The Effect of Road Design and Land Use on Gully Erosion: A Case Study of the Rural Access Roads in Embu District, Kenya

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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.

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DEDICATION

This work is dedicated to my daughters – Sheilla Wanjiku and Nancy Wangui for their patience and encouragement.

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation/Acronym	Description
ASK	Agricultural Society of Kenya
Asl	Above sea level
BBS	Broad Based Survey
DAO	District Agricultural Officer
EIA	Environmental Impact Assessment
FA	Focal Area
FAO	Food and Agriculture Organization
GCRIO	Global Change Research Information Office
GDP	Gross Domestic Product
GOK	Government of Kenya
HADO	Hifadhi Ardhi Dodoma
ILO	International Labour Organisation
KeRRA	Kenya Rural Roads Authority
Ksh	Kenya Shillings
KWS	Kenya Wildlife Service
Km	Kilometre
MDG	Millenium Development Goals
MoALDM	Ministry of Agriculture, Livestock Development & Marketing
MOPW&H	Ministry of Public Works and Housing
NALEP	National Agriculture and Livestock Extension Programme
NEMA	National Environment Management Authority
RELMA	Regional Land Management Unit
PRA	Participatory Rural Appraisal
SAT	Semi Arid Tropics
SIDA	Swedish International Development Agency
SIWI	Stockholm International Water Institute
SWC	Soil and Water Conservation

UN	United Nations
UNDP	United Nations Development Programme
US	United States
USDA	United States Department of Agriculture
WOCAT	World Overview of Conservation Approaches and Technologies.

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ABSTRACT

The study of soil erosion in Kenya is largely limited to agricultural and pastoral land. Little attention has been given to the effects of road design on soil erosion, although they cause more inconvenience than any other form of soil erosion The contribution of road design to gully erosion was investigated in Mbeti North and Municipality locations of Central Division of Embu District. The study was conducted on 2 minor roads (road A classified as E. No. 632 and Road B classified as D. No. 467) with a total length of 800 m. Methods used included interviews and discussions with stakeholders, visual observations, surveying, and measuring changes on sediment deposition. A total of six culverts were identified of which 4 (66%) were found to require rehabilitation and 83 % of them discharged onto steep slopes (>10%). Visual observations further revealed that the roads were designed to drain runoff at several points through mitre drains and culverts. Most of the mitre drains were blocked upstream leading to massive amounts of runoff flowing through the culverts and onto farm land causing gully formation. Gullies A and B were controlled using checkdams of brushwood and stone gabions respectively. By the end of the second season soil had accumulated substantially in both gullies. Gullies A and B had accumulated about 50 and 70 mm depth respectively. At this rate and all factors constant it may take approximately 20 years (considering current average depth of 1.4 m) for the two gullies to fill and heal completely.

CHAPTER I

INTRODUCTION

Agriculture plays a significant role in the national economy of Kenya and there is a direct relationship between its performance and overall economic growth (Ministry of Agriculture, 2004). Agriculture contributes approximately 26 per cent of Kenya's GDP directly and a further 27 per cent indirectly (Ministry of Economic Planning, 2005). Sustainable agricultural practices must however be based on the appropriate management of water and soil (Lal, 1994).

Soil erosion is a major problem worldwide (Zheng and Huang, 2002). Soil erosion rates in forests or grasslands in flat terrain range from as low as 0.001 to 2 tons per hectare annually (FAO, 2006). In areas with steep terrain with similar vegetation, erosion rates vary between 1 to 5 tons/ha/yr (Wikipedia, 2007). Pimentel *et al*., (1995) reported an estimate of 75 billion metric tons of soil removed from land by erosion worldwide. They also estimate an average rates of soil loss of 17 tons/ha/yr in the US and Europe, and 30 - 40 tons/ha/yr in Asia, Africa and South America. In Kenya, the average soil loss is approximately 7 tons/ha/yr (Thomas, 1997).

Soil erosion rates in Africa, Asia and South America are estimated to be about twice as high as in the USA (GCRIO, 2006). FAO, (2006) estimates that 140 million ha of high quality soil, mostly in Africa and Asia, will be degraded by 2010, unless better methods of land management are adopted. In the USA, soil has recently been eroded at about 17 times the rate at which it forms: about 90% of US cropland is currently losing soil above the sustainable rate of soil loss (GCRIO, 2006). Climate changes and rapid population growth cause increasing pressure on the East African highlands (Mati, 2005). The results of the pressure are manifold: intensified agriculture, decreasing amount of forestland, loss of biodiversity, intensified land degradation and soil erosion (Lal, 1995). Erosion and runoff can be a serious problem along roadsides, both during and after road construction (Jungerius *et al.*, 2002).

Poor road conditions have been a major obstacle for development in Kenya. Roads vary greatly and provide beneficial aspects by providing access to places while at the same time they can cause adverse environmental impacts especially if they are not to be self draining (Norconsult International, 2004). Roads are supposed to be designed to discharge road runoff as frequently as possible (Nyssen et al, 2002). When roads are poorly designed, severe soil erosion may result with devastating consequences. In addition to losing valuable soil resources, erosion results in an unhealthy environment for growing vegetation, pollutes waterways with sediment, and results in costly maintenance activities and repair damage (Hudson, 1995). Damage at a site may include rilled and gullied slopes, washed out ditches; damage to water bodies occurs when they become filled with polluting sediment making them susceptible to flooding and stream bank erosion. For instance in Kenya, the Municipality location of Central Division of Embu district was found to be badly eroded with many gullies on cropped land and also with poorly maintained road network during a Broad Based Survey (BBS) conducted in the area (Njuguna, 2004) and also during a Participatory Rural Appraisal (PRA) exercise conducted at Njukiri area (Kaboro, 2002) by a multi-disciplinary team led by the Ministry of Agriculture and Ministry of Livestock and Fisheries Development personnel of Central Division of Embu District.

One of the few studies of soil erosion related to roads in Kenya is by Orendain and Barrow (1986). They point out that the natural drainage is nearly always disrupted during the construction of new roads. Also in Kenya, measurements by Dunne and Dietrich (1982) showed that rural roads and footpaths in a densely populated area covered about 2 per cent of a catchment's area, but invoke 25 to 50 per cent of total soil erosion. In the East African Highlands, Moeyersons (1991) monitored and analysed progressive gully formation after road building in Rwanda. Ogbaghebriel and Brancaccio (1993) gave examples of gullies induced by roads on pediments in the Ethiopian Highlands. Elsewhere, and especially in North America, research on water erosion caused by road building has focused on forested areas (Montgomery, 1994; Baisley and Cameron, 1996; Gucinski *et al.*, 2000; Luce and Wemple, 2001; Croke and Hairsine, 2001).

In a study by Lal, (1990), it was concluded that soil erosion is one of the major land management problems threatening the economic productivity of agricultural land in tropics, this is because first, it leads to the removal of top soil and consequently to the loss of both applied and inherent plant nutrients. Rehabilitation of the farm land usually increases the cost of production to a level which is beyond the financial means of the ordinary farmer. When human activities accelerate erosion above a certain threshold, irreversible damage occurs to the land (Gipe, 1996). The result is reduced agricultural land productivity per unit area (Lal, 1990).

Against this background, a study was conducted to determine the contribution of road design to gully formation and consequently explore strategies and techniques for mitigating gully erosion that could possibly be incorporated into road design.

1.1 Problem statement

The high rate of population growth in Embu, both of human and livestock has resulted in over exploitation of natural resources to meet the ever increasing demand for cash crops, food, fodder and fuel. There is a great demand for extensive road network to access the settled areas and for farm input delivery and transportation of produce to the market. Little attention has been given to the contribution of road design to soil erosion, although they cause more inconvenience than any other form of soil erosion (Jungerius *et al.*, 2002). Roads especially rural feeder roads have been known to contribute enormously to gully erosion in cropped lands of the highlands in Kenya (Mati, 1992). Continued construction of several feeder roads without paying attention to their design will further aggravate the problem of soil erosion and gully formation in cropped land. Accelerated soil erosion may take place following road construction due to increased impermeable surfaces thus leading to streaming and ground loss (Wikipedia, 2007).

Many gullies in the cropped land in Embu District are formed due to water runoff from roads. The resulting gullies are very deep and hence hazardous to human beings and animals. The gullies have further lowered the value of land through reduced crop yield (Njuguna, 2004).

1.2 Justification of the study

Soil erosion is one of the major land management problems threatening the economic productivity of agricultural land in the tropics due to its negative effect on agricultural land productivity per unit area (Lal, 1990). Rehabilitation of the farm land usually increases the cost of production to a level which is beyond the financial means of the ordinary farmer. Solutions to problems associated with soil erosion especially those due to road design are very costly both at the household and national levels. At the former level, farmers are forced to spend their low incomes in purchase of additional food and farm inputs, while at the national level; the government has to spend foreign exchange in food imports and on expensive equipments for dredging the silted dams and channels.

Soil erosion is an important social and economic problem and an essential factor in assessing ecosystem health and function (GCRIO, 2006). Some social economics factors contribute to poor management of farms and consequently increased erosion and gully development. Gully erosion is more difficult and expensive to control than other types of soil erosion (Pathak *et al.*, 2005). This therefore calls for immediate investigation into the erosion problem because its socio-economic (such as effects on crop yields, reduced land quality and value, contribution to downstream sedimentation problems etc.) effects are costly, widespread and long lasting and hence need to be checked before the envisaged problem escalates (Zheng and Huang, 2002). Soil erosion due to poor road design can often be devastating and is often associated with gully formation on crop land.

1.3 Objective of the study

The overall objective of the study was to determine the effect of road design and land use on gully erosion in arable lands of Embu District.

1.4 Specific objectives

1. To determine the effect of road design and land use on gully erosion.
2. To determine the socio economic factors contributing to gully erosion.

1.5 Research questions

1. What is the effect of road design on gully formation?
2. What are the possible strategies and techniques that can be used to mitigate gully erosion and how can they be incorporated into road design and landuse prescription?
3. What are the social economic factors contributing to gully development

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Land degradation can be defined in many ways. In brief, it is any change in the land that reduces its condition or quality and hence its productivity or productive potential (Wikipedia, 2007). It occurs whenever the natural balances in the landscape are changed by human activity, through misuse or overuse of natural resources (Natural Resource Management, 2006). Soil erosion is one form of soil degradation along with soil compaction, low soil organic matter, loss of soil structure, poor internal drainage, salinization, and soil acidity problems (FAO, 2006). These forms of soil degradation, usually contribute to accelerated soil erosion. The agents of soil erosion are water and wind. Soil erosion is a naturally occurring process on all land (Wall *et al.*, 2003).

While erosion is an ongoing natural process, human activities accelerate erosion beyond the natural system. An estimated 4 million hectares of land in India and 29 million hectares of land in Africa are affected by severe gully erosion (Pathak *et al.*, 2005). The importance of soil conservation cannot be overemphasized. Soil is the base in which all the crops and livestock depend on for nutrients. In Kenya each year, the value of soil lost due to erosion is 3 to 4 times as high as the annual income from tourism (World Agroforestry, 2004). Erosion and land use change are very strongly related. Rates of soil loss accelerate to unacceptably high levels wherever land is misused. Soil erosion is therefore an integral part of both the natural and cultural environment (Lal, 1994). Poor landuse practices include deforestation, overgrazing, unmanaged construction activity and road building (Jungerius *et al.*, 2002). When human activities accelerate erosion above a certain threshold, irreversible damage occurs to the land (Gipe, 1996). This is the situation today in some parts of Embu District. However, improved landuse practices can reduce erosion, using techniques like terrace building and tree planting (Critchley, 2000). Although terracing steep lands in East Africa has been an indigenous technology among some communities, new methods have been evolving over the years as the need to be innovative with ever-decreasing space for cultivation grows with the population, especially in the densely populated and erosion-prone highlands (Hurni, 1993; Critchley, 2000).

Running water contribute a significant amount of soil loss each year in Embu (Ministry of Planning and National Development, 2001). Soil erosion by running water is a serious problem in the highlands of Kenya and more so in Embu District. The situation is further aggravated by gully erosion that is a serious problem on sloping land (Dabney *et al.*, 2004). Soil erosion also contributes to the siltation of water reservoirs and irrigation channels. It is the main source of sediment that pollutes rivers and fills reservoirs (Pathak *et al.*, 2005). A large proportion of sediments produced in the agricultural land, bare grounds, footpaths and roads are transported downstream and deposited into the rivers and dams causing serious siltation problem.

On steep land, there is often the danger of formation of gullies. Water running downhill cuts a channel deep into the soil; a gully head, where there is sudden fall, forms at the lower end but gradually works its way back uphill (Thomas, 1997). As it does so, it deepens and widens the scar which the gully makes in the hillside. Eventually, what started as a trickle of water can turn into a chasm tens of metres deep and wide (Hudson, 1995). Gullies reduce the productivity of farmland where they incise into land, and produce sediment that may clog downstream waterbodies (Zheng and Huang, 2002).

The damage caused by the gullies is significant compared to other forms of erosion as the sedimentation production from the gullies is higher than that from other types of erosion (Hilbon, 1997). The challenge is to prevent further accelerated erosion and to prevent new gullies from forming and to limit the headward expansion of existing gullies.

2.2 Soil erosion processes and control with particular reference to gully erosion and control

2.2.1 Soil erosion process

The four most widely recognized processes involved in water erosion are rain splash, interilll or sheet erosion, rill erosion and gully erosion (Mati, 2005, Evans and Cook, 1986). The companion processes of soil erosion and sedimentation by water involve the detachment, transportation and deposition of eroding material, often as intermittent, recurring events. Raindrop impact and flowing runoff are a major erosive agents (Hilbon, 1997). Both have the potential to detach soil and transport sediment. Yet their *modi* *operandi* are quite different. Rain falls dominantly downward, but runoff flows relatively horizontally. Rain acts uniformly over a large area, but runoff is concentrated on a small percentage land area (Hudson, 1995).

Where precipitation rates exceed soil infiltration rates, runoff occurs. Surface runoff turbulence can often cause more erosion than the initial raindrop impact (Wikipedia, 2007). Most of the rain struck the earth at velocities of between 5 and 9 m/s, but runoff velocities usually are less than 1 m/s (FAO, 2006).

The direct impact of raindrops on soil particles causes their detachment and gradual downhill movement - splash erosion (Thomas, 1997). Lighter aggregate materials such as very fine sand, silt, clay and organic matter are easily removed by the raindrop splash and runoff water: greater raindrop energy or runoff amounts might be required to move the larger sand and gravel particles (Poesen *et al.*, 2003).

Soil erosion by running water starts by washing away the top soil through the process of sheet erosion then rills are formed as water concentrates into channels (Hudson, 1995). Sheet erosion, which is a uniform removal of soil in thin layers from sloping land, occurs where the velocity of surface run-off is about 0.3 to 0.6 meters per second (FAO, 2006). Sheet erosion is barely detectable in the short term because it is a gradual process. However, over a long period, the consequent exposure of roots and subsoil can be easily observed (Hudson, 1995). Runoff occurs whenever there is excess water on the slope that cannot be absorbed into the soil or trapped on the surface. The amount of runoff increases if infiltration is reduced due to soil compaction or crusting (Wall *et al.*, 2003).

Rill erosion is the removal of soil by surface runoff in shallow channels deeper than 30 cm (FAO, 2006). Because of its higher surface-flow velocities, rill erosion has a greater capacity than sheet erosion to remove and transport soil. Rill erosion is much more intensive and noticeable than interill erosion (Hudson, 1995). It results primarily from soil detachment by concentrated runoff and occurs on only a small percentage of the land surface. Interill erosion is the removal of thin layer of soil over a wide area that may not be noticed compared with the obvious rill and gully erosion (Wall *et al.*, 2003). It results primarily from the detachment and transport effect of raindrop impact on bare soil surfaces (Hudson, 1995). The rate of interill erosion is only slightly affected by the steepness of the interill surface or by the location on the land slope since raindrop impact is relatively uniform all over an area of land (Kukal *et al.*, 2002). Rills may develop where runoff concentrates due to topographical variations, tillage marks or random irregularities on the land surface. Naturally, the steeper the slope of a field, the greater the amount of soil loss from erosion by water (Wall *et al.*, 2003). As slopes steepen, rain becomes a major detaching agent and transport by runoff increases. For any given condition, the lesser the available detached soil and the lesser the transport capability, the greater the limitation to soil erosion (Negassi *et al*, 2002).

Soil erosion by water increases as the slope length increases. In a study, Wall *et al.*, (2003), Critchley, (2000) and Kukal *et al.*, (1991) concluded that soil erosion by water increases as the slope length increases due to greater accumulation of runoff. Also in a study by Negassi *et al.*, (2002), it was found that steep gradient tended to increase the velocity of flow. The effect of slope length is important on steep slopes, but it is of little importance on slopes less than 1%. (Negassi *et al*, 2002). Runoff does not cause rill erosion until the flows shear characteristics exceed the soils resistance to them and the flows sediment transport capacity is greater than the available detached material. Thus, concentrated runoff may flow for a considerable distance down the slope before rilling starts. Once rilling begins, it may increase rapidly with greater flow accumulations and so rill erosion increases with the length of the land slope. It also increases with the slope steepness (Hudson, 1995). The amounts of interill, rill and gully erosion may vary greatly for different conditions (Thomas, 1997). Interill erosion occurs over a wide area of sloping land, unless there is abrupt change in soil characteristics or land cover (Poesen and Govers, 1990). Major concentrations of high velocity runoff water in these large rills remove vast amounts of soil. This results in large incised gullies occurring along depressions and drainage lines.

When rills are large enough, they are referred to as gullies or gully erosion. Gullies can thus be considered as large rills (Poesen *et al.*, 2003). The distinction between gully and rill is one of depth (Thomas, 1997). Gullies are among the most serious forms of water erosion. A gully is an incised, steep sided channel, with an eroding headcut and slumping sidewalls. In the literature, the term ‘gully’ is used for many different types of incised channels, which includes incisions in agricultural fields (Poesen *et al.*, 2003), shallow hillslope scars (Montgomery, 1999), and a large entrenched dry channel systems. A gully has also been defined as a relatively permanent steep-sided channel or a miniature valley cut by concentrated runoff but through which water commonly flows only during and immediately after heavy rains; may be dendritic or branching or it may be linear, rather long, narrow and or uniform width (FAO, 2006). Gully erosion is geographically a widespread problem (Zheng and Huang, 2002).

Gullies have relatively greater depth and smaller width than stable channels, carry larger sediment loads and display very erratic behaviour so that relationships between sediment discharge and runoff are frequently poor (Grissinger and Murphy, 1989). Erosion from stream and gully banks can generate upto 90 percent of the total sediment yield from a catchment (Olley *et al.*; 1993, Prosser and Winchester, 1996, Wallbrink *et al.*, 1998, Watson, *et al.*, 1998). Gullies are formed where many rills join and gain more than 30 cm depth (FAO, 2006). Gullies resemble large ditches or small valleys, but are metres to tens of metres in depth and width (Wikipedia, 2007). A gully is relatively deep that it would not be obliterated by normal tillage operations (Thomas, 1997).

Gullies are almost always associated with accelerated erosion and therefore with landscape instability (Zheng and Huang, 2002). Gully erosion is the most spectacular form of erosion causing serious damage to the landscape (Kukal *et al.*, 2002, Pathak *et al.*, 2005). Gully erosion is more difficult and expensive to control than other types of soil erosion (Pathak *et al.*, 2005). This therefore calls for immediate investigation into the erosion problem because its socio-economic effects are costly, widespread and long lasting. Soil erosion is an important social and economic problem and an essential factor in assessing ecosystem health and function (GCRIO, 2006). Recent studies conducted in Australia, China, Ethiopia and USA showed that the major part of the sediment in reservoirs might have come from gully erosion. Gully erosion generally does not begin until great quantities of runoff have accumulated (Thomas, 1997). Thus, the portion of the total sediment that is from interill areas, rills, or gullies may vary depending on the slope length and steepness, climatic patterns and soil conditions (Hudson, 1995).

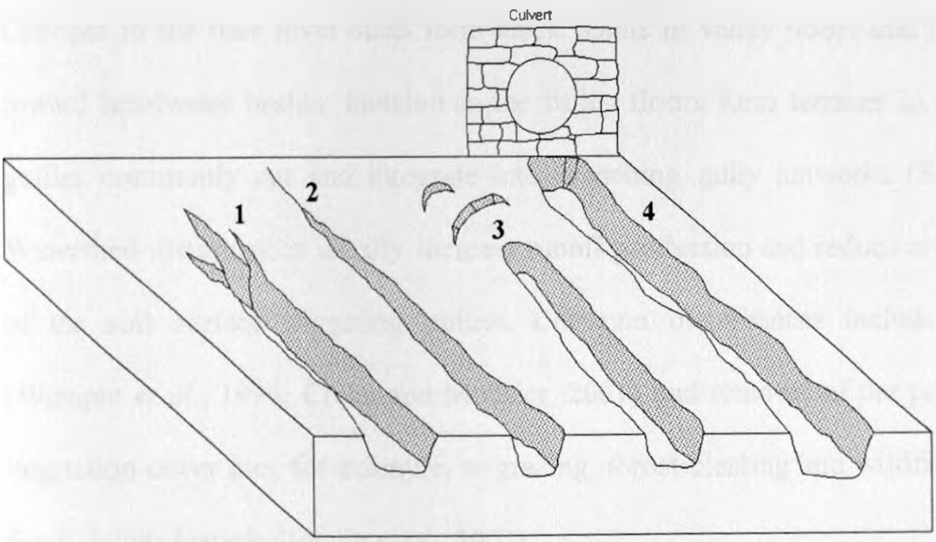

Fig. 2.1: Forms of gully heads (Nyssen *et al.*, 2002)

Figure 2.1: shows possible forms of gully heads: (1) digitate; (2) rilled-abrupt (Oostwoud *et al.*, 1999); (3) sunken soil upslope of gully head (Nyssen *et al.*, 2000a); and (4) gully head at outlet of pipe culvert

Gully erosion is usually attributed to changes in external and internal factors in the basin. External factors determine the magnitude of flow shear stress or stream power acting on the soil surface. These include tectonic uplift and base level lowering, climatic forces and natural anthropogenic disturbances (Schumm, 1999). The rate of gully erosion depends mainly on the run-off producing characteristics of the drainage area, the soil characteristics, the alignment, size and shape of the gully, and the slope in the channel (Negassi *et al.*, 2002)

Changes in the base level often form knick points in valley floors that migrate upslope toward headwater basins. Incision in the valley floors form terraces in which tributary gullies commonly cut and integrate into branching gully networks (Schumm, 1999). Watershed disturbances usually increase runoff production and reduce erosion resistance of the soil surface triggering gullies. Common disturbances include road building (Wemple *et al.*, 1996; Croke and Mockler, 2001) and removal of the protective surface vegetation cover due, for example, to grazing, forest clearing and wildfires (Prosser and Soufi, 1998; Instanbullouglu *et al.*, 2002).

Internal factors for gully erosion arise from the characteristics behavior of the erosion process itself, such as feedbacks between topography change, runoff generation and erosive power of overland flow (Bull, 1997). There is often no clear distinction between internal and external factors in gully erosion. Gully development is cited as an example of equifinality in geomorphology, as a range of different processes and triggering mechanisms can apparently generate similar forms (Schumm, 1999).

2.2.2 Factors determining gully growth

Various factors controlling gully development are catchment characteristics viz. area (Burkard and Kostaschuk, 1997), slope steepness (Kukal *et al.*, 1991), slope shape (Meyer and Martinz-Casasnovas, 1999), gully dimension parameters, surface runoff, precipitation, nature of soil, soil moisture and piping. The size and shape of a drainage area, as well as the length and gradient of its slopes have an effect on the run-off rate and amount of surface water. Therefore, all topographic characteristics should be studied in detail before gully control work begins (FAO, 2006).

Shape and size of catchment: If two catchments having the same area, different shapes, both having symmetrical drainage patterns, the distance to the outlet in the long catchment is greater than in the short one (Thomas, 1997). Therefore, the long catchment's gathering time (time of concentration) will be longer, its corresponding intensity lower, and its maximum run-off rate (Q max, cubic m/second). This explains why; if all other factors are equal, long narrow catchments have fewer flash floods than square or round catchments (FAO, 2006). The larger the watershed, the greater is the amount of run-off (Pathak *et al.,* 2005).

Length and gradient of the slope: On long slopes, there is generally an accumulation of water towards the base. To prevent the gully formation, this water (run-off) should be conducted safely downhill over a long distance to stable, natural water courses or vegetated outlets (Thomas, 1997). Otherwise, the water should be infiltrated into the ground by land treatment measures such as contour ditches (infiltration trenches), level terraces, staking, etc. The steeper the slope, the higher the velocity and the erosive power of the run-off (Pathak *et al.*, 2005). Watershed land treatment measures not only reduce the amount of surface water, but they also decrease its velocity, and so it's erosive power (FAO, 2006).

Nature of soil: Gully formation and development is influenced by various factors including the soil type, particularly its liability to washout and transport (FAO, 2006). Gullies develop particularly in soils with a texture that is between clay and sand or medium textured soils. This is because clay is rather erosion resistant and water infiltrates quickly in sand. The infiltration rate increases from clay to sand (for loamy sand 2.5 - 5 cm/hour), but resistance against erosion decreases (FAO, 2006).

Rainfall intensity and run-off: There is a relationship between rainfall intensity, rate of run-off, density of vegetative cover, and the size of a catchment area (Thomas, 1997). This relationship is generally expressed in equations. The Rational Formula which is used in engineering designs for gully and torrent control is a good way to demonstrate this relationship (FAO, 2006). Big storms can cause severe gullying. Intense rains coupled with soils prone to sealing and crusting, generate high runoff volume and concentrated flow (Lal, 1992). If the amount of rainfall is more than the holding capacity of the soil, there will be an increase in surface run-off, followed by surface erosion and gullying (FAO, 2006). In Embu, after the soil is completely saturated, almost all of the rainfall turns into run-off during the wettest months (Jaeztzold and Schmidt, 2006). In designing engineering measures such as check dams or diversions in gully and torrent control, the rate of run-off is more important than the amount of run-off (FAO, 2006). It has been suggested that differences in storm characteristics, such as storm intensity, frequency and seasonality, rather than the mean annual precipitation, are the primary factors in gully development (Bailing and Wells, 1990) and may infact be the key drivers in many fluvial systems (Tucker and Bras, 2000; Molnar, 2001; Tucker, 2004).

2.2.3 Causes and consequences of gully erosion

Most gullies are formed due to human activities. Some of the major causes of gully formation are overgrazing due to high cattle population, expansion of cultivation in steeper or marginal land, cultivation without taking care of surplus runoff water, deforestation due to clearing of vegetation, unsatisfactory waterways and improper design of culverts and other structures (Pathak *et al.*, 2005). Generally a gully is caused by a rapid accumulation of the surface runoff in an unstable landscape (Nyssen *et al.*, 2002). In a study by Montgomery and Dietrich, (1994), it was revealed that water erosion was the primary cause of gully development. A study by Ogbaghebriel and Brancaccio, (1993), concluded that gullies are created in those places where the road intercepts and concentrates runoff from the slopes, i.e. where it crosses hillslopes. According to Pathak *et al.*, (2005), inadequate drainage systems for roads such as small number of culverts and insufficient capacity of road ditches are some of the causes of gullies.

Gullies are most common in hilly areas. They are mainly associated with runoff from roads and built up areas (Thomas, 1997). If road cuts and fill slopes are not revegetated during or immediately following road construction, gullies may form on both sides of the road (Wemple *et al.*, 1996). Inadequate drainage systems for roads (small number of culverts, insufficient capacity of road ditches, etc.) are a major cause of gullying (Jungerius, *et al.*, 2002). Widening operations along roadsides do not often follow road construction but, where widening is practiced, the operation usually causes landslide erosion and then gullying during the first rainy season (FAO, 2006).

Water erosion is the primary cause of gully development (Zheng and Huang, 2002). Study by Montgomery and Dietrich, (1994), on the susceptibility of catchments to gully erosion, affirms the influence of both running water and mass movement on gully development. In the loess, loamy areas of Belgium, mass movements contributed significantly to the formation of rills and gullies (Poesen and Govers, 1990).

Some soils in Kenya are very prone to gully erosion. Examples are soils with high sodium content as found in the alluvial plains around lake Baringo; soils with high content of montimorilonite type of clay mineralogy, as found in black cotton soils of Mwea and Muhoroni areas; and soils in which the subsoil consists of non-cohesive material as found in Maai Mahiu and Olkaria areas (Thomas, 1997). Calcareous soils, with high content of silt sized calcium carbonate, behave as silty soils, i.e. filling and sealing the soil pores, decreasing the infiltration capacity, increasing surface runoff and consequently increasing soil erodibility.

Gully erosion means the loss of large volumes of soil. In high potential areas where there is intensive land use, gully erosion is often caused by runoff from roads and urban areas (Thomas, 1997). Deep gullies severely limit the use of the land, while suspended sediment causes water quality decline in rivers and streams (Natural Resource and Water, 2006). The fine colloidal clay particles suspended in runoff may clog groundwater aquifers, pollute water courses and affect aquatic life. Large gullies disrupt normal farm operations creating access problems for vehicles and stock (Boucher, 2006) and sometimes remove portions of land completely from production (Zheng and Huang, 2002). Gully erosion also causes depreciation in land value by lowering the water table and depleting the available water reserves. Buildings and infrastructures are also undermined by rapidly advancing gullies (Pathak *et al.*, 2005).

2.2.4 Processes of gully development

There are two main development stages of gully evolution: active and stable. At the active gully stage erosion is intense and the morphological characteristics are consequently far from constant. While this stage constitutes only about 5 per cent of the entire gully lifetime, more than 90 per cent of gully length, 60 per cent of its area and 35 per cent of its volume are formed in this period (Sidorchuk, 2006). During this stage the main processes are gully bed incision and widening, gully side slumping, and gully head growth (Thomas, 1997). Active gully sides are usually vertical but may adopt an oblique shape once they start to stabilize. This process may occur naturally but can be hastened by the adoption of various gully treatment measures. Runoff may enter a gully from the sides, causing secondary gullies or branching (Natural Resources and Water, 2006). The gully floor may be subject to further down cutting as secondary gullies advance up the channel. Sediment deposition below gully heads results in a 'steps and stairs' pattern.

While peak flows from intense rainfall causes considerable gully erosion, prolonged low flows resulting from an extended wet period can also create problems. Constant trickle flows through a drainage line can saturate the soil in the trickle zone making it structurally weak and very susceptible to erosion (Natural Resources and Water, 2006). The constant wet conditions may also weaken the vegetation which then provides less resistance to erosion. Gully depth is often limited by the depth of the underlying rock which means that gullies are normally less than 2 metres deep. However, on deep soils such as alluvial, colluvial and other soils, gullies may reach depths of 10 to 15 metres (Natural Resources and Water, 2006). Subsurface flow in dispersible soils can cause the saturation of gully sides leading to slumping of gully walls and the expansion of the gully. Under these circumstances, gully head advancement can occur with little or no surface flow (Hilbon, 1997).

Triggers of gully development: Gully erosion is commonly triggered by fluvial erosion following natural and anthropogenic disturbances or as a response to changes in climate and tectonic forces and base level drop (Istanbulluoglu *et al.*, 2005). Gully development may also be triggered by cultivation or grazing on soils susceptible to gully erosion. The process of gully erosion at the active stage is far from equilibrium; rather, the gully shows the characteristics of a self-organizing system that is close to crisis (Sidorchuk, 2006). Gully size (length, depth, area, volume) increases rapidly in time (Nyssen *et al.*, 2002).

Runoff concentration caused by furrows, contour banks, waterways, fences and tracks could also trigger gully formation. Increased runoff from land use changes such as tree clearing in the catchments or construction of new residential areas could be another factor. Gullies often develop from intense erosion caused by flow over a steep overfall at the top of the gully (Zheng and Huang, 2002). The road network has expanded rapidly but gullies have developed from failure to provide proper waterways to carry runoff to safe disposal areas (Thomas *et al.*, 2003).

Gullies could also start due to improper design, construction or maintenance of waterways in cropping areas. Poor vegetative cover e.g. from overgrazing, fires or salinity problems may also trigger a gully (Thomas *et al.*, 2003). Low flows or seepage flows over a long period, diversion of a drainage line to an area of high risk to erosion e.g. a steep creek bank or highly erodible soils can also start a gully (Hudson, 1995). Down cutting in a creek, causes gullies to advance up the drainage line flowing into it.

Channel erosion: Gully erosion is defined as erosion in channels where runoff water accumulates and removes soils from this channel area (Zheng and Huang, 2002). Gullies may develop in watercourses or other places where runoff concentrates. A watercourse is ordinarily in a state of balance where its size, shape and gradient are suitable for the flow it carries. If the balance is disturbed, for example by larger than normal flows, gully formation may begin (Hudson, 1995). In cultivation or pastures, advanced rill erosion can develop into gully erosion if no protective measures are taken. Cattle foot paths can be a starting point for a small rill that can develop into a large gully (Natural Resources and Water, 2006).

Headward extension: Gully development begins when runoff erosion carves rills and forms headcuts that often retreat along the tracks of pre-existing rills, in a process often called 'gullying' (Higgins, 1990). Undermining of headcuts by plunge pool erosion (Bennett *et al.*, 2000), piping and seepage erosion (Howard, 1995) and mass wasting of sidewalls (Dietrich and Dunne, 1993; Montgomery, 1999) are among gullying processes commonly observed in the field. Gully erosion is caused when runoff concentrates and flows at a velocity sufficient to detach and transport soil particles. A waterfall may form, with runoff picking up energy as it plunges over the gully head. Splash back at the base of the gully head erodes the subsoil and the gully eats its way up the slope (Natural Resources and Water, 2006). A phenomenon that may result to or that enhances gully erosion is piping (Natural Resources and Water, 2006). This is the type of erosion wherein the subsoil erodes from under the surface leaving tunnels. Tunnelling, sometimes referred to as pipping is an important mechanism for headward and lateral gully expansion in dispersible soils (Howard, 1995). When the dispersible subsoils become exposed, the gradient for water flow through cracks in the soil is increased causing more rapid seepage water flow and crack enlargement by tunnel erosion (Natural Resources and Water, 2006). The enlarged cracks develop into tunnels which carry a suspension of soil and water. The tunnels soon collapse causing rapid progression of the gully head. Tunnels develop particularly where the soils are highly sodic (Thomas, 1997). This is not a common phenomenon in Kenya.

Lateral enlargement: Gullies generally create far more capacity than they need to accommodate the runoff they are likely to carry (Natural Resources and Water, 2006). Widening of the gully sides may occur by slumping and mass movement especially on the outside curve of meander. Scouring of the toe slope can lead to mass failure of the side of the gully under gravity. This soil is then washed away by subsequent flows (Thomas, 1997).

Gully floor stabilization: The long term success of gully stabilization work depends on establishing a good vegetative cover on the gully floor which prevents further gullying and allows the gully floor to gradually silt up reducing the fall over the gully head (Natural Resources and Water, 2006). A series of weirs made from wire netting, logs or concrete can trap sediments, which encourage vegetative growth (Natural Resources and Water, 2006). Vegetative weirs can be established using species with erect growth form. The weirs should be carefully designed with a central spillway and correctly spaced.

The depth of spillway, according to FAO, (2006) is given by the equation:

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

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 the 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. 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 (Thomas, 1997).

Branches of dead shrubs or trees can play a useful role in stabilizing a gully floor by restricting access by grazing animals. They also retard runoff flows, which encourage further sedimentation (Natural Resources and Water, 2006). 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 (Hudson, 1995).

The main objective of brushwood check dams is to hold fine material carried by flowing water in the gully and to prevent bed scouring. They can also be used to stabilize a small (< 1 m high) gully head (Thomas, 1997). If well maintained, they can last for about 10 years. 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.

Gully sidewall stabilization: Slope stability depends on the angle of the slope and the soil type. A slope that is steeper than the angle of repose sloughs off and prevents growth and establishment of vegetation. Otherwise gully side slope stabilize fast once plants have become established. 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 (Hudson, 1995). As mentioned earlier, 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 (Thomas, 1997).

Furthermore splash erosion is 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.

Types and shapes of gullies: On the basis of their location in the landscape, two types of gullies have been distinguished: i.e. ephemeral gullies and gullies associated with banks (Hudson, 1995). Ephemeral gullies form where overland flow concentrates in the landscape, i.e. either in natural drainage ways or in, or along, linear landscape elements (e.g. parcel borders, field roads, plough furrows, etc). Ephemeral gullies result from concentrated flow erosion. Sediment detachment and removal is essentially a function of flow intensity. Gullies associated with banks form when a flowing river undermines its embankments causing the soil to collapse into the river (Hudson, 1995).

Shapes of gullies: On the basis of shape, gullies tend to be U-shaped, V-shaped or trapezoidal. The former occurs in cohesive soils with high clay content and the latter in sandier and less cohesive soils (Thomas, 1997). In the long term, many V-shaped gullies become U-shaped as the sides continue slumping until a stable angle develops. U-shaped gullies are formed where both the topsoil and subsoil have the same resistance against erosion. Because the subsoil is eroded as easily as the topsoil nearly vertical walls are developed on each side of the gully. V-shaped gullies develop where the subsoil has less resistance than topsoil against erosion. This is the most common gully form. Trapezoidal gullies can be formed where the gully bottom is made of more resistant material than the topsoil (FAO, 2006).

2.2.5 Gully control measures

Gully erosion is a major problem in East Africa, and with the high costs associated with gully rehabilitation, most gully control activities have, in the past, been implemented by the government or with external assistance (Mati, 2005). Controlling gully erosion can be difficult and costly. It may be justified on better quality soils where there is a reasonable chance of success or where the road or building is threatened by an advancing gully (Hudson, 1995). However, controlling gullies over large areas of poor soils may be impracticable. For this reason, gully prevention is better than cure (Thomas, 1997). Various techniques used to control gully erosion around the world have been discussed elsewhere (e.g. Hudson 1995). The search for inexpensive, durable, low maintenance techniques to control gully erosion has proven elusive (Gellis *et al*., 1995; Norton *et al*., 2002). Generally, gullies are formed by an increase in surface runoff. Therefore, minimizing surface runoff is essential in gully control. Watersheds deteriorate because of man's misuse of the land (FAO, 2006). Control of severe gully erosion usually requires engineering structures to avoid gully cutting (Mati, 2005). However, structural measures involve high investment and a high degree of technology. In some cases in Nepal, the lack of timely and adequate maintenance has resulted in spectacular failures of this type of control measure. The resultant erosion is often more serious than before the treatment (FAO, 2006). Gully control activities have been undertaken in the Arusha Region of

Tanzania (Assmo and Eriksson, 1994), where farmers have been innovative and successful in rehabilitating gullies on their farms and converting them to productive land.

Cultural practices: Often, gullies can be prevented if good land conservation measures are practiced on the farm. Good tillage and cropping practices increase the absorptive capacity of the soil resulting in less runoff and also protect the land surface from erosion (Thomas, 1997). Surface and tile water should be conveyed from lands through proper waterways so as not to create potential gully problems. Buffer strips should be located at potential gully start points such as open ditches or deep depressions. Regular monitoring is essential to detect early stages of gully formation (Hilbon, 1997).

A range of measures to prevent the development of gullies include the management of catchment to ensure runoff is not increased (Thomas, 1997). Lands capability should be assessed to ensure it is suitability for the proposed use. Roads, tracks and fences should be constructed in such a way that they cause minimal concentration and diversion of runoff (Nyssen *et al.*, 2002). Maintenance of adequate pasture cover by better stock management and location of watering points, stockyards, shade areas and gates away from gully prone areas, is another prevention method.

Fencing off and excluding livestock from land vulnerable to gully erosion, control of erosion on sloping, cultivated land by stubble retention and the construction and maintenance of contour banks and waterways will reduce chances of gully development (Mburu, 2000). Construction of water ways to appropriate specifications, stabilizing and maintaining them and ensuring that contour banks discharge into waterways at safe locations prevents gully formation (Pathak *et al.*, 2005). Spreading of flood flows on cultivated floodplains, avoiding practices that concentrate flood flows (Nyssen *et al.*, 2002) and avoiding the development of bare, compacted areas that may occur in school compounds or other heavily trafficked areas may also prevent gully formation. Development of steep areas and drainage lines should be avoided. Soil disturbance should be minimized, and topsoil should be stockpiled, respread and the area revegetated. Construction of flood detention systems below high runoff areas is essential (Pathak *et al.*, 2005).

Controlling gully heads: Options for controlling gully head erosion include diversion of runoff. Diversion banks divert runoff from the gully head to a stable outlet (Thomas, 1997, Nyssen *et al.*, 2002). Unfortunately, such outlets are difficult to find and often the instability may be transferred from one area to another (Natural Resources and Water, 2006).

Vegetative control measures: The exclusive use of vegetative measures for control of severe gullies often results in failure. Vegetation is the primary, long term measure in controlling gully erosion but structures may be needed to stabilize a gully head or to promote siltation and vegetative growth in the gully floor (Thomas, 1997). The end result can be effective control of gully cutting and dramatic reduction of surface erosion, at relatively low cost and high sustainability (FAO, 2006). Vegetation provides protection against scouring and minimizes the erosion risk by reducing flow velocity. As velocity falls, sediment is deposited forming an ideal environment for new vegetative growth (Thomas, 1997). Vegetation should be used wherever possible as this is a cheaper method of controlling gully than construction of gabions which are expensive and labour intensive (Gachene *et al.*, 2004).

Gullies can be a harsh environment in which to establish vegetation. They dry out very rapidly and usually have infertile subsoils (Thomas, 1997). During the rains runoff speeds are high and erosive. Some farmers have shown considerable initiative in stabilizing gullies and converting them to productive use for fodder, fruit or fuelwood (Mburu, 2000). Indigenous species should be considered, especially in an area where it is not desirable to introduce exotic species. Vegetation that grows vigorously with spreading, creeping habit is preferred (Thomas, 1997). The gully slope may be planted with trees, bushes, bananas and sisal to stabilize them and at the same time to meet the needs of grazing, fuel and timber (Mburu, 2000). Trees growing in gullies should not be too close and should have an open canopy to allow protective vegetation to grow on the soil surface (Hudson, 1995). Where subsurface flows are contributing to gully erosion, trees in the area above the gully head should assist by helping to dry out the soil profile and provide structural support to subsoil prone to slumping.

Gully control structures: The saying "A Stitch in Time Saves Nine" is also valid for gully erosion control. Often a potential large gully problem can be solved if discovered and controlled early in its formation (Hilbon, 1997). A full understanding of erosion processes at various stages of gully development is essential to achieve gully stabilization (Pathak, *et al.*, 2005). Many structures have been used in various places for gully erosion control. Gully control structures primarily prevent encroachment of gully heads into productive lands and stabilize the gully course. 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 (Thomas, 1997). Structures may be made of concrete, masonry, wood or other building material. They need various skills for their design and construction and may be expensive to implement. Even a well-designed structure carries with it an inherent risk of failure and they may be undermined or bypassed (Hudson, 1995).

Types of checkdams: A check-dam is a control structure built across the floor of a gully, a waterway or a drainage channel at predetermined intervals (Negassi *et al.*, 2002). Check dams are almost similar to silt traps, but are usually made of large stones placed across inflow channels (Nissen-Petersen, 2006). Two alternative materials, i.e. wooden material and stone material, for constructing a simple and cheap physical measure may be used (Thomas, 1997). Disadvantage of using the wooden ones is that they can easily rot and can also be attacked by termites. In most cases, check dams are used, 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. Niessen-Petersen, (2006) suggested that gully erosion should always be stopped at an early stage by means of check dams since gullies cause much damage to fields. Check dams may be situated so that they drown the gully head when the spillway is operating. Runoff is returned to the watercourse at a safer location or allowed to spread into a grassed area via a diversion bank. The success of these dams depends on a stable by-wash and outlet which can be difficult to obtain in erosion prone soils (Natural Resources and Water, 2006). 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 (Nissen-Petersen, 2006). They control channel erosion and stabilize gully heads. 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.

Gabions: Gabion checkdams may also be used. Gabions are wire-mesh boxes that are normally 1 m wide and 1 m high and filled with loose rocks stacked on top of each other and tied with wire (Negassi *et al*, 2002).

Brush structures: There are indications that brush structures may be preferable to stone structures. Structures may be subject to decay and become less effective with the passing of time. Vegetation on the other hand can multiple and thrive and improve over the years (Thomas, 1997). On the Zuni Reservation in New Mexico, Gellis *et al.,* (1995) observed that only five of 23 brush structures were damaged during his study and Norton *et al.* (2002) found that brush structures successfully endured 25-year recurrence interval flooding, with larger floods beneficially redepositing the woody material down the channel. Woody debris reduces flow velocity and the fraction of a flow's energy applied to sediment transport (e.g. Fetherston *et al.*, 1995), providing much of the flow resistance in some channels (e.g. Manga and Kirchner, 2000). Though at a different scale and setting, some hydraulic qualities of woody debris in larger perennial streams should be applicable across a wide range of scales and environments (Montgomery and Piegay, 2003). These hydraulic properties provide an effective method of slowing gully erosion.

Drop Structures: Drop structures allow runoff to drop vertically to a lower level, where energy is dissipated before flowing down the watercourse. They can be made of formed concrete, concrete blocks, gabions, timber or steel plate (Natural Resources and Water, 2006). A permanent drop structure with earthen extension bunds may be used to divert intercepted runoff. Current practice for riparian gully control involves blocking the gully with an earthen embankment and installing a pipe outlet (Dabney *et al.*, 2004). Placing grade stabilization structures at the head of erosion gullies aims to prevent further advancement of erosion. This is achieved by reshaping the earth floor of the channel to a stable grade and accommodating the fall of the gully in erosion resistant drop structures (Kennedy *et al.*, 2001). While the drop structure protects the eroding areas, reclamation of a portion of the degraded gullied area for production purposes, becomes an added feature. Land reclamation tends to require earth moving. Gully reclamation involves the creation of new terraces in the floor of the gully channels and sometimes also in the sidewalls (Thomas, 1997). However, Dabney *et al.,* (2004) in a study demonstrated that growth of small gullies can be controlled with carefully designed vegetative plantings that are less costly than drop pipe structures and have the additional benefits of pollutant filtration. Typically, terrace construction involves the destruction of preexisting soil structures and a loss of both soil humus and soil fertility.

Chute: Another option is the use of chutes - chutes are formed by battering gully heads to a designed slope which depends on the method used to stabilize it. Their role is to convey runoff safely to a lower level. Chutes are lined with erosion resistant materials such as greases, rock, rock mattresses, concrete or erosion control mats (Natural Resources and Water, 2006).

Reshaping and filling of gullies: The practicability of filling a gully depends on its size and the amount of fill needed to restore the gully to its desired shape. Steep gully sides can be reshaped (Natural Resources and Water, 2006). Topsoil should be stockpiled and respread over exposed areas to ensure the rapid establishment of vegetation. Stabilization of small gully heads of less than 1.5 m, where the discharge is not more than 0.1 m^3/s, may be done by reshaping and the use of grass sod or a brushwood carpet (Thomas, 1997). In Kenya, a gully that was situated about one kilometer from Embu town along Embu-Gachoka road that had been encroaching on the road was successfully filled by the Municipal council of Embu in the year 2003.

In Tigray region, gully reclamation for productive purposes has been practiced with favorable agronomic results. This has improved the potential for successfully cultivating banana, elephant grass and sugarcane on previously gullied land, albeit with complex socioeconomic implications (SIWI, 2001). For revegetation to take place in a gully the fertility and moisture conditions of the gully must be right (Mburu, 2000). Otherwise soil and slope amendments can be made before planting any vegetation. These may include fertilizer or manure application (Thomas, 1997).

Other amendments like Terracottem mixture (made up of an absorbent, mineral and organic fertilizers and growth stimulators) are too costly for Kenyan situations (Cotthem *et al.*, 1991). Annual crops can be used to provide a quick cover. It may be possible to divert water from the battered gully while grass is establishing. Gullies in cultivation can be filled when constructing contour banks. The banks must have sufficient capacity where they cross old gully lines as this is common site for contour bank failure (Natural Resources and Water, 2006).

2.2.6 Examples on success and failure of gully control in Kenya

In past, efforts to control gully have had mixed success (Hudson, 1995). There have been some very successful examples with the use of temporary structures and vegetation (Mati, 2000). In Kiama village, Gatanga Division of Thika, a gully was controlled using checkdams of gunny bags filled with soil and reinforced with wooden pegs and brushwood and creeping signal grass was planted on the floor and the sides. Observation after three years showed that the gully had already healed (Gachene *et al.*, 2004). In

Dodoma, farmer Raphael Chinolo and his wife controlled a gully system by planting bananas in deep pits (Critchley *et al.*, 1999). They would fill each pit with 20 liters of manure before planting. The pits capture runoff, but to give extra control of overland flow, they made terraces of earth bunds 0.6 m high, upon which they planted makarikari grass for stability. This way, they were able to stop gully development, increase crop production, improve soil fertility, harvest runoff water and reduce soil erosion. Study by Dabney *et al.*, (2004) demonstrated that growth of small gullies can be controlled with carefully designed vegetative plantings. It was important to control the gully since if it was allowed to continue unchecked; the gully may in time work back to the road (Hudson, 1995). Since usually no repairs take place during the rainy seasons, every additional rain shower could make the gully deeper (Nissen-Peterson, 2006). Innovative farmers have been able to convert gullies into productive land in Mwingi, Makueni and Kitui districts of Kenya (Mburu, 2000). Branches of dried up shrubs or trees can play a useful role in stabilizing a gully floor by restricting access by grazing animals (Mburu, 2000). They also retard runoff flows, which encourage further sedimentation (Natural Resources and Water, 2006). There are also examples where gabions have been used and have failed completely (Natural Resources and Water, 2006).

A study done by Njenga (1991) in Central Kenya indicates that 48% of the gullies which he studied were controlled by gabion check dams but the majority of them had failed. One of the main lessons is that gully control is unlikely to be effective if the landuse and conservation in the catchment area is neglected (FAO, 2006). This is particularly true in rangelands where gully control efforts have usually failed if the land has been denuded and there has been no effort to control grazing and restore cover to the ground. Fencing off the gullied area is highly desirable. Stock is attracted to gullied areas, especially if they include shade trees. These areas are then subject to heavy grazing and compaction (Natural Resources and Water, 2006). The HADO project with financial assistance from SIDA implemented in three geographically separate areas in the Dodoma Region - the Kondoa Eroded Area in Kondoa District, Mpwapwa District, used mechanical methods such as graders and other machinery to construct soil bunds for gully control (Hatibu and Mahoo, 2000).

2.3 Contribution of road to gully formation

Roads are a critical component of civilization. Developing and maintaining the economic activity that is vital for the quality of modern life would be difficult without roads. Roads provide access for people to study, enjoy, or contemplate natural ecosystems (Ariel and Gucinski, 2000). The rural road system conditions the development perspectives of agriculture and recreation, as well as some possibilities of agriculture related preservation of scenery and nature (Pauwels and Gulinck, 2000). The extreme weather changes i.e. prolonged dry periods followed by long wet periods damaged the roads and also contributed to the advancement of gully. In 1997 – the *el nino* period, plenty of runoff was experienced and a lot of damage done to the roads and the gullies (Njuguna, 2004). This period was followed by a prolonged dry period – the *la nina* in the year 2000. In Kenya for instance, the road network was extensively damaged during the 1997/98 *El-*

nino rains and priorities changed when key roads were damaged and had to be considered for rehabilitation at the expense of prioritized projects (Njuguna, 2004). This change of priorities and lack of adequate resources has resulted in some gravel roads deteriorating to earth roads (Ministry of Planning and National Development, 2001). In a study on the susceptibility of catchments to gully erosion, De Ploey (1990) emphasized the influence of both running water and mass movement.

Montgomery (1994) found that the main causes for gullying, after road building, are overland flow concentration by the establishment of artificial drains and increased catchment area. In a study by Zheng and Huang (2002), it was found that gullies often develop from intense erosion caused by flow over a steep overfall at the top of the gully. The road runoff was directed to steep land via culverts causing an overfall. Informal discussions with local informants produced several accounts which stated that the gully had become worse in recent years, and that they were not being given necessary attention. This correlated with a study by Adams and Watson, (2002). Although the road caused gully erosion may occur anywhere in the world, the problem is more severe in developing countries due to neglect in maintenance and lack of provision for safe outlets for excess runoff (Pathak *et al.*, 2005). Roadside gully formation is now a big problem for the road engineers (Jungerius *et al.*, 2002). Unless water can be discharged into well vegetated areas or natural waterways, it is necessary to construct artificial waterways designed to carry the runoff without causing erosion (Eriksson and Kidanu, 2009). Site condition particularly terrain slope where a road is located greatly influence subsequent road related erosion.

Road design variables are constrained by management considerations and site conditions so that the road designer has relatively few options when attempting to avoid road-related erosion. However carefully the measures against erosion are designed, they become rapidly outdated because a new road attracts settlement. Deterioration of surface drainage and erosion start at unforeseeable points where people choose to settle (Jungerius *et al.*, 2002).

Roads are a wide spread and increasing feature of most landscapes, have great ecological impacts, alter landscape spatial patterns and interrupt horizontal ecological flows strongly (Cao *et al.*, 2004). Among the most widespread forms of modification of the natural landscape during the past century has been the construction and maintenance of roads (Diamondback, 1990; Bennett, 1991; Noss and Cooperrider, 1994). Roads are often built into areas to promote logging, agriculture, mining and development of homes or industrial or commercial projects. Such changes in land cover and land and water use result in major and persistent adverse effects on the native flora and fauna of terrestrial (Seibert, 1993) and fresh water ecosystems (Schlosser, 1991: Allan and Flecker, 1993: Roth *et al.*, 1996).

2.3.1 Roads induced erosion

Road building almost always disturbs the natural equilibrium in an area (Nyssen *et al.*, 2002). Roads interrupt the natural drainage of an area. Experience in developing countries has often shown that roads are the major source of erosion (FAO, 2006). Effects however vary considerably depending on the geologic, climatic, landform, soil and vegetation properties of the area and upon the care taken to reduce erosion in all phases of the road development project.

Roads especially rural feeder roads have been known to contribute enormously to gully erosion in cropped areas of the highlands in Kenya (Mati, 1992). In a study in Kiambu District of Kenya, Mati, (1984) showed that over 50 percent of the gullies emanate from road drainage. The secondary and minor roads in the hilly areas are causing much damage and currently, little is being done to mitigate the problems. With the continuing global push for development of rural agricultural production systems, road building has steadily increased as a major infrastructural investment. However, the absence of ecologically sustainable design standards has led to increased and often severe soil erosion in agro-ecosystems that can little afford the loss of top soil (Zheng *et al.*, 1994; Cao, 2001). Thousands of acres of fertile farmland are being washed away every year by uncontrolled rainwater running off roads (Nissen-Petersen, 2006). In Kenya, gully erosion caused by the rural feeder roads is a new problem along the Kapingazi River Catchment in Manyatta and Central Divisions of Embu District. The extent and magnitude of gully erosion has lately gained importance in the face of diminishing farm sizes in both the humid and subhumid areas, and the improved road network with potential for gully formation (Gachene, 1989).

Road-related erosion often is caused by a concentration of water on a road (Bassel, 2002). Concentrated water discharge through culverts and drains can lead to soil erosion if drainage is not carefully planned and constructed (Ministry of Public Works, 1992). One cause of soil erosion is a misaligned road, track or path, which channels and concentrates runoff and leads to soil erosion and gully formation. In a study, Jungerius *et al.*, (2002) found that the position for a road in a climate with torrential rainfall was critical because all the water from the slope had to be discharged through the road surface and therefore if not well managed would cause gullying. Culverts are often far apart and places that received runoff from a relatively small drainage area before road building may receive important increases in runoff due to the increase in catchment area (Nyssen *et al.*, 2002). Effective erosion control requires an integrated approach, which considers government statutes and regulations, a broad knowledge of temporary and permanent erosion control methods; design, construction, and maintenance considerations; and new technology (Johnson, 2000).

Changes in the routing of surface flow may cause unusually high concentrations of runoff on hillslopes that can trigger erosion through channel downcutting, new gully or channel head initiation, or slumping and debris flows (Wemple *et al.*, 1996; Seyedbagheri, 1996). A FAO study conducted in El Salvador in the late 1970s found that as much as 25 percent of the erosion in upland watershed areas was caused by poorly designed roads and paths (FAO, 2003).

2.3.2 Contribution of roads to hillslope failure and gully erosion

Roads have been responsible for the majority of hillslope failures and gully erosion in most steep, forested landscapes subject to logging activity (Furniss *et al.*, 1991). Running water from the road drainage cuts a narrow, shallow trench in the ground. The trench slowly deepens and the deep, narrow shape of the rill encourages high velocities and in an attempt to reach a shallower gradient, the bare soil of the rill erodes. A sudden difference in ground level thus occurs at the head of the rill which accelerates erosion and formation of a gully. The gully then deepens, widens and extends up the catchment areas as it undermines and thus causes the gully head to collapse (Thomas, 1997). Erosion continues until runoff quantities and velocities once again in balance with soil type, the gradient and the established vegetative cover in the gully. Gullies, caused by the concentration of water on the road, can contribute to large volumes of sediment in streams over time (Bassel, 2002). Road construction through steep lands, without adequate provision for drainage, is a major cause of gully erosion. Inadequate drainage systems for roads such as small number of culverts, insufficient capacity of road ditches, etc are some of the causes of gullies (Pathak *et al.*, 2005).

2.3.3 Road location and its effect on riparian areas

Traditional road location, design and maintenance have generally had adverse effects on riparian areas (Norconsult International, 2004). Road locations, drainage methods, and maintenance practices have resulted in a net loss of both acreage and related values in riparian areas. Results of these activities include drainage of riparian ecosystems, reduced site productivity, loss of fish and wildlife habitat, reduced base flows with increased peak flows, gully development, and accelerated downstream sedimentation (LaFayette *et al.*, 1993). Organic pollutants such as dioxins and polychlorinated biphenyls are present in higher concentrations along roads (Benfenati *et al.*, 1992)

2.3.4 Road design

Agricultural programs often include farm-to-market roads to improve market access for products; it is vital that such roads be designed in an environmentally sound way. Construction of a stable road with minimal impact on the surrounding environment requires the consideration of many factors, including balanced cut and fill, proper drainage and disposal of water from the road prism, and conservation measures on exposed slopes. Several big-engineering methods have been developed to mitigate erosion of cut- and – fill slopes on forest roads (FAO, 2006)

The road network has expanded rapidly but gullies have developed from failure to provide proper waterways to carry runoff to safe disposal areas. It is estimated that Kenya has a road network of 150,600 km (Ministry of Public Works, 1992) and Embu District where the study was carried out, has 575.4 km of classified roads with Central Division having only 36.1 km. They are grouped into two broad categories which include classified and unclassified roads. The Ministry of Public Works is only responsible for planning, designing, construction and maintenance of classified roads. Responsibility for the unclassified roads is fragmented among several authorities such as Kenya Wildlife Services (KWS), which is responsible for all roads in the National Parks, Municipal Authorities and County Councils which are responsible for all roads in the areas of their jurisdiction and the forest department is responsible for all roads in the forest reserve (Sharawe, 1995).

2.3.5 Road drainage system

Roads are important for agricultural production which depends on good access to markets. Drainage system is one of the most important features of the road. By design, roads are supposed to be self draining (Nyssen *et al.*, 2002). Drainage consists of side drains, mitre (or turnout drains), culverts, catch water drains and scour checks (Fig 2.2). Thus the runoff from the road surface is supposed to be collected into side drains which discharge through mitre drains to grassland or through culverts to a stable waterway . However, there are many instances where the mitre drains discharge directly onto cropland causing serious erosion and where the discharge from the culverts has caused major gullies (Thomas *et al.*, 2003).

Furthermore, due to relaxed or non-existent road maintenance, the roads themselves have been affected by erosion and some have become impassable as a result. The lack of properly planned runoff disposal systems has led to defective drainage which has resulted in roadside gullies (Montgomery, 1994). Although the road caused gully erosion may occur anywhere in the world, the problem is more severe in developing countries due to neglect in maintenance and lack of provision for safe outlets for excess runoff (Pathak *et al.*, 2005).

Unpaved rural roads are a source of pollution. Erosion of unpaved roadways occurs when soil particles are loosened and carried away from the roadway base, ditch or road bank by water, wind or traffic or other transport means. Exposed soils, high runoff velocities and volumes, sandy or silty soil types, and poor compaction increase the potential for erosion (Environmental Protection Agency, 2006).

Loosened soil particles are carried from the roadbed and into the roadway drainage system. Particles most often settle out where they diminish the carrying capacity of the ditch, and in turn cause roadway flooding, which subsequently leads to more roadway erosion. Most of the eroded soil, however, ultimately ends up in streams and rivers where it diminishes channel capacity, causing more frequent and severe flooding; destroys aquatic and riparian habitat; and has other adverse effects on water quality and water related activities (Environmental Protection Agency, 2006).

2.3.6 Road rehabilitation, maintenance and runoff discharge

Roads should be designed in a way that keeps runoff interception, concentration and deviation minimal (Nyssen *et al.*, 2002). It is important for road drains and culvert outlets to be designed such that water is disposed off at non-erosive velocities (Montgomery, 1994). In early 1990's, soil conservation activities were introduced into road rehabilitation projects to protect land from damage caused by road drains (Mati, 1992).

Typical gravel road maintenance includes the routine blading and adding gravel as needed. Over time, additional work may be required as secondary ditches that build up along the shoulder line develop, and as the material shifts from the surface to the shoulder area. These problems cause disruptions to the drainage patterns and lead to erosion.

Roads are excellent catchment areas. Due to their hard surface, 1 km of a narrow 4 metre wide road can produce about 1,000 cubic metres of water from a rainfall of 300 mm only (Nissen-Petersen, 2006). It is essential that adequate provision be made throughout the road to efficiently collect and discharge rainwater falling onto the area of the road (Jungerius, *et al.,* 2002). Rainwater should be discharged as frequently as possible to minimize erosion damage to the road, the drainage system and the adjoining land. Discharge should be little and often (Ministry of Public Works, 1992).

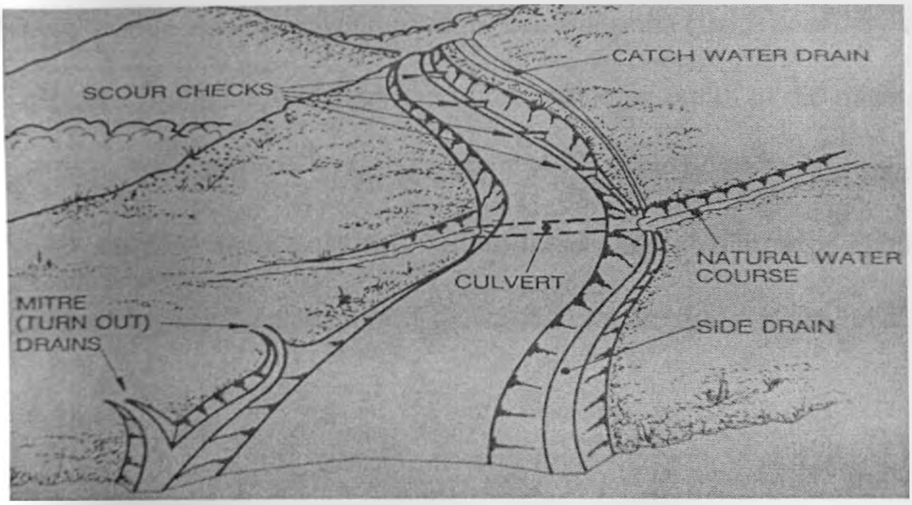

Fig. 2.2: Road drainage features: source Ministry of Public Works (1992)

2.3.7 Mitre drains

Mitre drains are drainage ditches, cut at an angle of 45° to the road alignment to divert water away from the road (Jungerius *et al.*, 2002). Mitre drains (or turn out drains) lead the water away from the side drains to the adjoining land (Fig 2.2). As a general rule, mitre drains should be provided every 20 metres, where possible. This ensures that the quantity of water being discharged at each mitre drain is small, and does not cause erosion damage in the drainage system or on the adjoining land. Where it is impossible to place mitre drains frequently, attention should be paid in providing at least one drainage outlet for a side ditch (using a mitre drain or culvert) every 100 metres. The maximum distance between the side drain outlets (by culvert or mitre drain) should normally be 200 metres. If it is impossible to meet this requirement, erosion control measures, such as ditch lining, should be considered (Ministry of Public Works, 1992).

The discharge water should be channeled to a shamba (field) boundary where possible in order to avoid damage to farm land. The minimum width of the mitre drains is 0.60 m and they should have a gradient of 2 - 5%. Gradients should be carefully checked to ensure that they drain positively within these limits (Ministry of Public Works, 1992). The recommended cross sectional dimension of mitre drains is as shown in Fig. 2.3.

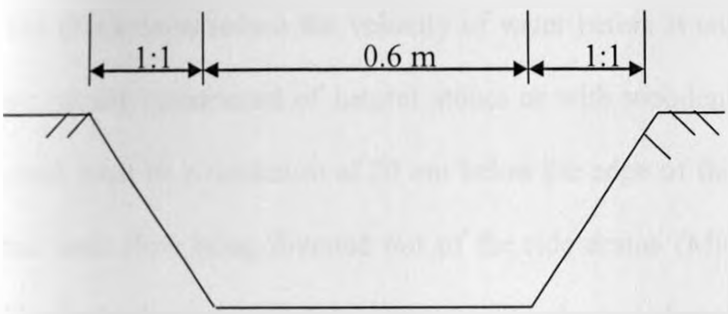

Fig. 2.3: Mitre drain cross section

2.3.8 Scour checks

Where longitudinal drain gradients are steeper than about 4% the water flows at high speed. Therefore, if no protective measures are taken, scouring is likely to occur on erodible soils. The simplest way of dealing with scouring is by reducing the volume of water by placing mitre drains at frequent intervals (Ministry of Public Works, 1992). In addition scour checks can be constructed to reduce the velocity of water. They hold back the silt carried by the water-flow.

There are situations where side drains on steep slopes have been properly lined and stepped but it is not a common technique. There are some examples of properly lined waterways to take road drainage to a watercourse or valley bottom. But again they are not common. The most effective measures are found along the major highways, where contractors have been obliged to take care of drainage example along the newly rebuilt Nairobi-Mombasa highway, a series of concrete check dams have been constructed (Nissen-Petersen, 2006).

The check dams reduce the velocity of water before it enters the culverts. Scour checks are usually constructed of natural stones or with wooden stakes. The level of the scour check must be a minimum of 20 cm below the edge of the carriageway in order to avoid the water flow being diverted out of the side drains (Ministry of Public Works, 1992). The interval at which scour checks are constructed depends on the gradient of the road (Table 2.1).

Table 2.1: Scour check spacing – source Ministry of Public Works, 1992

Gradient of Road	**Scour Check Spacing**
4% or Less	Not required
5%	20 m
8%	10 m
10%	5 m

2.3.9 Road culverts

Culverts are closed conduits constructed below the road surface (Jungerius *et al.*, 2002). Norconsult International, (2004) suggest that hydrological impacts can be minimised by allowing unimpeded flow of water, i.e. through installing adequate box or pipe culverts in the road design. Concrete ring culverts are placed to allow runoff to cross from one side of the road to the other (Fig. 2.2). Due to maintenance problems with smaller sizes, the standard ring size is 600 mm diameter. The levels of culverts are fixed with careful consideration of the existing water course levels. The objective is to make the least change to the vertical and horizontal alignment of the watercourse. The finished levels should then be determined with relation to the culvert (Ministry of Public Works, 1992). Water issuing from culverts is more concentrated and more turbulent and therefore more erosive than water in open drains (Jungerius *et al.,* 2002). According to FAO, (2006), many culvert installations have failed due to insufficient protection by wing walls and have thus been washed away. In a study of 25 minor roads with a total length of 149 km in Nyeri District, Mati, (2000) found that of the total 321 culverts identified, 171 (53%) required channel rehabilitation and 68% of the culverts discharged onto steep slopes (>10%). The maintenance of the drainage system needed to be regular and discharge from the culverts on steep slopes required the construction of an artificial water way to discharge this water safely.

2.3.10 Lining side drains

If a side drain is more than 200 m long without a mitre drain or culvert outlet and its gradient is greater than 3%, there will be a serious risk of erosion. Every effort should be made to avoid such situations. Where they are unavoidable then consideration should be given to lining the ditch invert and lower sides with hand packed stones. These should be well bedded and wedged into place with smaller stones and soil (Ministry of Public Works, 1992). Side drain lining may be necessary for sections of road with sunken profile. It is also effective for short steep sections of road where the drains have a gradient of more than 8% and there is an erosion risk.

2.3.11 Road gradient

The desirable minimum gradient is required for adequate drainage and the absolute maximum gradient will be acceptable over a maximum length of 100 m (Ministry of Public Works, 1992). Table 2.2 shows suitable gradients for different types of terrain. Gradients and crossfall can be checked simply using Abney level or line level.

Table 2.2: Gradients in relation to terrain – source Ministry of Public Works, 1992

Gradients		
Standard	**Flat and Rolling Terrain**	**Hilly Terrain**
Desirable Minimum	2%	2%
Desirable Maximum	8%	10%
Absolute Maximum	10%	12%

2.4 Road design and landuse

The amount, rate and intensity of land use and land cover change are very high in developing countries (Rao and Pant, 2001). In addition, the spatial pattern in the landscape may influence a variety of ecological processes, such as water runoff and erosion, as well as soil nutrient levels (Fu and Chen, 2000). According to Njuguna, (2004), land in the study area was cultivated all the time leaving no time for it to recover.

Roads are an increasing feature of most landscapes, having a major ecological effect in altering landscape spatial patterns in addition to interrupting a variety of horizontal ecological flows (Pauwels and Gulinck, 2000; Sari *et a*l., 2002; Li *et al.*, 2003; Peng and Lu, 2003; Tian and Liu, 2003). Such impacts are even more prevalent in mountainous regions where the fragmentation effects of roads are pervasive, significantly altering landscape structure within multiple forest cover classes on a variety of ecological scales (Sari *et al.*, 2002). While the presence of roads and associated traffic flows is a primary source of landscape fragmentation, the actual ecological impact of this fragmentation depends on a number of variables including plant species and road design characteristics (Jaarsma *et al.*, 2002).

2.5 Volume of rainwater running off roads

The volume of rainwater running off a murram or tarmac road from a rain shower can be estimated as follows (Nissen-Petersen, 2006):

$$V = L \times W \times E \times R/1000 \qquad \text{(eqn. 2.1)}$$

Where V is the volume of water (m^3)

L is the length of the section of road (m)

W is the width of the road (m)

E is the runoff efficiency

R is the rain shower (mm)

For example due to their hard surface, 1 km of a narrow 4 metre wide road can produce about 1,000 cubic metres of water from a rainfall of 300 mm only (Nissen-Petersen, 2006).

2.6 Stoniness and rockiness of arable lands

Detailed determination of the presence of stones and rocks is important with regard to soil management and cultivation of crops. The presence of stones and/or rocks outcrops reduces the arable area and the volume of soil available for root growth, hence the availability of moisture and nutrients. Stoniness and rockiness can be classified as shown in table 2.3:

Table 2.3: Measures of stoniness and rockiness (Meester and Legger, 1988)

Stoniness	**% Soil cover**	**Rockiness**	**%Soil cover**
None	< 0.01	None	< 2
Fairly stony	0.01 – 1	fairly rocky	2 – 10
Stony	1 – 3	Rocky	10 – 25
Very Stony	3 – 15	Very Rocky	25 – 50
Exceedingly Stony	> 15	Exceedingly Rocky	> 50

CHAPTER 3

MATERIALS AND METHODS

3.1 Research Site

The study was conducted in the Central Division of Embu District, in Eastern Province of Kenya (Fig 3.1). The district lies between approximately latitudes 0^{o} 8'' and 0^{o} 35'' South and longitudes 37^{o} 19'' and 37^{o} 42'' East and occupies a total area of 729.4 km^2 (Jaertzold and Schmidt, 2006).

The study area falls under the Kapingazi River catchment. This area has steep rolling hills with many farms having an average acreage of one hectare and with percentage slopes of upto 55% (Njuguna, 2004). It is an area that is badly eroded with few soil conservation structures. The Division has a good road network composed of tarmac and earth roads though poorly maintained (Njuguna, 2004). Some roads become impassable during the rains and dusty during the dry season due to lots of dust that is dislodged from the roads due to the heavy vehicular traffic.

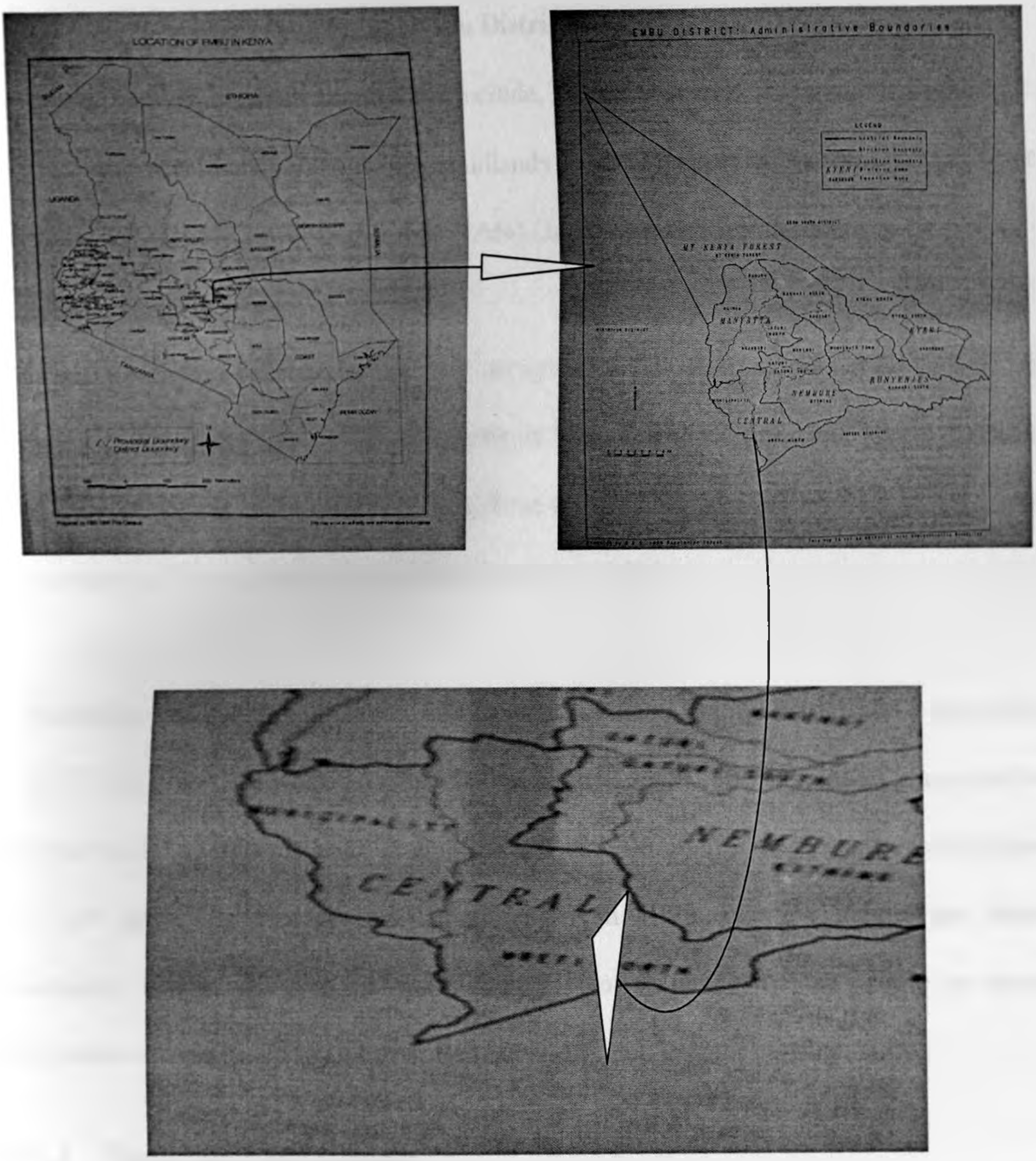

Fig. 3.1: Map of Kenya showing the location of Embu District and the study area.

3.1.1 Agro-ecological zones in Embu District

Agro-ecological zones in the district include, lower highlands (LH), lower highlands 1 (LH1), upper midlands (UM), Upper midlands 2 (UM2), upper midlands 3 (UM3), upper midlands 4 (UM4), lower midlands 4 (LM4) (Jaetzold and Schmidt, 2006).

About 30% of the district's total area is occupied by forests. The area (29%) occupied by mount (Mt.) Kenya forest falls under parts of Manyatta, Runyenjes and Kyeni divisions. The forest area is thinly inhabited with about 0.1% of the total population of the district (Ministry of Planning and National Development, 2001).

According to the 1999 Population and Housing Census, Embu District had a population of 278,196 people (District Statistics Office, Embu, 2000). The population was projected to rise to 293,144 people in 2002 and 325,490 in 2008 at an inter-censual growth rate of 1.7 per cent. The average population density in 1999 was 564 people per square kilometer. Central Division had the highest population density at 785 people per square kilometer and projected to rise to 869 in 2008 (District Statistics Office, 2000).

3.1.2 Topography and Climate

Topography: Being one of the districts that form part of Kenya's eastern highlands, the landscape of Embu District is characterized by typical highlands and midlands and other topographical features which include hills and valleys. The highlands are found in areas whose altitudes range from 1500 to 4500 m asl as at the foot of Mt. Kenya and cover parts of Manyatta, Kyeni and Runyenjes divisions. The midlands dominate most areas of

Nembure and Central Divisions and the altitudinal range is about 1200 to 1500 m above sea level (Jaetzold and Schmidt, 2006).

The hilly terrain has both the negative and positive effects on development of the district. The most profound negative effect has been on the road network which is faced with problems, including high construction and maintenance costs. Also the steep hills and valleys which characterize most parts of the district, coupled with intensive cultivation of crops renders those areas highly susceptible to soil erosion, making it necessary for the farmers to practice terracing which is costly (Ministry of Planning and National Development, 2001).

Climate: In Embu District, rainfall pattern is bimodal with two distinct rainy seasons. The long rains fall between March and June, while the short rains are experienced from October through to December. The amount of rain received depends on the altitude, but averages 1495 mm per year, but for an altitude above 1700 metres above sea level, however, the pattern changes to a trimodal pattern which has a peak in July/August (Jaetzold and Schmidt, 2006).

Temperatures in the district range from a minimum of 12.3°C in July to a maximum of 27.8°C in March (Meteorological Department, 2007).

3.1.3 Landuse and soils

Embu District has an agro-ecological profile that is typical of the windward side of Mt. Kenya. At the peak of Mt. Kenya, the soils are imperfectly drained; shallow to moderately deep, and dark reddish brown in colour, very friable, acid humic to peaty, loam to clay loam with rock outcrops and ice in the highest parts (Jaetzold and Schmidt, 2006).

The upper highlands of the district are so wet and steep that forestry is the best land use practice. The forest reserve zone is characterized by humic andosols which are well drained, very deep, dark reddish brown to dark brown, clay loam to clay with thick acid humic top soil. They then evolve into volcanic foot ridges which have soils developed on igneous rocks. These soils include ando-humic nitisols with humic andosols found in parts of Manyatta, Runyenjes, Nembure and Kyeni Divisions (Jaetzold and Schmidt, 2006).

In Central Division and lower parts of Nembure, Runyenjes and Kyeni divisions, the volcanic foot ridges consists of humic nitisols with an acid humic topsoil. The remaining lower areas of Runyenjes, Central and Kyeni divisions have well drained and very deep ferralsols. The hilly terrain of the district has had a profound effect on the soils, resulting in low to moderate soil fertility levels (Jaetzold and Schmidt, 2006). The land use is mainly on subsistence crop and livestock farming which is composed of the planting of food crops mainly maize and beans and the keeping of dairy cows under stall (zero grazing) system due to small land sizes (Njuguna, 2004). The cash crop grown in this area is mainly coffee with some macadamia nuts trees.

3.1.4 Research approach

Study location: The study was conducted on two roads in Embu District, Central Division in two locations i.e. Mbeti North Location and Municipality Location (Fig. 3.1). The two roads had different gradients and different widths. The slope of the cultivated land was also different. The road in Mbeti North was under construction and had more traffic.

Two gullies coded as A and B, were studied. Gully A was located on Mr. Simon Njiru's farm situated about 4 km from Embu town on the left hand side of the Embu – Kibugu road. This road is class E - No. 632 (Ministry of Public Works Embu, 2007). Minor roads or class E roads provide access to minor centres in an area (Sharawe, 1995). The farm is situated immediately after the junction to Embu ASK showground on the way to Kibugu shopping center. In the year 1999, an attempt to control this gully was made by a team of agricultural officers led by the headquarters team of the Soil and Water Conservation Branch of the Ministry of Agriculture. This team used stone check dams held by wires and poles. They had also put loose stone apron. These check dams were however washed away by the strong force of water. Prior to the Ministry's intervention, Mr. Njiru had attempted to control the gully using brushwood but it had equally failed. This was due to underestimation of peak runoff rate.

The second gully, gully B was located on Dennis Munyi's farm about 8 km from Embu town on Mutunduri-Manyatta road and about one kilometer from Mutunduri Market junction. This road is class D - No. 467 which is under construction (Ministry of Public Works, 2007). Secondary roads or class D roads are roads which link urban centres to each other, to larger centres or to higher class roads (Sharawe, 1995).

Gully A and B were in an area having bimodal rainfall patterns distributed throughout the year. Both areas had an undulating topography with slopes ranging from 10 to 40%. Drainage is towards Kapingazi River or its tributaries (Ministry of Planning and National Development, 2001).

The soil near the gully A and B was generally well drained and deep. The entrenchment of the area by gullies is also explained by the depth of the soil profile which was more than 3 m.

3.2 Determination of volume of soil eroded from the gullies

3.2.1 Measurement of gully geometry

The gully was approximately wedge shaped and the formula (eqn 3.2) by Gillespie (1981) was used in estimating the volume of the gully.

The depth of gullies was measured with a tape measure, a quickset and a graduated staff. Reduced levels were established using the quickset every two metres after establishing a temporary bench mark. The graduated staff was placed at the top of the gully to begin with and then at floor of the gully. Back sights, intermediate sights and fore sights readings were established and recorded. The differences in foresight, intermediate sights and back sights established the reduced levels at every two metres of the gully floor. The difference in reduced level gave the depth at every two meters (Thomas, 1997).

The widths of the surface and the floor of the gullies were established by gully survey method. A quickset level was used to establish the contours of the gullies. The contours were then mapped and a cross sectional profile drawn.

The length of the whole gully was determined using a measuring tape. One end of the tape measure was held by one person at the immediate end of the headscarp and another person held the other end of the tape and stretched it to the tail end of the gully and the measurement recorded (Fig. 3.2). Arrows represent the direction of runoff flow.

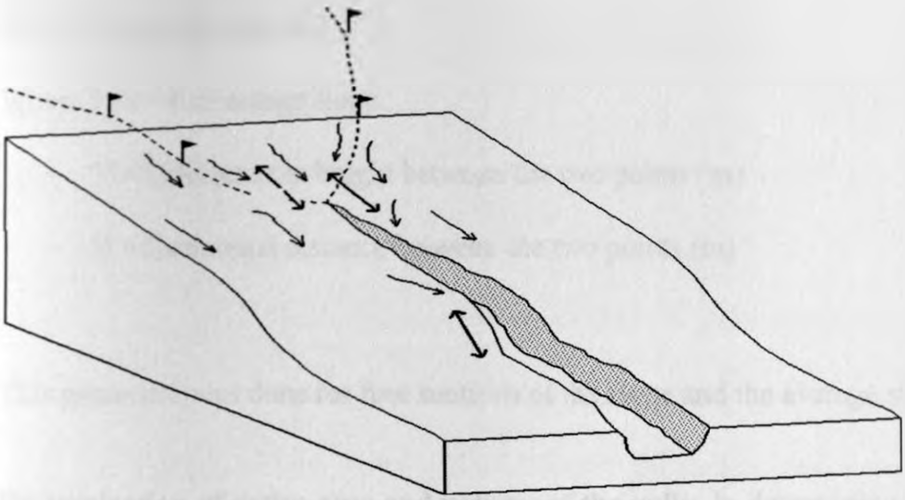

Fig. 3.2: Measuring gully characteristics (Nyssen *et al.*, 2003).

The gradient of the soil surface at the gully head is measured in different ways by different authors. Montgomery and Dietrich (1988) worked with the steepest slope gradient of the soil surface along the gully, Vandaele *et al.*, (1996) used the slope gradient of the soil surface In this study, I chose to measure the slope gradient of the soil surface over a distance of 10 m, parallel to the gully, of which 5 m were upslope of the gully head and 5 m downslope (Rutherfurd *et al.*, 1997). The gradient of the gullies was established by using a quickset, a measuring tape and a graduated staff (Nyssen *et al.*, 2002). To find the percentage slope between two points say B and C, a quickset was placed at a convenient point A upslope of the gully and readings taken on staff at B and again at C. The difference in readings gave the difference in height. The distance between B and C was measured using a measuring tape by securing one end of the tape on point B using a peg and stretching the tape by walking down the gully to point C (Thomas, 1997). The measurement was then recorded. The slope was calculated using the formula:

% S = V/H x 100 (eqn 3.1)

Where % S = Percentage slope

V = Difference in height between the two points (m)

H = Horizontal distance between the two points (m)

This procedure was done for four sections of the slope and the average slope determined.

Determination of active area and volume of the gully. In determining the active area of the gully the top widths and lengths already measured were used. This was drawn to scale on a graph paper and the area estimated by counting the squares and using the scale.

In determining the volume of the gully/soil removed from the gullies, each gully was divided into sections of regular shape (Fig. 3.3). The volume of the soil from a section was calculated using the universal prismodial formula (Equation 3.2).

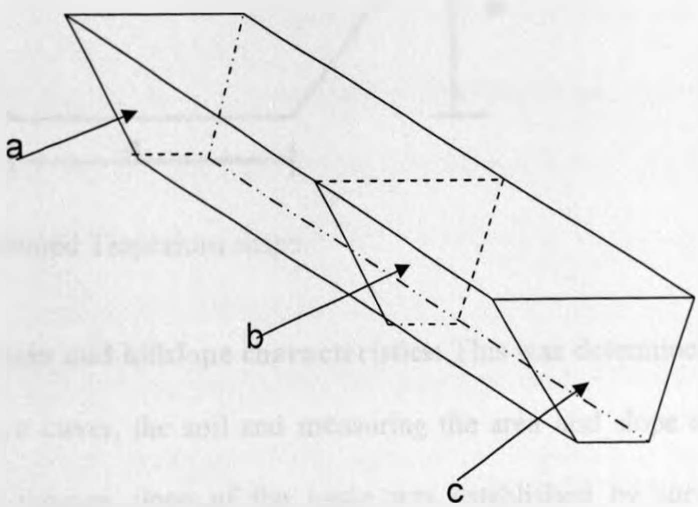

Fig. 3.3: Assumed gully wedge shape (Gillespie, 1981)

$$V = \frac{L\,(a + 4b + c)}{6} \quad \text{(eqn 3.2)}$$

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 at half way between a and c (m^2)

c = Surface area of vertical plane at large end of gully cross-section (m^2)

The cross sectional area of plane a, b, and c was determined by assuming the separate sections had a trapezoidal shape (Fig. 3.4) and using the formula used for determining area of a regular trapezium i.e.

$$\text{Area} = y\,(x+ z)/2 \quad \text{(eqn 3.3)}$$

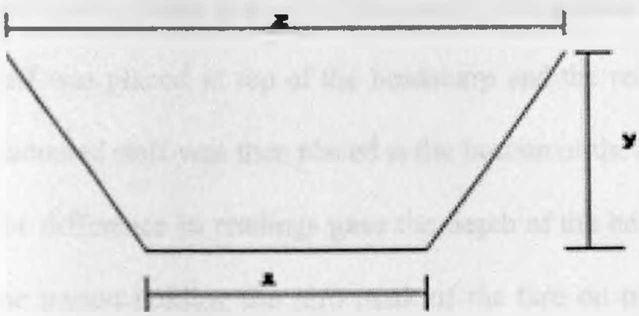

Fig. 3.4: Assumed Trapezium shape

Drainage basin and hillslope characteristics: This was determined from observation on the vegetative cover, the soil and measuring the area and slope of the basin (Thomas, 1997). The average slope of the basin was established by surveying the basin and establishing contours. The average slope was then determined after measuring horizontal distances in four different sections and contour differences and then using equation 3.1. The size of the catchment area was estimated by using topographic maps and liaising with residents since they knew own farm sizes and size of their neighbours' land. In this way they were therefore able to assist in giving reasonable figures on catchment size (Eriksson and Kidanu, 2009). They can also contribute own perception of level of runoff from an area (high medium or low).

3.2.2 Gully headscarp characteristics

Forms of gully heads in the study area were at outlet of pipe culvert (Nyssen *et al.*, 2002). The morphology of the headscarp that composed of the shape, size (depth and width) and slope were determined. The size was determined by measuring the depth using the graduated staff and a quickset and width of the headscarp using a measuring tape. A convenient bench mark was established and a quickset fixed in that point. The graduated staff was placed at top of the headscarp and the readings by the quickset recorded. The graduated staff was then placed at the bottom of the head scarp and the readings recorded. The difference in readings gave the depth of the headscarp. The width was measured by one person holding the zero mark of the tape on one side of the headscarp and another person stretching the tape measure along the width of the headscarp. Erosion pins (round iron 0.5'' diameter rods) were installed upstream of the headscarp to monitor the advance of the headscarp (Thorne, 1981). The measurement was done using a tape measure and stretching it from the top of the pin to the point at the soil surface. The scouring/deposition were monitored for two seasons (long and short rains of 2006).

3.3 Determination of the Effect of Road Design Techniques and Land use on Gully Formation

Width and design of feeder roads, mitre and side drains: The average width of the feeder road was determined by the use of a tape measure. Measurements were taken in different points of the road and recorded and the average width determined by summing up all the widths and dividing by the number of widths measured.

The widths of the mitre drains and side drains were also measured by one person holding the tape at zero mark and another person stretching the other end of the measuring tape along the width of the mitre drain and side drain. The measurements were done at different points and the average widths determined. Number and types of drainage features such as side drains, mitre drains and culverts were established by observation, visual inspection and recorded.

Culverts diameters and spacing and distances between mitre drains: Road design techniques used in the two roads under study i.e. the culverts diameter, culvert spacing, width of the road, design of side and mitre drains and disposal of road runoff were measured and recorded. This was determined by measuring the distance from one culvert to the other and from one mitre drain to the other using a measuring tape. The diameter of the culverts was also determined by measuring it with a tape measure. The recommended design of the mitre drains, side drains, culvert diameter and spacing and road width was also established from the literature. How regularly the road was maintained was established from ministry of roads and the traffic density was estimated by counting the vehicles passing over one hour and recorded.

The depth of the side drains and mitre drains were established by using a measuring tape. Several measurements were done and the average determined. The conditions; maintenance, state of the culverts, side drains and mitre drains, were determined by comparing the measurements with the recommendations. The dimensions established were compared against the recommended dimensions as given by the Ministry of Public Works, (1992), and FAO, (2006).

Gradients of the mitre drains and roads: The gradients of the two roads and mitre drains were measured using a quickset level and a graduated staff in different points and the average calculated. The reduced levels were read from a temporary bench mark and the backsight, intermediate sights and foresights read and recorded. The difference in height between two points was determined from the reduced levels and horizontal distance between the two points. The horizontal distance was measured using a tape measure. The gradient was then calculated from the difference in height and the horizontal distance.

Rainfall measurement: Daily rainfall measurement was done using a rain gauge. The rain gauge was at the KARI-Embu and Embu ASK showground sub weather stations. The rainfall measurement was used to determine runoff volumes and runoff rates.

Rainfall intensity was related to amount of scouring/deposition of the gully and advance of the gully head.

The runoff rate was estimated using the Rational formula: (Thomas, 1997)

$q = CiA/360$ (eqn 3.4)

Where

q = runoff rate (m^3/s)

C = runoff coefficient, dimensionless (between 0 and 1)

i = rainfall intensity (mm/h)

A = area of catchment (ha)

Land use and soil conservation techniques: This was determined by observation/visual inspection and interviewing fifteen (15) individual farmers with the aid of a semi-structured questionnaires (Annex 1.). The Ministry of Agriculture officials in the Central Division of Embu District were also consulted on agricultural aspects such as; the farming systems in use, methods/tools used for land preparation, when the land is prepared for planting and the techniques used in controlling runoff from the road and soil erosion.

The crops grown and average yields per hectare were also derived from the questionnaire surveys, informal interviews and observation (Watson *et al.*, 1998). Information on classification of the roads under study was obtained from the district roads officer. The history of the gullies such as when the gully started, causes of gully, gully erosion and general soil erosion problems in the area was obtained from 15 randomly selected farmers within the vicinity of the gully and the extension officers working in the area through administration of semi-structured interviews. The farmers had lived in that area for more than ten years, and further questionnaires were also administered to the farmers to determine; the community's perception on the gullies, the socio economic factors contributing to gully erosion and the impact of the gully on the environment and livelihood. Information contained in the questionnaire included such aspects like erosion, road runoff problems, gully development, gully rehabilitation, technical advice received on gully rehabilitation/control and farm yields (Annex 1).

3.4 Determination of vegetative cover, surface stoniness and rockiness of the gully catchment

An area of 10 m by 10 m was studied and the species within noted through visual analysis and recorded. Surface stoniness was also assessed for the catchments by collecting samples from three areas within the catchment and percentage of stones assessed by sieving and separating the soil from the rocks/stones. The volume of stones/soil was then measured to get percentage stoniness.

3.5 Strategies and techniques for mitigating against gully erosion.

A Participatory methodology (e.g. van Veldhuizen *et al.*, 1997, Kibwana, 2000) involving all the stakeholders was used in finding out issues to do with the likely causes of the gullies, strategies and techniques to mitigate against gully erosion that could be incorporated into road design and landuse described. These issues were discussed and agreed upon during group discussions in a one day workshop organised in the field. The process was made as participatory as possible to elicit community ownership of the process and activities (Eriksson and Kidanu, 2009). The stakeholders involved included the farmers, local administration, agricultural extension workers and an irrigation officer.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Study Gully A

4.1.1 Rainfall analysis, land use, causes of gully and soil conservation techniques

Rainfall analysis: The rainfall was highest during the short rains with the month of November 2006 recording the highest rainfall of 438 mm (Fig. 4.1). The highest rainfall (105 mm) for the long rains was recorded in May 2006 (Meteorological Department, 2006). In both cases the road runoff culminated into extensive gully erosion.

In 2007, the highest rainfall (300.3 mm) was recorded October during the short rains while the highest amount (250.5 mm) was recorded during long rains in April 2007 (Fig. 4.1). On the average the year 2006 had more rainfall than 2007 (Meteorological Department, 2007).

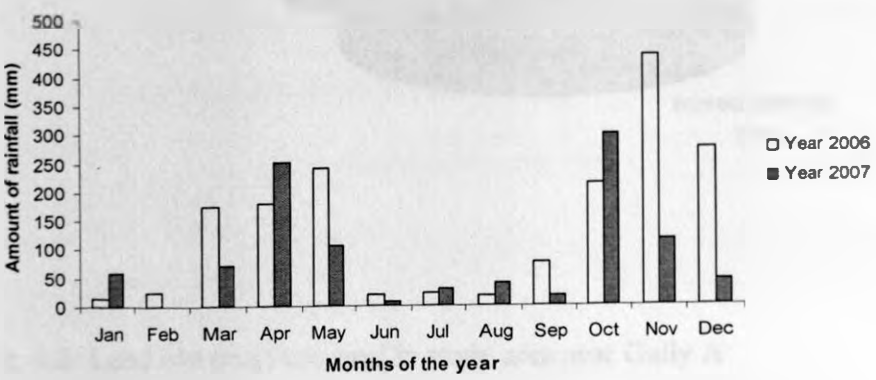

Fig.4.1: Annual rainfall for Gully A in the year 2006 and 2007

Land use, causes of gully and soil conservation techniques: The farmers in this area were small scale subsistence farmers. The average acreage was 1 ha. Most of the farmers practiced mixed farming (Fig. 4.2) i.e. farming crops and rearing of livestock- mostly the dairy cows (over 80%). About fifteen percent were farming crops alone and about five percent were on animal husbandry. The crops grown were mainly maize, beans and bananas. Coffee farming was on the decline due to low producer prices. This agreed with the findings of Kaboro, (2002) which stated that poverty levels were on the rise due to low producer price for coffee. The farmers used hand tools in land preparation and in weeding. There was absolutely no mechanization due to the terrain that was rather steep in most of the places. Njuguna, (2004) indicated that not a single tractor was available for land preparation due to the terrain.

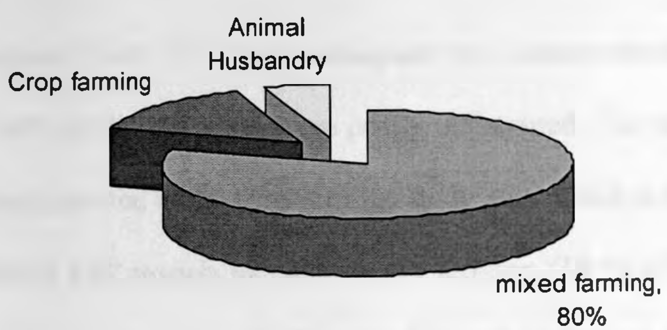

Fig. 4.2: Land use practices used in study area near Gully A

The land was prepared twice in a year for planting since this area had two rainfall seasons. The land is intensively cultivated leaving no fallow periods. In the study area the farms appeared to have low nutrient levels. Most of the coffee on the farm was neglected. Fifty percent of the farmers said it was due to increased poverty brought about by low producer prices of coffee which led to farmers neglecting their farms. This was in agreement with findings of Kaboro, (2002) that stated that there was an increase in poverty in the area brought about by low coffee prices. The average yield of maize, beans and coffee was 1.8, 0.5 and 5 tonnes per hectare respectively. This was rather low compared to the optimum production for that area which was 4, 1.1 and 10 tonnes per hectare respectively as documented in Njuguna, (2004). The farmers attributed this to declining soil fertility and the high cost of farm inputs which agreed with the findings of Kaboro, (2002).

Most of the farmers (over 70%) had inadequate soil conservation structures on their farms and over 90% of the structures were poorly maintained. The farmers use these soil conservation structures due to the terrain of the study area which is steep. The structures used for controlling soil erosion included bench terraces (10 % of the farmers) in the steep areas and fanya juu terraces (70 % of the farmers) in the less steep areas (Fig.4.3). Twenty percent of the farmers practiced other forms of conservation such as agroforestry, trashlines and grass strips. The “fanya juu” terraces were the most popular soil conservation structures. In a study, Thomas (1997) and Wenner (1981) stated that the success of the “fanya juu” terraces among smallholder farmers in the region has largely been due to its simplicity and easy replicability across a wide range of agro-climatic zones and slopes. Farmers also said that the farms with soil conservation structures had more yields which agreed with studies by Ngigi, (2003) which showed that there was a substantial increase in yield on land with "fanya juu" terraces compared to non-terraced land. Increased gully erosion from the road resulted in loss of soil and yield and a decrease of the cropped area. This was in agreement with the study by Nyssen *et al.*, (2002) that stated that increased loss of soil results in loss of crop yield and obstruction of tillage operations.

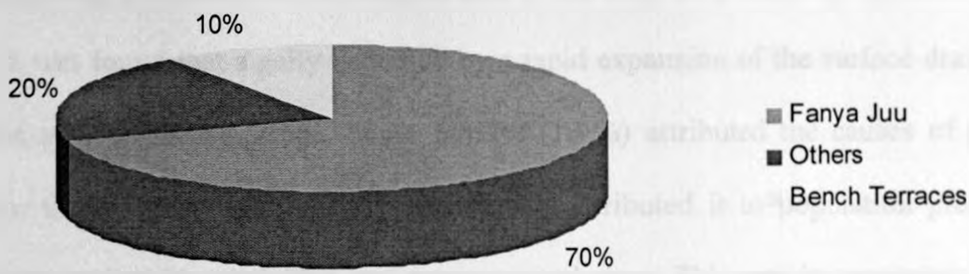

Fig. 4.3: Soil conservation methods that were being used by farmers near Gully A

Farmers invested little or nothing towards maintenance of the soil conservation structures. Farmers attributed this to increased poverty levels brought about by low producer prices of coffee and macadamia nuts. Forty percent of the farmers said social economics factors such as poor prices of farm produce contributed to poor management of farms and consequently increased erosion and gully development. Factors such as the low coffee prices led to reduced disposable income and the farmers could not afford to pay labour for soil conservation activities. These factors also led to increased immigration of the young people from the rural areas to urban centres thus affecting labour availability.

Causes of gully erosion in Gully A: Eighty percent of the farmers were of the agreement that concentrated road drainage into the farm coupled with poorly protected natural waterway caused the initiation of gullying. From the interviews, 60 % of the farmers said that most gullies started immediately the culverts were placed. In this case the water was directed through a culvert into the cropped land (Plate 4.1). In a study by Nyssen *et al.*, (2002), it was found that a gully is caused by a rapid expansion of the surface drainage system in an unstable landscape. Some farmers (10 %) attributed the causes of gully formation to dwindling land sizes. Thirty percent attributed it to population pressure causing the land to be subdivided into uneconomical sizes. This was in agreement with the findings of Kaboro, (2002) that stated that land sizes were becoming smaller and smaller due to population pressure. This has led to cultivation of land above 55% slope. Farmers also cultivate along the road reserves and some encroach into the road.

Plate 4.1: Culvert draining road runoff into Gully A

4.1.2 The effect of road design on the volume of soil removed from Gully A

Gully geometry: The depth at the gully head was 2.5 m then it reduced slightly towards the middle (2.2 m) and progressively became shallower towards the tail (1.4 m). This implied that the gully was medium sized as described by Thomas, (1997). The depth of the soil profile which is estimated at more than 4 m (Jaetzold and Schmidt, 2006) would partly explain depth characteristics of the gully. Gully depth is often limited by soil depth to the underlying rock which means that gullies are normally less than 2 metres deep. However, on deep soils such as alluvial, colluvial and other soils, gullies may reach depths of 10 to 15 metres (Natural Resources and Water, 2006). The runoff from the road directed to the land through culverts coupled with the deep soil profile, led to gully development.

The gully was wide at the head (3.1 m), and enlarged in the middle section (3.5 m) due to undercutting and collapse of the side wall (Plate 4.3) and narrow (1.7 m) towards the outlet. The width ranged from 1.7 to 3.5 m with an average of 2 m. The horizontal length of the gully from the headscarp to the tail was 30 m.

The bedslope of the gully ranged from 12 to 26 % with the highest gradient being recorded in the middle. The gully floor was deeper in the middle of the gully and this would explain the higher gradient registered since the runoff was able to scour the soil deeper. This implied active gully erosion. In controlling gully erosion, the aim can vary from full reclamation for agricultural production to stabilizing the gully to prevent further damage (Eriksson and Kidanu, 2009). The aim in this study was to stabilize the gully and also use it for production purposes.

Area of gully catchment and amount of soil removed from the gully: The entire catchment for this gully was 10 ha. The average gradient of the catchment was 20%. The average gully cross-sectional area was 4.1 m^2 with the highest being 6.4 m^2 (middle of the gully since it was the deepest section) and the lowest being 0.6 m^2 (at the tail since it was the shallowest). The active surface area of the gully was 0.05 ha. The total gully volume was 280 m^3, i.e. the volume of soil eroded from an area of 0.05 ha. (5,600 tons/ha). The soil removed was thus equivalent to the volume of the gully. In a study by Jungerius *et al.*, (2002) it was found that there is a strong correlation between roadside gullies and decrease of soil cover. This was the case in this study since an estimated 280 m^3 of soil had been removed thus reducing the soil cover by a similar margin.

Drainage basin and hillslope characteristics: The landuse and land cover of the basin was composed of crops such as coffee, maize, beans, macadamia nuts and bananas. The soils were clay loam (Jaetzold and Schmidt, 2006). The slope length was 30 m. The topography was rather steep with the average slope of the land being 20%. This steep gradient was contributing to the high speed and therefore erosive runoff.

Gully headscarp, floor and sidewall characteristics: The gully cross section was V shaped with some sections having beds that had scoured into the underlying hard soil layer. The depth of the headscarp was 3.6 m and the width was 4.2 m. The average slope was 40%. The soil from the headscarp was washed away in the two seasons thereby enlarging the headscarp.

Most of the gully floor had little or no vegetation except the section in which the farmer had planted some bananas. This was due to heavy runoff experienced during the study period that swept the floor clean of top soil. These findings agreed with what Thomas, (1997) had documented. The subsoil that was left behind was of low fertility. Under such conditions, manure is required to establish a banana stool or any other type of vegetation.

The gully had also hanging sidewalls with negative side slopes which indicated that collapse could occur on wetting or on slight disturbance. This implied that the gully had not attained a stable slope and shape in most of its length (Thomas, 1997).

4.1.3 Effect of road design and land use on gully formation

Width and design of feeder roads and drainage aspects: The width of the feeder road ranged from 6.5 to 7.6 m with an average of 6.0 m. The recommended width is 9 m. The road width varied due to encroachment in some sections caused by population pressure and land scarcity. This was in agreement with the findings of Njuguna, (2004) that stated that population pressure was causing land scarcity for subsistence farmers in Njukiri area of Embu District. This road encroachment was also major cause of mitre drain destruction and blockage.

The major drainage features in this road were culverts, side drains and mitre drains. Two culverts and three mitre drains were in this section. The average width of the mitre drains was 0.8 m and the average width of the side drains was 1.0 m. These were inadequate to convey water safely according to Ministry of Public Works (1992) recommendations. The other issue here was that they were in bad shape and condition. The mitre drains were blocked by soil in some places and some culverts were blocked reducing their ability to carry runoff. In a study by FAO, (2006) it was concluded that when side drains are dug, care should be taken to make them shallow but wide. In this study, the side drains were shallow and also wide. Water in thin layers flows slowly without causing much erosion and the grass that will gradually grow in the drain will further slow the flow. Gradients not steeper than 1 to 250 are unlikely to cause erosion in ordinary soils (FAO, 2006). In this study, the gradient was less than this since it was 0.3%.

The scour checks were missing in this road. The check dams reduce the velocity of water before it enters the culverts. The interval at which scour checks are constructed depends on the gradient of the road (Ministry of Public Works, 1992). The road had an average gradient of 9% and so it required some scour checks. In this case, if the scour checks were to be constructed, the interval should be 7.5 m as recommended by Ministry of Public Works, (1992).

The infrequent grading of this earth road caused disruption of runoff and clogging of the mitre drains leading to concentration of runoff in the lowest point and therefore causing gully development. Due to relaxed or non-existent road maintenance, the roads can be affected by erosion and may even become impassible during heavy rains (Thomas *et al.*, 2003). Inadequate drainage systems for roads (small number of culverts, insufficient capacity of road ditches, etc.) are a major cause of gullying (Pathak *et al.*, 2005). The number of culverts along this section should have been four according to recommendations of Ministry of Public Works, (1992). Widening operations along roadsides do not often follow road construction but, where widening is practiced, the operation usually causes landslide erosion and then gullying during the first rainy season (Johnson, 2000).

Culverts diameters and spacing and distances between mitre drains: Culverts in this road were made of concrete pipes. The road culvert at gully A had a diameter of 600 mm which was adequate to cater for expected runoff, since diameter fell within the recommended range for the rural areas. Road culverts are constructed having diameters of 300, 450, 600, 900 and 1200 mm depending on expected runoff discharge (Ministry of Public Works, 1992). At a diameter of 600 mm the culverts were able to discharge all the expected runoff without clogging up with soil. Unfortunately this water was directed through unprotected waterway and into steep slopes of more than 10% and therefore contributed to the formation of the gully.

Inadequate road drainage systems due to small number of culverts and insufficient capacity of road ditches are some of the predisposing factors to gully formation (Pathak *et al.*, 2005). The fact that the natural waterway was in a cropped land further aggravated the situation.

The distance between one set of culverts to the next was 150 m. The distance of one mitre drain to the other averaged 30 m, indicating that they were adequately spaced for that slope. Depending on the gradient, mitre drains should be spaced 20 to 250 m apart, using the closer intervals where rainfall is heavy, the soil is prone to erosion, or the gradient is steep (FAO, 2006). This ensures that the quantity of water being discharged at each mitre drain is small, and does not cause erosion damage in the drainage system or on the adjacent land. Where it is impossible to place mitre drains frequently, attention should be paid in providing at least one drainage outlet for a side ditch (using a mitre drain or culvert) every 100 metres.

The maximum distance between the side drain outlets (by culvert or mitre drain) should normally be 200 metres (Ministry of Public Works, 1992), which was not the case for the studied roads. Mitre drains were on the average 30 metres apart and in some places were non existent altogether due to blockage. Culvert were far apart over 150 metres. Since it was hard to meet this requirement, erosion control measures, such as ditch lining, should have been considered (Ministry of Public Works, 1992). Maintenance of most mitre drains was wanting and this definitely reduced their capacity to manage road runoff. For instance the volume of runoff in February 2006 was approximately 5.76 m^3 just from the road catchment of which were far beyond the capacity of the mitre drains.

According to Jungerius *et al.*, (2002) the design of the road may meet the erosion control qualifications at the time of construction, but the amount of development along the road once established is clearly out of control and the consequences for road drainage cannot be foreseen. For example in the study area there was a lot of encroachment into the road reserves by farmers cultivating the riparian area.

Gradients of the Mitre drains and the Road: The average gradient of the mitre drains and the road was 1 and 9% respectively. The gradient of the mitre drain was within the acceptable range since according to FAO, (2006) mitre drains should have a gradient of

0.8% (1 in 125). Mitre drains are used along high level roads to prevent build-up of water in the side drains. The mitre drain should block off the water flow in the side drain with a bolster block at an angle of about 30 degrees and lead the water well away from the road with a wide, shallow channel (FAO, 2006). The water is discharged 30 to 40 m away from the road over as large area of land as possible to prevent erosion. This was not possible in the area under study due to land pressure. This agreed with Njuguna, (2004) findings which stated that population pressure had culminated to land fragmentation.

4.1.4 Landuse, surface stoniness and rockiness of the gully catchment

Since the gully was located within the cropland, most of the vegetation comprised of crops. The major crops grown were maize, beans, coffee and bananas. The soils in this area are clay loam (Jaetzold and Schmidt, 2006) with very few stones (> 0.01% soil cover) and none rocky (> 2% soil cover) according to classification given by Meester and Legger, (1988). This meant that the stones for road construction had to be ferried from other places meaning that road design had to take these factors into consideration. Most of the gully floor had little or no vegetation except for the sections in which the farmer had planted some bananas.

The gully floor had an average slope of twenty percent. 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 (Thomas, 1997).

4.1.5 Gully control techniques incorporated into road design and land use prescription.

Gully control: Gully A was controlled using checkdams of posts and hedgewood (Fig. 4.1). A lot of time and energy was used in building these checkdams. In a study by Nyssen *et al.*, (2002), it was concluded that if checkdams are built in the new gullies; it takes a lot of resources. In a study in Central Kenya highlands, Gachene *et al.*, (2004) stated that vegetation should be used wherever possible as this is a cheaper method of controlling gully than construction of gabions which are expensive and labour intensive. Bananas were planted to reduce the speed of the runoff since it was relatively small with an average width of two metres. Dabney *et al.*, (2004) in a study on erosion processes in gullies demonstrated that growth of small gullies can be controlled with carefully designed vegetative plantings. In this study area there was a lot of vegetation and brushwood was used for control. In a study in Nyeri District of Kenya, Mati, (2000) found that in areas where vegetation is easily accessible, brushwood check-dams can be used for gully control. 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. The checkdams constructed were made up of tree branches laid and tied in between two rows (Fig. 4.4) of posts firmly stuck in the ground as in Hudson, (1995).

Strong posts of about 10 cm diameter and dug in about 30 cm into the gully floor were used as suggested by Gitonga, 1993 in a study at Olkaria, Kenya. This was strong enough to withstand the most intensive rainstorm. 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, 2006). An apron was made to reduce erosion on the floor.

In the first season some soil was deposited at a depth of 20 mm. In the second season, the soil reached about 50 mm in thickness. The profile changed as depicted in Fig 4.5. At this rate the gully could totally be healed in about 15 - 20 years.

In this case the gully was controlled for productive use. The farmer established some banana stool in the gully and they are doing relatively well. But due to low infertility of the soil in the bottom of the gully, a lot of manure had to be applied to establish the banana plants (Thomas, 1997).

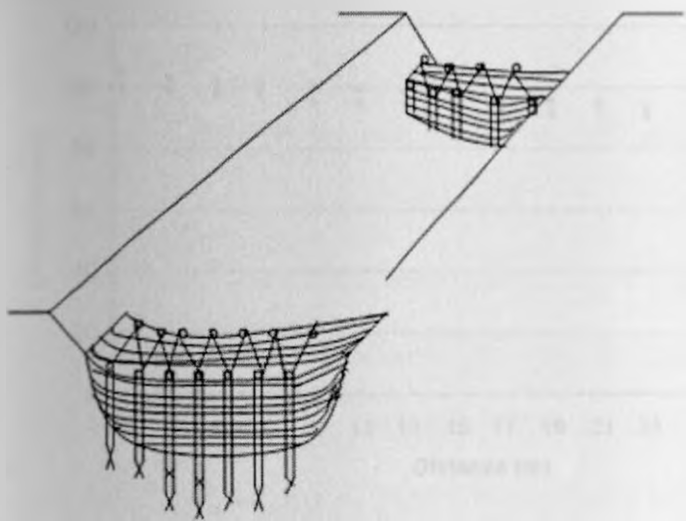

Fig. 4.4: Gully control method used in the study area- double posts, wire, and brushwood. Source Wenner (1984)

Long profile of Gully A: Fig 4.5 shows the profile of gully A before and after control. The ground gradient was steep in the beginning then progressively the gradient reduced towards the lower end. After gully control, the profile changed slightly due to soil deposition. The soil deposited ranged from a depth of 20 to 70 mm over the two rain seasons. In a study by Gitonga, 1993, soil was deposited up to 70 cm after gully control using brushwood checkdam which was relatively high as compared to the highest deposition in this study of 7 cm. This can be attributed to the fact that the Olkaria study area had soils that were mainly loamy sand and so were easily eroded. The soils in study area of Gully A were clay loam which is not easily eroded.

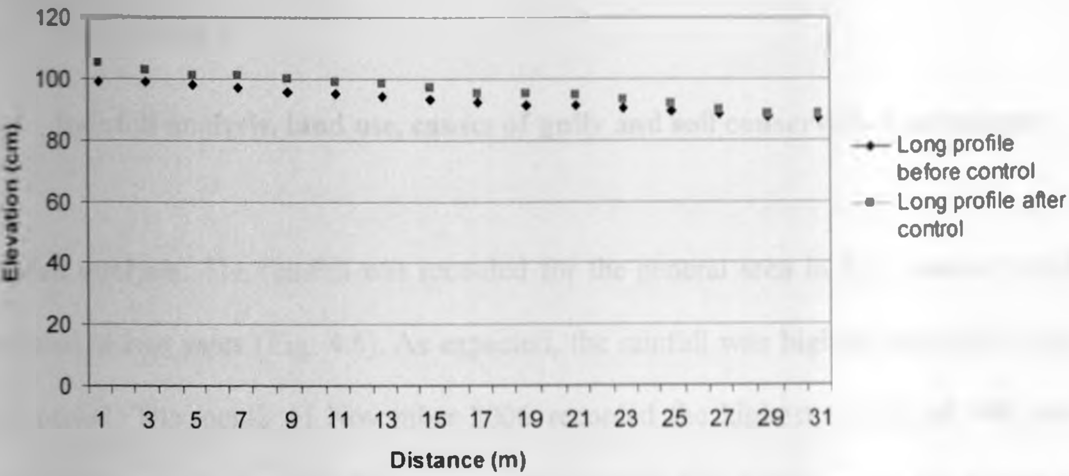

Fig. 4.5: Long Profile of Gully A before and after Gully Control

Plate 4.2: A badly maintained side and mitre drain that was draining into gully A

4.2 Study Gully B

4.2.1 Rainfall analysis, land use, causes of gully and soil conservation techniques

Rainfall analysis: The rainfall was recorded for the general area in four seasons which translated to two years (Fig. 4.6). As expected, the rainfall was highest during the short rains period. The month of November 2006 recorded the highest rainfall of 446 mm. During the long rains period, highest rainfall recorded was 269.8 mm in the month of May 2006 (Meteorological Department, 2006). High runoff rate experienced at that time.

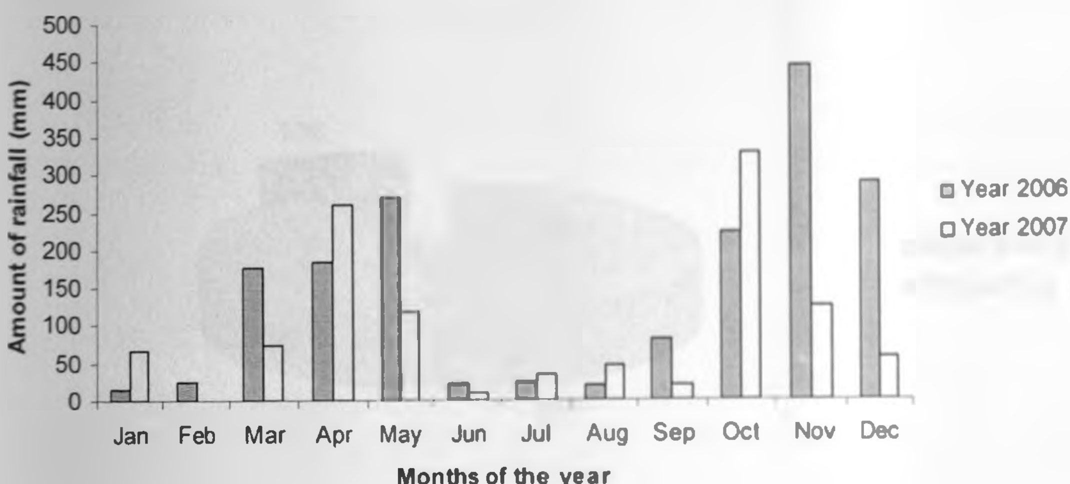

Fig. 4.6: Annual rainfall amount for Gully B in the year 2006 and 2007

In 2007 the highest rainfall amount of 329.3 mm was recorded in the month of October for the short rain period (Fig. 4.6). The long rains had the highest in April at 260.5 mm. On the average the year 2006 had more rainfall than 2007 (Meteorological Department, 2007).

Land use, soil conservation techniques and causes of Gully B: The farmers in this area were small scale subsistence farmers. Most of the farmers practiced mixed farming i.e. farming crops and rearing of livestock- mostly the dairy cows (over 90%). About ten percent were growing crops alone (Fig. 4.7). This was also in agreement with the findings of Njuguna, (2004). The crops grown were mainly maize, beans and bananas. Coffee farming is on the decline due to low producer prices (Kaboro, 2002). The farmers used hand tools in land preparation and in weeding. There was absolutely no mechanization due to the terrain that was rather steep in most of the places. This was also in agreement with the findings of Njuguna, (2004).

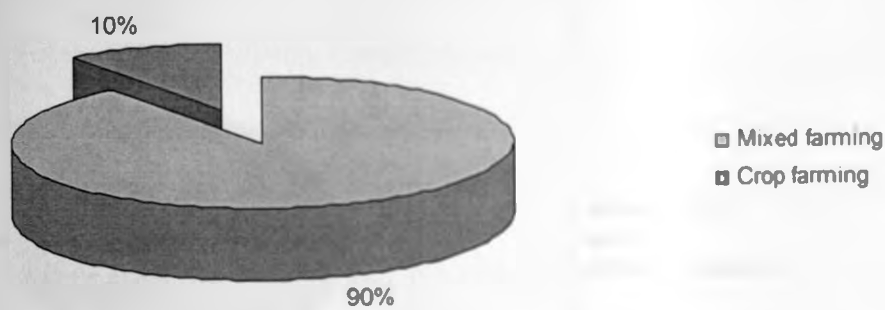

Fig. 4.7: Land use practices near study Gully B

The land is prepared twice in a year for planting since this area has two rainfall seasons. The average yield was 1.8 tons per hectare for maize against an optimum yield of 5.4 tons/ha, 5 tons/ha for coffee against optimum of 10 tons/ha and 0.5 tons/ha of beans against 1 ton/ha. This was rather low but was attributed to declining soil fertility and the high cost of farm inputs (Njuguna, 2004).

Most of the farmers (over 80%) had some form of soil conservation structures in their farms although most of the structures (over 70%) were poorly maintained. The structures used (Fig. 4.8) for controlling soil erosion included bench terraces (10% of farmers) in the steep areas and fanya juu terraces (60% of farmers) in the less steep areas. Thirty percent of the farmers used other soil conservation measures such as trashlines and agroforestry. Trashlines were also used after harvesting although farmers destroyed them during land preparation. Thirty percent used trashlines or had no soil conservation structures.

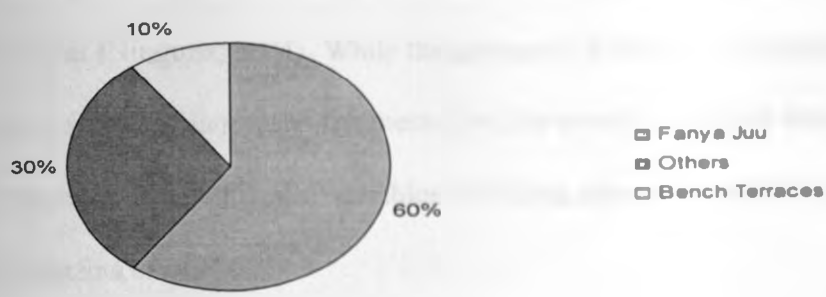

Fig. 4.8: Soil conservation measures used by farmers near Gully B

Road design techniques used in this study were culverts, side and mitre drains. Water concentrated by culverts can be directed on contour and, for example, spread in areas with a good vegetation cover (Nysen *et al.*, 2002). The disposal of road runoff is to a natural waterway whenever possible but in this case all the natural waterways were under cultivation due to land pressure. A plan for safe disposal of the drainage water must always be done with full involvement of the land owners for them to appreciate the need for discharge of water over their land and to assure them of the fact that efficient erosion control measures will be put in place to prevent erosion damages to their land (Eriksson and Kidanu., 2009).

Out of the 15 farmers interviewed, 20 % attributed the causes of gully formation in the cropped land to dwindling land sizes. 40% attributed the causes to population pressure and they mentioned that land is subdivided into uneconomical sizes (Kaboro, 2002). This has led to cultivation of land above 55% slope. Farmers also cultivate along the road reserves and some encroach into the roads. Land is also cultivated all the time leaving no time for it to recover (Njuguna, 2004). While the presence of roads and associated traffic flows is a primary source of landscape fragmentation, the actual ecological impact of this fragmentation depends on a number of variables including plant species and road design characteristics (Jaarsma *et al.*, 2002).

This information was also correlated with that given by the agricultural officers in that area and also by the employees of the Ministry of Works. An increase in vegetation cover by adjusting land use structure (e.g. intercropping) could greatly decrease the total sediment production caused by gully erosion, although gully erosion rates from the agricultural areas of the catchment can vary considerable in space and time (Poesen et al., 1996a).

Causes of gully erosion for Gully B: During the interview, farmers and other stakeholders said that gullies started immediately the culverts were placed. Just like in gully A, this gully was also caused by road runoff directed into the farmland through a road culvert. According to Jungerius *et al.*, (2002), water issuing from culverts is more concentrated and more turbulent and therefore more erosive than water in open drains.

Most of the farmers (80%) said the gullies were caused by the water from the culverts. Mrs. Wawira Munyi has settled in the area for the last fourteen years and when she moved in, she found the gully already in place. This road is under construction and there is a lot of disturbance in the watershed such as digging of murram by heavy machinery. Watershed disturbances usually increase runoff production and reduce erosion resistance of the soil surface triggering gullies. Common disturbances include road building (Wemple *et al.*, 1996; Croke and Mockler, 2001).

4.2.2 The effect of road design on the volume of soil removed from Gully B

Gully geometry: The depth increased from the gully head (0.7 m) to the middle (2.1 m) and became progressively shallower towards the outlet (0.4 m) The soil near the gully was well drained and deep. The depth of the soil profile which is estimated at more than 3 m (Jaetzold and Schmidt, 2006) would partly explain depth characteristics of the gully.

The runoff coupled with the deep soil profile was therefore capable of gullying since a lot of water was directed to the land through culverts (Nyssen *et al.*, 2002).

The gully was generally wide at the head (3.5 m), becoming increasingly wider in the middle section (5.5 m) due to under undercutting (Plate 4.3) and progressively narrower (1.9 m) towards the outlet. The average width was 4 m and the horizontal length of the gully was approximately 50 m from the headscarp to the tail. This implied an active gully that was still growing. While this stage constitutes only about 5 per cent of the entire gully lifetime, more than 90 per cent of gully length, 60 per cent of its area and 35 per cent of its volume are formed in this period (Sidorchuk, 2006). During this stage the main processes are gully bed incision and widening, gully side slumping, and gully head growth (Thomas, 1997).

The gradient of the gully ranged from 15 to 30% with the highest gradient being recorded in the middle (30%). The soil was deeper in the middle of the gully and this would probably explain the higher gradient registered since the runoff water was able to scour the soil harder. One of the factors controlling gully growth is slope steepness (Kukal *et al.*, 1991)

Volume of soil removed from the gullies: The active surface area of the gully was 0.08 ha. The average gully cross-sectional area was 5.2 m^2 with the highest being 6.4 m^2 in the middle and the lowest being 1.8 m^2 towards the bottom. The total gully volume was estimated to be 340 m^3, i.e. the volume of soil eroded from an area of 0.08 ha. (4,250 tons/ha).

Drainage basin and Hillslope characteristics: The vegetative cover for the basin was cultivated vegetation composed of crops such as coffee, maize, beans and bananas. The soils were clay loam (Jaetzold and Schmidt, 2006). The average slope of the land was averaging 25%. In a study, Poesen *et al.*, (1998), found that erosion of a given substrate begins with the critical combination of slope and catchment area. The gully cross section was V- shaped with some sections having beds that had scoured into the underlying hard soil layer (Thomas, 1997).

Gully headscarp, floor and sidewall characteristics:-The depth of the headscarp was 2.1 m and the width was 3.2 m. The average slope was 30%. The headscarp was extending as erosion continued. This implied an active gully. Most of the gully floor had little or no vegetation. The only vegetation was the one overhanging from the sides which was mainly the blacken fern. Due to the great force of runoff during the rains, most of the fertile top soil was probably washed away and so was the vegetation. It was a harsh condition in which to establish vegetation (Thomas, 1997). The gully had also hanging sidewalls with negative side slopes which indicated that collapse could occur on wetting or on slight disturbance (Plate 4.3). This implied that the gully had not attained a stable slope and shape in most of its length which were in agreement with the findings of Sidochuk, (2006).

Plate 4.3: An overhanging sidewall of gully B

The major processes of erosion were bed scouring, undercutting (Plate 4.3) 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 due to undercutting. Similar erosion processes had been identified at Olkaria in a study done by Gitonga, (1993).

4.2.3 Effect of road design and land use on gully B formation

Width and design of feeder roads and drainage aspects: The width of Mutunduri-Manyatta road ranged from 15 to 25 m with an average of 18.0 m. This road is under construction and has a relatively large traffic. At one time over twelve cars passed in a space of five minutes. The road has an average slope of 10%. This road was self draining. By design, roads are supposed to be self draining (Thomas *et al.*, 2003). Road-related erosion often is caused by a concentration of water on a road (Bassel, 2002).

Concentrated water discharge through culverts and drains can lead to soil erosion if drainage is not carefully planned and constructed (Ministry of Public Works, 1992). Infrequent maintenance of the earth road caused disruption of runoff and clogging of the mitre drains leading to concentration of runoff in the lowest point and therefore causing gully development. This was in agreement with the findings of Eriksson and Kidanu, (2009) that stated that infrequent maintenance of the roads led to clogging of mitre drains. Therefore road design, management, and restoration need to be more carefully tailored to address the full range of ecological processes and terrestrial and acquatic species that may be affected (Trombulak and Frissel, 1999).

The drainage features in this road were culverts, side drains and mitre drains. Four culverts and three mitre drains were in this section. The average width of the mitre drains was 0.8 m and the average width of the side drains was 1.0 m.

The scour checks were missing in this road. The side drain were badly maintained (Plate 4.4) with no scour checks. Scour checks reduce the velocity of water before it enters the culverts. In a study done in Nyeri District of Kenya, Mati, (2000) found that scour checks were necessary on very gentle slopes. The road had a gradient of about 10% and so it required some scour checks. The interval at which scour checks are constructed depends on the gradient of the road (Ministry of Public Works, 1992).

Poorly functioning road drainage is common on roads which are due for maintenance and improvement as these roads were either constructed with inadequate drainage system or the system is not functioning well any more (Eriksson and Kidanu, 2009). The infrequent grading of this earth road caused disruption of runoff and clogging of the mitre drains leading to concentration of runoff in the lowest point and therefore causing gully development. Due to relaxed or non-existent road maintenance, the roads can be affected by erosion and during the rains they may become impassible (Thomas *et al.*, 2003). There is also no clear policy direction on the responsibility of control of runoff from the road servitude to adjacent land. This uncertainty over the apportioning of responsibilities for erosion control measures has effectively restricted the consultations between public bodies (responsible for roads) and land owners. In fact, as landowners experience soil erosion damages caused by road drainage, they have become unwilling to allow water discharge onto their land. This desperate reaction then limits the possibilities of addressing the soil erosion problems in amicable and sustainable manner (Eriksson and Kidanu, 2009).

If road cuts and fill slopes are not revegetated during or immediately following road construction, gullies may form on both sides of the road. In a study by Jungerius *et al.*, (2002), it was concluded that there is a strong correlation between roadside gullies and decrease of soil cover. Inadequate drainage systems for roads (small number of culverts, insufficient capacity of road ditches, etc.) are a major cause of gullying (Pathak *et al.*, 2005). Widening operations along roadsides do not often follow road construction but, where widening is practiced, the operation usually causes landslide erosion and then gullying during the first rainy season. Currently, the Ministry of Roads (MoR) and Road Authorities are responsible for soil erosion control within the road reserves but damages due to runoff from the roads to areas beyond the road reserve are most of the time not addressed by any of them and left to the land owners' predicament. (Eriksson and Kidanu, 2009).

Culverts diameters, spacing and distances between mitre drain: The road culvert contributing water to Gully B was found to have a diameter 900 mm (Plate A3) which fell within the recommended diameter range of 600 – 1200 mm as recommended by Ministry of Public Works, (1992). At a diameter of 900 mm the culverts were able to discharge all the water without clogging up with silt. It is unfortunate that they were draining into farmland with steep slopes of more than 10% and therefore causing gully formation.

A study by Norconsult international, (2004) found that along the Thika-Kamae-Magumu road, a few drains were water logged, due to the inadequate gradient in the construction of the drains and on the Machakos Turnoff-Ulu-Sultan Hamud road, the culverts constructed were inadequate to cater for the flow of water. For economic reasons, several small streams are generally collected and pass through the road in one culvert position. The combined small streams now discharging from the culvert may cause severe soil erosion and headward retreat (Jungerius *et al.*, 2002).

The distance between one set of culverts to the next was 150 m. The distance between culverts should be limited to 100 m, as stated by Croke and Hairsine (2001). The distance of one mitre drain to the other averaged 30 m. As a general rule, mitre drains should be provided every 20 metres, where possible (Ministry of Public Works, 1992). This ensures that the quantity of water being discharged at each mitre drain is small, and does not cause erosion damage in the drainage system or on the adjoining land.

According to FAO, (2006), mitre drains should be spaced 20 to 250 m apart depending on the gradient, using the closer intervals where rainfall is heavy, the soil is prone to erosion, or the gradient is steep. The maximum distance between the side drain outlets (by culvert or mitre drain) should normally be 200 metres (Ministry of Public Works, 1992). In most of the cases it was not. Mitre drains were on the average 30 metres apart and in some places mitre drains were non-existent. Culvert were far apart over 150 metres. Since it was hard to meet this requirement, erosion control measures, such as ditch lining, should have been considered (Ministry of Public Works, 1992). Channel excavation was needed to provide artificial waterways for the discharge of water drained from the road (Mati, 2000). Maintenance of most mitre drains was wanting and this definitely reduced their capacity to carry road runoff. For instance the volume of runoff in February 2006 was approximately 6.86 m^3 just from the road catchment. The mitre drain should be designed to carry a higher volume than this (Eriksson and Kidanu, 2009).

Gradients of the Mitre drains and the Roads: Mitre drains and culvert were far apart and some places mitre drains were nonexistent due to the gradient of the road and also the layout of the surrounding land. The width of mitre drains wherever they were situated was less than the recommended due to clogging caused by irregular or non maintenance.

The width was less than 0.5 m in most cases. The slope of the drains was well within the recommended gradient. It ranged from 1 - 4%. The minimum recommended width of the mitre drains is 0.60 m and they should have a gradient of 2 - 5%. Where a side drain has very steep gradient, additional measures in the form of checks or gabions may be necessary. These checks will silt and form steps, thus decreasing the gradient and slowing the flow. Gradients should be carefully checked to ensure that they drain within these limits (Ministry of Public Works, 1992). The runoff from the road surface is supposed to be collected into side drains which discharge through mitre drains to grassland or through culverts to a stable waterway (Thomas *et al.*, 2003). The mitre drains in this case were discharging into the cropped land.

Plate 4.4: Badly maintained side drain along Mutunduri road next to Gully B discharging into cropped land.

4.2.4 Landuse, surface stoniness and rockiness of the gully catchment

Since the gully was located within the cropland, most of the vegetation comprised of cultivated crops. The major crops grown were maize, beans and bananas. Some farms had some coffee though neglected. The soils were clay loam (Jaetzold and Schmidt, 2006) with very few stones (> 0.01% soil cover) and none rocky (> 2% soil cover) according to classification given by Meester and Legger (1988). High landscape degradation is caused by low rock fragment content (on average 2 per cent) of the soils which decreases the resistance to concentrated flow erosion (Poesen *et al.*, 1999) Most of the gully floor had little or no vegetation due to reduced fertility brought about by the washing away of the topsoil .

4.2.5 Gully control techniques incorporated into road design and land use prescription.

Control of gully B: Gully B was classified as a large gully using the classification given by Thomas, (1997). It was controlled using stone gabions (Plate 4.5) following wide consultation and recommendations of the stakeholders. From the discussions with the local informants they stated that gullies have become worse and they were not given attention. This agreed with the findings by Adams and Watson (2002) that stated that gullies had become worse in recent years and that they were not given necessary attention. In a study in Machakos District of Kenya, Mutiso, (1991), Wamalwa (1991), and Mutiso, (1996) argued that within Kenya, sustainable development strategies must draw on the indigenous knowledge about the environment. In a study on soil erosion and conservation activities on land affected by road drainage: a case study of Nyeri District in Kenya, Mati, (2000) found that gabions were needed mainly for rehabilitation of large gullies.

In a study in Australia, Kennedy *et al.*, (2001) found that rock-filled gabions are significantly more flexible than wooden or concrete structures but are frequently undercut. In this case we tried to key in the gabions as much as possible to avoid undercutting. The natural vegetation to that area namely shrubs such as the bracken fern started growing on the sides and some on the bottom of the gully. Probably due to infertility of the soil on the bottom of the gully the vegetation was scanty which agreed with Thomas, (1997) who stated that infertile soils at the gully bottom was the main cause of scanty vegetation.

In this study it was impossible to divert the runoff as this was the lowest point on the slope of the road. Options for controlling gully head erosion include diversion of runoff (Kennedy *et al.*, 2001). Unfortunately, such outlets are difficult to find and often the instability may be transferred from one area to another (Natural Resources and Water, 2006). In Ethiopia, gully control has been carried out mainly using stone check dams, with U-shaped and parabolic spillways. These check dams have been quite effective in smaller and average size gullies, but bigger ones needed more sophisticated control structures (Wolde-Aregay, 1996). Controlling gully erosion can be difficult and costly (Mati, 2005). It may be justified on better quality soils where there is a reasonable chance of success or where the road or building is threatened by an advancing gully (Hudson, 1995). In this study, a farm and a road were threatened. After the control the long profile changed as shown in Fig 4.9.

Plate 4.5: Gabions put in Gully B to control erosion

Long profile of Gully B: This was found as depicted in Fig 4.9. The ground gradient was steep in the beginning then progressively the gradient reduced towards the lower end. After gully control, the profile changed slightly due to soil deposition. The soil deposited ranged from a depth of 40 to 70 mm over two rain seasons. At this rate, (under similar conditions) it might take approximately twenty (20) years for the gully to heal completely. The soil deposited was mainly silty clay from the road runoff. In a study by Gitonga, (1993) in Olkaria, Kenya, it was found that the average deposition in the upstream of loose stone checkdam was 57 cm in one rainfall season which was relatively high as compared to the average deposition in this study of 6 cm. This can be attributed to the fact that the Olkaria study area had soils in which the subsoil consists of non-cohesive material (Thomas, 1997). Calcareous soils, with high content of silt sized calcium carbonate, behave as silty soils, i.e. filling and sealing the soil pores, decreasing the infiltration capacity, increasing surface runoff and consequently increasing soil erodibility. The soils in study area of Gully B were clay loam which is not easily eroded (Thomas, 1997).

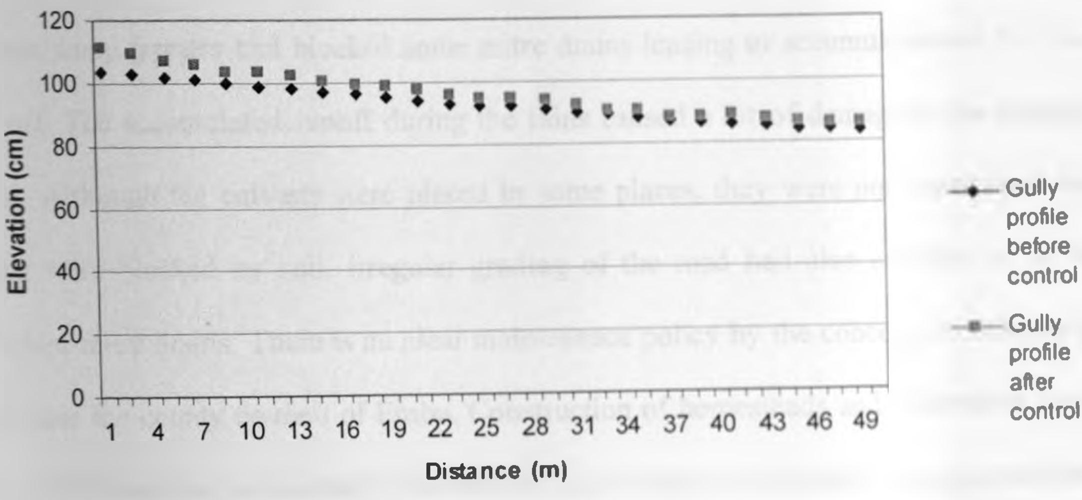

Fig. 4.9: Long profile of Gully B before and after gully control

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The gullies under study were found to have been started by road runoff caused by blocked mitre drains and some culverts up the road. In trying to reduce damage to their farms, some farmers had blocked some mitre drains leading to accumulation of the road runoff. The accumulated runoff during the rains caused a lot of damage to the cropped land. Although the culverts were placed in some places, they were not maintained and most were blocked by soil. Irregular grading of the road had also contributed to the blocked mitre drains. There is no clear maintenance policy by the concerned authority in this case the county council of Embu. Construction of homesteads and cultivation along the natural waterways has lead to accelerated gully erosion. Population pressure and land subdivision to small units brought about by land inheritance has led to cultivation with no fallow period and cultivation of land with more than 55% slope.

If cost-benefit analysis were to be used as the sole criterion, gully control would rarely be justified. In many instances the cost of control far exceeds the value of the land that will be saved. However, the cost may be justified if gully control reduces the risk of road damage. Some gully control measures are extremely expensive, and resource-poor farmers cannot afford to invest in them. This means that gully preventive or control measures must produce short-term benefits in terms of increased yield, availability of more land for cultivation, and reliable crop yields through improved soil-water use.

5.2 RECOMMENDATIONS

1. Farmers should desist from blocking mitre drains by encroaching into road reserves and the community and/or the concerned authority should make an effort in unblocking the culverts and mitre drains seasonally.

2. The policy on road drainage should be enforced such that the Public Works Department ensures that water is directed to either natural waterways or alternatively they should fund the construction of an artificial water way for safe disposal of road drainage.

3. Emphasis should be put in place such that roads are designed in a way that keeps runoff interception, concentration and deviation minimal. This should be done by discharging the flow to safe places for example in areas with vegetation or natural waterways at regular intervals.

4. Scour checks should be designed, constructed and well maintained at the shoulders of the road to reduce the velocity of the runoff.

5. Good erosion control measures should preferably start from the top of the catchment, with the objective of reducing water runoff towards the road.

6. It is essential that road construction be accompanied by effective soil conservation measures. Scour checks should be put in place. The engineer in charge of road construction should make sure that runoff does not damage the adjoining land. Planning of any infrastructural development such as houses should take into consideration safe disposal of runoff water.

7. Further investigations should be done to relate culvert sizes to amount of runoff during the peak rainfall season and also the most appropriate distance from one mitre drain to the other. The most cost effective way of disposing road runoff with minimum damage in densely populated farmlands should also be investigated. The reasons behind the failure of gullies that have been controlled using gabion check dams should also be investigated mostly

    i) inadequate or total lack of spillway

    ii) inadequate keying to the bottom and sides

    iii) inadequate or lack of apron to the lower side of the structure

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7.0 ANNEXES

Annex 1: Gully erosion assessment:

Embu District of Eastern Province - Individual Farmers Interview

Name of the enumerator……………………………………………………………………

Date of Interview……………………………………………………………………………

Division…………………………………Location…………………………………………

Sub-Location…………………………… Village……………………………………………

I] PERSONAL INFORMATION

Name of the farmer……………………………………………………

Name of the respondent………………………………………………

Relationship with the farmer…………………………………………

Sex Male ☐ Female ☐

Age 10-20 ☐ 20-30 ☐

20-30 ☐ 30-40 ☐

40-50 ☐ 50-60 ☐

70-80 ☐ over 80 ☐

Household head

Male headed ☐

Female headed ☐

Child headed ☐

Education level

Primary ☐

Secondary ☐

Tertiary ☐

How long have you lived in this area

0-5 years ☐

6-10years ☐

11-15years ☐

Over 16 years ☐

Farm size ....(acres)

What crops do you grow and what animals do you keep?...

What is the average yield for the various enterprises mentioned?.........................

II] SOIL EROSION

Do you have any problem with soil erosion in your farm? Yes ☐ No ☐

If yes, list them

....

....

In your opinion, what do you think causes the erosion in your farm?

....

....

What soil conservation structures do you have in your farm?.......................................

Do you have a problem of runoff in your farm? Yes ☐ No ☐

If yes, what is the source of runoff?..

☐ Road runoff

☐ Runoff from the roof catchment

☐ Runoff from the farms above

☐ Other source

Specify...

Does the runoff cause any damage? Yes ☐ No ☐

If yes, what type of damage?

....

....

....

Do you have a gully on your farm? Yes ☐ No ☐

If Yes, what do you think is the cause of the gully? ....

....

When did the gully start?...

Did it start immediately the road was constructed? Yes ☐ No ☐

When was the road constructed?..

When was the road last repaired? ....

Has the gully affected agricultural production on your farm? Yes ☐ No ☐

If yes, specify..

....

Is the gully an impeachment of other activities? Yes ☐ No ☐

If yes, specify..

....

Have you tried rehabilitating the gully? Yes ☐ No ☐

If yes, specify how

....

....

Have you ever received technical advice on gully rehabilitation?

Yes ☐ No ☐

If yes, when and from whom...

....

Are there reduced yields in your farm since the formation of gully?

Yes ☐ No ☐

If yes, please quantify..

In your opinion what are the social economic impacts associated with soil erosion and gully development in your area

....

Any other comments..

....

Annex 2: Rainfall, evaporation and temperature data

Table A1: Rainfall figures for 2006 and 2007 (Meteorological Department, 2007)

a) Rainfall recorded in mm in year 2006 at Gully A

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	14.2	24	175	181	243	20	22.5	17.6	75	215.2	438	275
Days with rain	4	1	8	20	18	6	8	5	7	15	24	12

b) Rainfall recorded in mm in year 2007 at Gully A

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	60.2	TR	70.7	251	105	8.2	30.1	39	16.8	300.3	115.6	45.4
Days with rain	4	0	8	14	15	2	9	13	6	16	13	8

c) Rainfall recorded in mm in year 2006 at Gully B

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	15.3	24	177.2	184.8	269.8	22.7	23.5	19.8	80.1	225.2	446	290
Days with rain	4	1	8	20	18	6	8	5	7	15	24	12

d) Rainfall recorded in mm in year 2007 at Gully B

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	66.9	TR	73.7	260.5	117.1	9.9	33.4	45.7	18.9	329.3	125.7	57.4
Days with rain	4	0	8	14	15	2	9	13	6	16	13	8

Table A2: Temperatures and Total evaporation (Meteorological Department, 2007)

a) Total Evaporation

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	61.4	153.6	NA	89.3	106.5	79.2	62.1	75.2	103.4	140.4	108.9	94.4
2007	126.4	147.5	161.5	132.7	122	97.9					129.3	142.4

Total Evaporation in mm

Source: Meteorological Department, 2007

Temperatures

b) Mean Maximum

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	25.9	27.8	27.5	24.9	24.6	23.7	20.8	21.2	24.4	25.9	24.2	24.3
2007	24.8	27.6	27.7	26.6	24.4	22.9	21.2	21.8	23.1	25.6	24.6	24.6

Temperature in ^{o}C

c) Mean Minimum

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	12.7	13.1	15.2	16	15.1	13.7	13.5	13.8	14	15.2	15.2	12.3
2007	13.4	14.3	15	16.4	15.7	14	13.8	13.8	12.6	15.4	14.5	13.4

Temperature in ^{o}C

Annex 3: Data on Long Profiles of the Gullies

Table A3: Gullies long profile data before and after control

Gully A

Distance (m)	Height Before	Height After
0	99.11	105.3
2	98.8	102.9
4	97.78	101
6	97.02	100.9
8	95.77	99.8
10	95.15	99.1
12	94.4	98.6
14	93.39	97
16	92.18	95.2
18	91.55	95.2
20	91.2	94.6
22	90.45	93
24	89.24	91.8
26	88.39	90
28	87.36	88.6
30	87.16	88.5

Gully B

Distance (m)	Height Before	Height After
0	103.4	110.9
2	103	109.6
4	101.9	107.2
6	101	106
8	99.9	103.6
10	99	103.3
12	98	102.3
14	97	100.6
16	96.1	99.2
18	95	98.8
20	94	97.4
22	93	95.6
24	92.4	94.7
26	92	94.4
28	91	93.8
30	90.1	92
32	89	90.2
34	88	90.2
36	87	88.3
38	86.3	88
40	86	88.4
42	85	87.5
44	84.2	86.5
46	84	85.7
48	83.3	85.7

Annex 4: Runoff coefficient values for use with the Rational formula

Table A4: Runoff coefficient values for use with the Rational formula
Source: Hudson, N. 1995. Soil Conservation p. 107

Topography and Vegetation	Soil Texture		
	Open Sandy Loam	Clay and Silt Loam	Tight Clay
Woodland			
Flat 0-5 per cent slope	0.10	0.30	0.40
Rolling 5-10% slope	0.25	0.35	0.50
Hilly 10-30% slope	0.30	0.50	0.60
Pasture			
Flat	0.10	0.30	0.40
Rolling	0.16	0.36	0.55
Hilly	0.22	0.42	0.60
Cultivated			
Flat	0.30	0.50	0.60
Rolling	0.40	0.60	0.70
Hilly	0.52	0.72	0.82
Urban Areas	30% of area Impervious	50% of area impervious	70% of area impervious
Flat	0.40	0.55	0.65
Rolling	0.50	0.65	0.80

Annex 5: Spacing of check dams

Table A5: Spacing of check - dams (m) - Source: Wenner, 1984

	Height of dam crest above gully floor									
	0.3 m	0.3 m	0.3 m	0.6 m	0.6 m	0.6 m	0.9 m	0.9 m	0.9 m	
Gradient of Floor %	wood and gabion 1:1 slope	post-brush/ stone	stone wall with	wood and gabion 1:1 slope	post-brush/ stone	stone wall with	wood and gabion 1:1 slope	post-brush/ stone	stone wall with	
4			15			30			45	
6			7.5			15			23	
8			5.2			10			15	
10			4.0			7.7			12	
12			5.2			6.3			9.3	
14			2.7			5.3			7.8	
16			2.3			4.6		6.7		7.4
20			1.8		3.7		4.5	5.4		6.7
24			1.7		3.1		3.9	4.5		6.1
28		1.4		1.7	2.7		3.4	3.9		5.4
36		1.1		1.5	2.1		3.0	3.0		4.4
40		1.0		1.4	1.9		2.9	2.7		4.2

Annex 6: Pictures of the gullies and road drainage features

Plate A1: Blocked culvert near Gully A

Plate A2: Water directed into the farms through mitre drains

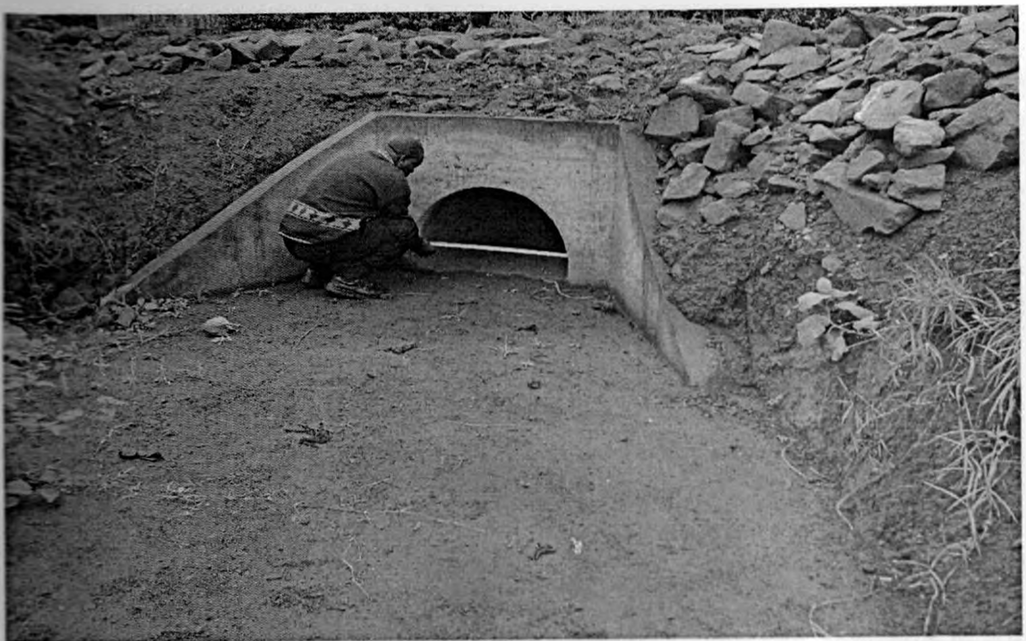
Plate A3: Measuring the diameter of a culvert dispatching water into Gully B


Plate A4: Controlling soil from entering the culvert using stones and bags filled with soil.

Plate A5: Head of gully showing the gully B extending headward

Plate A6: Culvert discharging water from the road into Gully A

Annex 7 Contours of the gullies

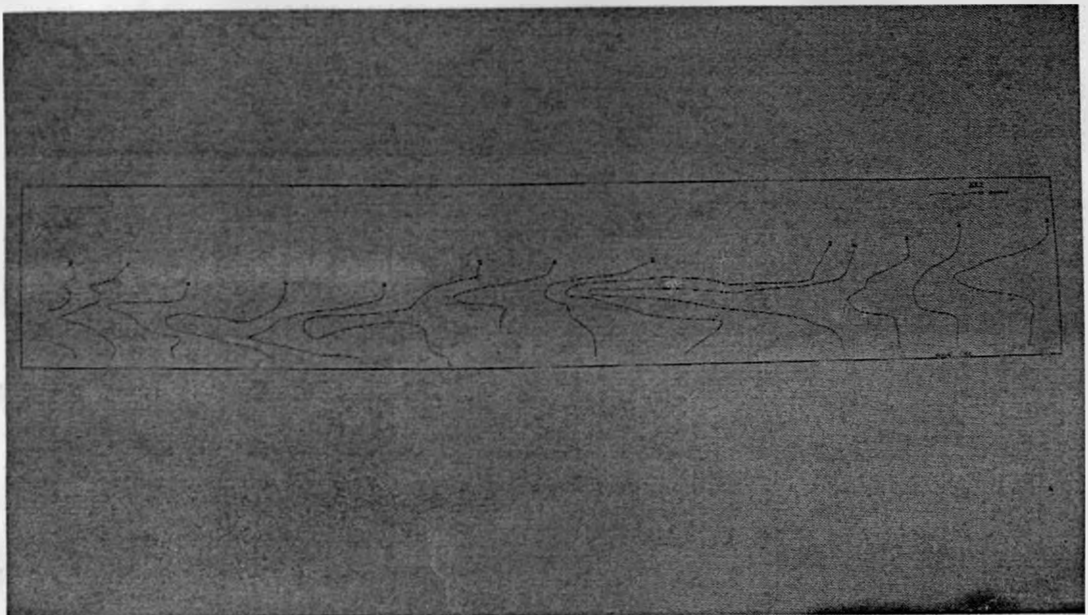

Fig. A1: Contours of Gully A

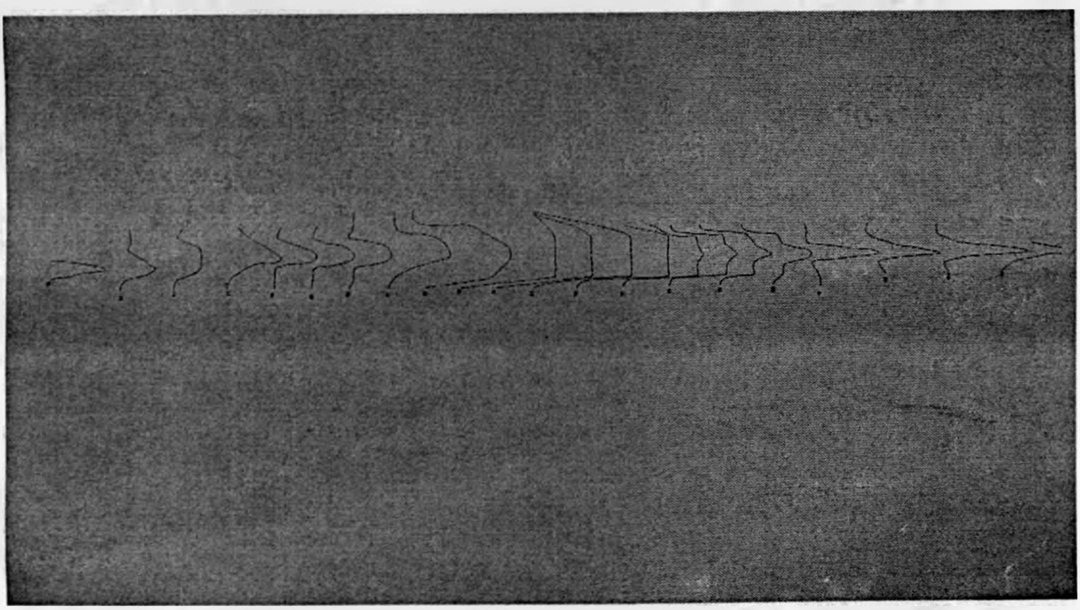

Fig. A2: Contours of study Gully B