods of gully development it has usually proved impossible to correlate gully development directly with soil and vegetation properties, and even correlation with climatic variables has been difficult. To overcome this problem a laboratory flume has been built which simulates gully erosion (Selby, 1970b). The flume allows known volumes of water to run over one box containing an undisturbed soil and vegetation sample and then to fall on to a lower sample. Sediment produced by the erosion of the samples is then collected and analysed and correlated with the properties of the soil and vegetation of the sample boxes.

Eight flume tests of samples, from each of the three vegetation areas of the Otutira catchment, have been carried out. The experiments have shown (Selby and Hosking, in prep.) that soils beneath scrub vegetation are more easily eroded than those beneath pasture grass vegetation when the same volume of water washes over the surface of the ground. Ungrazed grass is slightly less effective in protecting soil than is grazed grass. This effect is largely explained by the binding effect of plant roots and organic matter on the soil particles. Gully erosion of pumice soils is attributable to the low density and easy entrainment of the soil particles. The best prediction equation derived from a stepwise multiple regression analysis accounted for 85 percent of the erosion in terms of only three variables –

First step:

Predicted erosion = 1240.714 – 246.606*** (PTC1) (Where $R^2 = 0.646$)

Second step:

Predicted erosion = 998.881 – 410.462*** (PTC1) + 58.118*** (ORG1) (Where $R^2 = 0.829$)

Third step:

Predicted erosion = 1023.085 – 358.356*** (PTC1) + 50.819*** (ORG1) – 2.800(SHER) (Where F: 37.905*** and $R^2 = 0.850$)

where PTC1 is mineral particles greater than 6.35 mm diameter, ORG1 is the percentage of fine organic matter in the sample and SHER is the shearing resistance of the soil.

There is one very important rider to this conclusion. In the flume tests the same volume of water with the same energy was passed over the samples from each of the three classes of vegetation. It has been shown above, however, that under natural conditions runoff is always much greater under pasture than under scrub or ungrazed grass, hence an equal erosive force is never placed on the soils under natural conditions, and although soils beneath scrub may be inherently more erodible it does not follow that they are actually liable to great erosion.

CONCLUSIONS

Causes of Erosion

Three experiments have been described, from which a number of conclusions about the causes of erosion of pumice soils may be derived.

It has been shown that surface water runoff is greater from developed areas in pasture and less from areas covered by scrub and ungrazed grass vegetation. The major causes of runoff from pastures are very intense precipitation falling on a soil with low moisture content. Infiltration studies support this conclusion.

Infiltration is relatively low under pasture grass vegetation and greater under scrub and ungrazed grass. The high infiltration under ungrazed grass indicates that it is not grass vegetation alone which causes low infiltration rates but modifications of the soil by land use practices. An important effect is the compaction by machines and animals, which reduces soil porosity.

Where an equal shear stress is placed on soils beneath scrub and pasture vegetation, scrub soils are more easily eroded. Shear stresses are, however, probably never equal in natural conditions, since runoff is always greater, in intense storms, from pasture areas. Erosion of pumice soils is attributable to the low density and easy entrainment of the soil particles. The binding effects of plant roots and organic matter in the soil reduce the liability to erosion.

Prevention of Erosion

Analysis of the causes of erosion indicates that a number of land use practices may assist in the prevention of erosion.

The land must be protected against the effect of very intense storms, particularly those which occur when soil moisture content is very low. Such storms are most likely to occur after long dry periods during the summer. Field experience suggests that the maintenance of a close grass sward and the avoidance of overstocking are most effective in protecting the soil. Maintenance of a close grass sward on pumice soils during a dry summer is extremely difficult, and vulnerable areas should therefore be left in scrub or planted with trees. Vulnerable areas are valley floors and steep slopes.

High infiltration rates may be promoted by leaving valley floors as water absorption areas from which vehicles and animals are excluded so that the soil is not compacted. The vegetation cover may be scrub, forest or ungrazed grass but it is to be expected that farm forestry will be the most economic use for such areas. Absorption areas should be effective because it is short-duration high-intensity rain that they must temporarily impound and allow to infiltrate rather than prolonged rain.

Soil stability may be maintained by keeping a complete vegetation cover on the land and by promoting a vegetation with a strong, dense root system. This will, at the same time, increase the proportion of organic colloids in the soil. All forms of activity which cause soil exposure, and especially the formation of ruts and channels, must be avoided.

The experiments undertaken were not designed to provide information on the effectiveness of practices such as contour furrowing or terracing. Field evidence, however, suggests that these should be used only in carefully selected experimental areas, as indiscriminate use could result in the formation of local rills and channels, and subsurface pipes. Land development is likely to be most successful where the vegetation and land use allow the vegetation and soils to be highly absorbent of water and where plant root systems bind the soil. Increased runoff from roads and building sites must be routed to prevent it breaking the vegetation cover.

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