GULLY DEVELOPMENT AND CONTROL ON A VOLCANIC ASH SOIL AT OLKARIA, KENYA

by

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DECLARATION

I hereby declare that this thesis is my original work and has not been presented for a degree in any other university. All facts and opinions have been distinguished and attributed to the respective sources.

Signed:...Gitonga...........Date:...30/6/94....
M. Gitonga

This thesis has been submitted for examination with my approval as the principal university supervisor.

Signed:...D.B. Thomas.............. Date:...30.6.94...
Prof. D.B. Thomas

DEDICATED TO MY BELOVED PARENTS.

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LIST OF ABBREVIATIONS

Abbreviation	Description
a.s.l	above sea level
Av.	Average
B/wood	Brushwood
C_r	Clay ratio
Dep	Deposition
D_r	Dispersion ratio
FAO	Food and Agriculture Organization
F_i	Flocculation index
Geoth. PJT	Geothermal Project
I	Intensity
I_{10}	10-minute maximum rainfall intensity
I_{30}	30-minute maximum rainfall intensity
KPC	Kenya Power Company
KPLC	Kenya Power and Lighting Company
KSh.	Kenya Shilling
KWS	Kenya Wildlife Service
L/stone	Loose stone
Met.	Meteorological
MRG	Manual Rain Gauge
no.	number
N/A	Not Applicable
Q_p	peak discharge
sp.	species
TBRG	Tipping Bucket Rain Gauge
USDA	United States Department of Agriculture

ABSTRACT

A study on two gullies (A and B) on a volcanic ash soil in a semi-arid area at Olkaria, in Hell's Gate National Park, was done to determine the main gully development processes, characteristics that contribute to gullying and to test low cost measures of control. Gullying was common in this study area where geothermal power development was taking place. The study on gully A included its morphometry, development processes, catchment, soil, and rainfall characteristics, and tests on various control measures. Similar investigations were done on gully B except that they were less detailed and did not include rainfall characteristics and tests on control measures.

The main development processes observed were bed scouring, undercutting and sidewall collapse. Observations revealed that a rainfall event that caused the most bed scouring of 68.0 cm had a I_{30} of 24.4 mm/hr which yielded runoff of 0.21 m^3/s into the gully. This bed scouring was more than that caused by a later rainfall event, with a I_{30} of 28.8 mm/hr, that produced runoff estimated at 1.40 m^3/s which scoured the bed for only 20.0 cm. It was deduced that erosion of the gully bed depended, to a large extent, on the erodibility of the bed which was in contact with the runoff and the moisture condition or rainfall amount 5 days prior to a runoff event. The erodibility of the volcanic ash soil at Olkaria was rated high and it was established that land use changes, like overgrazing and unprotected disposal of geothermal development waste water downhill, contributed to gullying.

Results of control measures showed that brushwood and loose stone check dams had an average deposition in their upstream of 51.0 cm and 57.0 cm respectively but the former check dams were more stable than the latter since brushwoods were secured between posts unlike the loose stones. The main problem encountered on brushwood check dams was key failure. Conversion of the channel of gully A to a grassed parabolic waterway did not prevent bed scouring but minimized undercutting and sidewall collapse. A reshaped and grassed gully sidewall got rilled and its loose soil at the toe region was undercut by runoff making grass establishment difficult. Tests done on four grass species, on an adjacent land which had been bulldozed in an unsuccessful attempt to fill the gully, showed that star grass (*Cynodon dactylon*) had the highest survival rate.

Due to the high erodibility of the volcanic ash soils, disturbed or overgrazed lands should immediately be revegetated to avoid gully erosion. Once gullies have started minimization of the main erosion processes can be done through the installation of loose stone and brushwood check dams (to prevent bed scouring) and a grassed parabolic waterway (to minimize undercutting and sidewall collapse). Shaping of the gully wall needs further investigation since the resultant erosion hazards can prevent vegetation growth.

1.0 INTRODUCTION.

1.1 Background Information.

The area selected for a study on gully erosion and its control was at Olkaria on the southern side of lake Naivasha (fig. 7). The site was within the Hell's Gate National Park in Naivasha division of Nakuru district where the Kenya Power and Lighting Company are developing geothermal power in the Kenyan Rift Valley. Volcanic ash soils occupy large areas of the Kenyan Rift Valley floor. They have high susceptibility to erosion by water due to their low cohesion. As a result of poor land management, some of the areas have been incised by deep gullies which have been neglected. In addition, the vegetation cover of the area is sparse leaving the soil partly bare, especially after burning. Before geothermal resource development at Olkaria, the area (see figs. 7 and 8) was mainly inhabited by Maasais who owned large herds of animals which overgrazed the land and left tracks. This led to wind erosion due to bare ground and loose soil during the dry periods. This was also observed in Longonot area with similar climatic and edaphic characteristics but having a flatter terrain than that at Olkaria. In the event of high intensity-short-duration storms the loose soil was washed away leaving very deep gullies. Areas which were not overgrazed or disturbed were left unaffected. Later the Maasais were evicted from the area with subsequent recovery of vegetation.

The gullying problem was aggravated by the geothermal drilling activity at Olkaria whose discharges (mainly hot saline water) were channelled downslope causing the formation of deep gullies. These discharges cold alter the soil's physical and chemical properties to increase its erodibility, not to mention their effects on vegetation and soil fauna. Soil disturbance or earth movement, i.e. cutting and filling by machinery, together with soil cover removal have also played a role in the formation and development of gullies due to soil loosening and exposure through devegetation. In addition, temporary access roads get gullied if abandoned and tarmacked roads concentrate and drain runoff into gullies resulting to their expansion. Occasional fires, like the one of 1991, have a devastating effect on vegetation with subsequent increase in runoff and therefore increase in gully erosion.

Attempts to reduce soil erosion were taken by the Kenya Power and Lighting company in conjunction with the Kenya Wildlife Services. For instance, grazing of livestock was prohibited in the park and consequently there was re-establishment of grass cover and shrub growth on the earlier overgrazed areas. An environmental section was set up to alleviate environmental degradation by engaging in some rehabilitation works. Some denuded surfaces were safely sloped, compacted and grassed

(Ojiambo, 1989) and well discharges were safely disposed of. Consequently many gullies healed and the rate of gully formation and development reduced. However erosion was still continuing on land adjacent to some of the geothermal drilling sites and needed attention (KPC, 1992).

Failure to address the issue of environmental consequences of large development projects has occurred for many years. Nowadays there is a need to evaluate alternative locations and development methods to improve the overall quality of development planning. Not until pressure comes from donor agencies will some countries review the environmental consequences of such projects (FAO, 1982).

1.2 Justification and Objectives of the Research.

A need arises to evaluate the environmental impacts of development activities on land and find remedial measures to counter the detrimental ones. It was therefore important that research work be carried out in an area where development activities have contributed to gullying and to find appropriate gully control measures. Also there is a rapid increase in small scale settlement in the Kenyan Rift Valley floor which has a great potential for wind and water erosion.

On the volcanic ash soils of the Rift Valley little research has been done on gully formation and development processes and the methods of controlling gully erosion. Many gully erosion surveys have been done without looking at the processes involved which could aid in selecting appropriate measures of control. Very little information is available on low cost measures of control which could be used by small scale farmers. Therefore, low cost measures have to be tested, in spite of the risk of failure, and an understanding of the processes involved may be used to recommend good land management practices and suitable measures of control. This will hopefully increase or sustain agricultural production, save infrastructure and other assets from destruction, prevent siltation over the steam conveying pipes at the geothermal power station and conserve natural and planted vegetation mainly for livestock and wildlife use.

The research was done with the following objectives:

- To find out the processes involved in gully formation and development.
- To determine the climatic, soil and land use characteristics that contribute to gully erosion.
- To test alternative low cost measures for gully control and rehabilitation.

2.0 LITERATURE REVIEW.

2.1 Gully Formation and Development.

Soil erosion in general has taken place and always will. It is an aspect of geomorphogenesis. 'Normal', geologic, or 'natural' erosion results from forces of nature. However due to man's interference with the ecosystem, accelerated or anthropogenic erosion occurs. As population pressure builds upon our limited land resource man's land use activities tend to disrupt the soil's natural metastable equilibrium which lead to various forms of soil erosion. These forms are divided into interill, rill, gully and stream bank erosion (Hudson, 1985). In addition Kilewe (1987) includes raindrop erosion as a form of erosion. Whichever the classification, good measures of soil erosion control can be assessed through research.

The contribution of each form to soil erosion depends on characteristics of an area and therefore varies from one place to another. Thornes (1976) quotes Rhoades et al (1975) who found that the gullied portion of an eroded grassland watershed in U.S.A. produced 51% of all sediment, but occupied an area of only 1%. But Leopold et al (1966) quoted by Thornes (1976) found that mass movement, gully head extension and channel enlargement were small contributors of sediment (and therefore soil erosion) compared to sheet erosion on unrilled slopes in U.S.A. Thornes (1976) however mentioned that gullies are important contributors to soil erosion.

Gullies have been defined differently by various authors. According to Troeh et al (1980) and Bennett (1939) gullies are channels that are too large to be obliterated or crossed by a normal tillage implement in tillage operations. Hudson (1985) defines a gully as a steep-sided eroding water course which is subject to intermittent flash floods. He excludes those that are gentle sided and those that have stabilized.

After their study of gully development at the Njemps Flats in Baringo, Wijdenes and Bryan (1990) noted that all actively expanding gully systems have their activity caused by sudden intense storms, climatic changes, changes in catchment hydrology leading to increased peak discharge; reduced surface resistance due to devegetation or changes in soil physical and/or chemical properties; and changed hydraulic conditions in formerly stable system caused by base level decline related to lake levels or bed scour in a major stream. In general, the factors involved in gully erosion are highlighted in the following section.

2.1.1 Factors involved in gully formation and development:

Rainfall characteristics and runoff. The influence of rainfall erosivity on soil erosion is not always clearly seen because soil erosion is related to two rainfall events, i.e. the short duration intense storms whereby the infiltration capacity of the soil is exceeded and long duration low intensity storms which saturate the soil. Although most soil erosion from hillsides and transport of sediment in rivers occurs in relatively frequent rainfall events of moderate magnitude, extreme events can be dramatic and have long lasting effects. For instance, extreme rainstorms having a return period of 100 years may start headward advance of gullies and initiate the formation of new gully heads. Instances of fresh gullying have also been noted to relate to extreme rainfall events with return periods of over 10 years (Morgan, 1986). The effects of these extreme rainfall events are long lasting and the time required for an area to recover from gullying, for instance, is up to 50 years as evidenced by Burkham (1972) quoted by Thornes (1976). Burkham, after investigating channel changes of Gila river in Safford valley in Arizona, attributed the recovery to lateral accretion and vegetation growth.

The erosion or deposition of soil by rainfall events is conditioned by the time since the last event of a similar magnitude. The recovery of sediment yield patterns and therefore erosion or deposition from the shocks due to the last event may take some time. Also the relation between the work done by the event and the simple flow volume or rainfall may be poor during the period of the event. This may be due to effects of preparation of the material or lack of it, prior to a runoff event (Thornes,1976).

Soil erodibility. The resistance of a soil to erosion is influenced broadly by its physical and chemical properties, topographic features like slope of the land and the management of the land. However the most important are the soil physical and chemical properties (Morgan, 1986). Erodibility will therefore vary with soil texture, aggregate stability, shear strength, infiltration capacity and organic matter content. For example, soils high in silt and fine sand are the most erodible. They encourage surface sealing and are least resistant to detachment (Morgan, 1986; Barber et al, 1979). In Sweden, for instance, gullies are commonly found where silt borders a less erodible soil (Jannson, 1982). Also many secondary and unpaved roads in U.S.A. loess areas have eroded into gullies and waterways because loess has a high content of silt which makes it vulnerable to erosion(Jannson, 1982).

Sand percentage is inversely related to clay content and increasing sand implies increased soil erodibility. The type of clay mineral present in a soil affects the aggregate stability and hence erodibility of a soil which decrease with increase in aggregate stability. For instance, at moist moisture contents soils with a 1:1-type lattice clay have a greater cohesion and therefore greater aggregation than the soils with a 2:1-type lattice clays (Gachene, 1982).

Several other indices of soil erodibility have been used. Some of the simple and commonly used indices include clay ratio which basically assumes that sand and silt increase erodibility, while clay decreases it (Morgan, 1986). For instance, a high silt:clay ratio favours development of large gullies (Ichim et al, 1990). However in Kenya huge gullies have been observed on black cotton soils (which are high in 2:1 type lattice clay) in Nyakach. Dispersion ratio has been used to measure the ease of soil dispersion in water. Wischmeier et al (1971), who were quoted by Morgan (1986), have used organic matter, soil texture, soil structure and permeability as indicators of a soil's erodibility. Organic matter in the soil decreases soil erodibility (Jannson, 1982). Also saline and/or sodic soils are prone to gully erosion as exemplified by huge gullies observed in some parts of Baringo and West Pokot districts of Kenya.

Effect of topography (slope). Erosion will often increase with increase in slope steepness and length due to increases in runoff velocity and volume. In general steep and long slopes are more erodible by water than flat land due to greater effect of erosive forces, scour and transport on steep land (Hudson, 1985; Morgan, 1986). It is therefore expected that gully erosion vulnerability increases with slope steepness and length.

Land management or human factors. The effect of land management on soil erodibility is of paramount importance. For instance, a land use that deprives the soil of its cover may lead to gully initiation and further gullying may occur due to increased runoff yield from the low cover or bare gully catchment. Therefore a land use that is intensive and productive without soil degradation is called for.

2.1.2 Types of gullies and their mode of formation.

Based on the mode of gully formation and development there are mainly two types of gullies, viz: continuous and discontinuous.

Continuous gullies. These develop in different vegetation types ranging from bare soils to forested deep soils with dense vegetation. They mainly develop where concentrated runoff from a slope rapidly increases in volume and velocity causing cuts or where the incision is continuous in time on the same groove (Bennet, 1939). The increase in runoff volume and velocity may be caused by land being left bare through overgrazing, land clearing and burning of bushes, livestock and wildlife trails, roadcuts, to mention a few. The continuous gully, according to Heede (1976), begin its downstream course with many finger-like extensions into a headwater area. It starts high up on the slope and continues its course down to the main valley floor. Due to scouring, the bed erodes and the gully deepens and widens rapidly in the downstream direction. A continuous gully may also form through fusion of discontinuous gullies.

Discontinuous gullies. These start by an abrupt headcut. An observation done on Alkali Creek watershed in Colorado by Heede (1976) showed that discontinuous gullies begin to form at locations on the mountain slopes that had an abrupt slope break. The headcut may be located at any position on the hillslope and may intersect the end of a slope and get terminated. Formation of an initial furrow scarplet can result due to reduction in soil resistance through overgrazing, trampling, fire or other agents. With subsequent storms the erosion feature progresses upslope leaving a fan at its toe region. A vertical headcut is formed as the channel forms and channel storage is reduced with an increase in peak flows. Large peak flows have greater velocity and scouring power and thus gullying is aggravated.

A discontinuous gully rapidly decreases in depth downstream developing a bottom gradient less than the original valley floor. Where there is a slope break (slope intersection) a sediment fan is built from where a new gully may begin with a headcut. Headward advance of discontinuous gullies does not always depend on headcutting process. Piping upslope of the headcut may occur whereby the pipes can collapse to give a rapid extension of the gully. Heede (1976) quotes Hamilton (1970) who observed that the formation of discontinuous gullies can also be explained by piping collapse. Piping occurs when infiltrated water comes into contact with a less permeable layer. The water washes some fine soil particles downhill. This creates a pipe that widens and then collapses to form a gully head or a gully. Heede (1976) observed this in soils high in exchangeable sodium percentage (ESP) which decreased the soil's permeability. Piping can increase infiltration through creation of a rough soil surface with small depressions and therefore may increase revegetation process of a gully.

2.1.3 Mechanics and processes involved in gully development.

For both continuous and discontinuous gullies, Ireland et al (1939) quoted by Bradford et al (1978), proposed the stages of gully development as channel erosion by downward scour, headcutting and rapid widening, followed by healing and stabilization; the main processes being downcutting and headcutting.

The potential of loessial soil (similar to andosols according to Troeh et al, 1980) to collapse upon saturation by water is a contributing factor to gullying. In a study on loess soils in Iowa, Piest et al (1973) found that mass wasting of gully banks and headcuts were the prime erosion processes, not bed scouring due to the tractive force or stream power. They also found that height of water table, soil cohesive forces, shear strengths, rate of infiltration, weight of soil mass and seepage forces of percolating water were the main factors determining gully bank stability. Tension cracks decrease gully wall stability and pore water pressure increases due to water infiltrating into the cracks. This often results in slope failure. Similarly Bradford et al (1978) observed that decrease in soil strength due to infiltration is a major cause of instability of gully walls in deep loess hills of western Iowa. Also undercutting of a gully wall toe almost always leads to bank sloughing or failure. Even without undercutting they observed that "popouts" (which resulted from increased pore water pressure) led to overhangs which later collapsed into the gully bed. The fallen debris may be responsible for reduction in sidewall slopes if they are not transported by runoff. They fall against the gully wall due to gravity and increase resisting forces consequently increasing the gully wall stability (Bradford et al, 1978).

Gully banks tend to retreat rapidly and parallel to themselves. In the process a small compacted slope foot segment and a wide flat depositional basin are created. As the walls retreat the trench becomes wider and shallower. The results of a 6 1/2 year period of erosion pin measurements in a desert gully in Southern Arizona indicated that gully morphogenesis was in most cases controlled by the retreat of sidewalls and deposition in the gully basin that was occasionally interrupted by piping collapse of the gully floor. The piping was caused by seepage of irrigation waters from arable fields (Martin, 1990).

In western Iowa Bradford et al (1978) observed and explained failure of gully headscarps. Popouts or alcoves form at the base of the gully head; the overhang so formed is weakened by water leading to columnar sloughing and later entrainment of the material by water to the downstream. The material may cover the popout and therefore stabilize the head due to reduced slope, but transport of the material helps in sustaining the process of mass wasting and debris removal.

The gully bed at the headscarp base can show lowering due to plunge water action (fig. 1). This is aggravated in case a weak horizon is reached through undermining or caving due to back trickle, seepage and spray water. Daniels and Jordan (1966), as quoted by Handy (1973), observed that headwall undercutting in a loess soil was not a normal feature of most headwalls but he observed undercutting during headward advance of knickpoints or minor headscarps in the gully. They also found that there was extensive and immediate sidewall slumping near the loess headwalls.

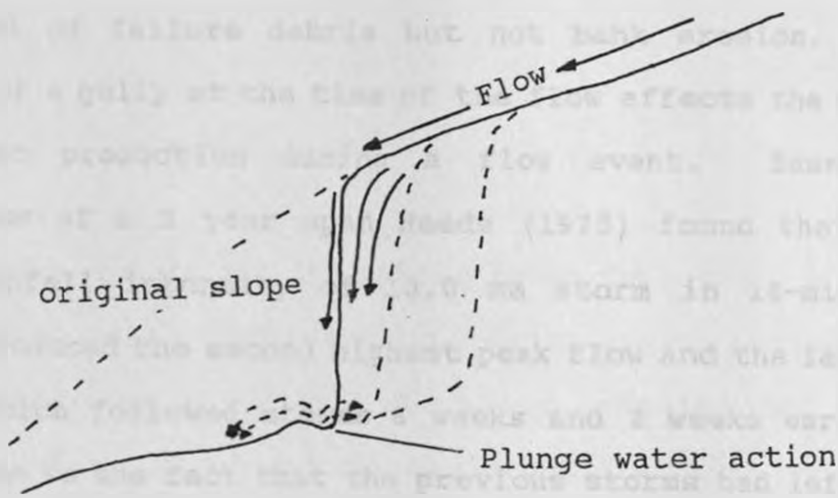

Fig. 1. Waterfall erosion at gully head and advancement of gully towards the upper edge of the watershed (source: Hudson, 1985).

In his study on dynamics of gully head recession on an aeolian covered plains of a savanna environment, Olofin (1990) concluded that much of the eroded material is lost through mass wasting arising from a sequence of undermining, collapse of undermined materials and the subsequent removal of collapsed material. It is appropriate to intervene and prevent removal of collapsed material in order to break this sequence and therefore stop or inhibit gully head recession.

Roloff et al (1981) noted that failure events followed rainy periods and the bottom of the failure slab coincided with the seepage zone. However gully wall stability seemed unrelated to the overland flow and there was no evidence of soil scoured from the gully boundary. Overland flow was responsible for the removal of failure debris but not bank erosion. The stability of a gully at the time of the flow affects the rates of sediment production during a flow event. Based on observations of a 3 year span Heede (1975) found that the lowest rainfall intensity of 10.0 mm storm in 16-minutes duration produced the second highest peak flow and the largest sediment which followed storms 8 weeks and 2 weeks earlier. This was due to the fact that the previous storms had left the gully in a raw and unstable condition, with overhanging walls.

During rains, gully side slopes shear off leaving nearly vertical walls. Fallen debris forces future runoff against the channel wall leading to undercutting and consequently more bank cleavage. As a result of the deposition, side slopes become stable and vegetated since growth of vegetation is favoured by increased soil moisture. The gentler slope and porous nature of fallen debris and deposits lead to more water infiltrating. Once plants become established the gully wall slopes stabilize rapidly (Heede, 1975).

The extension of gullying may continue until it reaches a non-erodible rockscarp or until slope decreases especially at the foot of the catchment. This was observed by Chakela (1981) in his studies on erosion and sedimentation in reservoirs in Lesotho. He noticed that gully headward advance was restricted or checked by presence of a bedrock scarp.

2.1.4 Gully geometry

Gully geometry and growth is related to or influenced by soil properties and soil stratification. Gully growth accelerates when it reaches a soil layer with low cohesive and shear strength. Where a subsoil is resistant to rapid cutting, because of fine soil texture or toughness, V-shaped gullies develop (FAO, 1986). U-shaped gullies form where both surface and subsoil are easily erodible due to gully wall widening and failure as it deepens (see fig. 2). But Hunt (1972) contradicted the idea by saying that V-shaped gullies form in a homogenous ground and U-shaped ones in areas where the topsoil is tougher than the underlying layers giving steeper walls, and broader and flatter bottoms. In case of U-shaped gullies both authors might be correct but Hunt's explanation of formation of V-shaped gullies is less obvious than FAO's.

FAO (1986) continues to describe trapezoidal gullies as being those that are formed where the gully bed has a more resistant material than the topsoil and subsoil because erosion on the banks exceeds that of the bed.

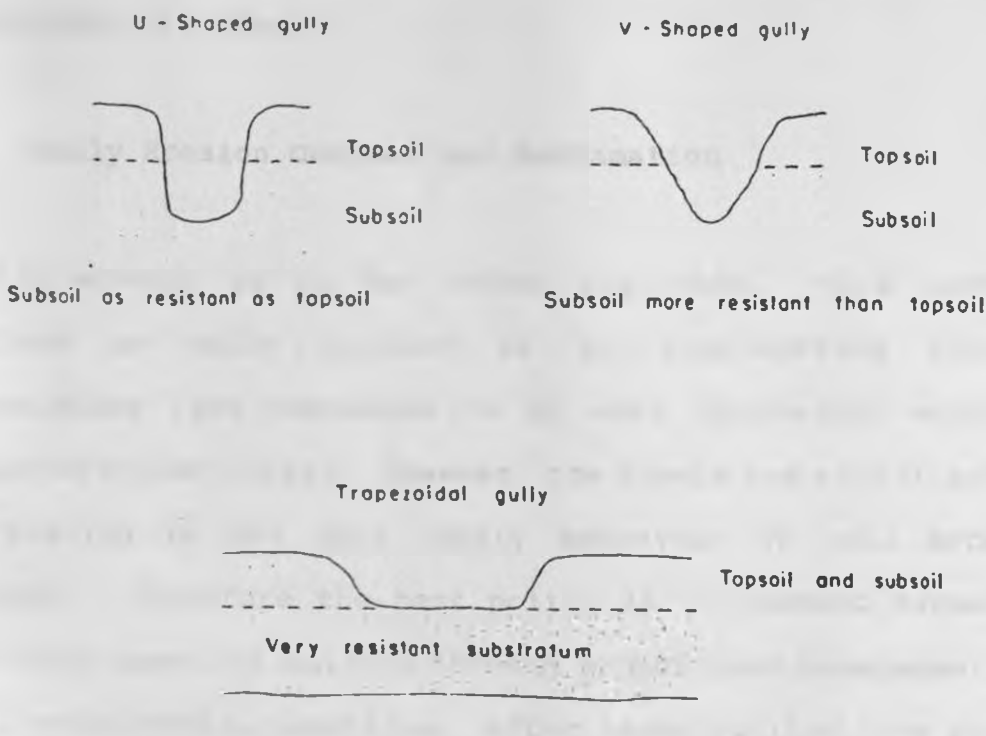

Fig. 2. Gully classes based on shape of gully cross-section (source: FAO, 1986).

Gully long profiles have a tendency to be convex, with a slight concavity at the downstream end. These gullies belong to the stage of vigorous expansion (Ichim et al, 1990).

By doing a detailed morphometric analysis of seven gully systems in Moldavian Tableland in Romania, Ichim et al (1990) discovered strong positive correlations between gully length and drainage basin area, the length of the gully and its depth, and the size of the gully excavation and the size of the gully basin. An analysis of geometry can be indicative of the correlation with environmental factors such as the land management practices.

2.2 Gully Erosion Control and Reclamation

"Gully erosion is so far rather neglected. This fact is serious as gully erosion is an accelerating process devastating land resources to an ever increasing extent", lamented Wenner (1984). However, the repair and stabilization of gullies is the most costly endeavour of soil erosion control. Therefore the best policy is to prevent formation and development of gullies through proper land management and soil conservation practices. After large gullies have formed it is uneconomical to reclaim them because the cost usually surpasses the benefits (FAO, 1977; Wenner, 1984). However there is need to stabilize the large gullies for the sake of protecting the nearby infrastructure and to enhance accessibility. Furthermore a stabilized gully can be used for forestry, crop and fodder production if the relevant plants are grown on its sides and bed (if soil conditions allow). In U.S.A, where land is plentiful, treatment of gullies aims at stabilizing them through mechanical and biological means to stop further incursion into agricultural land. The gullies also serve as good habitats for wildlife (Verma, 1981).

2.2.1 Principles of gully erosion control and reclamation.

The principles of gully control as highlighted by FAO (1986) include:

- Improvement of gully watershed or catchment to reduce the peak surface runoff and its velocity;
- Diversion of surface water above the gully area;
- Stabilization of gully walls, bed and the head by structures and revegetation, i.e. bio-engineering measures.

FAO however left out a crucial first procedure of fencing off the area to be treated to avoid interference especially in areas where grazing is unrestricted. Hudson (1985) gave two broad principles of gully control. The first one is to determine the cause of the gully and counter it with some measures. The second one is to either restore the hydraulic balance or improve the gully channel so that it can accommodate more runoff. Therefore efforts to control or reclaim gullies should be carried out with a clear understanding of what they are expected to achieve.

The decision on whether to undertake a control programme or measure also depends on the activity of the gully. The gully may have already reached the bedrock making it unworthy to control unless it is reclaimable. Wenner (1984) recommended that U-shaped gullies may not need vegetation since erosion may be so low that natural revegetation will occur. However revegetation cannot occur on the steep sides of the gully which may need reshaping and revegetation.

An important parameter used in the selection and design of gully control structures and systems is the expected peak runoff rate since runoff is the main erosion agent in gully formation and development (Verma,1981).

2.2.2 Estimation of the peak runoff rate.

The quantity of runoff from a storm depends on many factors: the topography, vegetation, the infiltration rate, the soil storage capacity, the moisture conditions of the catchment at the onset of the storm and, more important, the storm characteristics:- rainfall amount, intensity and duration. Estimation of rates of runoff is done using several empirical formulae that were developed in specific situations and hence should be applied cautiously. Furthermore most of them do not take into account the antecedent moisture conditions (Hudson, 1985; Linsley et al, 1988).

There are many ways of quantifying the factors highlighted above. Runoff coefficient represents the ratio of the rate of runoff to the rate of rainfall and it is obtained from tabulated values in some soil conservation books (Hudson, 1985). Catchment characteristics are also represented broadly in most formulae used.

The rational method is a popular method of estimating peak rate of runoff for small catchments despite its shortcomings. It is given by the equation:

$$Q = CIA / 360 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

Q is rate of runoff in m^3/s

C is a dimensionless runoff coefficient

I is intensity in mm per hour

A is area in ha.

It has an advantage of being used to estimate maximum runoff rate even when little information is recorded (Hudson, 1985). However it gives a substantial overestimate of design flows

(Linsley et al, 1988). Hiemstra and Reich (1967), quoted by Linsley et al (1988), found that the rational method overestimated in approximately two-thirds of the basins in a test sample and the average of the calculated peaks was about twice the observed peaks.

Intensity, I, used in the formula is dependent on the time of concentration of a catchment which can be estimated from Kirpich formula (equation 4). It is difficult to estimate a correct runoff coefficient, C, since it is dependent on the antecedent soil moisture state of the catchment and therefore varies with storm durations (Noort and Stephenson, 1982).

On the other hand, Cook's method (developed for use in tropical Africa conditions) is very simple to apply and, unlike rational method, it requires minimum of recorded data. Catchment characteristics (cover, soil type and slope) are estimated from tabulated values which, together with the area of the catchment, are used to read runoff directly from a table (Hudson, 1985).

2.2.3 Measures of gully control and reclamation.

Heede (1976) looked at the mechanics of gully erosion and concluded that effective gully control must stabilize both the channel gradient and channel headcuts. However he left out the stabilization of gully sidewalls which is also important. In general two kinds of measures are recommended for the control. These include vegetative and bio-engineering measures. In addition engineering measures alone are rarely recommended because they are costly.

Vegetative measures. Although structures are necessary for gully control it is preferable to control and reclaim gullies by use of vegetation because vegetation can multiply, thrive and is less expensive than structures which require skills for design and construction. Vegetation provides physical protection against scour by reducing flow velocity through increased hydraulic resistance of the channel. This enhances deposition with subsequent denser vegetation than before. The eventual trapping of silt may continue until the gully is filled. Plants suitable for gully control should be able to thrive well in poor conditions and provide a good cover by creeping and spreading habit (Hudson, 1985).

It is difficult to reach the longterm goal of gully control by revegetation if the gully conditions, e.g. soil condition, are unconducive. For revegetation to take place in a gully the fertility and moisture conditions of the gully must be right. Otherwise soil and slope amendments can be made before planting any vegetation. These may include fertilizer or manure application (if economical), topsoiling of conservation structures to be revegetated, ridging and trenching to enhance water harvesting and moisture availability, to mention a few. Other amendments like Terracottem mixture(made up of an absorbent polymer, mineral and organic fertilizers and growth stimulators) are too costly for Kenyan situations (Cotthem et al, 1991).

Seldom can vegetative measures stabilize gully headcuts because of the impact of concentrated flow on plants, especially the young ones (Heede, 1976). However with sloping or reshaping of gully headcuts and walls the effect of runoff on plants can be minimized (Angel, 1981). This is done when the height of the fall is less than 2-3 m. Also any planting across the channel is useless in preventing gully erosion in gully bends. They should be planted along the foot of the gully bank and not on the infertile and mobile sand of the floor (Wenner, 1984). Revegetation of the catchment is also vital.

Engineering measures. There are temporary and permanent ones. In most cases they have proved to be ineffective, very expensive and therefore rarely recommended to be used alone. For instance, gabion check dams have been used widely in Kenya to control gully erosion but have failed in most situations. A study done by Njenga (1991) in Central Kenya indicate that 48 % of the gullies which he studied were controlled by gabion check dams but the majority of them had failed. The reasons behind the failure of the structures need to be investigated. If engineering measures are used together with vegetation they are referred to as bio-engineering measures.

Bio-engineering measures. Usually physical structures are expensive and often ineffective, in which case the resultant erosion is more than before the measure. Also the exclusive use of vegetative measures in gully erosion control often fails. This therefore calls for bio-engineering measures of gully control and reclamation (Sthapit and Tennyson, 1991). Engineering structures aid the revegetation process especially in the critical locations where erosion is active and conditions are adverse for plant growth. They may even increase the fertility of the gully bed by enhancing deposition of sediments and water harvesting on the upstream. This depends on the effectiveness of the structure to hold back the sediments.

2.3 Gully Control Structures and Systems

Many structures have been used in various places for gully erosion control. The selection of such control structures for a particular situation depends on the availability and cost of the materials used, the gully morphometry, the value of the infrastructure or investment to be saved and the objective of the control (Heede, 1976; Wenner, 1984).

Two alternative materials, i.e. wooden material and stone material, for constructing a simple and cheap physical measure are presented by Wenner(1984). In most cases check dams are employed, especially the porous ones which, compared to others, release part of the flow reducing the head of water and then the dynamic and hydrostatic forces against them (Ho et al, 1978). Other cheap ways of controlling gully erosion include the use of grass or grass and stone lined parabolic waterways and gully sidewall stabilization through reshaping and revegetation of the reshaped side.

2.3.1 Gully stabilization structures.

Check dams are built across gullies to trap sediment thereby reducing channel depth and slope in a stepwise manner. They have a high risk of failure and therefore are used together with agronomic measures that persist longer than the check dams. However they should be carefully designed with a central spillway and correctly spaced (Morgan, 1986). The depth of spillway, according to FAO (1986), is given by the equation

$$D = (Q/CL)^{2/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where D = spillway depth, m

Q = design peak runoff rate, m^3/s

L = effective length of spillway, m

C = a constant taken as 3 for brushwood, loose stone, log and boulder check dams; 1.8 for gabions and masonry check dams.

This approach assumes that the spillway approximates to a broad crested weir. The effective length of the spillway is highly dependent on the channel cross-section width. Keying of the structure into the sides and floor should be done to increase the stability of the structure. A key of 0.6 m deep and 0.6 m wide is recommended, but deeper keying is required in case of a fissure or a crack, to about 1.2 m or even 1.8 m deep (Morgan, 1986). Aprons are installed downstream of the check dams, which are 1.5 and 1.75 times the height of the structure if the gully floor slope is less than 8.5% and more than 8.5% respectively. The return period used in the estimation of the design peak runoff rate is usually 25 years but Wenner (1984) recommended 10 years for temporary structures, a period that they may last.

Loose stone check dams. According to Heede (1976) the most effective and inexpensive dams are built of loose rock. Loose stone check dams are made of small rocks of good gradation placed across the gully (see fig. 3). They control channel erosion and stabilize gully heads (FAO, 1986). Design specifications are covered by authors like Wenner (1984) and FAO (1986). However it is worth mentioning that the optimum height for loose stone check dams is about 0.6 m, which may change with gully cross-sections at the dam sites.

The cost of installing a loose stone check dam is dependent on rock volume which is also dependent on the dam height. The tangible benefit got from the check dams is sediment deposits retained by them, as well as the prevention of bed scouring (Heede, 1976).

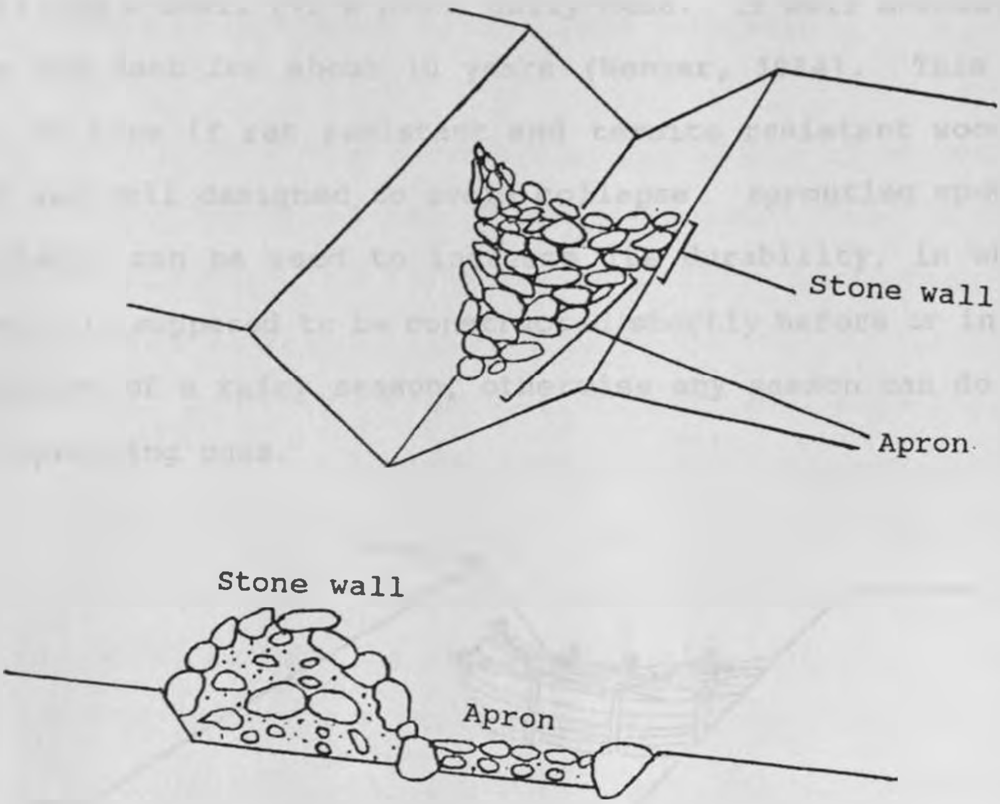

Fig. 3. View of gully section with a loose stone check dam. (Source: Wenner 1984).

Brushwood check dams. Brushwood check dams (usually referred to as wooden check dams or double-row post-brush dams) are silt trapping dams that are built across gullies to control bed scouring and aid revegetation. They are made up of tree branches laid and tied in between two rows of posts firmly stuck in the ground as shown on fig. 4 (Hudson, 1985; Wenner, 1984). The main objective of brushwood check dams is to hold fine material carried by flowing water in the gully and to prevent bed scouring (FAO, 1986). They can also be used to stabilize a small (<1 m high) gully head. If well maintained they can last for about 10 years (Wenner, 1984). This can only be true if rot resistant and termite resistant wood is used and well designed to avoid collapse. Sprouting species of plants can be used to increase its durability, in which case it is supposed to be constructed shortly before or in the beginning of a rainy season, otherwise any season can do for non-sprouting ones.

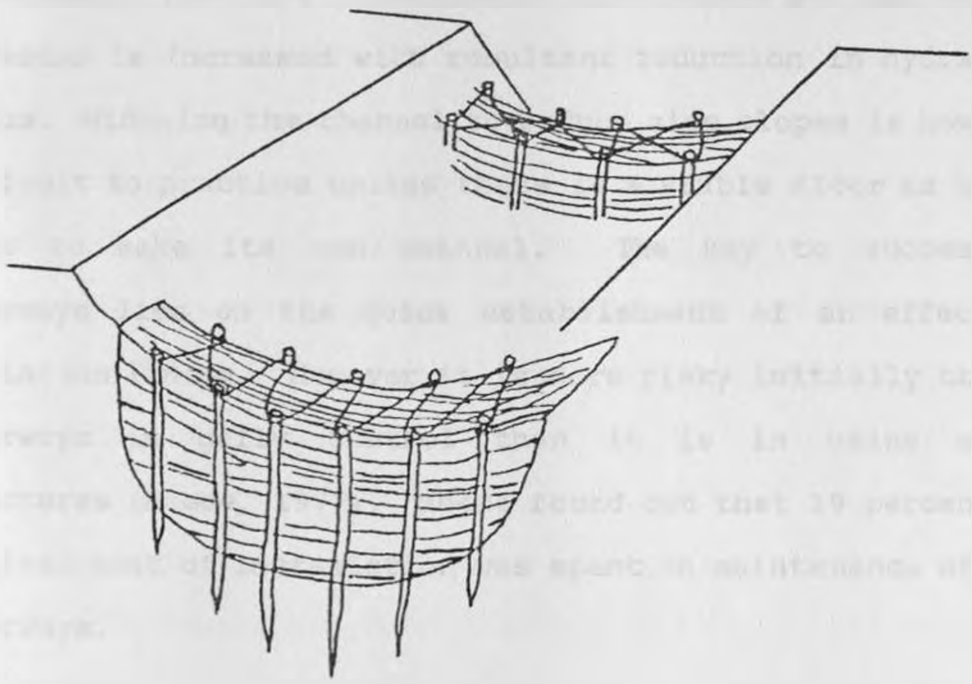

Fig. 4. **A brushwood check dam gully section view (source: Wenner, 1984).**

2.3.2 Grass or grass and stone lined waterway.

Waterways and check dams change the flow regime by decreasing the erosive forces of the flow to a level that permits vegetation to grow. The modification of flow in waterways can be achieved by installing check dams in the channel resulting in a gentler gradient of bed and alternatively widening the cross-section of flow making the channel slopes gentler. Consequently the flow is shallower than before and the wetted perimeter is increased with resultant reduction in hydraulic radius. Widening the channel to reduce side slopes is however difficult to practice unless there is a stable floor as water tends to make its own channel. The key to successful waterways lies on the quick establishment of an effective vegetation lining. However it is more risky initially to use waterways in gully control than it is in using check structures (Heede, 1977). Heede found out that 19 percent of original cost of installation was spent on maintenance of the waterways.

2.3.3 Gully sidewall stabilization.

Slope stability depends on the angle of the slope and the soil type. Bolton (1984) gave an idea that a typical soil slope streaming with water has its stable angle being one-half of its internal friction angle. A slope that is steeper than the angle of repose sloughs off and prevents growth and establishment of vegetation (Brown et al, 1986). Otherwise gully side slopes stabilize fast once plants have become established (Heede, 1976). For revegetation to take place a gentle slope of less than 33 % is generally recommended which has less erosion hazards like rilling, splash and inter-rill erosions (Brown et al, 1986). It is worthy to note that the battering of gully walls and cut slopes involves exposure of less fertile sub-soil and bare ground that is subject to erosion which may prove difficult to revegetate (see fig. 5).

Furthermore splash erosion and rill erosion are increased with exposure of more soil surface to raindrop impact and runoff. In addition the gully banks have problems related to soil moisture regimes which change frequently. However a slope angle of 35° is recommended for vegetation to establish with low erosion hazards on the volcanic ash soils at Olkaria (KPC, 1992). Wenner (1984) does not recommend bank sloping of deep gullies because gully sidewalls eventually slant themselves in due course.

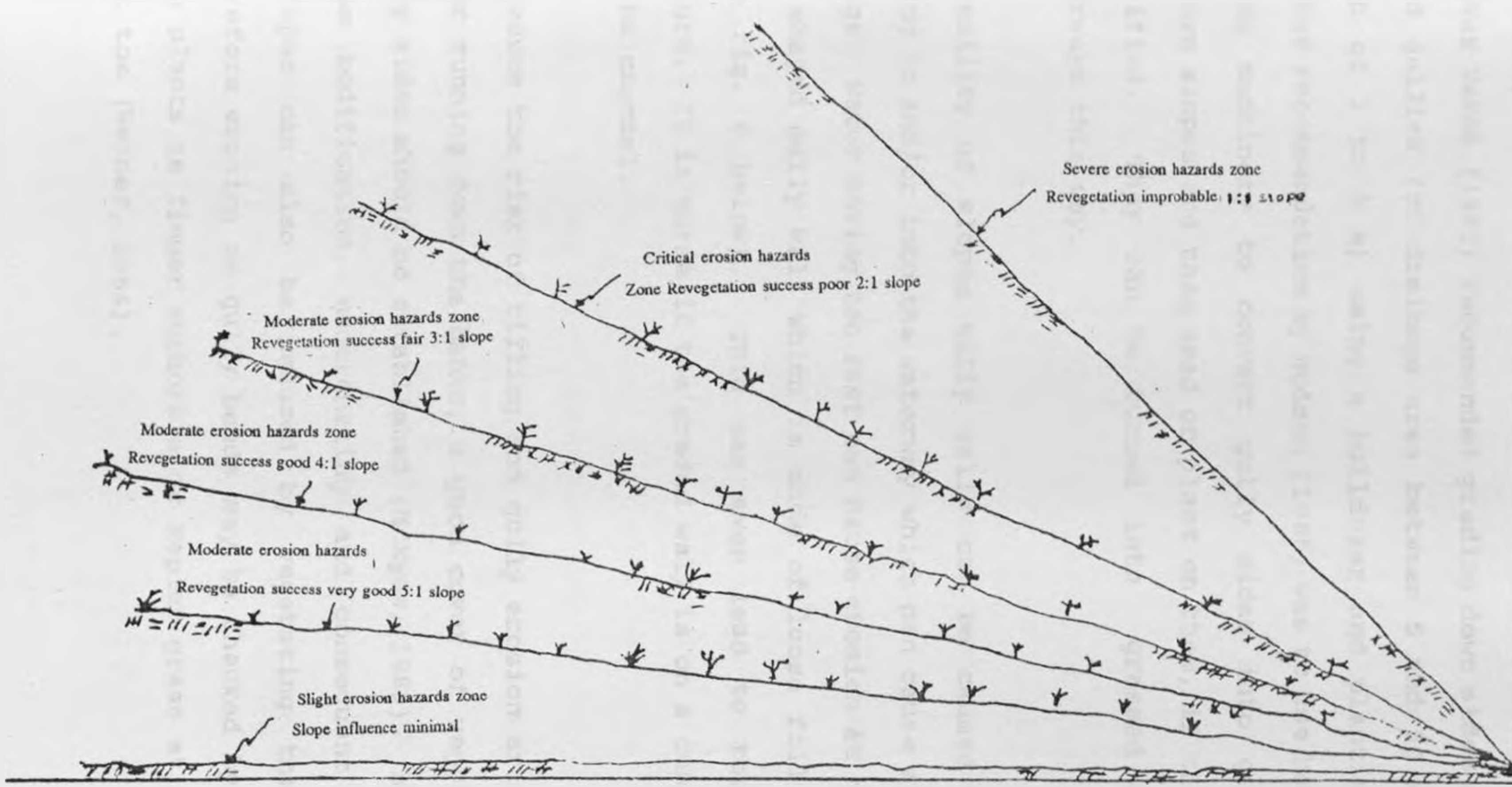

Fig. 5. Influence of percentage slope on revegetation (source: Brown et al, 1986)

However Verma (1981) recommended grading down sides of medium sized gullies (of drainage area between 5 and 50 acres and depth of 3 to 5 m) using a bulldozer and planting grass. Another recommendation by Hudson (1985) was to use heavy earth moving machinery to convert gully sides into gentle and uniform slopes and then seed or plant on them, if the cost is justified. They can be turned into grassed parabolic waterways this way.

Instability of sloped gully walls can be caused by water moving in and/or into the waterway which can cause structural damage. Water moving too fast can cause erosion at the toe of the shaped gully wall which is made of loose fill material (see fig. 6 below). This can even lead to total slope failure. It is worse if the graded wall is on a concave bend of the channel.

To reduce the risk of rilling and gully erosion arising from water running down the banks, a good cover of vegetation on gully sides should be established (Mckyes, 1989). Apart from slope modification, undercutting and consequent sidewall collapse can also be reduced by vegetating their toes. Therefore erosion on gully bends may be checked by planting such plants as finger euphorbia or Napier grass at the gully wall toe (Wenner, 1984).

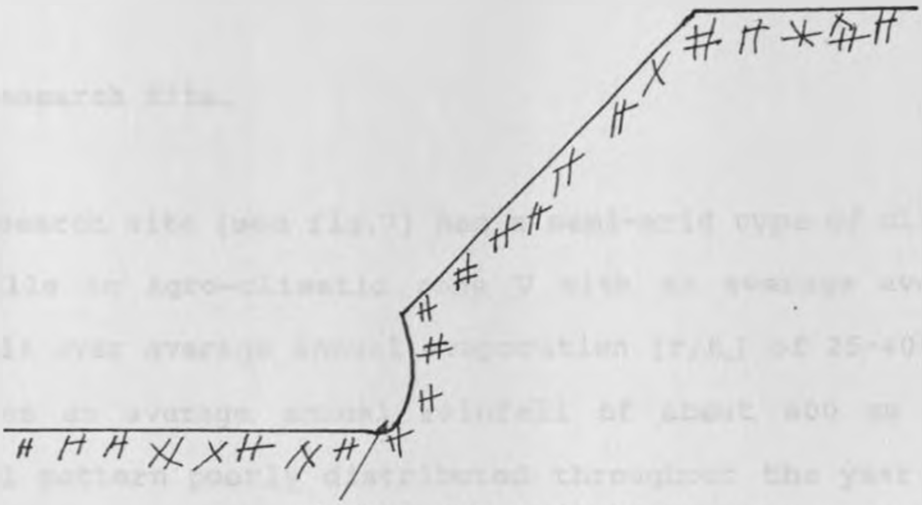

Fig. 6. Erosion due to water flow at the toe region of a gully wall (source: Mckyes, 1989).

Gullies vary greatly in conformation, soil characteristics and runoff patterns. Finding low cost measures which are appropriate in any given situation has to be based on an understanding of the processes taking place and the likely impact of alternative interventions. Blanket solutions are rarely available and most control measures, such as the ones described in this study, inevitably involve an element of trial and error.

3.0 MATERIALS AND METHODS.

3.1 Research Site.

The research site (see fig.7) has a semi-arid type of climate and falls in Agro-climatic zone V with an average average rainfall over average annual evaporation (r/E_0) of 25-40%. It receives an average annual rainfall of about 600 mm in a bimodal pattern poorly distributed throughout the year. The average potential evapotranspiration of the area is 1650-2300 mm (Sombroek et al, 1982) with a mean annual temperature of 26°C (Jaetzold and Schmidt, 1983).

The area has sparse vegetation with dominant and persistent plants being shrubs and short trees, e.g. *Tarconanthus camphoratus* (leleshwa) and *Acacia drepanolobium* (Whistling thorn). The dominant grasses present include oil grass (*Cymbopogon afronadus*) and red oat grass (*Themeda triandra*). Star grass (*Cynodon dactylon*) and Rhodes grass (*Chloris gayana*) are localized especially in valley bottoms and gullies. The area has a quite diverse topography due to tertiary vulcanicity. Generally the topography is undulating with almost enclosed low places surrounded by volcanic cones. Fault scarps, fissures and steam jets are found in the vicinity of the research site. There are hills and flattish terrains.

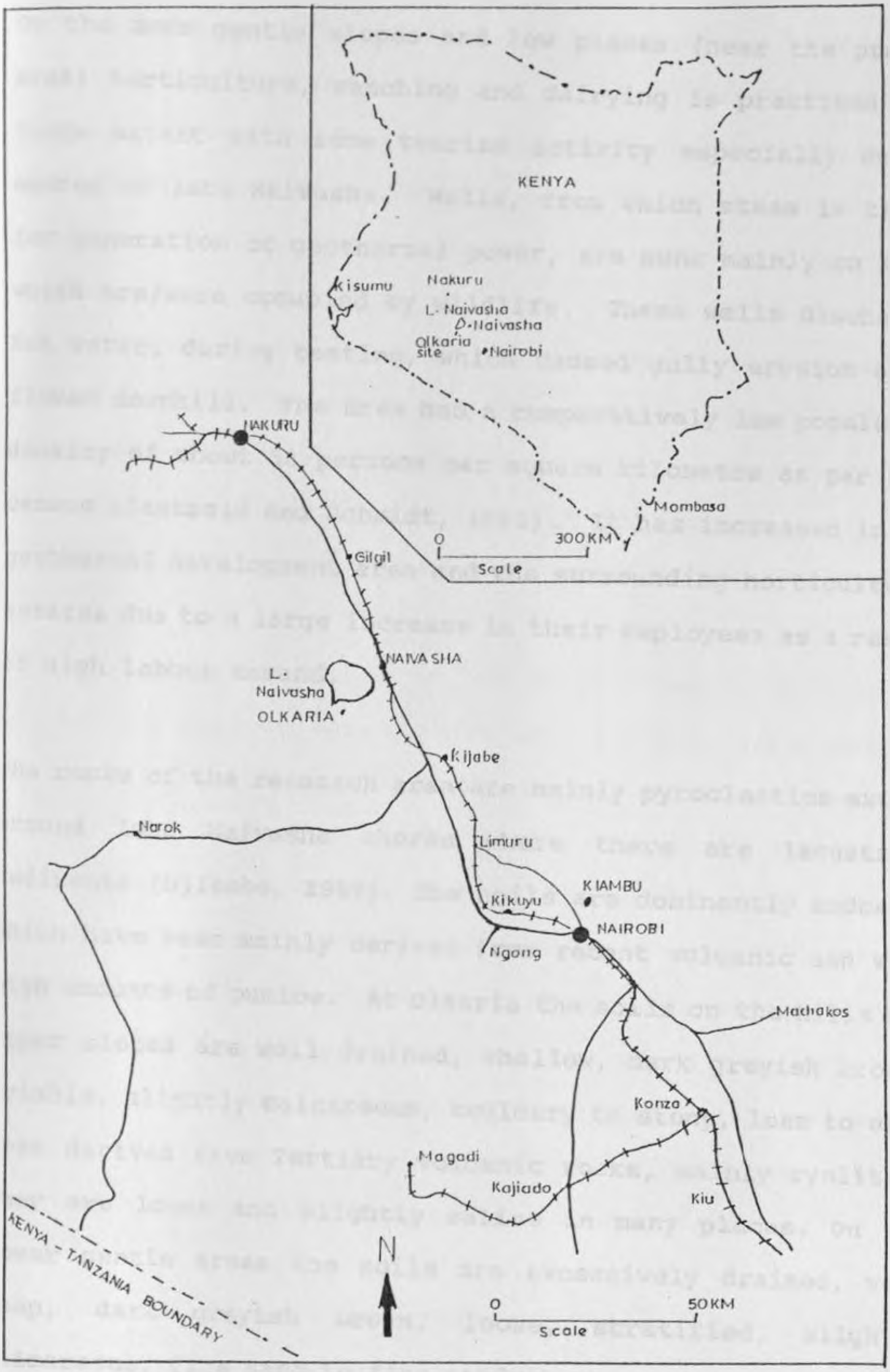

Fig. 7 Location of the project site (source: KPC, 1992)

On the more gentle slopes and low places (near the project area) horticulture, ranching and dairying is practised to a large extent with some tourism activity especially on the shores of lake Naivasha. Wells, from which steam is tapped for generation of geothermal power, are sunk mainly on hills which are/were occupied by wildlife. These wells discharged hot water, during testing, which caused gully erosion as it flowed downhill. The area had a comparatively low population density of about 52 persons per square kilometre as per 1979 census (Jaetzold and Schmidt, 1983). It has increased in the geothermal development area and the surrounding horticultural estates due to a large increase in their employees as a result of high labour demand.

The rocks of the research area are mainly pyroclastics except around lake Naivasha shores where there are lacustrine sediments (Ojiambo, 1989). The soils are dominantly andosols which have been mainly derived from recent volcanic ash with high amounts of pumice. At Olkaria the soils on the hills and upper slopes are well drained, shallow, dark greyish brown, friable, slightly calcareous, bouldery to stony, loam to clay loam derived from Tertiary volcanic rocks, mainly ryolites. They are loose and slightly saline in many places. On the lower gentle areas the soils are excessively drained, very deep, dark greyish brown, loose, stratified, slightly calcareous, fine sand to fine sandy loam or silt developed on recent volcanic ashes and other pyroclastics. They are generally cohesionless soils (KPC, 1992). The soils are highly erodible and readily crust under raindrop impact to yield high runoff rates (Barber and Thomas, 1981). These soil properties, together with low organic matter and deep soil profiles, explain their entrenchment by deep gullies (Ojiambo, 1989) especially when soil cover is removed. No wonder big gullies have formed in a short time at Olkaria either after a rainstorm or when concentrated waste water is discharged from the wells, which can occur even in dry periods. Natural erosion is rife on the volcanic ash soils of the Rift Valley.

Many gullies had developed in this area although the majority of them had healed. More gullies were forming, especially on roads and roadsides, although the rate of formation was lower than in the beginning of the geothermal power development activities. Subsequently most of the wells' discharge was piped to reservoirs and later recharged into underground aquifers through some recharge wells. However the activity of some gullies was being maintained by rainfall runoff, hot water from accidental collapse of well sumps and, to a small extent, overflow from two large water tanks located up the catchment of gully A (See fig. A.1 in appendix A).

The work was done on two active gullies A and B (fig. 8) whereby a detailed analysis was carried out on gully A and a brief one on B. During the first rainy season of the study, gully A was studied in detail but only brief observations on the processes of development were done on gully B. Their morphometric characteristics were also determined. Assessment of the effectiveness of different control measures was done on gully A. Visual analysis through a scoring procedure was used to indicate the extent of development processes and growth vigour of vegetation on trial. The score description is as follows: 0-none; 1- very little; 2- little; 3- moderate; 4- much; and 5- very much. Such a scoring procedure was used because of the difficulties involved in the quantification of the erosion processes. The histories of the gullies and gully erosion problem in the area were obtained from aerial photo interpretation and oral interviews to establish land use changes and the possible causes of gully erosion in the study area.

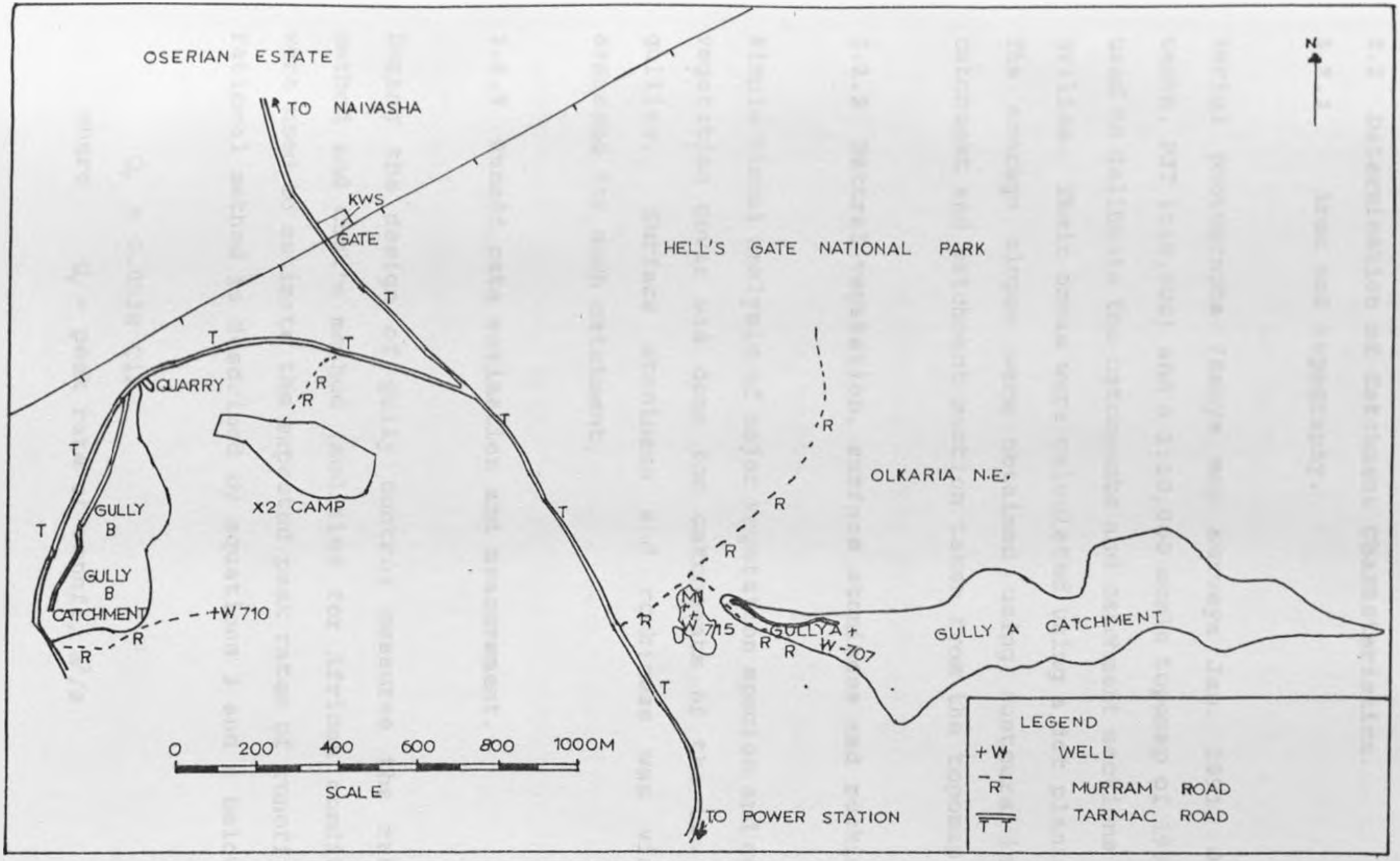

Fig. 8 Location of the two study gullies drawn from a 1: 10,000 scale topomap of the area

3.2 Determination of Catchment Characteristics.

3.2.1 Area and topography.

Aerial photographs (Kenya map surveys Jan. 1991, Olkaria Geoth. PJT 1:10,000) and a 1:10,000 scale topomap of 1991 were used to delineate the catchments and catchment sections of the gullies. Their areas were calculated using a dot planimeter. The average slopes were obtained using contours in each catchment and catchment section taken from the topomap.

3.2.2 Natural vegetation, surface stoniness and rockiness

Simple visual analysis of major vegetation species and general vegetation cover was done for catchments of the two study gullies. Surface stoniness and rockiness was visually assessed for each catchment.

3.2.3 Runoff rate estimation and measurement.

During the design of gully control measures the rational method and Cook's method (modified for African conditions) were used to estimate the expected peak rates of runoff. The rational method is described by equations 3 and 4 below.

$$Q_p = 0.0028\ CiA \qquad (3)$$

where Q_p = peak rate of runoff, m^3/s

C = runoff coefficient, dimensionless.

i = rainfall intensity in mm per hr for the design return period and for a duration equal to the "time of concentration ", T_c, of the watershed.

A = the watershed area in ha.

$$T_c = 0.0195\ L^{0.77}\ S^{-0.385} \qquad (4)$$

where T_c = time of concentration of the catchment in minutes

L = maximum length of flow in m.

S = watershed gradient in m per m or the difference between the elevation of the outlet and most remote point divided by L (Schwab et al, 1981).

On the storm basis peak discharges were estimated from channel observations in the gully using the continuity equation (equation 6) and Manning's formula (equation 7) which assumes steady and uniform flow conditions.

$$Q = V.A \tag{6}$$

$$V = n^{-1} R^{2/3} S^{1/2} \tag{7}$$

Where Q is the discharge in m^3/s.

V is the velocity in m/s.

A is the cross-sectional area in m^2.

R is the hydraulic radius in m.

n is the Manning's roughness coefficient.

S is the gully bed slope in m per m.

(Hudson, 1985).

The main source of error when using channel section is in applying the Manning's equation and in the estimation of the roughness coefficient, n. In natural streams n is about 0.035 and since q is inversely proportional to n, an error of 0.001 in n represents about 3 percent in discharge. Also the cross-section measured after a peak flow may not be that which existed at the time of peak. A gully channel may scour during the rising stages and redeposit material during falling stages. However an error of about 10 percent may be expected in a slope-area estimate of flow under the most favourable conditions (Linsley et al, 1988).

A culvert was installed in the study gully A to create a convenient cross-section for easy estimation of peak storm discharges. After the culvert failure good cross-sections were selected after each runoff event and highest water marks taken. The cross-sectional dimensions were taken using a tape measure.

3.3 Gully Parameters.

3.3.1 Gully surface area.

Scaled outlines of October 1992 and March 1993 of study gully A were drawn from survey data got using a theodolite. Similarly the outline of study gully B was drawn from survey data of April 1993. The area of each outline was estimated using a dot planimeter.

3.3.2 Gully cross-sectional areas and volume

Measurements of gully widths were taken at height intervals of 0.5 m every 10 m throughout the length of the gullies. The outlines of the cross-sections were drawn on graph papers and their areas determined using the graph paper grid. The volume of the gullies was determined using the universal prismoidal formula (see equation 8 below) that assumes a wedge shaped cross-section of the gullies as shown in fig. 9 below.

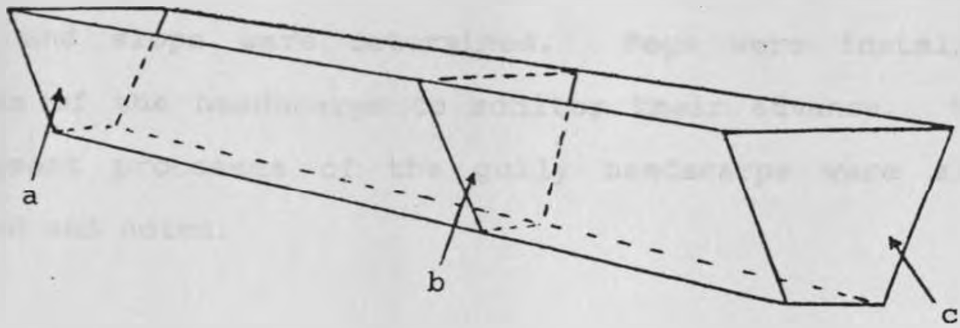

Fig. 9. Assumed gully wedge shape (after Gillespie, 1981).

$$V = \frac{L(a + 4b + c)}{6} \qquad (8)$$

Where	V	=	Volume in m^3
	L	=	Distance between sections a and c.
	a	=	Surface area of vertical plane at small end of gully cross-section (m^2)
	b	=	Area of vertical plane half way between a and c (m^2)
	c	=	Surface area of vertical plane at large end of gully cross-section (m^2) (Gillespie, 1981).

3.3.3 Gully headscarp characteristics

The morphology of the headscarps, i.e. shape, size (depth and width) and slope were determined. Pegs were installed upstream of the headscarps to monitor their advance. The development processes of the gully headscarps were also observed and noted.

3.3.4 Sidewall characteristics.

The gullies were divided into sections of 10 m length. The cross-sections at each 10 m interval was taken and drawn to depict sidewall morphometry. Other sidewall characteristics noted and given scores (to indicate their prominence) included signs of undercutting, popout failure, slumping, splash erosion, rilling, tunnelling, caving and wash erosion. Presence of overhanging material was also noted.

3.3.5 Floor characteristics and gully length.

Slope, shape and base length were noted for each 10 m interval section and so was their uniformity or variation downslope. Erosion pegs (round iron 0.5" diameter rods) were installed at approximately 10 m intervals to monitor bed scouring or depositions at the peg sites. This technique has been used by Thorne (1981) with success in the assessment of bank stabilization. But he claimed that the erosion pegs increased the tensile strength of the soil and hence reinforced the soil though not significantly. However Hudson (1985) says it is a method of quite low accuracy especially in a gully where there are many variations in morphology. Vegetation on the bed was also noted. The lengths of the gullies were determined from their plans.

3.4 Assessment of Soil Parameters.

A deep gully wall in gully A formed a good study site. Profile description was done in situ and samples were taken for field and laboratory analysis.

3.4.1 Soil profile description.

This was based on the Kenya Soil Survey procedure (Kenya Soil Survey Staff, 1987).

3.4.2 Soil texture determination.

Soil texture was determined in the field by feel and particle size distributions of chemically and non-chemically dispersed samples were determined in the laboratory using the hydrometer method as described by Hinga et al (1980). The two particle size distributions of the topsoil were used for determinations of clay ration (C_r), dispersion ratio (D_r) and flocculation index (F_i). These erodibility indices are described below.

$$C_r = \frac{\%\ \text{sand}}{\%(\text{silt + clay})}$$

$$D_r = \frac{\%\ (\text{silt + clay})\ \text{undispersed sample}}{\%\ (\text{silt + clay})\ \text{dispersed sample}}$$

$$F_i = \frac{\%\ \text{total clay}\ -\ \%\ \text{dispersed clay}}{\%\ \text{total clay}}$$

NB: The higher the flocculation index, the more stable is the clay and the higher the clay ration the higher is the rate of erosion.

"The dispersion ratio is the ease with which soil particles can be brought into suspension by the action of the raindrops or runoff" (Kilewe, 1987). The higher it is the more easily the soil can be dispersed and the higher is the erosion rate.

3.4.3 Organic matter content.

Organic matter contents of various soil samples for the whole profile were determined in duplicate using Walkley-Black procedure described by Nelson and Sommers (1986).

3.4.4 Bulk density.

Bulk density is the ratio of the mass of oven dry solids to the bulk volume of the soil. Core samples were taken for the whole soil profile and oven dried at 105 °c to constant weights. They were weighed and the volume of the core rings calculated. Oven dry weights for each sample was divided by the volume of the respective rings to obtain the bulk density (Klute, 1986).

3.5 Rainfall Measurement.

Manual rain gauge located in a weather station near the study gullies was used to measure daily rainfall amounts. Rainfall amounts and durations of various rainstorms were obtained from a data logger connected to a tipping bucket rain gauge in the weather station.

3.6 The Control Treatments Applied.

Control treatments were applied to the sidewall and floor of gully A:

3.6.1 Gully sidewall stabilization.

A shallow (about 1.75 m high) sidewall section 1-2 (see fig. B.1 in appendix B) of the study gully A was reshaped to an angle of 35°. Three different grass species, i.e. Rhodes grass (*Chloris gayana*), star grass (*Cynodon dactylon*) and woolly finger grass (*Digitaria milanjiana*) were obtained locally and planted on 9 plots extending to the adjacent land. The grass splits were planted at a spacing of about 20-30 cm by 30 cm in plots of 2 m x 4 m replicated 3 times on the gully side and the adjacent land (see fig. 10). The site for each replicate was randomly selected. The manhours taken for slope reduction of the sidewall, grass collection and planting was noted for cost analysis. The performance of the grasses was assessed based on the surviving number of splits and their growth vigour observed in each plot. The survival rate of the grasses was recorded as a percentage of the total planted splits.

Grass performance trials were also carried out on land in the vicinity of the study gully A which had been denuded when a bulldozer scraped off the topsoil in a vain attempt to fill the gully. This was done to determine grass(es) that could be used to revegetate the area in order to cut down inflow through the gully sides and therefore reduce rilling and gully branching.

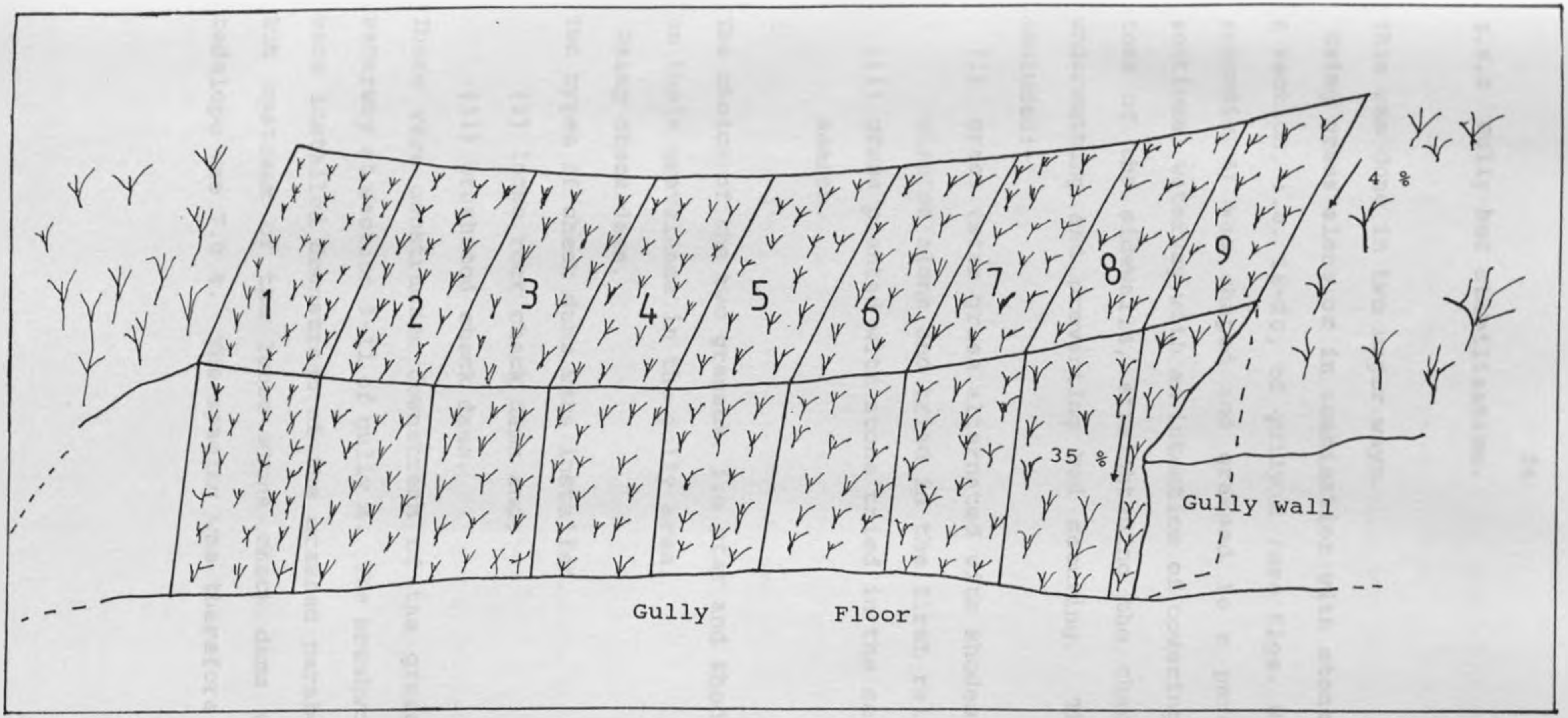

Fig. 10. A plan of the reshaped gully wall showing experimental plots 1 to 9 planted with 3 grass species

3.6.2 Gully bed stabilization.

This was done in two major ways.

Using grass alone or in combination with stone.

A section, i.e. 16-20, of gully A (see figs. B.1 and B.4 in appendix B) was shaped and grassed to a parabolic cross-sectional waterway with an intention of covering the undercut toes of the sidewalls, straightening the channel to avoid undercutting and preventing bed scouring. The treatments included:-

(i) grass (star grass alternated with Rhodes grass) planted alone and tried in the first rainy season.

(ii) grass planted with stone tried in the second rainy season.

The choice of the two grasses, i.e star and Rhodes, was based on their prevalence in the gully area.

Using check dams.

Two types of check dams were installed.

(i) loose rock check dams and;

(ii) brushwood check dams.

These were constructed downstream of the grassed parabolic waterway at section 9-11 of gully A. The brushwood check dams were installed downstream of the grassed parabolic waterway but upstream of the loose stone check dams where channel bedslope was 7.0 %. The spacing was therefore 7.2 m. Loose rock check dams were constructed on the lower steeper section of the gully whose bedslope was about 14.8 %. Consequently the spacing was 3.4 m. The spacing was calculated making an assumption that the final gradient of the channel between the check dams would be 0 %. However the spacing was slightly altered in some situations to avoid inappropriate locations in the gully. To assess their performance round iron rods (0.5" in diameter) were installed at upstream ends of the control structures to measure either erosion or deposition on storm basis.

3.7. Interviews and Aerial Photo Interpretation on Land Use Changes.

An unstructured type of interview was done on 40 elderly people who had stayed at the place for 10 or more years to answer questions like:-

(1) What and how was the land use in the past?

(2) What were the changes in land use since then and how did they contribute to gully erosion?

Changes on vegetation, resettlement, occupation and the effect of the Olkaria Geothermal Development project were included.

Aerial photo interpretation was done to establish major land use and landform changes using aerial photographs of 1982, 1986, 1988 and 1991 (January and September).

4.0 RESULTS AND DISCUSSION.

4.1 Study Gully A.

4.1.1 Gully morphometry and gully development processes.

The observed characteristics of the gully are highlighted and discussed in this section.

Gully length, surface area, cross-sectional areas and volume.

The gully had a horizontal length of 306.4 m. The active surface area of the gully in January 1991 (based on a sketch from aerial photographs) was 0.14 ha and in October 1992 it had eroded to an area of about 0.17 ha. The average gully cross-sectional area was 13.6 m^2 with the highest being 39.5 m^2 and the lowest being 2.4 m^2. The total gully volume was estimated to be 4005.7 m^3,i.e. the volume of soil eroded from an area of 0.17 ha. The active surface area at the end of the rainy season was 0.23 ha with the total volume of the gully being estimated at 4344.9 m^3 (figs. A.3 and A.4 in appendix A; tables C.1 to C.4 in appendix C).

Gully headscarp characteristics.

The study gully had its long profile broken by a lower headscarp 3.6 m high and at distance of 109 m from the upper gully headscarp. The two headscarps were nearly vertical with hanging tops at the beginning of the study as seen on plates 1 and 2. The main headscarp was 5.8 m high. Initially the lower headscarp had a lot of slumped material at its base (plate 1) which was later entrained by inflow that occurred on the 16th of February, 1993 when a 30-minute maximum intensity storm of 28.8 mm/h was experienced. The peak flow was 1.40 m^3/s, the highest in the season.

However this runoff event did not have significant change on the upper headscarp (plate 2) which retreated appreciably later after 4 days of inflow emanating from the overflowing water tanks in the catchment. The upper headscarp retreated 3 m upstream mainly by headwall collapse after it was soaked with water. Immediately below the headscarp a lot of sidewall collapse occurred, an observation similarly got by Daniels and Jordan (1966) on a loess soil.

(1) Lower (2) Upper

Plates 1 and 2. Lower and upper headscarps of gully A in December 1992. Notice the slumped soil blocks at the base of the lower headscarp.

There was a good grass cover above the upper headscarp which might have significantly improved its stability although it might have encouraged infiltration and percolation, and therefore its collapse.

The lower headscarp retreated for only 0.5 m on the 16^{th} of February and caused culvert failure (which had been installed to create a good section for estimating runoff) since it tipped over. The lower headscarp did not have significant retreat since it had a hard layer of soil that restricted its advance upstream and a good star grass cover at its upstream (see plate 3). The hard soil layer (about 15 cm thick) might have formed after the evaporation of geothermal well discharge. Above the lower headscarp the gully floor slope was 2-3 % and heavily grassed (plate 3), a condition which encouraged infiltration thus reducing runoff volume and velocity. The presence of a lower headscarp indicates that the gully was likely to reactivate at this section once the hard layer of soil eroded. Based on the above observations, headcutting was not a prime erosion process on the gully contrary to the observations of Piest et al (1973) which showed that mass wasting of the gully headmass was a major erosion process on a loess soil.

Floor and sidewall characteristics.

The average slope of the gully floor was 10.5 % with a complex shape (fig. B.4 in appendix B) which had certain active parts being convex and others being concave fluvial fans. This implied that the gully had not attained a stable slope and shape in most of its length. Most of the gully floor had little or no vegetation except for a short section above the lower headscarp which was heavily vegetated with star grass (plate 3). This latter section had a slope of about 2-3 % (a stable gradient). Moreover the section was wide and shallow. It was however liable to erosion later since the headscarp was still retreating though slowly.

In general the gully cross-section was U-shaped with many sections having beds that had scoured into the underlying hard soil layer to give a complex shape (figs. B.1 and B.2 in appendix B). The gully had also hanging sidewalls with negative side slopes which indicated that collapse could occur on wetting or on slight agitation. The hanging sidewalls were underlying a thin crusted topsoil layer formed on scraped land adjacent the gully wall which might have impended infiltration of rainfall thus increasing sidewall stability.

Plate 3. A section immediately upstream of the lower headscarp of gully A that was heavily vegetated by star grass.

The major processes of erosion were bed scouring, undercutting and sidewall collapse (slumping). The minor processes identified included rilling on gully sides, splash erosion on gentle sidewalls and gully floor, wash erosion and caving. Popout failure and tunnelling or piping were not evident. This might be attributed to lack of high pore water pressures or lack of lateral water flow due to the low and short duration rainfall and deep soil profile that is rarely, if ever, saturated. The average scores of the development processes throughout the gully are given in table 1 below and show that sidewall collapse (slumping) was the main erosion process observed in the gully. The average scores were for the entire gully but differences occurred from one gully section to another.

Table 1. Erosion and deposition extent given by average scores estimated for various processes observed in gully A.

Process	Av. score during the 1st rainy season
Slumping	4
Undercutting	3
Bed scouring	3
Rilling	2
Deposition	2
Splash erosion	1
Wash erosion	1
Caving	1

Undercutting was evident in the steeper and meandering gully sections where the impact of runoff on the toe of the gully wall was substantial. It was observed that these sections were also prone to slumping. At the deeper sections of the gully, slumping occurred due to gravity even after slight wetting (either by overland flow or directly by rainfall) of the vertical gully sidewalls (see plate 4). On the contrary Roloff et al (1980) observed that gully wall stability seemed unrelated to overland flow in a deep loess.

Plate 4. A major sidewall collapse at a deep section (19-20) of gully A.

In some cases slumping was preceded by both undercutting and wetting or undercutting alone. Even without wetting or undercutting overhanging, dry loose material could slough into the gully due to their non-cohesive nature. Failure of this kind occurs where shear stress becomes equal to the shear strength of the soil at a particular point (Bolton, 1984). Large blocks of soil, cracked from the main soil body, could be seen which later collapsed into the gully upon wetting and through gravity under their own weight (see plate 5).

Plate 5. Block of soil cracked from the gully wall in section 15-16 of gully A.

Rilling occurred where adjacent land sloped inwards thus causing inflow into the gully. In some cases a rill joined the gully at an angle causing sidewall collapse. Splash erosion was minimal because most gully sidewalls were nearly vertical or vertical. A few signs of wash erosion were seen as whitish soil material on gully walls washed in by runoff from adjacent land. However wash erosion and caving were insignificant erosion processes.

Deposition was observed in certain gully floor sections (see fig. B.2) which had a slope of 2- 3 % or less and those which had a check dam in their downstream (except for check dam no. 4). Due to low velocities and presence of good vegetation cover, sediment settled and some of it was trapped by the vegetation. At peg no.15 (appendix F and fig. B.4 in appendix B) a deposition of 9.7 cm occurred on the 22/1/93 but was later scoured during the following runoff event of 23/1/93. Later redeposition and scouring occurred on 23/2/93 and 28/2/93 respectively. This cyclic phenomenon resulted from variations in transport capacity of runoff and impendence of flow by slumped materials.

4.1.2 Soil parameters.

Soil profile description

According to the Kenya Soil Survey profile description that was done (appendix D), the soil near the gully was generally well drained, deep, grayish olive, stratified, slightly calcareous, weak sub-angular blocky in structure, slightly sticky and non-plastic, very friable gravelly silt to gravelly sandy loam developed from recent volcanic ash. This explains its loose nature and consequently high erodibility. The entrenchment of the area by deep gullies is also explained by the depth of the soil profile which was estimated as more than 4 m.

Bulk density

The average bulk density at the profile site was 1.08 g/m^3 with a profile variation as shown in table 2 below. There was no generalized trend in this profile variation since the highest bulk density was at topsoil (0-45 cm layer), probably because of the low content of pumice in the layer, and the least being that of soil layer 125-210 cm. According to Gachene (1982) these soils, with a bulk density of 1.08 g/cm^3 which is slightly > 1.05 g/cm3, may be classified as being highly erodible. However, unless backed by other soil physical and chemical properties like texture and organic matter, bulk density may not give a direct or clear indication of a soil's erodibility.

Table 2. Soil bulk density at various soil strata of gully A wall.

Depth (cm)	Bulk density (g/m^3)
0-45	1.12
45-125	1.06
125-210	1.05
210-290	1.08
290-390	1.10
390+	1.09

Soil texture.

The high silt and sand textural component of this soil, as indicated in table 3, implies that the soil is highly erodible. The continuation of this property down the profile explains the deep gullies found in this area.

Table 3. Particle size distributions of soil samples from various soil layers of gully A wall.

Soil layer(cm)	% sand	% silt	% clay	Textural class (U.S.D.A.)
0-45	80	18	2	loamy sand
45-125	78	18	4	loamy sand
125-210	68	27	5	sandy loam
210-290	80	19	1	loamy sand
290-390	71	27	2	loamy sand
390+	73	24	3	loamy sand

The U-shaped cross-sections of these gullies can also be explained by lack of significant textural variation down the profile, except at soil depth 125-210 cm, where it is sandy loam. The other layers are loamy sand whose erodibility does not differ very much from that of sandy loam.

Soil organic matter.

The organic matter of the soil was very low with the average content being 0.52 %. Assuming that the soil was low in other cementing agents the low organic matter indicates high erodibility of the soil. The variation of the organic matter down the profile is indicated in table 4 below.

Table 4. Organic carbon and organic matter content of soil samples from various soil profile layers of study gully A wall.

Soil layer (cm)	% org. C	% O.M.
0-45	0.74	1.28
45-125	0.42	0.72
125-210	0.18	0.31
210-290	0.25	0.43
290-390	0.10	0.17
390+	0.12	0.21

Soil erodibility indices.

On the basis of the topsoil organic matter content, flocculation (aggregate) index, silt/clay ratio and bulk density of topsoil, a soil factor rating of 3 was arrived at using the Kenya Soil Survey erodibility rating procedure, ignoring the interaction that exists between them (Gachene, 1982). The area being in an agro-climatic zone V the climate factor was rated at 2 and that of slope at 5. The sum factor was therefore 10 indicating that the soil's erodibility was high. The high silt to clay ratio of 4 and the high dispersion ratio of 0.9 (table 5) also indicated that the soil's erodibility was high.

Table 5. Topsoil (0-45 cm) sand, dispersed silt, undispersed silt, total clay, natural clay, F_i, C_r and D_r.

Sand %	Silt disp. %	Silt undisp. %	Total clay %	Natural clay %	F_i	C_r	D_r
80	18	17	2	1	0.5	4	0.9

disp. = dispersed ; undisp. = undispersed.

4.1.3 Catchment characteristics.

Area and topography.

The entire catchment was 25.3 ha and its average slope was 13.7 %. The gully catchment was divided into sections on the basis of differences in slope and soil cover for the purposes of estimating peak discharge using Cook's method, a modification for African conditions, and the rational formula. The area and slope of each catchment section are shown in table 6 below. A map of the entire gully catchment showing these catchment sections is depicted in appendix 1, fig. A.1.

Table 6. Area and slope of gully A catchment and its sections.

Catchment section	Area (ha)	Slope (%)
A	3.4	16.5
B	13.3	8.0
C	6.0	20.0
D	2.6	10.4
	Total = 25.3	Av. = 13.7

Soil cover (natural vegetation, surface stoniness and rockiness) and land use.

The natural vegetation varied between the catchment sections. In general the main grass species were oil grass (*Cymbopogon afronadas*), woolly finger grass (*Digitaria milanjiana*) and red oat grass (*Themeda triandra*) in the order of prevalence. Star grass (*Cynodon dactylon*) was found near the study gully and on the fertile valley bottoms. Rhodes grass (*Chloris gayana*) was mainly found in the gully. The main shrub was leleshwa (*Tarconanthus camphoratus*) with a few trees of whistling thorn (*Acacia drepanolobium*) (see plate 6). Two bare and compacted well pads of wells 707 and 714 were in the catchment and the former one was adjacent to the study gully (fig. A.1 in appendix A). Only sections A and C had small portions with stones and rock outcrops which had presumably insignificant effect on infiltration and therefore runoff. Small bare parts of the catchment had soil crusts on the surface. Otherwise most of the catchment had a good vegetation cover of wooded grassland with leleshwa having a burnt canopy which was recovering after the fire in 1991. The good vegetation cover encouraged infiltration of rainfall and therefore the catchment yielded little runoff especially in the beginning of the rainy season when the rainfall intensities were low.

Plate 6. Part of gully A catchment showing vegetation cover.

The gully catchment was mainly under wildlife grazing with small parts covered by two well pads that had their soil compacted. The land near the gully had low vegetation cover due to earlier bulldozing of soil in an unsuccessful attempt to fill the gully. This encouraged runoff into the gully and rilling on the gully sides.

4.1.4 Estimated runoff rate and runoff sources.

Using the above mentioned catchment characteristics, together with available rainfall characteristics, the design peak runoff was estimated as 1.6 m^3/s (with a 10 year return period) using the rational method (see appendix E.1.1). However an estimate of 1.8 m^3/s was obtained using Cook's method (a modification for African conditions) as shown in appendix E.1.2, which was higher than that estimated using the rational method. Therefore a need arises to evaluate the reliability of the two methods for the estimation of the peak runoff rates in Kenya. After each rainfall storm that occurred during the first rainy season of the study, runoff rates were estimated from water level marks in the gully channel using the continuity equation and the Manning's formula and the results are tabulated on table 7.

There were three sources of runoff into the gully, i.e. rainfall, overflow of water from the water storage tanks and sometimes the collapse of the well 707 sump pond. The latter two sources were usually accidental and therefore were seldom experienced. The well 707 sump pond collapsed only once at the preliminary stage of the study discharging a lot of hot waste water into the gully (plate 7). On only two occasions during the study period did water overflow into the gully from the water storage tanks located on the upper part of the catchment (figure A.1 in appendix A).

The correlation of rainfall characteristics with gully erosion in this gully therefore becomes difficult due to the effects of the other sources of runoff which, when they produced inflow into the gully, they left it in a raw/soaked and unstable condition.

Plate 7. Hot water discharged into gully A from a collapsed sump pond of well 707.

4.1.5 Rainfall characteristics, runoff and gully erosion

The total amount of rainfall during the first rainy season of the study period was 386 mm. This rain fell during the months of November to February which is a rare happening. Much of this season's rain normally falls during the months of October and November. The months of December, January and February are usually dry. The second rainy season had unusually low rainfall amount of 126 mm which fell during the months of March to June (fig. 11 and appendix G).

The first rainy season was characterized by rainfall with low intensities. The highest maximum 30-minute rainfall intensity (I_{30}) during this period was 29.2 mm/h. On only two occasions did the I_{30} exceed 25 mm/h (table 7) contrary to tropical rainstorms that are characterized by short duration, high intensity storms which normally exceed 25 mm/h (Morgan, 1986). During this first rainy season rainfall runoff was only recorded 7 times with the highest peak runoff rate being estimated at 1.40 m^3/s, using Manning's formula and the continuity equation (see tables 7 and 8). Consequently the effect of these runoff events on gully erosion, especially bed scouring, and gully erosion control treatments applied was observed 7 times. The other two runoff events observed resulted from overflowing water storage tanks located at the upper part of the catchment (fig. A.1 in appendix A).

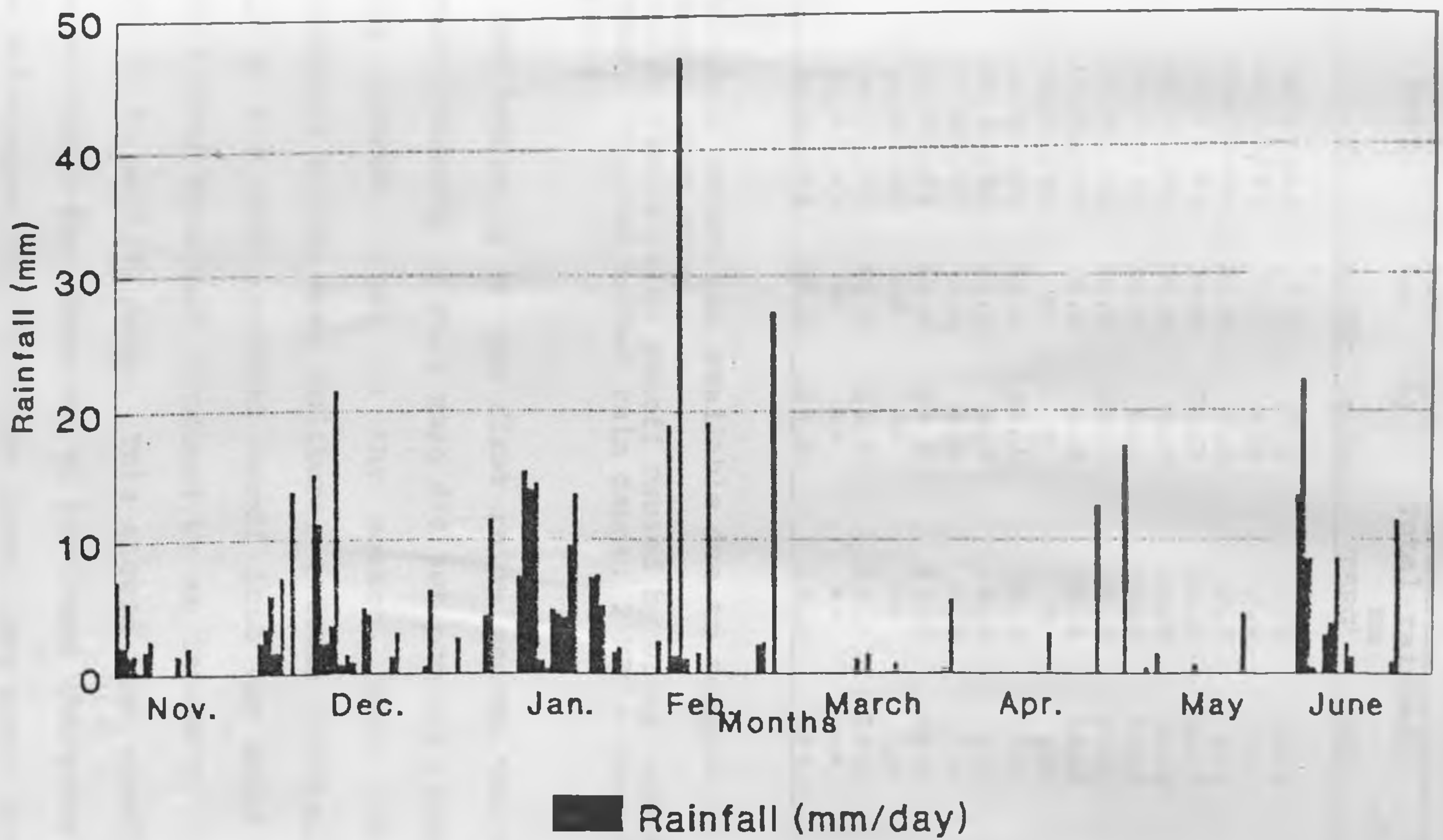

Fig. 11. Rainfall distribution during the months of the study

Table 7. Rainfall intensities and estimated peak runoff rates (using Manning's formula) for various rainfall storms during the first rainy season of the study.

Date	I_{10}	I_{30}	Total rainfall mm		Q_p m^3/s
	mm/hr	mm/hr	TBRG[1]	MRG[2]	
08/12/92	7.2	7.2	11.0	11.4	0
09/12/92	7.2	4.8	2.4	3.1	0
10/12/93	16.6	7.2	3.6	3.7	0
11/12/93	30.0	21.2	21.0	21.6	0
08/01/93	20.4	6.8	11.0	11.6	0
14/01/93	14.4	9.6	14.0	15.3	0
15/01/93	24.0	15.6	14.4	13.9	0.01
16/01/93	8.4	4.2	13.8	14.4	0
02/01/93	*	*	*	9.5	0.06
23/01/93	44.4	24.4	12.2	13.6	0.21
26/01/93	13.2	8.0	6.0	7.1	0.04
27/01/93	6.0	4.8	8.8	7.4	0
11/02/93	38.4	29.2	41.0	46.9	0.05
14/02/93	**	**	**	1.4	0.04
16/02/93	60.0	28.8	18.2	19.2	1.40
23/02/93	**	**	**	**	1.32
28/02/93	30.0	25.6	25.6	27.2	0.43

* Rainfall record not available due to failure of tipping bucket rain gauge.
** No or little rain; runoff caused by water tank's overflow.
1 TBRG = Tipping bucket rain gauge; 2 MRG = Manual rain gauge.

In the beginning of the first rainy season the maximum 30-minute intensity of 21.2 mm/h did not produce runoff into the gully whereas later in the season, when the soil was presumably having more moisture, a lower rainfall intensity (I_{30}) of 8.0 mm/h produced runoff into the gully (table 7), even higher than that produced by an intensity (I_{30}) of 15.6 mm/h on an earlier date. This showed that runoff rate from the catchment also depended on catchment characteristics like the antecedent soil moisture conditions apart from rainfall intensities.

Erosion of the gully bed, banks and headscarps was related or affected by seasonal changes occurring between rainfall events. A runoff rate of 0.21 m^3/s scoured the gully bed by 68.0 cm and that of 1.40 m^3/s magnitude lowered the bed by only 20.0 cm (table 8). Most of the soft soil material was scoured by the 0.21 m^3/s leaving a hard layer which was difficult to scour. The highest I_{30} of 29.2 mm/h caused a bed scour of only 5.0 cm at the measured location of the gully bed. Therefore it is not easy to relate runoff rates with erosion on the gully bed since it is also dependent on the variations of soil resistance to erosion as the depth of the gully channel increases and rainfall amount 5 days prior to flow.

Table 8. Storms, flows and gully bed erosion in gully A.

Date	Storms						Q_p	Gully bed scour
	Rainfall amount mm	Duration min.	Max. I mm/h		mm of rain in periods prior to flow			
			I_{10}	I_{30}	5 days	1 day	m^3/s	(cm)
15/1/93	12.4	60	24.0	15.6	22.6	15.3	0.01	0
22/1/93	*	*	*	*	15.2	4.3	0.06	6.0
23/1/93	12.2	30	44.4	24.4	23.6	9.5	0.21	68.0
26/1/93	5.8	80	13.2	8.0	27.4	0	0.04	17.0
11/2/93	25.2	250	38.4	29.2	22.8	1.4	0.05	5.0
16/2/93	18.2	50	60.0	28.8	49.6	0	1.40	20.0
28/2/93	25.6	160	30.0	25.6	18.7	14.1	0.43	8.2

* Rainfall data from the tipping bucket rainfall recorder was not available due to its failure. Max.I= Maximum intensity

Visual observations showed that much of undercutting and sidewall collapse occurred during and after the storm event of 16/2/93 when the amount of rainfall 5 days prior to the event was 49.6 mm, which undercut and soaked part of the sidewalls causing sidewall collapse. Wetting of the soil material on gully sidewalls directly from rainfall or by inflow from adjacent land enhanced slumping of the walls. All the rainfall events in the first rainy season had little effect on the gully headscarps mainly due to the good vegetation cover on their upstream.

4.1.6 Gully erosion control treatments.

Gully sidewall stabilization.

The shaped gully wall section had plots 5, 6, 7, 8 and 9 (illustrated on fig. 10) moderately rilled in the beginning of the first rainy season. The other plots (1-4) were not rilled because the land adjacent to them was gentle sloping unlike in the rilled plots where it was steeper. The average survival rates and growth vigour of the grasses on the plots are shown in table 9 below. The erosion features observed are also given in table 9 below. Star grass had the highest survival rate. The cost of reshaping and grassing the gully wall was KSh. 2.65 per m^2.

Table 9. Grass performance and erosion on plots on the reshaped gully A wall, 1 month after planting grass.

Grass sp.	Plot	Survival rate (%)	Growth vigour (score)
Star	6	80	
	8	90	
	9	90	
Av.		87	3
Woolly finger	5	80	
	3	20	
	1	80	
Av.		60	3
Rhodes grass	2	25	
	4	30	
	7	20	
Av.		25	2

Average erosion scores

Splash erosion:	3
Rilling:	2
Undercutting at slope toe:	1
Slumping:	1

Two months after planting, rilling, undercutting, slumping and splash erosion on the reshaped gully wall section occurred such that some of the then establishing grass was uprooted and washed downstream. Therefore it became difficult to quantify the performance of the test grass species. The erosion processes which were observed in this section and their respective scores are given below.

Rilling:	4
Slumping:	4
Splash erosion:	3
Undercutting:	3

Later in the season after having successive rainstorms, part of this section was severely rilled and its toe (made of very loose soil material) was undercut and slumped (see plate 8). This made grass establishment, even on the unslumped parts, very difficult.

Other grass performance trials carried out near the gully (which was grassed to reduce inflow into the gully and therefore minimize rilling) showed that star grass had the highest survival rate of about 99 %. Also tried were oil grass (98 %), woolly finger grass (90 %) and Rhodes grass (36 %) (table 10). However Rhodes grass had the best spreading characteristics such that its ground cover was more or less the same as that of star grass at the end of the first rainy season.

Plate 8. Part of the reshaped gully A wall showing rilling and soil washing at its toe region.

Therefore for fast rehabilitation of denuded area under this kind of environment star grass and woolly finger grass can be used either singly or in a mixture. Due to its good spreading characteristic Rhodes grass can be added to the mix. Oil grass has a high survival rate but it is tufted, its growth vigour is very low and therefore it can take a long time to establish a good ground cover that can resist erosion by overland flow and rain drops.

Table 10. Grass performance on plots on earlier bulldozed land adjacent to gully A, 1 month after planting.

Grass sp.	Plot	Survival rate (%)	Growth vigour (score)
Star	1	100	4
	4	98	4
	11	100	3
Av.		99	4
Oil grass			
	2	100	2
	9	98	2
	12	96	2
Av.		98	2
Woolly finger	5	92	3
	8	93	3
	10	88	3
Av.		91	3
Rhodes grass			
	3	30	3
	6	33	3
	7	46	3
Av.		36	3

Gully bed stabilization.

Grassed parabolic waterway.

Initially establishing a grassed parabolic waterway seemed a possible and low cost way to control erosion of the gully bed and rehabilitate the study gully. However, the grass splits planted in the parabolic waterway in the beginning of the rainy season, i.e. early November 1992, did not establish well and replanting was done in mid-December 1992. Rainfall during the month of November 1992 was very little (total monthly rainfall was 39 mm) with most of the days being dry. During the month of December 1992 it became wetter whereby the total rainfall was 92 mm providing a better soil moisture condition for grass establishment. However the grass did not establish well before the January and February 1993 rains which scoured the parabolic waterway (plate 9).

Plate 9. Scoured bed of the grassed parabolic waterway of gully A after the first rainy season.

Runoff concentrated at the middle of the channel enhancing bed scour due to increased shear forces. Shortly before the scour, performance of grass splits of star and Rhodes grasses were monitored for survival rate and the results are given on table 11.

Most of bed scouring of the parabolic waterway occurred on 23rd January and 16th February 1993 when 30-minute maximum intensities were 24.0 and 29.0 mm/h respectively which produced respective runoff discharges of 0.21 m^3/s and 1.40 m^3/s (see table 8). The grass in the middle of the channel was uprooted leaving only that on the sides which established due to good soil moisture and aeration on the loose soil material, and had no interference from runoff (see plate 9).

Despite the problem of bed scouring the grassed and straightened channel checked undercutting and therefore reduced sidewall collapse. It did not prevent sidewall collapse which resulted from wetting of the gully sides by inflow from adjacent land and directly from rainfall. The cost of making the grassed parabolic waterway was KSh. 1 per m^2 taking only labour into account.

Table 11. Grass performance (survival rate) and gully development processes, 2 months after planting, on the grassed parabolic waterway in gully A.

Gully section	Average survival rate(%)	Erosion signs
16-17 (Star)	70	Bed scouring Slumping
18-19 (Star)	66	Bed scouring Slumping
17-18 (Rhodes)	27	Bed scouring Deposition
19-20 (Rhodes)	25	bed scouring Side rilling Slumping

The average grass performance was as follows:
Star grass : 68%
Rhodes grass : 26%

Check dams.

Loose stone check dams generally performed better than brushwood check dams although they were on a steeper gully section than brushwood check dams. However on the 16th of February 1993, a high intensity short-duration rainstorm with an I_{30} of 28.8 mm/h produced a runoff rate estimated at 1.40 m^3/s magnitude that had a devastating effect on the loose stone check dams (see table 12).

Some of the earlier deposited sediments on the upstream of the check dams were transported downstream and the loose stone check dams got breached when they lost some of their stones to the runoff. Loose stone check dam no. 4 (the most upstream of the loose stone check dams) did not prevent bed scouring since water went round and undercut the gully at its southern shoulder causing gully wall collapse and most of the earlier deposition was washed downstream. The poorer performance of this check dam than the others might be attributed to its position upstream of the other loose stone check dams whereby it received most of the runoff impact and probably, due to reduced velocity of the water, the others received less impact and therefore were less vulnerable to breaching and undercutting at their shoulders and keys.

Plate 10. Deposition upstream of loose stone check dam no. 2 at the end of the first rainy season.

A brushwood check dam (plate 11) can resist larger flows than loose stone check dam if built of strong posts of about 10 cm diameter and inserted about 30 cm into the gully floor. Even with the most intensive rainstorm brushwood check dams neither collapsed nor had their parts moved by water except for water going round their sides.

Plate 11. Brushwood check dam no. 1 shortly after the first runoff event during the study.

However brushwood check dam no. 2 had its northern side shoulder undercut and the gully wall collapsed at its key region causing water to go round it (see plate 12). On repair runoff later found its way through the disturbed key region on the southern shoulder of the check dam.

Plate 12. Brushwood check dam no. 2 after the first rainy season. Notice key failure on the right.

Due to major slumping of the gully sidewall near the brushwood check dam no. 1 its spillway was blocked and water was directed towards its shoulder. Consequently water went round the check dam through its southern shoulder. A lot of erosion occurred on this side mainly through undercutting and sidewall collapse. Despite all these problems the brushwood check dams managed to perform their major function of controlling bed scouring in the gully section. In table 11 it is clear that the most effective check dam was loose stone check dam no. 3. This check dam caused a rise in gully floor level between peg no. 14 and the check dam (peg no. 11 is upstream of this check dam) as seen on appendix F. The keying of this check dam was done on a harder soil material than for the other check dams and hence it did not have a major key failure.

Table 12. Deposition or erosion (cm) on the upstream of check dams in gully A during the first rainy season of the study.

Check dam	Deposition or erosion (cm) on date: 15/1	22/1	23/1	26/1	11/2	14/2	16/2	23/2	28/2	Total Dep. (cm)
B/Wood										
1	5.5	7.5	0.8	-0.8	7.2	4.4	-11.7	12.0	6.5	31.0
2	10.0	10.0	17.9	0	1.7	-1.8	-3.7	15.6	1.3	51.0
3	6.0	8.4	16.3	1.8	2.8	20.6	-42.1	56.1	0.6	70.0
Av.										51.0
L/stone										
1	20.0	12.0	9.0	2.4	0.5	21.4	-36.7	33.6	-17.3	45.0
2	19.0	-5.4	11.5	1.4	-6.5	36.2	-61.8	64.5	0	59.0
3	27.0	5.4	15.5	1.3	-0.2	32.1	-21.1	37.4	1.2	99.0
4	20.5	8.1	-6.8	11.6	-4.7	-18.8	26.1	-9.7	-2.2	24.0
Av.										57.0

Dep. = deposition

The results of deposition upstream of the check dams were influenced, to a small extent, by the morphology of the gully at these locations. However they gave a rough idea of the performance of these check dams. They indicated the changes of gully floor levels immediately upstream of the check dams. The effect of these check dams on the gully bed can also be seen on appendix F at pegs 5, 6, 10 and 11 which were upstream of the check dams, with peg no. 7 showing lowering of the gully floor upstream of the loose stone check dam no. 4 due to the check dam failure to prevent bed scouring.

The steeper the slope the higher the number of the check dams constructed and therefore the higher the cost of installation per metre of the gully bed. The cost of construction varied from one check dam to another due to variations in gully morphology and slope at their locations. Only labour was costed since the construction materials were obtained locally and free, with the cost of implements used in the installation being minimal. Brushwood check dams were constructed at an average cost of KSh. 7.15 per metre of the gully floor. That of loose stone check dams was KSh. 9.45 per metre corrected for a slope of 7.0 % for both check dams in order to compare their costs fairly.

4.2 Study Gully B.

4.2.1 Gully morphometry and development processes.

The gully (see fig. A.5) was 588.6 m long covering almost the entire catchment length. Its long profile had an average slope of 8.2 %. The gully's total active surface area was estimated at 0.37 ha from survey data of April 1993. Its average cross-sectional area was 9.7 m^2 ranging from 0.9 m^2 to 25.8 m^2 (table C.5 in appendix C). The volume of the gully then was estimated at 5683.3 m^3 (table C.6 in appendix C), which was the volume of the soil eroded from an area of 0.37 ha.

The gully had one upper and healed headscarp, and two lower ones (see fig. B.5 in appendix B). The most downstream one was still actively retreating. There was no runoff going through the main headscarp which was heavily grassed and sloping at an angle of 38.5 %. The gully cross-sections were generally U-shaped with the walls being vertical as shown on fig. B.3 in appendix B.

The main gully development processes observed in the gully were undercutting, sidewall collapse, bed scouring and deposition whose average scores were 3, 4, 2, and 3 respectively. The upper section (from the main headscarp to peg no. 14, fig. B.5 in appendix B) of the gully had healed because runoff was diverted from its main headscarp, when a quarry was excavated above it, to the tarmac road drainage channel. However the runoff later entered the gully through mitre drains on the middle and lower sections causing gully branching. Only little dry soil creeps were observed on the almost vertical sidewalls in the healed section. Most of this healed section had a lot vegetation growing on the slumped soil material on the gully side toes and bed. The most active part of the gully was that between peg no. 17 and 40, a section that had bends which encouraged undercutting and therefore sidewall collapse. The lower and the remaining part of the gully was a depositional zone that was vegetating.

4.2.2 Gully catchment characteristics.

The total area of the catchment was estimated at 12.6 ha with approximately 3.1 ha of bare ground which was mainly occupied by a quarry, a murram road and a tarmac road. The catchment had a vegetation cover of wooded grassland mainly composed of oil grass (*Cymbopogon afronadus*), red oat grass (*Themeda triandra*), Leleshwa (*Tarconanthus camphoratus*), whistling thorn (*Acacia drepanolobium*) and a few traces of star (*Cynodon dactylon*) and Rhodes (*Chloris gayana*) grasses which were seen only near the gully (see plates 13 and 14).

Plate 13. Part of gully B catchment showing vegetation cover and horticultural development in the background.

On the ground surface were many pebbles and stones mainly of pumice and there were few rock outcrops in an adjacent valley that joined the gully. Many rills formed and developed into shallow and narrow gullies on the quarry with a risk of undermining the adjacent tarmac road (plate 14). A murram road on the upper part of the catchment was eroding and draining runoff into the gully through a natural valley and the tarmac road drains. The runoff needed to be safely diverted away from the gully.

Plate 14. The eroding quarry in the study gully B catchment.

The estimated runoff from the gully catchment was 1.2 m^3/s using the rational formula and 1.7 m^3/s using the Cook's method (modified for African conditions) as shown in appendix E.

In comparison, the study gully B was eroding more than gully A, especially at its (gully B) middle section, because the adjacent tarmac road was contributing a lot of runoff into this gully section. This also resulted to rapid erosion of mitre drains or branches coming from the tarmac road unlike in gully A which had only one short branch that was eroding due to runoff and waste water discharge from the adjacent well 707. The quarry and the tarmac road on gully B catchment contributed a lot of runoff into the gully. The study gully A had sections which had reached bedrock and was deeper near the lower headscarp unlike in gully B. No attempts had been made to control gully B whereas gully A had a section which had been filled with soil by a bulldozer but became entrenched again.

4.3 Interviews and Aerial Photo Interpretation.

4.3.1 Interviews.

Oral reminiscences of 40 local inhabitants showed that there was an effect of the land use changes on gully formation and development. They all said that before the Maasai herdsmen were prohibited from grazing in the Hell's Gate National Park their animals overgrazed during the dry periods leaving the ground almost bare with loose soil and animal tracks on the surface. Most of the people interviewed were KPC workers who had lived in the park since 1983 and, some of them, earlier.

Incidences of soil erosion by wind were evident and runoff events from the first rainstorms were very erosive initiating gullies and causing enlargement of the then existing ones. When the area was Maasai free and overgrazing stopped a marked regeneration of vegetation cover was seen on the earlier denuded land. Many gullies healed due to immense reduction in runoff and the growth rate of some gullies was reduced. However waste water from steam wells, which was channelled through natural waterways and healed gullies, caused a new phase of gully initiation and development. Nowadays the waste water is piped to reservoirs and later discharged into the ground through recharge wells. In a few cases gully formation and development had been enhanced by broken pipe water and overflow from water tanks. For instance, the development of the study gully A had been affected by overflow from the water tanks which were on its catchment (fig.A.1 in appendix A). Eighty percent of those interviewed attributed the development of this gully to the overflow.

4.3.2 Aerial photo interpretation.

Apart from helping in the delineation of the catchments and outlines of gullies aerial photographs also aid in checking land use and landform changes overtime.

The aerial photographs of 1982, in the month of January (scale

1:10,000), showed no signs of gullying in most of the study area except for natural waterways which were vegetated. Only a murram road was gullied in gully A catchment. There were minimal development activities and minimal disturbance of the environment as evidenced by absence of steam wells, cleared land and water pipes. Most of the respondents during the interviews did not agree with this for they said that the Maasai herdsmen overgrazed the land making it prone to gully erosion.

The 1986 and 1988 aerial photos showed similar features except for Maasai homesteads ("manyattas") that appeared only on the 1986 photos. Neither the study gully A nor well 707 were present. A well 714 was visible in the upper part of the gully catchment but absence of water tanks was noticed. The immediate catchment of the study gully A had its topsoil and vegetation scraped into the gully in an attempt to fill it (plate 15).

Plate 15. Bulldozed middle section of gully A, December 1992.

This was observed in the aerial photos of January 1991 which showed the middle portion of the gully blocked with soil. The gully branch that headed towards well 707 (fig. A.3 in appendix A) was also blocked. The scraping enhanced the gullying process since the land adjacent to the gully was devegetated and had its slope increased towards the gully consequently increasing inflow and rilling of the gully wall.

Vegetation cover of the area was seen to be denser on the January 1991 aerial photos than on those of 1986 which may imply that land use change from livestock overgrazing to only wildlife and geothermal development may have caused vegetation regeneration. However other factors like the time of the year the aerial photos were taken and the then prevailing weather condition could have made the difference. A better ground cover was observed in September 1991 aerial photos despite a huge fire which burned through the area in March 1991 and reduced cover of grass and litter on the ground. Subsequent rain led to considerable erosion but vegetation recovered fast probably due to the fertile nature of the soils.

The study gully B was not visible on 1982 aerial photos but the road (presently adjacent to it) was present but it was not tarmacked. The 1988 aerial photos indicate that the gully had formed but not to a large extent and there were mitre drains which led to the gully from the murram road. The quarry (presently above the gully) was not dug and the gully must have formed due to increased runoff from the catchment. In January 1991 the gully had fully formed and the adjacent road was tarmacked. The vegetation on its catchment (like on gully A) was denser in 1991 than in 1986 which may indicate a change to a better land use that encouraged revegetation. However the effect of geothermal power development could be seen on this gully's catchment which had some bare land, a gullying murram road and a gullying quarry that produced the runoff which enhanced gully erosion.

5. CONCLUSIONS AND RECOMMENDATIONS.

Conclusions.

1) The main processes of gully development on the volcanic ash soil were undercutting at bends, sidewall collapse, bed scouring and deposition on the gentle (< 3 % gradient) floor sections of the gully.

2) Bed scouring was poorly related to runoff due to the effect of antecedent moisture conditions of the gully bed and differential resistance of the soil material in contact with the runoff at the time of the runoff event.

3) The volcanic ash soil of the study site has a high erodibility due to its low organic matter content and high flocculation index and a high dispersion ratio. Therefore the high soil erodibility is a major factor contributing to gully initiation and development in this area.

4) Land use changes that leave the land with little or no cover as a result of overgrazing, fire and scraping/bulldozing of the land and unprotected disposal of waste water downhill, will lead to gullying on this volcanic ash soil.

5) Loose stone check dams and/or brushwood check dams can

prevent gully bed scouring despite the key failure problem. They are cheap and moderately effective means of controlling bed scouring.

6) Conversion of the gully channel into a grassed parabolic waterway can straighten the channel bed and minimize undercutting at the bends and subsequent sidewall collapse but may not control bed scouring.

7) Reshaping the gully sidewall to an angle of 35° may not work due to subsequent erosion hazards, i.e. the practice may expose the sidewall to rilling, splash erosion, undercutting and sidewall collapse of the loose soil material at the toe region. This makes vegetation establishment very difficult.

Recommendations and research needs.

1) Cost effective measures of gully erosion control should be selected and designed to counter the major gully erosion processes of undercutting, sidewall collapse and bed scouring. Undercutting and sidewall collapse can be minimized by straightening the gully bed and planting star grass or/and Rhodes grass in it thus turning the bed into a grassed parabolic waterway. On the other hand bed scouring can be controlled by installing loose stone and/or brushwood check dams on the gully bed. Maintenance of the gully control

measures on storm basis may make them more effective. However more tests should be done on:

a) grass and stone lined parabolic waterway and/or stone thresholds as an improvement on the resistance of the grassed parabolic waterway against bed scouring before grass establishment.

b) single or double row posts stone check dams to improve on the stability of the loose stone check dams. Better keying methods for check dams should also be devised taking the loose nature of the volcanic ash soil into account, e.g. keying using polyfelts.

c) use of such plants as finger euphorbia to prevent undercutting at gully banks and therefore minimize sidewall collapse. Also trials should be made to establish whether lining a gully bend with stones or brushes can prevent undercutting.

d) control of gully headscarp erosion through reshaping and lining it with either stones or brushwoods and planting grass on it.

e) stable cut slopes on the volcanic ash soil that will enable reshaping of the gully sidewalls with minimal erosion hazards which permit revegetation. There is a need to protect the reshaped gully sidewall through mulching and through establishment of vegetation like finger euphorbia at its toe before reshaping.

2) Due to the erodible nature of the volcanic ash soil a land use that leaves the land with little or no cover should be avoided. Disturbed land, especially on the hilly terrain, should be revegetated with star grass, woolly finger grass and/or Rhodes grass without delay to avert soil degradation through formation of gullies. Diversion of runoff from the gully may lead to formation of new gullies and therefore should be done cautiously.

3) Further investigations should be done to relate soil factors and soil conditions that explain the gully development processes on these volcanic ash soils. For instance, the effect of antecedent soil moisture content on runoff yield and gully erosion should be investigated. A comparative analysis can be done on gullies under different climatic, edaphic and land use conditions and its implications on the management of the different gully systems.

6. REFERENCES.

Angel, L.W. (1981). Revegetation of a critical black soil gully. The Journal of Soil Conservation Service of NSW. 37. No. 4: 197-200.

Barber, R.G., Moore, J.R. and Thomas, D.B.(1979). The erodibility of two soils from Kenya. Journal of Soil Science, 30: 579-590.

Barber,R.G. and Thomas, D.B. (1981). Infiltration, surface runoff and soil loss from high intensity simulated rainfall in Kenya. Research contract No. R/HQ 1977-3/AGL. Faculty of Agriculture, University of Nairobi, Kenya.

Bennet, H.H. (1939). Soil Conservation. McGrawHill, New York and London.

Bolton, M. (1984). A guide to Soil Mechanics. Macmillan publishers Ltd, London.

Boardman, J., Foster, I.D.L. and Dearing, J.A. (eds.). (1990). Erosion on Agricultural Land. British Geomorphological Research Group Symposia Series. John Wiley and sons.

Bradford, J.M., Piest, R.F. and Spomer, R.G. (1978). Failure sequence of gully headwall in Western Iowa. IDSA-ARS. Soil Science Society of American Journal, 42: 323-328.

Brown, D., Richard, G.H., Lee, C.R., Skogerboe, J.G., Price, K.E.R.A, Page, N.R., Clar, M., Kort, R., and Hopkins, H. (1986). Reclamation and Restoration of Problem Soils and Disturbed Lands. Noyes Data Corporation, New Jersey, U.S.A.

Burkham, D.E. (1972). Channel changes of the Gila River in Safford Valley, Arizona, 1846-1970. USA Geological Survey, Professional Paper, 655-G, 23 pp.

Chakela, Q.K. (1981). Soil Erosion and Reservoir Sedimentation in Lesotho. UNGI Rapport No.54, pp 150. African Publishing Company.

Cotthem, V.M., Beel, C., Dannels, P., Dekeyzer, J., Vyvey, Q., and Gent. (1991). Restoring the natural vegetation on strongly eroded volcanic ash soils of Cape Verde. Soil Technology, 4: 183-189.

Daniels, R.B. and Jordan, R.H.(1966). Physiographic history and the soils, entrenched stream systems,and gullies of Harrison County, Iowa. USDA-SCS Tech. Bull. 1348.

FAO (1977). Guidelines for Watershed Management. FAO Conservation Guide 1, Rome.

FAO (1982). Environmental Impact of Forestry: Guidelines for its Assessment in Developing Countries. FAO Conservation Guide 7, Rome.

FAO (1986). Gully Control. FAO Watershed Management Field Manual. FAO Conservation Guide 13/2, Rome.

FAO (1988). Landslide Prevention Measures. FAO Watershed Field Manual, 13/4, Rome.

Gachene, C.K.K.(1982). Assessing the relative erodibility of some Kenyan soils using a rainfall simulator and the prediction of relative erodibility factors. MSc. thesis, University of Nairobi.

Gillespie, P.D. (1981). Development of gully erosion at the head of Bango Creek near Yass, NSW. Journal of the soil conservation service of NSW. 37: No. 1: 6-12.

Hamilton, G.H. (1977). The assessment of soil erodibility. Journal of the Soil Conservation Service of NSW 3: 106-107.

Hamilton, T.M. (1970). Channel-scarp formation in western North Dakota. US Geol. Surv. Prof. Paper. 700-C: 229-232.

Handy, R.L. (1973). Collapsible loess in Iowa. Soil Science Society of American Proceedings. 37: 281-284.

Hiemstra, L.A.V. and Reich, B.M.(1967). Engineering judgement and small area flood peaks. Hydrology Papers No. 19, Colorado state university, U.S.A.

Heede, B.H. (1975). Stages of development of gullies in the West. In: Present and Prospective Technology for Predicting Sediment Yield and Sources. ARS-S-40.

Heede, B.H. (1976). Gully Development and Control. The Status of our Knowledge. USDA Forest Service Research Paper RM-169, Fort Collins, Colorado, 80521.

Hinga, G., Muchena, F.N. and Njihia, C.N.(1980). Physical and Chemical Methods of Soil Analysis. Internal publication. Miscellaneous soil paper No. M17, KSS, Nairobi, Kenya.

Ho, C.W., Tuan, C.H., and Liou, J.C. (1978). Experiment and drainage methods in Taiwan, 1. Experiment and analysis on drainage methods. Abstracts of soil and water conservation research in Taiwan (4013).

Hudson, N. (1985). Soil Conservation. Batsford Academic and Educational. London.

Hunt, C.B. (1972). Geology of Soils. Their Evaluation, Classification and Uses. W.H. Freeman and Company. San Francisco.

Ichim, I., Mihaiu, G., Surdeanu, V., Radoane, M. and Radoane, N. (1990). Gully Erosion on Agricultural Lands in Romania. In: Boardman, J., Foster, I.D.L., and Dearings, J.A. (eds.). Soil Erosion on Agricultural Land. John Wiley and sons, 55-67.

Ireland, H.A., Sharpe, C.F.S., and Eargle, D.H. (1939). Principles of gully erosion in the Piedmont of South Carolina. In: Bradford, J.M., Piest, R.F. and Spomer R.G. (1978). Failure sequence of gully headwalls in western Iowa. IDSA-ARS. Soil science society of American Journal. 42: 323-328.

Jaetzold, R. and Schmidt, H. (1983). Farm Management Handbook of Kenya, vol. IIB. Ministry of Agriculture, Nairobi, Kenya.

Jannson, M.B. (1982). Land Erosion by Water in Different Climates. Dept. of Geography, Uppsala University. UNGI Rapport No. 57.

Kenya Soil Survey Staff (1987). Manual for Soil Survey and Land Evaluation. Miscellaneous Soil Paper No. M24. KSS, Nairobi, Kenya.

Kilewe, A.M. (1987). Prediction of Erosion Rates and Effects on Topsoil Thickness on Soil Productivity. PhD thesis, University of Nairobi, Kenya.

Klute, A. (1986). Methods of Soil Analysis. Part 1-Physical and Mineralogical Methods. Second edition. Published by Madison, Wisconsin, U.S.A.

KPC (1992). Environmental Impact Assessment. Unpublished draft report. Geothermal project, Olkaria, Kenya.

Leopold, L.B., Emmett, W.W. and Myrick, R.M. (1966). Channel and hillslope processes in a semi-arid area. USA Geol. Surv. Prof. Papers, 352-G, 193-253.

Linsley, R.K., Kohler, M.A, and Paulhus, J.L.H. (1988). Hydrology for Engineers. SI metric edition, McGraw-Hill Book Co.

Martin, J.H. (1990). Evaluation of an anthropogenic desert gully system. In: Walling, D.E. Yair, A. and Berkowiz, S (eds.). Erosion, Transport and Deposition Processes. IAHS Publication No. 189: 65-76.

Mckyes, E. (1989). Agricultural Engineering Soil Mechanics. Elsevier science publishing co. Inc. 665, New York, U.S.A.

Ministry of water development. (1978). Rainfall frequency atlas of Kenya, Nairobi.

Morgan, R.P.C. (1980). Implications. In: Kirkby, M.J. and Morgan, R.P.C.(eds.). Soil Erosion. A publication of the British Geomorphological Research Group. John Wiley and Sons. New York.

Morgan, R.P.C. and Kirkby, M.J.(eds., 1980). Soil Erosion. A publication of the British Geomorphological Research Group. John Wiley and Sons. New York.

Morgan, R.P.C. (1986). Soil Erosion and Conservation. Longman Scientific and Technical, England.

Njenga, P.M. (1991). A study of gully control techniques in Kenya's Central Province. A field study report for the M.Sc. in Soil and Water Management, Agricultural University, Norway.

Noort, T.H.T., and Stephenson, D. (1982). Flood peak calculation in South Africa. Water systems research programme. Johannesburg.

Ojiambo, S.B. (1989). Soil erosion problems around Olkaria Geothermal field, Kenya. A paper presented at the 6th International Soil Conservation Organisation (ISCO) conference in Kenya and Ethiopia. KPLC, Geothermal section, Kenya.

Olofin, E.A. (1990). The dynamics of gully head recession in a savanna environment. In: Walling, D.E., Yair, A. and Berkowiz, S. (eds.). Erosion, Transport and Deposition Processes. IAHS Publication No.189: 135-144.

Piest, R.F., Bradford, J.M. and Wyatt, G.M. (1973). Soil erosion and sediment transport in gullies. Am. Soc. Civil Eng. Annu. and Nat. Civil Eng. Meeting, New York.

Piest, R.F., Bradford, J.M. and Spomer, R.G. (1975). Mechanisms of erosion and sediment movement from gullies. ARS-40, 162-176.

Rhoades, E.D., Welch, N.H. and Coleman, G.A. (1975). Sediment yield characteristics from unit source watershed. USDA , ARS-S-40, 125-129.

Roloff, G., Bradford, J.M. and Scrivner, C.L. (1981). Gully development in the deep loess region of Central Missouri. Soil Sc. Soc. of Am. Journal 45: 119-123.

Schwab, G.O., Frevert, R.K., Edminster, T.W. and Barnes, K.K. (1981). Soil and Water Conservation Engineering. John Wiley and Sons, Inc., New york.

Sombroek, W.G., Braun, H.M.H. and Van der Pouw, B.J.A (1982). Exploratory Soil map and Agro-climatic Zone map of Kenya. Scale 1: 1,000,000. KSS, Nairobi, Kenya.

Sthapit, K.M. and Tennyson, L.C. (1991). Bio-engineering erosion control in Nepal. Measured management project, FAO. Abstracts of Tropical Agriculture, 16: 45.

Thorne, C.R. (1981). Field measurements of rates of bank erosion and bank material strength. In: Erosion and Sediment Transport Measurements. Proceedings of the Florence Symposium, IAHS publ. No. 133: 503-512.

Thornes, J.B. (1976). Semi-arid Erosional Systems: Case studies from Spain. London School of Economics and Political Science.

Troeh, F.R., Hobbs, J.A. and Donahue, R.L. (1980). Soil and Water Conservation for Productivity and Environmental Protection. Eglewood Cliffs, New Jersey.

Verma, B. (1981). Classification of Ravines for Optimum Utilization in India. ICAR bulletin No. R-11/K-1. Central Soil and Water Conservation Research and Training Institute, Research Centre, Kota-324002, India.

Wenner, C.G. (1984). Gully Erosion and Gully Control in Kenya. A report on visit in Nov.- Dec. 1984.

Wijdenes, D.J.O. and Bryan, R.B. (1990). Gully development in the Njemps Flats, Baringo, Kenya. University of Toronto.

Wischmeier, W.H., Johnson, C.B. and Cross, B.V.(1971). A soil erodibility nomograph for farmland and construction sites. Journal of Soil and Water Conservation. 26: 189-192.

Wright, A.C.S. (1964). The "Andosols" or "Humic Allophane" Soils World Soil Resources Report 14. A meeting in the classification and correlation of soils from volcanic ash. Tokyo, Japan.

7. APPENDICES

Appendix A. Catchment maps of study gullies and gully outlines.

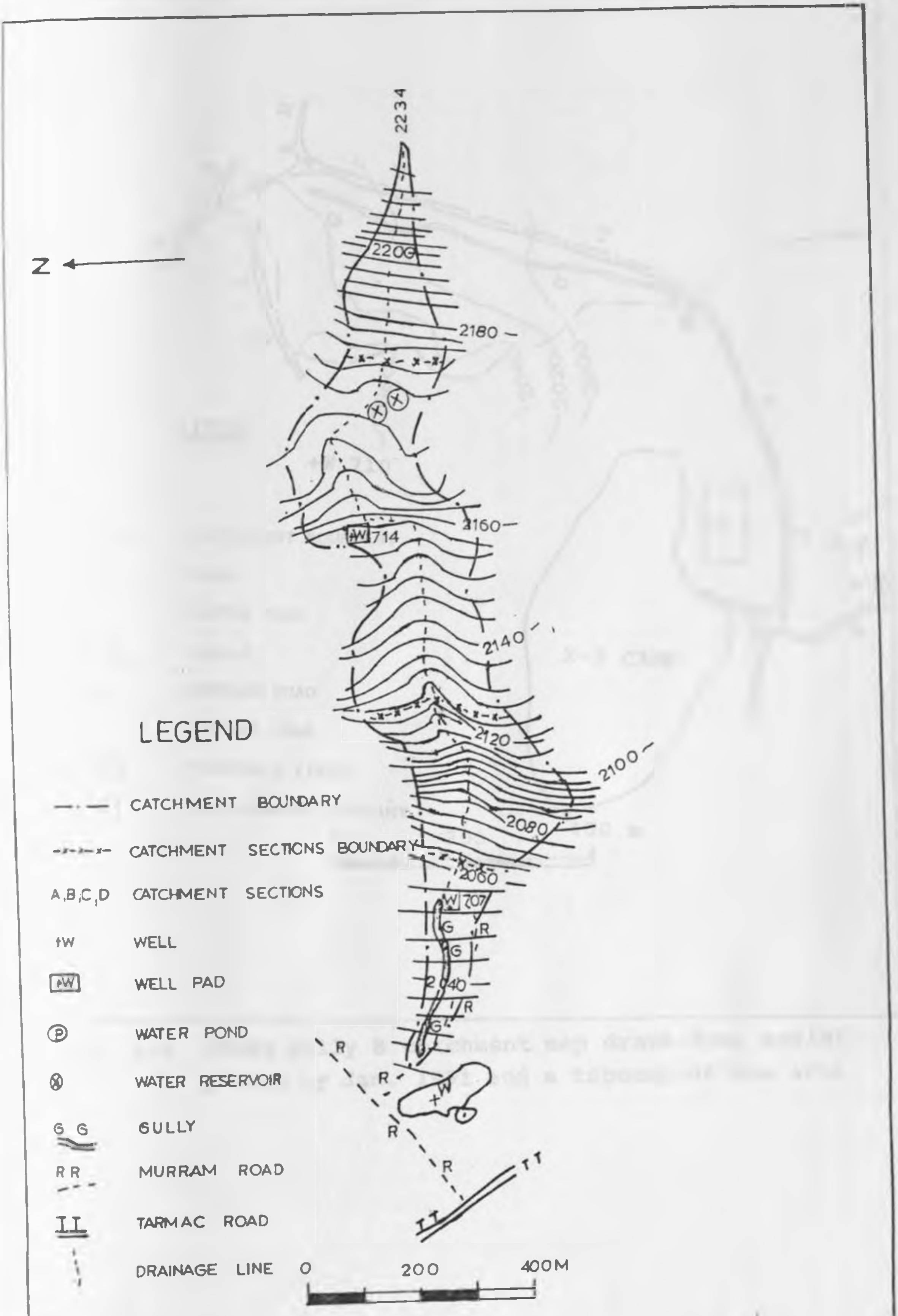

Fig. A.1 Study gully A catchment map drawn from aerial photos of Jan. 1991 and a topomap of the area

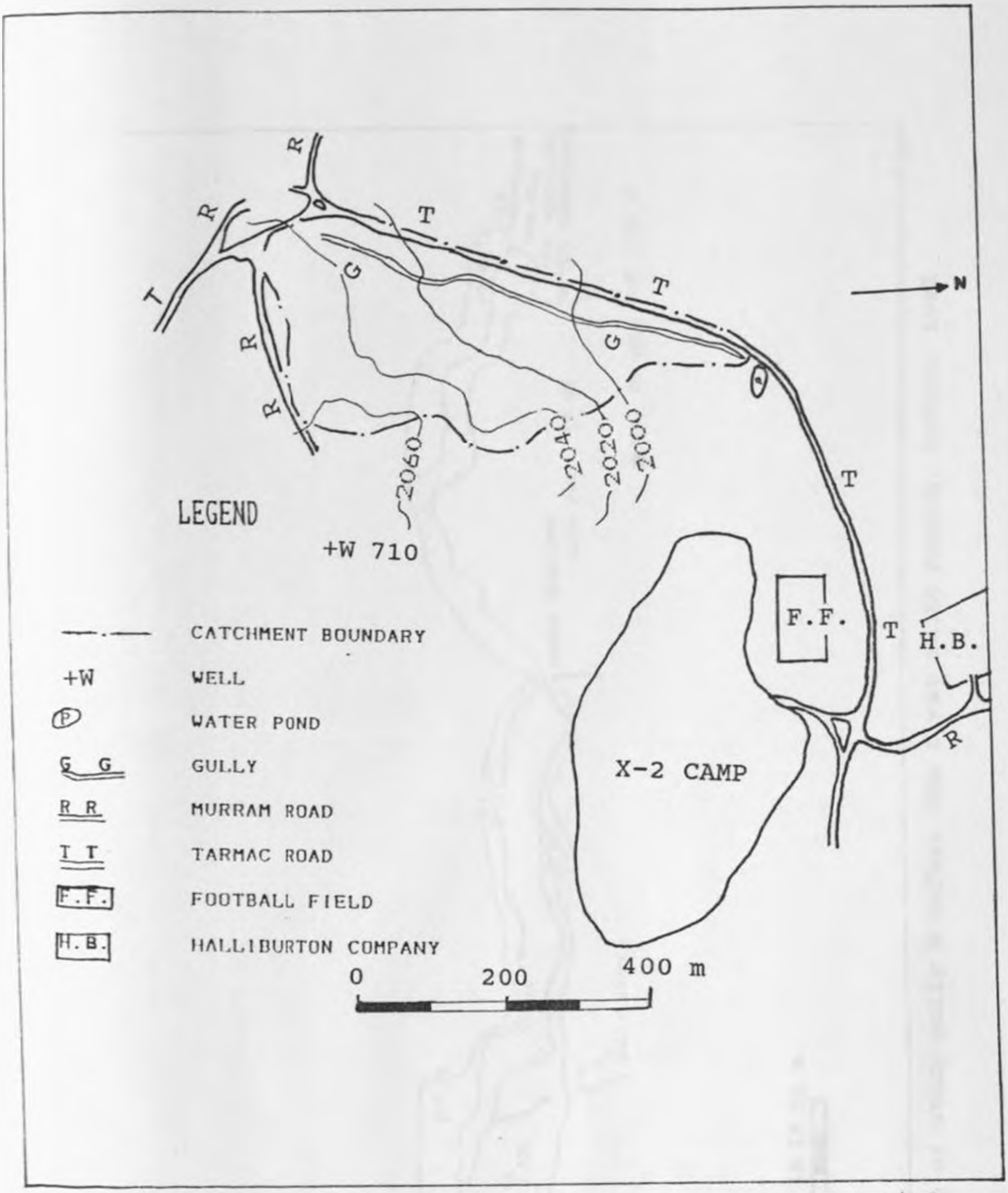

Fig. A.2 Study gully B catchment map drawn from aerial photos of Jan. 1991 and a topomap of the area

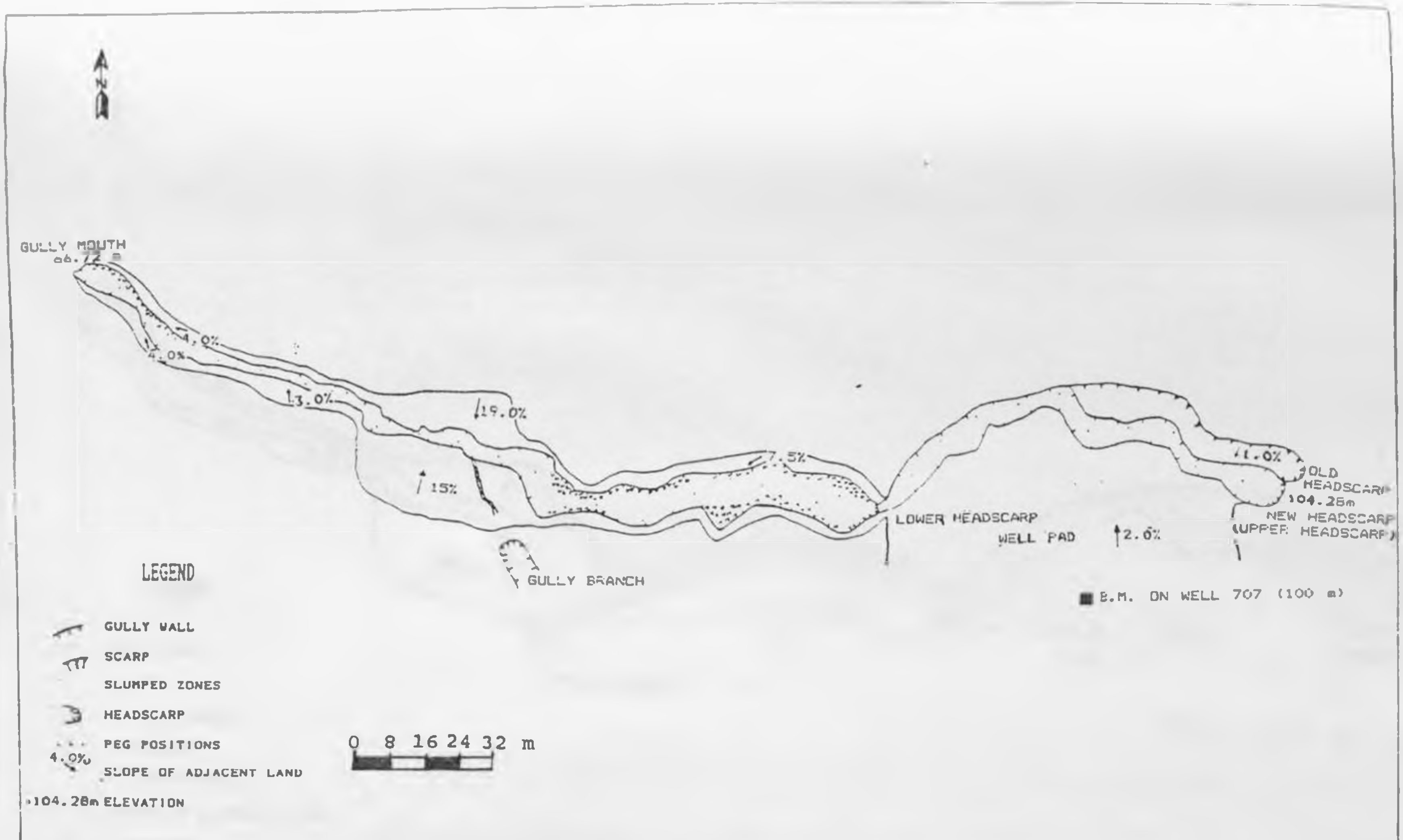

Fig. A.3 Planimetric map of study gully A before the first rainy season, October 1992

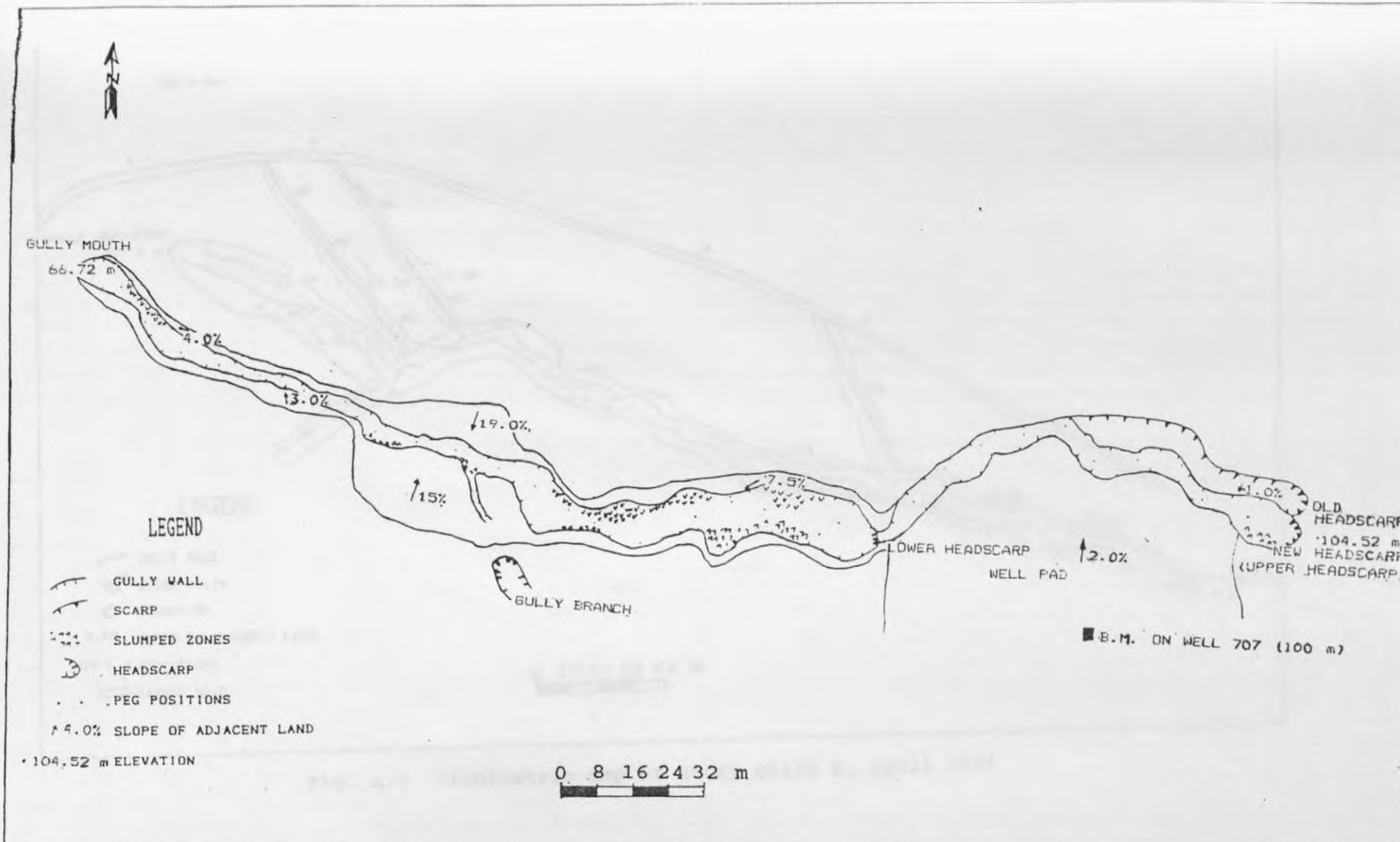

Fig. A.4 Planimetric map of study gully A at the end of the first rainy season, March 1993

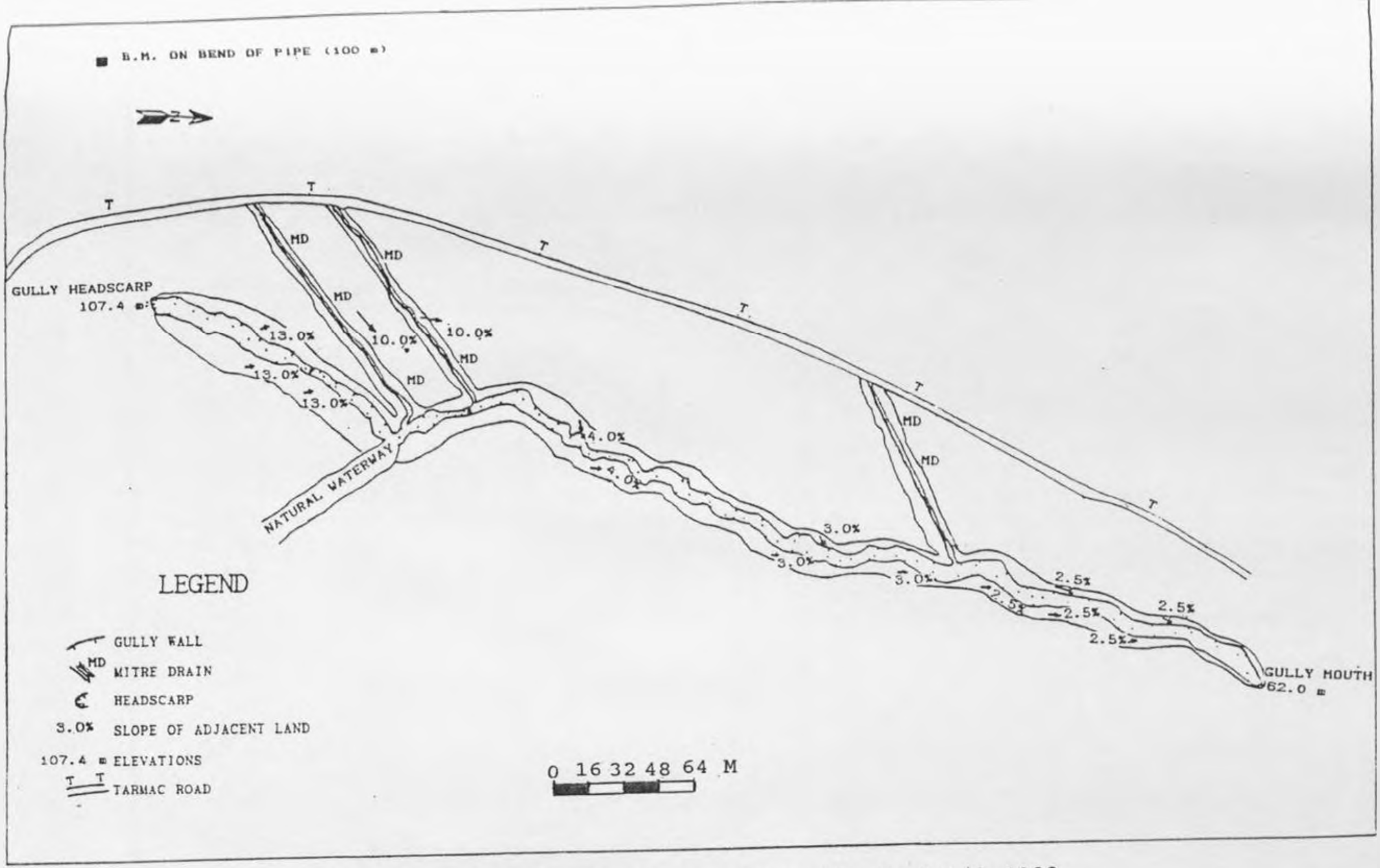

Fig. A.5 Planimetric map of study gully B, April 1993

Appendix B. Cross-sections and long profiles of the study gullies.

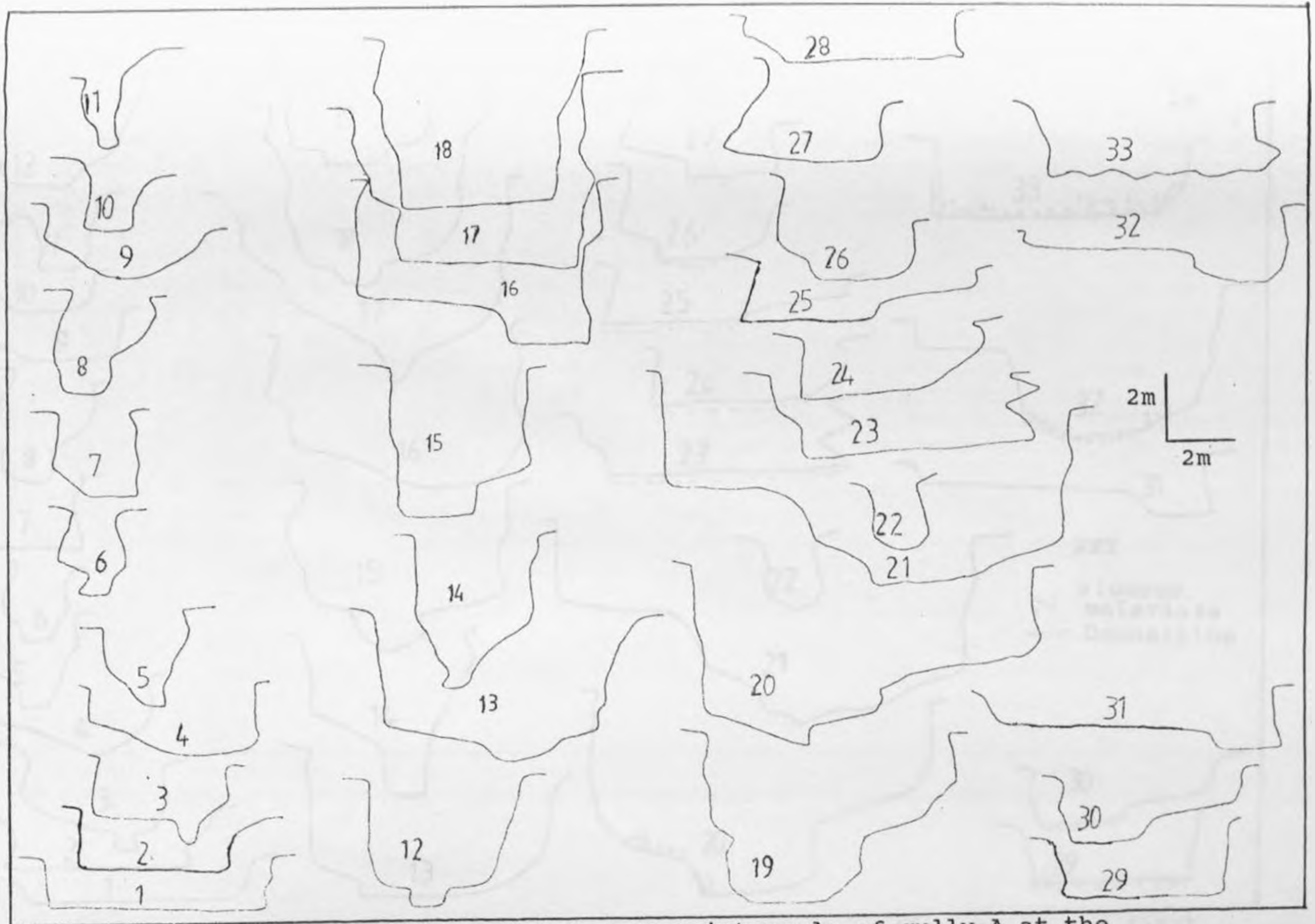

Fig. B.1 Cross profiles at every 10 m intervals of gully A at the beginning of the first rainy season, October 1992

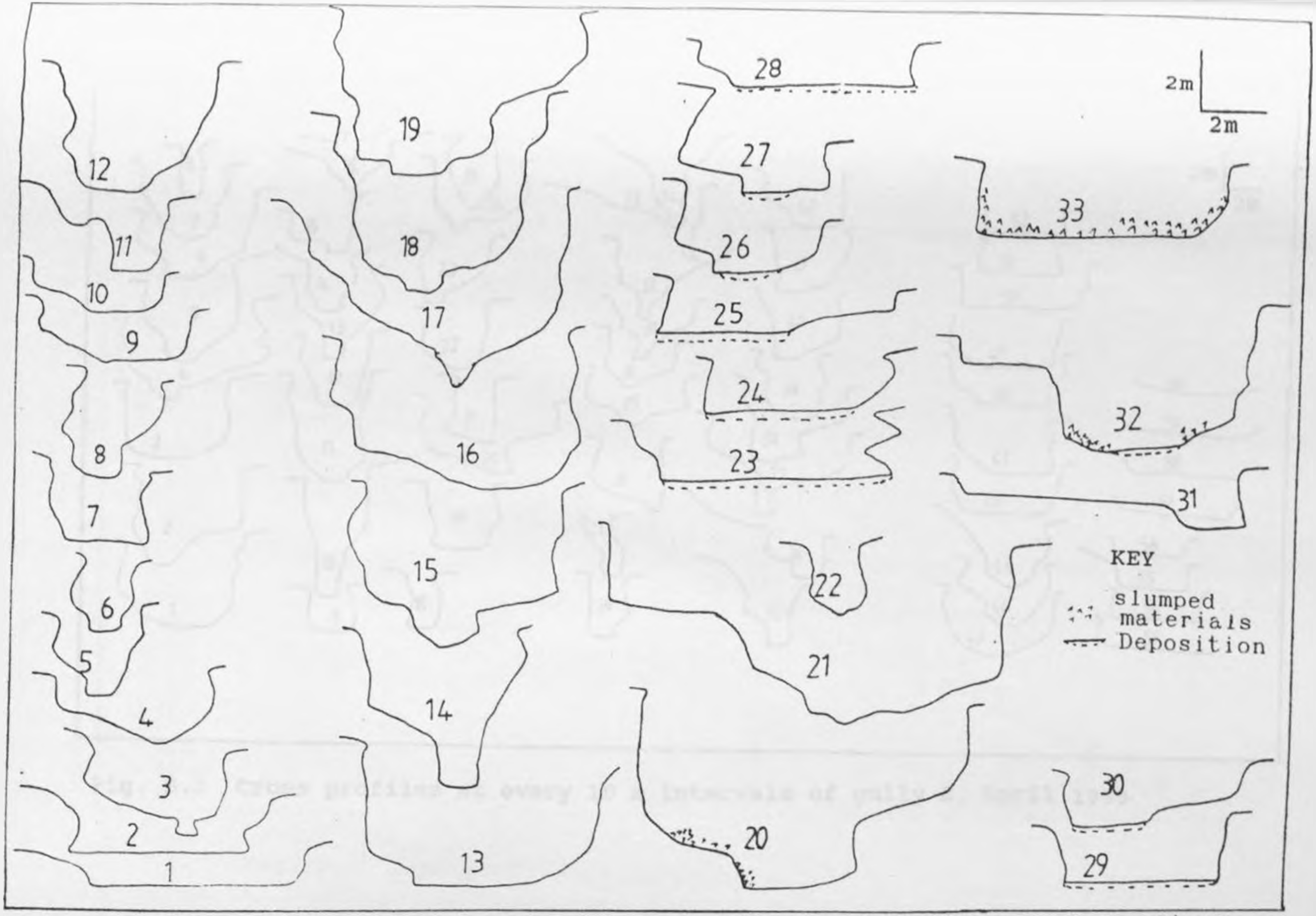

Fig. B.2 Cross profiles at every 10 m intervals of gully A at the end of the first rainy season, March 1993

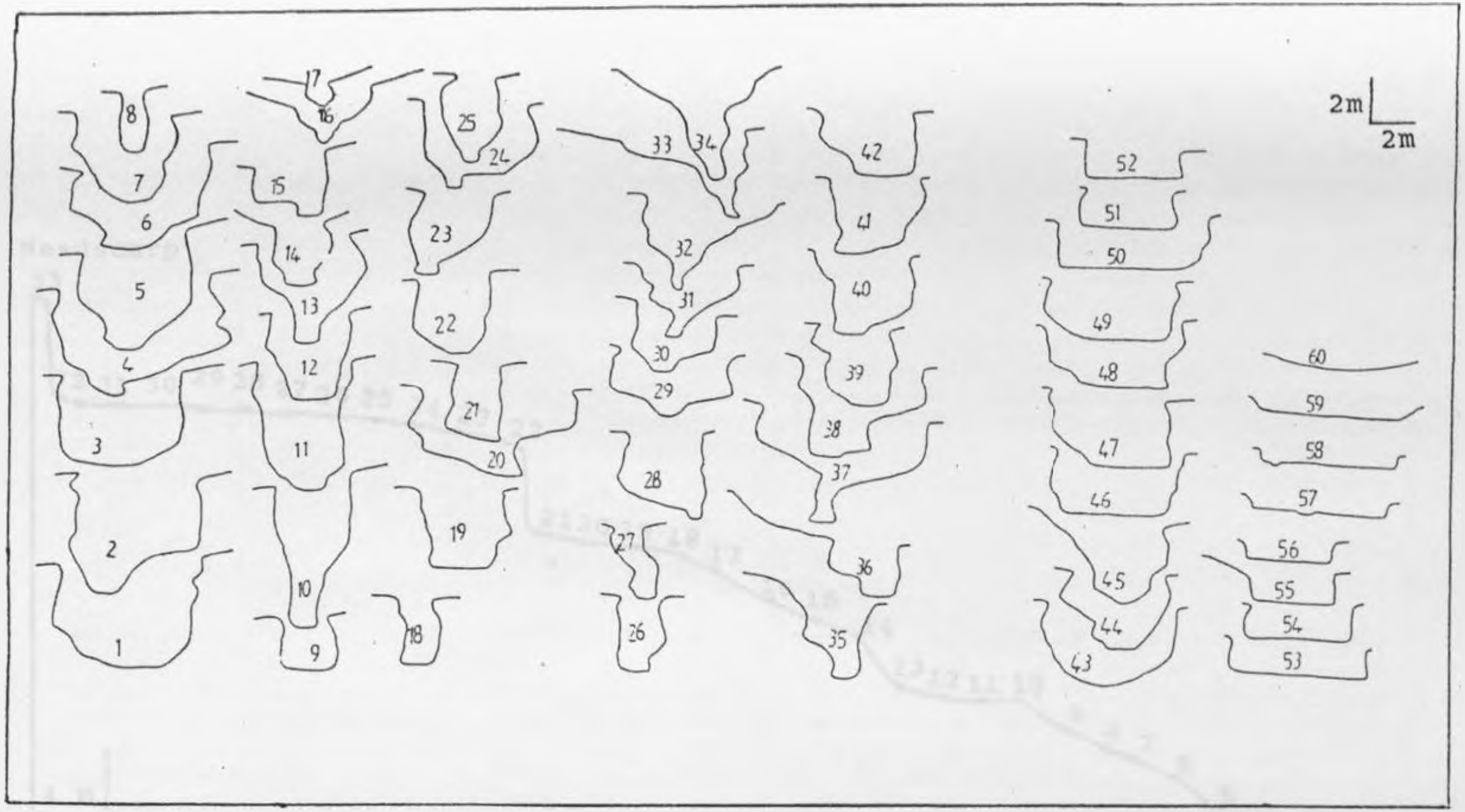

Fig. B.3 Cross profiles at every 10 m intervals of gully B, April 1993

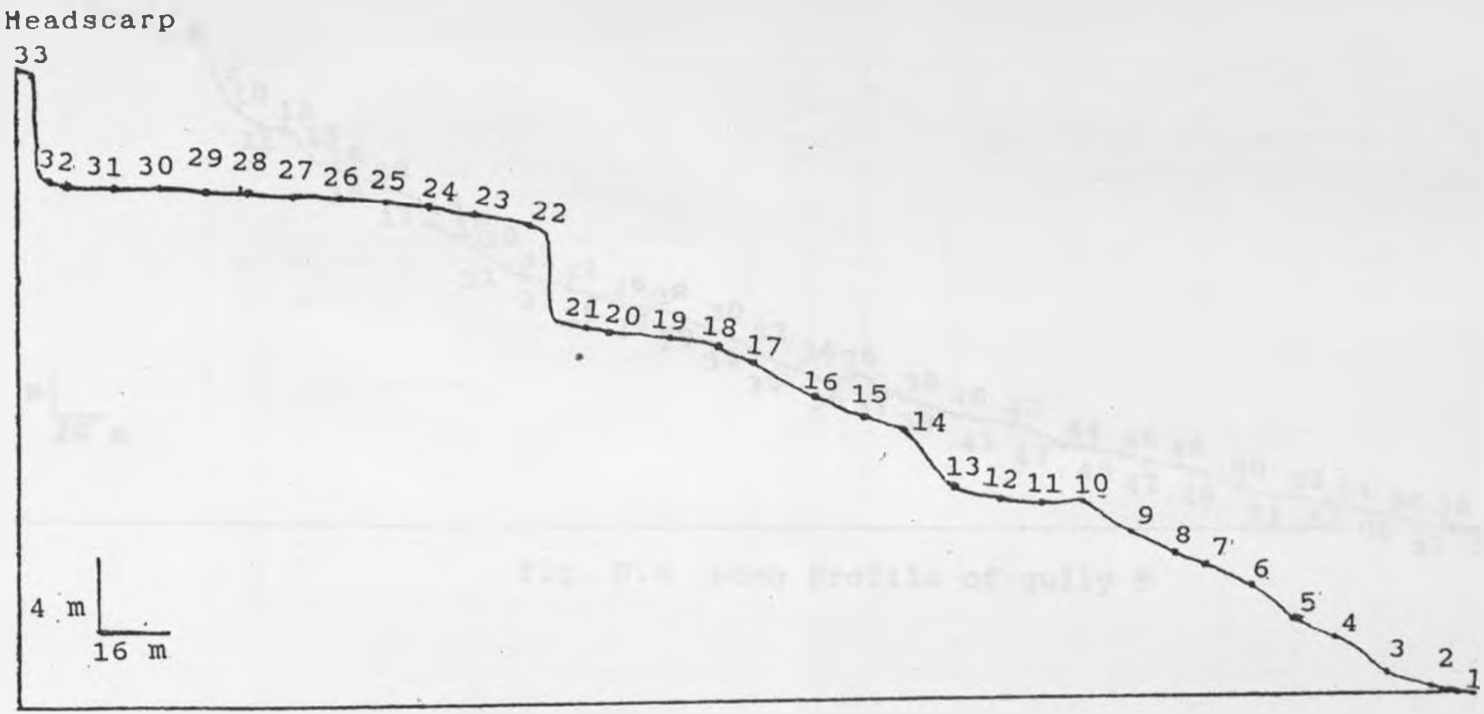

Fig. B.4 Long profile of gully A

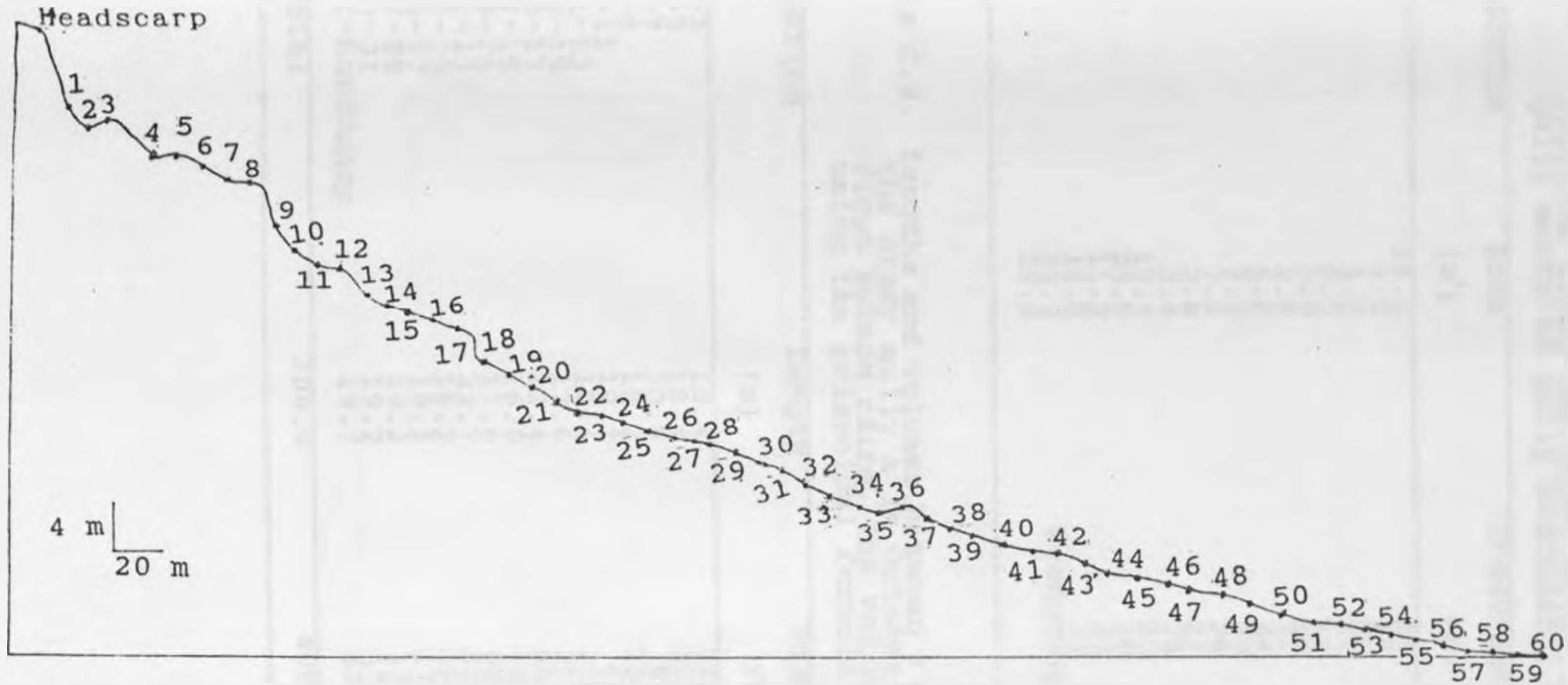

Fig. B.5 Long Profile of gully B

Appendix C. Gully cross-sectional areas and volumes of soil eroded between the sections.

Table C.1. Gully A cross-sectional areas at various cross profiles along the study gully, starting from gully mouth to gully headscarp, October 1992.

Cross-section no.	Area (m^2)	Cross-section no.	Area (m^2)
1	10.0	18	27.0
2	8.0	19	28.4
3	4.5	20	39.5
4	8.5	21	48.2
5	5.0	22	3.0
6	3.8	23	13.9
7	5.8	24	9.5
8	7.5	25	10.0
9	7.2	26	8.6
10	2.8	27	9.1
11	2.4	28	8.9
12	13.4	29	10.2
13	25.9	30	7.5
14	11.3	31	9.0
15	15.5	32	10.9
16	29.2	Headscarp(33)	13.5
17	29.8		

Table C.2. Lengths and volumes between 3 cross-sections of the study gully A in October 1992, before the first season rains. The volumes were calculted using the prismoidal formula.

Section	Length (m)	Volume (m^3)
1-3	18.4	142.6
3-5	18.4	133.4
5-7	20.0	85.8
7-9	19.2	137.6
9-11	19.2	66.0
11-13	18.4	250.7
13-15	17.6	254.2
15-17	22.4	605.6
17-19	16.0	443.0
19-21	17.6	688.2
21-23	22.7	279.9
23-25	19.2	198.2
25-27	19.2	171.6
27-29	19.2	175.6
29-31	19.2	156.6
31-Headscarp	19.7	216.7
Total	306.4	4005.7

Table C.3. Gully A cross-section areas at approximately 10 m intervals along the gully profile at the end of the first rainy season, March 1993.

Gully section no.	Area (m^2)	Gully section no.	Area (m^2)
1	7.8	18	25.5
2	10.3	19	27.8
3	9.0	20	42.8
4	8.0	21	45.6
5	5.0	22	3.0
6	3.0	23	13.5
7	7.0	24	7.0
8	6.5	25	9.0
9	6.6	26	8.0
10	4.2	27	8.8
11	5.0	28	7.8
12	14.2	29	8.5
13	25.2	30	7.2
14	14.5	31	8.5
15	23.5	32	23.8
16	29.0	Headscarp	11.0
17	29.0		

Table C.4. Lengths and volumes between 3 cross-sections of the study gully A at the end of the first rainy season, March 1993.

Section	Length (m)	Volume (m^3)
1-3	18.4	177.9
3-5	18.4	141.1
5-7	20.0	120.0
7-9	19.2	126.7
9-11	19.2	90.9
11-13	18.4	266.8
13-15	17.6	315.9
15-17	22.4	629.1
17-19	16.0	423.5
19-21	17.6	717.5
21-23	22.7	229.9
23-25	19.2	161.6
25-27	19.2	159.4
27-29	19.2	155.2
29-31	19.2	195.5
31-Headscarp	22.7	433.9
Total	309.4	4344.9

Table C.5. Areas of cross profiles of gully B, April 1993.

Section	Area (m^2)	Section	Area (m^2)
Headscarp	10.4	31	7.2
1	22.5	32	5.1
2	20.8	33	7.2
3	17.8	34	10.8
4	25.8	35	10.2
5	17.2	36	5.0
6	16.5	37	17.2
7	12.2	38	14.8
8	2.5	39	9.2
9	4.8	40	10.2
10	13.0	41	9.5
11	17.8	42	9.0
12	10.2	43	16.0
13	13.4	44	10.4
14	5.2	45	8.8
15	5.8	46	13.7
16	3.8	47	11.0
17	0.9	48	13.8
18	3.5	49	12.5
19	9.4	50	13.0
20	12.2	51	6.0
21	4.2	52	5.2
22	9.2	53	6.8
23	8.5	54	5.8
24	13.1	55	4.6
25	7.0	56	2.4
26	5.0	57	3.2
27	3.5	58	3.0
28	9.5	59	3.2
29	11.2	60	2.8
30	7.5		

Table C.6. Distances and volumes between sections of the study gully B, April 1993.

Section	Length (m)	Volume (m^3)	Section	Length (m)	Volume (m^3)
Headscarp-2	19.2	387.7	30-32	16.6	115.1
2-4	20.8	407.3	32-34	19.2	143.5
4-6	19.2	356.0	34-36	19.2	181.6
6-8	19.2	217.6	36-38	16.0	236.7
8-10	17.6	101.2	38-40	21.6	223.2
10-12	19.2	302.9	40-42	20.8	198.5
12-14	19.2	222.4	42-44	19.2	266.8
14-16	19.2	102.4	44-46	20.8	198.9
16-18	20.8	37.6	46-48	21.6	257.2
18-20	19.2	171.4	48-50	23.2	296.8
20-22	18.4	117.3	50-52	23.2	163.0
22-24	20.0	187.6	52-54	20.0	127.2
24-26	20.8	159.7	54-56	20.0	88.6
26-28	13.6	64.6	56-58	18.4	56.3
28-30	22.4	231.5	58-60	20.0	62.5
Total				588.6	5683.3

Appendix D. Soil profile description.

Survey area: Olkaria in Naivasha division of Nakuru district.
Elevation: 2000 m a.s.l.
Land form: Hillslope.
Slope: 12%.
Land use: Wildlife grazing; geothermal power development.
Climate: Semi-arid.
Parent material: Recent volcanic ashes and pyroclastics.
Drainage: Well drained.
Ground water level: Unknown.
Rock outcrops and surface stones: None.
Evidence of erosion: Gully erosion.
Presence of salts or alkali: slight.

Human influence: Ground surface scraped/ bulldozed.

SITE : Gully wall

LAYER	**DEPTH (cm)**	**DESCRIPTION**
I	0-45	Grayish olive (5Y5/2) dry and olive black (7.5Y3/2) moist; gravelly silt; sub-angular blocky structure; soft when dry, very friable when moist, slightly sticky and non-plastic when wet; non-calcareous; high root density; gradual and wavy transition to......
II	45-125	Yellowish brown (2.5Y5/4) dry and dull yellowish brown (10YR5/3) moist; gravelly sandy loam; sub-angular blocky structure; soft when dry, very friable when moist, non-sticky and non-plastic when wet; non-calcareous; moderate root density; diffuse

		and smooth transition to......
III	125-210	Dull yellow (2.5Y6/3) dry and brown (10YR4/4) moist; gravelly sandy loam; sub-angular blocky structure; soft when dry, friable when moist, slightly sticky and slightly plastic when wet; slightly calcareous; low root density; diffuse and wavy transition to......
IV	210-290	Dull yellowish brown (10YR5/4) dry and dark brown (10YR3/3) moist; gravelly sandy loam; sub-angular blocky structure; slightly hard when dry, very friable when moist, slightly sticky and non-plastic when wet; slightly calcareous; very low root density; gradual and smooth transition to......
V	290-390	Grayish olive (7.5Y5/2) dry, grayish olive (5Y4/2) moist; fine sand; sub-angular blocky structure; slightly hard when dry, very friable when moist, slightly sticky and slightly plastic when wet;slightly calcareous; no roots seen; diffuse and smooth transition to......
VI	390+	Dull yellow (2.5Y6/4) dry, brown (10YR4/6) moist; sandy loam; sub-angular blocky; slightly hard when dry, friable when moist, slightly sticky and slightly plastic when wet; slightly calcareous and no roots seen.

Appendix E. Estimation of peak rate of runoff.

E.1. Gully A.

E.1.1 Rational formula.

$$Q_p = 0.0028CiA \text{ (see equation 3).}$$

Parameters:

C: Runoff coefficient for the catchment.

$c_1 = 0.30$ for an open sandy loam on a hilly (15.6 % slope) woodland covering 53% of the catchment, i.e. sections A, C and D (fig. A.1).

$c_2 = 0.25$ for a rolling (8 % slope) bushed grassland on open sandy loam covering 47 % of the catchment, i.e. section B (fig. A.1).

Therefore weighted $C = 0.30 \times 53/100 + 0.25 \times 47/100$
$= 0.28$

$i = i_{tc}$

Using Kirpich formula (equation 4):

$t_c = 0.0195L^{0.77}S^{-0.385}$ minutes

Therefore $t_c = 0.0195 \times 1770^{0.77} \times 0.137^{-0.385}$
$= 13.28$ minutes $= 0.22$ hours
(Hudson, 1985).

$i_{tc} = 80$ mm/hr for a return period of ten years at a nearby Naivasha water supply reservoir (Ministry of Water Development, 1978)

A: area of the catchment is 25.3 ha

$$Qp = 0.0028 \times 0.28 \times 80 \times 25.3$$
$$= \underline{1.6}\ m^3/s.$$

E.1.2 Cook's method with modifications for African conditions.

Catchment sections' characteristics and their respective values of catchment characteristics (CC).

<u>Sections A, C, and D (See fig. A.1):</u>

Proportion of the catchment occupied by these sections = 0.53.

Catchment characteristics: steep bushed grassland with deep and well drained soils, CC = 15 + 10 + 20 = 45.

Section B (see fig. A.1):

Proportion of the catchment occupied by this section = 0.47.

Catchment characteristics: rolling bushed grassland with deep and well drained soils, CC = 15 + 10 + 15 = 40.

Therefore the weighted CC = 0.53 x 45 + 0.47 x 40 = 42.6.

Therefore Q_p = 2.3 x 0.8 = 1.8 m^3/s (0.8 is a correction factor for the shape of the catchment). (Hudson, 1985; Morgan, 1986).

E.2. Gully B.

E.2.1. Rational formula.

$Q_p = 0.0028CiA.$

C: Runoff coefficient:

c_1 = 0.3 (for hilly bushed grassland on open sandy loam covering 9.5/12.6 proportion of the catchment)

c_2 = 0.5 (for rolling land on a 30 % impervious soil type with impeded drainage).

i_{tc}: maximum rainfall intensity for a duration equal to the time of concentration, t_c, of the catchment.

$t_c = 0.0195\ L^{0.77}\ S^{-0.385}$

L = 680 m, i.e. length of the catchment.

S = 11.2 % = 0.112, i.e. slope of the catchment.

Therefore, tc = 0.0195 x $680^{0.77}$ x $0.112^{-0.385}$ = 6.9 = 7.0 minutes = 0.1 hr.

i_{tc} = 100 mm/hr (Ministry of Water Development, 1978).

Therefore Q_p = 0.0028 x 0.35 x 100 x 12.6 = 1.2 m^3/s.

E.2.2. Cook's method, modified for African conditions.

The catchment was divided into 2 portions, i.e. a bare and very low infiltration or impervious portion (portion 1, 3.1 ha) and a vegetated portion (portion 2, 9.5 ha).

CC values.

Portion 1: Area = 3.1 ha or 3.1/12.6 proportion of the entire catchment.

parameter	CC
Cover- bare	25
Soil type and drainage	40
Slope (hilly/steep)	20

Total $CC_1 = 85$

Portion 2: Area = 9.5 ha.

characteristics	CC
Cover - shrub + medium grass/ bushed grassland	15
Soil type and drainage - Deep and well drained	10
Slope - hilly or steep	20

Total $CC_2 = 45$

Therefore weighted CC = (3.1/12.6) x 85 + (9.5/12.6) x 45 =
= 55

Therefore Q_p = 2.1 x 0.8 = 1.7 m^3/s (Hudson, 1985; Morgan, 1986).

Appendix F. Erosion and/or deposition processes.

Table F. Erosion pin measurements showing either deposition (positive) or erosion (negative) at regular intervals on the test gully A bed after various storms during and after the first rainy season, 1993.

Peg no.	Deposition/erosion (cm) on date: 15/1	22/1	23/1	26/1	11/2	14/2	16/2	23/2	28/2	After 1^{st} season
1	8.0	-1.0	0	0.5	0	0.3	5.8	0	0	13.6
2	1.0	3.0	0.5	-0.6	-10.0	17.2	8.3	-16.1	0	3.3
3	-6.0	-3.7	-12.9	0.6	-5.8	-9.8	-2.0	1.8	23.7	-14.1
4	-2.0	7.5	-7.3	0.4	-0.1	-1.2	-1.3	1.9	0.6	-1.5
5	-1.0	9.0	-5.4	2.7	-9.2	12.8	21.0	3.3	3.6	36.8
6	12.0	9.3	0.6	1.0	4.3	-14.3	-23.3	40.7	1.1	31.4
7	-5.0	-1.0	0.1	-0.6	-6.6	-6.4	-8.0	29.3	1.0	2.8
8	-17.0	0.2	1.6	-0.3	0.6	-2.4	-4.5	-18.2	0	-40.0
9	-18.0	1.9	0.8	-0.4	1.4	-0.9	-1.6	-8.6	2.6	-22.8
10	8.8	10.3	17.9	0.6	1.7	-1.8	-4.0	15.6	1.3	50.4
11	7.0	12.1	17.3	0	1.2	11.8	21.7	4.3	18.3	93.7
12	3.5	6.0	19.4	0.2	0.7	12.7	-19.6	5.7	0.5	29.1
13	5.0	7.0	2.8	0.3	0.1	13.4	-32.4	6.5	5.3	8.0
14	-	-	-	-	-	-	-	-	2.6	2.6
15	9.0	9.7	-9.7	2.9	0	-19.7	-17.9	48.5	-17.0	5.8
16	2.8	1.2	-2.5	-0.8	0	-0.7	-4.3	2.9	0	-1.4
17	-0.2	-6.3	-68.0	-17.0	2.0	-2.9	-2.0	-2.4	-8.2	-105.0
18	0	-7.0	-22.2	2.2	7.1	-10.2	-9.3	11.9	-9.7	-37.2
19	-2.5	-3.0	-14.0	10.3	0.5	-4.9	-6.7	2.2	0	-18.1
20	0	-0.8	-16.9	1.9	54.5	-10.3	-49.6	-5.3	5.7	-20.8
21	3.0	-6.2	-2.9	0.8	3.2	-3.4	-11.1	17.4	-3.0	-2.2
22	-1.0	-0.3	0.6	0.2	0	-1.9	-1.7	10.0	-19.4	-13.5
23	1.0	-0.8	0.7	-0.2	0	3.5	10.5	6.2	0.7	21.6
24	1.0	0.5	7.8	0.6	9.8	4.4	7.3	14.9	-2.9	43.4
25	0	1.1	-1.1	1.0	0	4.9	5.7	17.1	8.2	36.9
26	0.5	0.9	0.4	0	0	5.2	2.9	3.4	21.4	34.7
27	0.8	0	0.7	0.2	-1.7	5.0	3.8	10.3	0	19.1
28	0	0	0.2	0	0	3.0	4.2	7.4	0	14.8
29	0.5	0	6.4	0.4	0.6	1.7	2.0	14.7	2.9	29.2
30	0.5	0	4.4	0	14.8	3.4	5.4	-2.9	-0.7	24.9
31	0	0	-5.2	1.3	35.3	-1.1	-0.5	-8.6	13.9	35.1
32	0	0	8.2	0.3	11.0	5.0	3.4	11.6	6.1	45.6
33	0	1.4	-6.0	0.4	0	17.2	1.7	4.6	0.6	19.9

Appendix G. Daily rainfall during the months of the study at Olkaria North East meteorological station.

Date	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
	Rainfall (mm) in the month of							
1	7.1	0	0	0	0	0	0	0
2	2.4	0	2.7	0	0	0	17.2	0
3	5.5	13.8	0	0	0	0	0	13.4
4	1.6	0	0	0	0	0	0	22.3
5	0.3	0	0	0	0	0	0	8.5
6	1.9	0	0	0	0	0	0.5	0.5
7	2.7	15.1	4.4	2.5	0	0	0	0
8	0	11.3	11.6	0	0	0	1.5	2.9
9	0	2.5	0	18.9	0	0	0	3.8
10	0	3.7	0	1.4	0	0	0	8.5
11	0	21.6	0	46.9	0	0	0	0
12	1.5	0.9	0	1.2	0	0	0	2.3
13	0	1.5	7.3	0	0	0	0	1.3
14	2.1	1.0	15.3	1.5	1.2	0	0	0
15	0	0	13.9	0	0	0	0.5	0
16	0	5.0	14.4	19.2	1.5	0	0	0
17	0	4.5	1.1	0	0	0	0	0
18	0	0	0.4	0	0	3.2	0	0
19	0	0	4.9	0	0	0	0	0
20	0	0	4.5	0	0	0	0	1.0
21	0	1.3	4.3	0	0.9	0	0	11.5
22	0	3.2	9.5	0	0	0	0	0
23	0	0	13.6	0	0	0	0	0
24	0	0	0	0	0	0	4.5	0
25	0	0	0	2.2	0	0	0	0
26	0	0	7.1	2.5	0	0	0	0
27	2.5	0.6	7.4	0	0	12.5	0	0
28	3.5	6.2	5.2	27.2	0	0	0	0
29	5.9	0	0	N/A	0	0	0	0
30	1.8	0	1.6	N/A	0.4	0	0	0
31	N/A	0	2.0	N/A	5.6	N/A	0	0
Total	38.8	92.2	131.2	123.5	9.6	15.7	24.4	76.0