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EROSION HAZARD ASSESSMENT IN THE UPPER EWASO NG'IRO BASIN OF KENYA: APPLICATION OF GIS, USLE AND EUROSEM.

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Dedication,

This thesis is dedicated to Nikasius, Munene, Karimi, Gitonga and Wambogo.

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B. M. Mati.

Erosion hazard assessment in the Upper Ewaso Ng'iro basin of Kenya: Application of GIS, USLE and EUROSEM.

ABSTRACT

A methodology was developed for assessing soil erosion hazard in the Upper Ewaso Ng'iro basin of Kenya, using Geographic Information Systems (GIS), the Universal Soil Loss Equation (USLE) and the European Soil Erosion Model (EUROSEM). The USLE was used in a GIS environment by creating thematic maps of R, K, L, S, C and P and then calculating soil loss by raster-grid modelling with Arc/Info GRID.

The rainfall erosivity factor (R) was derived from relationships between rainfall amount and erosivity using erosion plot data from within the catchment. The nature of the relationship was found to be a function of agro-climatic zones of the region. Mean annual erosivities ranged from 145 to 990 J m^{-2} hr^{-1}. For a given amount of rainfall, erosivity was higher in zone IV than in the wetter zones II-III. The soil erodibility factor (K) was estimated using the USLE nomograph and data from laboratory analysis of field samples collected from representative major soil mapping units. The K-values were low to medium, ranging from 0.10 to 0.25 over 84 percent of the basin. The topographic factor (LS) was obtained by creating Digital Elevation Models (DEMs) of the basin with TOPOGRIDTOOL of Arc/Info. These were then used to determine the slope steepness and length factor values, calculated with raster-grid modelling. Although DEMs proved a useful tool, maximum values of both steepness and length had to be set in this reconnaissance study to achieve reasonable results. A finer resolution of input data and a smaller grid cell size are needed for accurate determination.

The cover and management factors (C) were obtained by determining the land cover types within the basin using remotely sensed data (SPOT 1 colour composite prints) and ground truthing studies. The factor values were estimated from USLE guide tables and measurements of cover from plots and test sites. Some 70 percent of the basin is covered by rangelands. The conservation practice (P) factor values were estimated from USLE guide tables and then applied to areas where soil conservation had been introduced according to maps obtained from the Ministry of Agriculture. The USLE was validated using data from erosion plots. A value of $R^2 = 0.645$ was obtained between predicted and measured values but the standard error was rather high (e = 5.745 t ha^{-1} yr^{-1}). Using an annual soil loss of 9.0 t ha^{-1} yr^{-1} as tolerance level, some 36 percent of the basin was found to experience unacceptably high erosion rates. Most of this area was communal grazing land and cropland where soil conservation measures had not been applied. A critical land cover type within the grazing land is shrubland, where vegetation cover is less than 40 percent and high erosion risk was predicted and confirmed by field surveys.

EUROSEM could not be integrated within a GIS in the time available for research. It was therefore simulated outside GIS environment, where it was applied to Embori and Mukogodo plot data using separate data sets for calibration and validation. Calibration was used to obtain input parameters for saturated hydraulic conductivity, cohesion and Manning's roughness coefficients. Validation gave correlation coefficients of 0.907 and 0.840 for predictions of storm runoff and soil loss respectively at Embori; the corresponding values for bare soil plots at Mukogodo were 0.895 and 0.577. However, EUROSEM predicted runoff poorly ($R^2 = 0.570$) and failed to predict soil loss at all the vegetated plots at Mukogodo. The model was applied to simulated vegetation covers of barley, maize, grass and forest for a 36.7 mm rainstorm at Embori. The simulated soil losses showed an exponential decrease with increasing cover. At a threshold cover of 70 percent, soil loss diminished to zero under grass and forest and decreased to a minimum value under barley and maize. These results support the USLE simulations, which showed that areas with more than 70 percent cover (such as forest) had a low erosion hazard, even with steep slopes and high rainfall erosivities.

This research has demonstrated that GIS can be used with the USLE to assess and quantify erosion hazard, giving results that can be used for conservation planning. EUROSEM can be applied successfully to bare soil and cropland, but application to other land covers requires further investigation. Land cover and topography are the main factors controlling the spatial distribution of soil loss in the Upper Ewaso Ng'iro basin. Future conservation activities should be concentrated on the rangelands.

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CHAPTER I

INTRODUCTION

1.1 The problem of soil erosion

One of the most important tasks for good land use planning at regional and national levels is the preparation of a comprehensive database of the available natural resources, the relative risks of degradation, the type and location of land degradation and the reasons why it occurs in the region. Confirmation that there is, in fact, land degradation taking place is not always obvious or an easy task. It involves mapping lands which are being degraded or at risk, identifying the land users responsible, and developing solutions and means to reach them (Blackie 1989). The FAO (1993) defines soil degradation as "the sum of geological, climatic, biological and human factors which lead to the degradation of the physical, chemical and biological potential of soil, and endanger biodiversity and survival of human communities". The FAO lists six types of land degradation, two of which are wind and water erosion. As most of the studies on soil erosion have concentrated at the plot or microscale level (Lal 1997) there is a need for many land use plans, to develop cost-effective methods of evaluating soil erosion and its effects at regional and watershed scales.

Soil erosion is a serious global problem responsible for the loss of billions of tons of sediments from land to the oceans each year (Morgan 1995; Hudson 1995). Erosion is responsible for the destruction of productive land, sedimentation of reservoirs, desertification, declining soil fertility and crop yields, and it can lead to temporary or permanent abandonment of the affected land (Lal 1988; Hudson 1983). Soil erosion has been on the increase throughout the world especially in the twentieth century. According to Oldeman et al (1990), about 85 percent of land degradation in the world is associated with soil erosion, most of which has occurred since the end of World War II, causing a reduction in productivity of about 17 percent.

1.1.1 Erosion problems in the tropics

The Global Land Assessment of Degradation (GLASOD) estimates degradation of cropland and pasture to be most extensive in Africa, affecting 65 percent of the cropland and 31 percent of the rangelands (Oldeman et al 1990). Africa is a large continent and taken as a whole, it has adequate natural resources to sustain agricultural production, without undue land degradation. The FAO (1995) estimates that 44 percent of the land in sub-Saharan Africa has potential for rainfed crop potential. However, two thirds of this land is concentrated in a few countries such as Zaire, Rwanda, Uganda, and Nigeria. The rest is within part of the fragile ecosystem where constraints in climate, soils, terrain and population pressure, coupled with limitations in social-political and economic policies (Hudson 1983) make them highly susceptible to soil erosion. In this group are countries such as Lesotho, Ethiopia, Madagascar, Rwanda, Sudan, Swaziland, Tanzania, Morocco, Tunisia and Kenya (Millington et al 1989).

Accelerated erosion in the tropics is largely due to human activities such as gradual intensification of cultivation, shorter shifting cultivation cycles, cultivation of very steep slopes, deforestation for timber and fuelwood, agricultural expansion, overgrazing and highway construction. In Africa, soil erosion is mainly the result of poor soil management on farms, grazing land and other cleared areas. Roughly, Africa loses 47 t $km^{-2} yr^{-1}$ (Lo 1990). According to Lal (1993) the Savannah regions of West Africa are the most susceptible to erosion, losing between 5 and 200 t $km^{-2} yr^{-1}$. Other factors associated with erosion are socio-political such as land tenure, land availability, farm size, capital, labour, and lack of appropriate technology (Hudson 1983; Hurni 1993). In East Africa (Ahn 1977) erosion is affected mostly by the amount of cover and farming systems.

Soil erosion has been associated with increasing population, which drives the demand for more land for agricultural expansion, resulting in the deforestation of mountain slopes, over-exploitation of the soil resources and general land degradation (Darkoh

1993; Hudson 1983). However, there is evidence (Tiffen et al 1994) that, in some areas, population growth has helped reverse soil degradation, boosting improvements in the utilisation and management of resources, including soil conservation activities. This kind of positive trend is usually preceded, however, by periods of deterioration. Also, Tiffen et al (1994) point out that this trend is driven by socio-economic changes so that, as the population densities increase, conservation activities are enhanced by incentives such as favourable land tenure policies and good marketing outlets. The increased shortage of land and the readily available labour encourage the need to conserve the scarce natural resources.

1.1.2 Soil erosion in Kenya

Documentary evidence of soil erosion in Kenya dates back to the 1930s, when Maher (1937) reported serious degradation of the then Ukamba Reserve comprising the present day Machakos and Kitui districts. The relatively improved security in the Reserve from cattle rustlers had led to increased livestock populations, resulting in overgrazing of the dry ecosystem and severe degradation (Pereira and Beckley 1952). Since then, other studies have shown alarmingly high sediment losses in both the humid and semi-arid areas (Ogwenyi et al 1993; Barber 1982; Dunne 1977; Edwards 1979). Soil erosion has therefore been identified as one of the most pressing agricultural problems presenting a major threat to land productivity in Kenya (Kilewe and Thomas 1992). Erosion has been considered of much greater importance than salinity or alkalinity as it affects larger areas and usually causes damage that cannot be reversed. The areas in Kenya (Figure 1.1) known to suffer relatively high levels of erosion include Machakos, Kitui, Taita Taveta, Kajiado, Kilifi, Kwale, the steep cultivated slopes of the Mt. Kenya and the Nyandarua Range covering Embu, Meru, Muranga, and Kiambu, the semi-arid areas covering Samburu, Isiolo, Keiyo Valley, West Pokot and most of the North Eastern Province (Ogwenyi et al 1993).

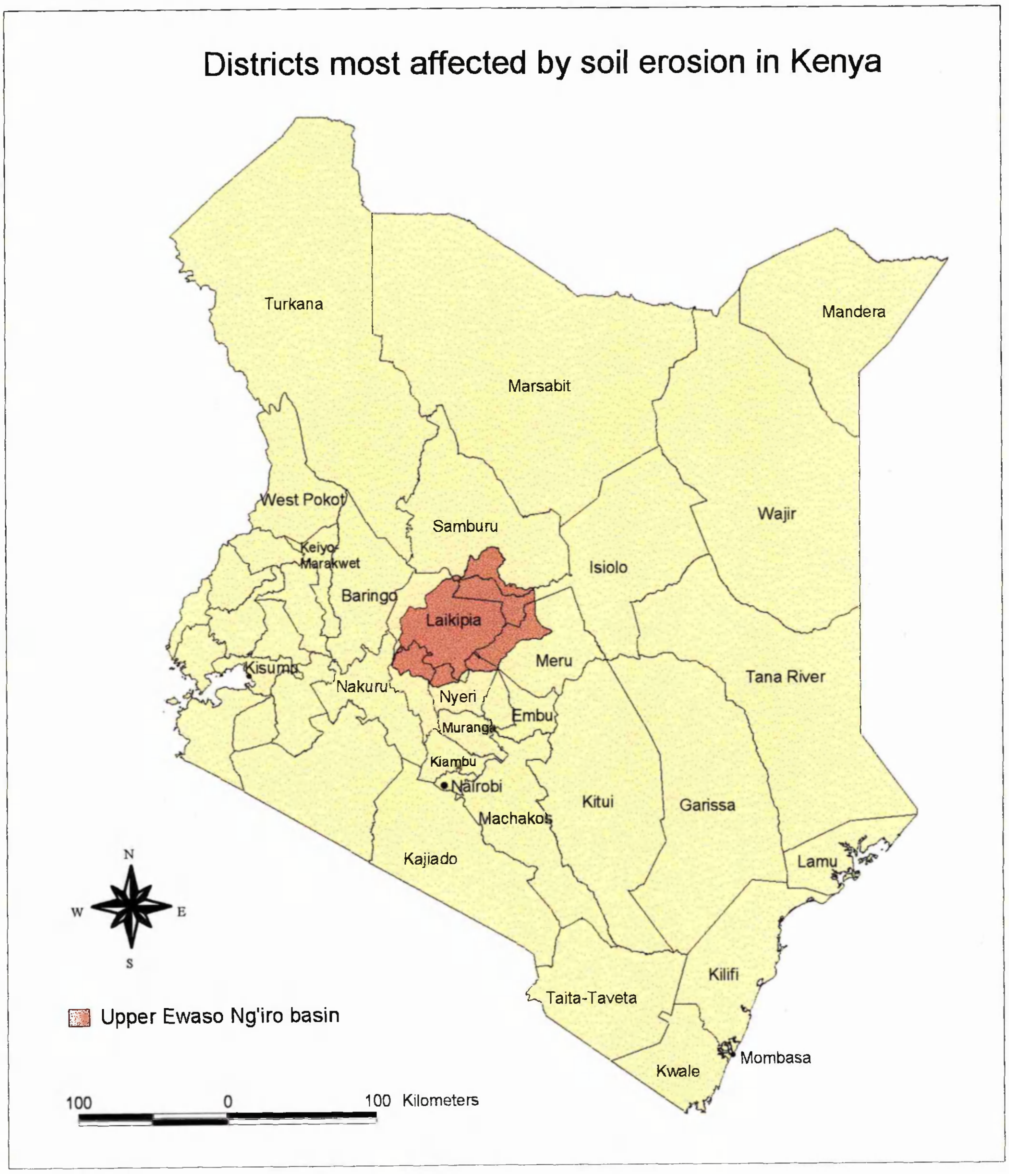

Figure 1.1 Districts most affected by soil erosion in Kenya

The sources of high sediment yields in Kenya have been identified as cultivated lands in the humid areas, which suffer rill and interill erosion, overgrazed rangelands and stream banks (Khroda 1989; Kilewe and Thomas 1992; Ogwenyi 1979). Gully erosion has been a common hazard, especially in association with roads and footpaths (Gathuru et al 1989; Mati 1989; Mati 1993). Landslides have also been identified as causing severe erosion on the steep slopes of mountains, especially the Nyandarua range, where forest cover has been removed and replaced with cultivated crops including tea (Larson 1989). The increasing problem of soil erosion in Kenya can be blamed not only on the physical and socio-economic constraints, but also on bad policies and a lack of priorities that can balance human activity with the environment (Deacon and Darkoh 1987). The most affected areas have been the arid and semi-arid lands (ASAL) of the country. The subject of this study, the Upper Ewaso Ng'iro basin, is predominantly ASAL.

The ASALs make up 80 percent of the total land area of Kenya. They are mainly hot and dry, with highly variable rainfall (in space and time) and evaporation rates which are twice the annual rainfall. The soils have low organic matter content due to low vegetation density and microbial activities. The soil-water storage is rather limited and the soils are very susceptible to degradation. About 20 percent of the total population in Kenya lives in the ASAL areas, while 35 percent of the cattle and over two-thirds of the goats and sheep are found here (Jaetzold and Schmidt 1983). Population growth in the ASAL areas is increasing rapidly due to immigration from the high potential areas, which are already over-utilised, as pressure to create more farms to accommodate the rapidly growing population in these areas increases (Kilewe and Thomas 1992). The grazing lands previously available for livestock and wildlife are degraded by human activities such as cultivation, charcoal burning and overgrazing. The resulting decline in vegetation cover means less fodder for the animals, and the vicious cycle of overgrazing, denudation and soil erosion can continue indefinitely unless something is done to stop it (Herlocker et al 1993). In addition, the anticipated global climate change will have far reaching effects in many parts of Kenya (Ottichilo et al 1991). These range from increases in temperature and evapotranspiration rates, to shifts in agro-ecological zones. It is anticipated that there will be changes in geophysical resources, including increased soil erosion, especially in the dry areas. Therefore, there is an urgent need to plan mitigation strategies to prevent future adverse effects. However, future plans rely on a knowledge of the problems in each area. The Upper Ewaso Ng'iro basin was selected for this study because these types of problems are experienced in the region, yet it has received little research attention in comparison to other drainage basins of Kenya. However, the unique historical background of the basin is also an important contributory factor to the problems of soil erosion as described in the following section.

1.1.3 A brief history of land degradation in the Upper Ewaso Ng'iro basin

It is not easy to visualise the problems of land degradation in the Upper Ewaso Ng'iro basin, and make viable resource planning and management decisions without understanding the history of the "land issues" of the region. The first explorer to visit the Upper Ewaso Ng'iro basin was Thomson (1887). At that time, it was reported that most of the region, especially the Laikipia Plateau, was unoccupied by human populations and wild animals roamed the land. In the early years of the 20th Century, the Laikipia Plateau was largely inhabited (Government of Kenya 1962) by pastoralists (the Maa-speaking people or the Laikipiak) and some hunter-gatherer groups (the Ndorobo). European settlers started arriving around 1910. They put most of the land under large-scale ranches, while wheat and barley were grown on the higher (wetter) slopes of Mt. Kenya. The Maasai and the Ndorobo were either moved to lands near Narok, or constrained into Mukogodo Division, an area having a harsh and fragile environment (Herren 1987). Evidence from the early settlers suggests that the region was teeming with game of all descriptions, but that people and domestic animals were few in number. Administration of the area was difficult and much effort was devoted to the prevention of inter-tribal fighting and allocation of grazing areas (Government of Kenya 1962). The concentration of people and livestock alongside the existing wildlife in the dry and fragile environments in the north of the Upper Ewaso Ng'iro basin had its toll on natural resources such as vegetation, water and the soil. The result was widespread overgrazing, soil erosion and general land degradation which is evident to date.

After independence in 1963, many European owned farms and ranches were bought by African land buying groups and subdivided. These new settlements spread from the wetter areas to the drier parts of the plateau originally used for ranching (Huber and Opondo 1995). The incoming African settlers brought with them a background of mixed farming, mostly for subsistence. Due to high rates of immigration, population growth in these settlements has been very high, reaching 9 percent per annum in the 1970s. As the farm sizes are small (some less than a hectare), the land under small scale agriculture has been subjected to intensive cultivation and overgrazing (Kohler 1987). In such a fragile environment, these are conditions that lead to high erosion susceptibility and land degradation .

1.1.4 Soil erosion in the Upper Ewaso Ng'iro basin

Documentary evidence of soil erosion in the Upper Ewaso Ng'iro basin dates back to the early 1940s, when Edwards (1943) reported that the region along the full length of the Ewaso Ng'iro river, and areas around Isiolo, were the among the most degraded parts of the then Northern Frontier District. Towards the end of the "shifta period" in the late 1960s, land degradation had increased in areas around Isiolo (Herlocker et al 1993). During the shifta war, the Boran and their stock had been confined into small areas around a few settlements in Isiolo. The resulting overgrazing and land degradation was serious especially in the lower footslopes of the Nyambene Hills. Since then, the problem of soil erosion has accelerated. The Ministry of Water Development (1992) has indicated that the Ewaso Ng'iro carries 1,045,035 tons/year of suspended sediments at Archers' Post, which is the basin outlet. This is one of the highest sediment yields in Kenya.

There are many reasons for the increasing erosion hazard. They include traditional pastoral practices, such as the burning of rangelands during the dry season in order to kill ticks and hasten grass regeneration. The FAO (1971) reported that extensive burning around the Ewaso Ng'iro and the Nyambene hills had resulted in vegetation changes from shrub and bush to the dwarf species prevalent to date. According to Herlocker et al (1993) the grass quality and cover had decreased, with a decline in perennial species and a prevalence of annual species. Among the pastoralists, land use is linked to the availability of water and fodder. During the dry season, livestock are usually moved upstream along the banks of the Ewaso Ng'iro, when most of its tributaries dry out and fodder is scarce (Thurow and Herlocker 1993). At this time of the year, even the wildlife migrate upstream in search of fodder and water. The resulting overgrazing and trampling, and the compaction of the soil along animal tracks encourages high runoff losses. When the rains come, the usually dry watercourses suddenly swell so much that they become huge impassable ephemeral streams locally known as "lagas". These carry large quantities of sediments down into the Ewaso Ng'iro. Ondieki (1993) recorded sediment transport rates of 1080 tons/km^2 from an ephemeral stream in the Mukogodo subcatchment

Another problem is insecurity in the northern parts of the Upper Ewaso Ng'iro basin. This has especially affected Isiolo area, where cattle rustling and bandit attacks occur (Herlocker et al 1993). This has forced many pastoralists to reduce their migratory patterns and settle in areas around major towns, resulting in overgrazing of these areas.

In the higher altitudes of the basin, encroachment by small scale farms onto mountain forests and the expansion of settlements onto the drier rangeland ecologies (Hubber and Opondo 1995) are taking its toll. Most of the small scale farmers have retained the traditional land use practices of the wetter areas they came from (Wiesmann 1992). They have replaced ranching and beef production with mixed farming of cultivated maize, beans and potatoes, and a few dairy animals. As some of the crops are not suited to the physical and climatic conditions of the region, crop failure is quite common. Faced with little capital to buy fertilisers (Bachman 1995) and the need to feed crop residues to the livestock, little organic matter is available to replenish the soil fertility. The result is increased strain on natural resources, especially water, firewood, wildlife and the soil.

Another problem is the lack of employment or income generating opportunities to provide a viable alternative to subsistence farming, especially for the squatter populations in the large scale farming areas (Kohler 1987). As they do not own the land, the squatter farmers have no motivation for conservation due to land tenure constraints. Even to those employed, owning land and farming are considered necessary due to the low wages. With little conservation inputs into the farming systems, soil degradation usually results. The deforestation of the natural forest from the mountain slopes has reduced the soil-water storage capacity, causing increased runoff (Njeru and Liniger 1994) and the possibilities of soil erosion. The overall effect on the catchment hydrology is increased peak flows during the rains and less dry-weather flows in the rivers.

1.2 The need for erosion hazard assessment

Published data on soil erosion in the Upper Ewaso Ng'iro basin has been limited. This may be partly due to the more pressing need for the development and supply of water for domestic, livestock and crop production. In this regard, hydrological studies date back to the 1930s, when Tetley (1940) made surveys of the Laikipia District for water supply to the ranching areas. Since then, other hydrological and water conservation studies have been done (Government of Kenya 1962; Ministry of Water Development 1992; Liniger 1991; Thomas 1994; Ondieki 1987) including soil surveys and agroforestry studies (Mbuvi and Kironchi 1994; Kironchi et al 1992; Njeru and Liniger 1994; Bachmann 1995). Most of these studies have concentrated on the slopes of Mt. Kenya leaving out much of the western, eastern and the semi-arid areas of the north.

In assessing the economics of soil conservation in Kenya, Pagiola (1990) identified the assessment of erosion under natural conditions as an important research need. In the Upper Ewaso Ng'iro basin, available data on soil loss is mostly in relation to sediment yield in the Ewaso Ng'iro and its tributaries (Government of Kenya 1962; Ministry of Water Development 1992; Ondieki 1993), or soil loss from small plots and case studies in small catchments (Mutunga 1994; Liniger 1991; Akal 1992). The causes and sources of erosion in the Upper Ewaso Ng'iro basin have not been quantified in ways which can be used for land use planning at the basin level. This study primarily aims to fill that gap.

Although the other drainage basins in Kenya have received more attention than the Upper Ewaso Ng'iro basin (Ogwenyi et al 1993; Sutherland and Bryan 1989), it is not possible to transfer directly the results from these areas to the Upper Ewaso Ng'iro basin, as the region is quite unique in topography, soils, land use and climate. In any case, the studies for these other areas were done to address the specific problems of those areas. Therefore, it was necessary to assess soil erosion hazard in the Upper Ewaso Ng'iro basin based on prevailing conditions.

Assessment of soil erosion for a large basin such as the Upper Ewaso Ng'iro requires that the land is divided into zones of similar characteristics such as topography or vegetation, so that the different erosion classes can relate more accurately to the processes occurring in the region and the respective conservation strategies that would be required. The level of detail of this type of assessment depends on the objectives and size of the area. The assessment aims at providing a tool to simulate erosion accurately even in areas not adequately covered by the assessment exercise. The dominant variables include rainfall erosivity, soil erodibility, slope steepness, length of the slope segments, surface roughness, vegetation cover, land use and management. Due to the complexity of the variables involved and since they interact in a wide spatial domain, simplicity and the ability to transfer from data-rich to data-poor areas becomes very important. The use of Geographic Information Systems (GIS) is one way of achieving this (Burrough 1986).

1.2.1 The need for GIS

Application of Geographic Information Systems (GIS) in assessing soil erosion and providing a tool for planning conservation strategies, have advanced in recent years (Mellerowicz et al 1994). This has been due to improvements in the availability of digital data, cheaper and user friendly software and the need to handle large spatially oriented databases. One advantage of using GIS is that different themes can be put in the database, and a model programmed into the GIS to determine the optimal combination of the themes. The database can then be interrogated rapidly and the results displayed as either maps or tables. GIS therefore enables the evaluation, adjustment and comparison of different scenarios rapidly and economically, as compared to empirical methods (Bird 1989).

The current study has drawn experience from other studies from the region, most of which are concentrated within the Laikipia District. A GIS database for the Laikipia Research Programme (LRP) (Hoesli and Klingl 1995) was first initiated in 1989 when data with a strong spatial component were incorporated into the PC Arc/Info GIS facilities at the LRP offices at Nanyuki, Kenya. Since then, some maps have been produced showing vegetation cover, erosion risk, grazing assessment and land ownership for specific areas within the Laikipia District (Klingl 1993) which forms part of the Upper Ewaso Ng'iro basin.

At the start of this study in 1995, it was necessary to obtain complete coverages of the basic GIS data on soils, topography, climate and land use of the Upper Ewaso Ng'iro basin. However, the available GIS data (Kohler 1987; Berger 1989; Klingl 1993; Hoesli 1995; Hoesli and Klingl 1995; Flurry 1987; Decurtins 1992) covered either small sub-catchments, the Laikipia District alone, or the part of the basin covered by one Landsat image, leaving out the corners of the basin around Wamba, Archers' Post, Nyambene hills and the Nyandarua mountains. It was therefore necessary to develop a GIS database for this study from original sources. To use this GIS database to predict soil loss spatially and quantitatively requires appropriate erosion models.

1.2.2 The case for modelling

Choosing a model to predict soil erosion in a large watershed is difficult because different forms of erosion have different causes, and are influenced by different factors. For instance, it is difficult to get a model that predicts interill, rill and gully erosion simultaneously, taking into account the diversities in catchment characteristics such as multiple vegetation covers. Yet in practice, erosion processes take place under such conditions. The modeller has to be guided by the objectives of the study. In addition, predicting soil erosion depends on both the temporal and spatial scale. Changes of scale and time usually go together, and at different scales, certain erosion processes seem to be dominant (Millington 1981; Kirkby 1998). At scales of runoff plot and single slopes, process-based models such as Water Erosion Prediction Project (Flanagan et al 1991) and European Soil Erosion Model (Morgan et al 1992) become relevant. At the catchment scale, details of micro-topography are integrated, and erosion studies rely more on thematic maps, Digital Elevation Models (DEM) and remote sensing (Kirkby 1998). The regional scale is important for decision makers, but it is difficult to predict erosion accurately from physically-based models. The USLE has been used at this scale (Tomas and Coutinho 1994; Folly 1997) although such use exceeds the model's limits. At coarser resolutions, climate and lithology are the main factors considered in erosion prediction.

Erosion hazard can be evaluated using a factorial scoring system (Morgan 1995) but this may yield results that are not very accurate. However, improvements can be achieved by linking risk assessment with erosion models which quantify erosion rates but different models can give different predictions. An integrated approach is usually required that includes erosion mapping, risk assessment and historical analysis (Morgan 1993). Erosion hazard at coarse resolutions is most commonly quantified using annual soil loss rates (Herweg 1996). These serve as an indicator of what may be called "non-sustainable land use", and as a means of determining whether future erosion rates will be higher or lower than present ones. Comparing annual erosion rates to a pre-selected tolerable soil loss provides a relatively reliable tool for the formulation and management of environmental and development plans at watershed, regional and national scales. The assessment of erosion in the Upper Ewaso Ng'iro basin was intended to provide such a tool and therefore planned with the following objectives:

1.3 Objectives of the research

1.3.1 Main objectives

The main objective of this study was to assess the soil erosion hazard in the Upper Ewaso Ng'iro North basin of Kenya, and to use geographic information systems (GIS) and erosion prediction models to determine the main factors associated with soil loss in the basin.

1.3.2 Specific objectives

(i) To assemble the baseline information and compile a GIS database for the Upper Ewaso Ng'iro North basin, necessary for the assessment of erosion, model simulations, analysis and presentation of results.

(ii) To predict erosion hazard in the basin, in both spatial and quantitative scales.

(iii) To determine the main factors associated with soil erosion in the Upper Ewaso Ng'iro basin, which could form a basis for conservation planning.

The next chapter describes the main characteristics of the study area, the Upper Ewaso Ng'iro basin.

CHAPTER II

THE UPPER EWASO NG'IRO BASIN

This chapter presents an introduction to the study area, the Upper Ewaso Ng'iro basin, in which the spatial extent, physical features, climate, soils and land use are briefly described. The figures presented in this chapter have all been produced during the course of this study.

2.1 Location of the Upper Ewaso Ng'iro basin

Out of the five major drainage basins that make up the Kenyan topography, the Ewaso Ng'iro North is the largest, being 210,226 km^2. The Upper Ewaso Ng'iro North basin (or simply Upper Ewaso Ng'iro basin) constitutes the upper stream section of this drainage area, covering 15,251 km^2. It is situated between latitudes 0° 20' south and 1° 15' north and longitudes 36° 10' east and 38° 00' east as defined by the natural topographic divide(Figure 2.1). It drains from the Rift Valley escarpment to the west, the Nyandarua mountains in the south west, the Mt. Kenya to the south, the Nyambene Hills in the east, the Mathews Range in the north while the downstream control is at Archers Post.

The Upper Ewaso Ng'iro basin traverses the administrative districts of Nyeri, Nyandarua, Laikipia, Meru, Nyambene, Isiolo and Samburu (Figure 2.1). The Laikipia District occupies about 50 percent of the entire area. The biggest town in the region is Nanyuki, situated 200 km north of Nairobi. Although the main Ewaso Ngiro river originates from the Nyandarua mountains, most of the flow comes from tributaries that drain Mt. Kenya (Decurtins 1992). Whereas the surface flow from the Ewaso Ng'iro river disappears into the Lorian Swamp in Kenya, subsurface flows continue eastwards to recharge rivers inside Somalia, which eventually drain into the Indian Ocean.

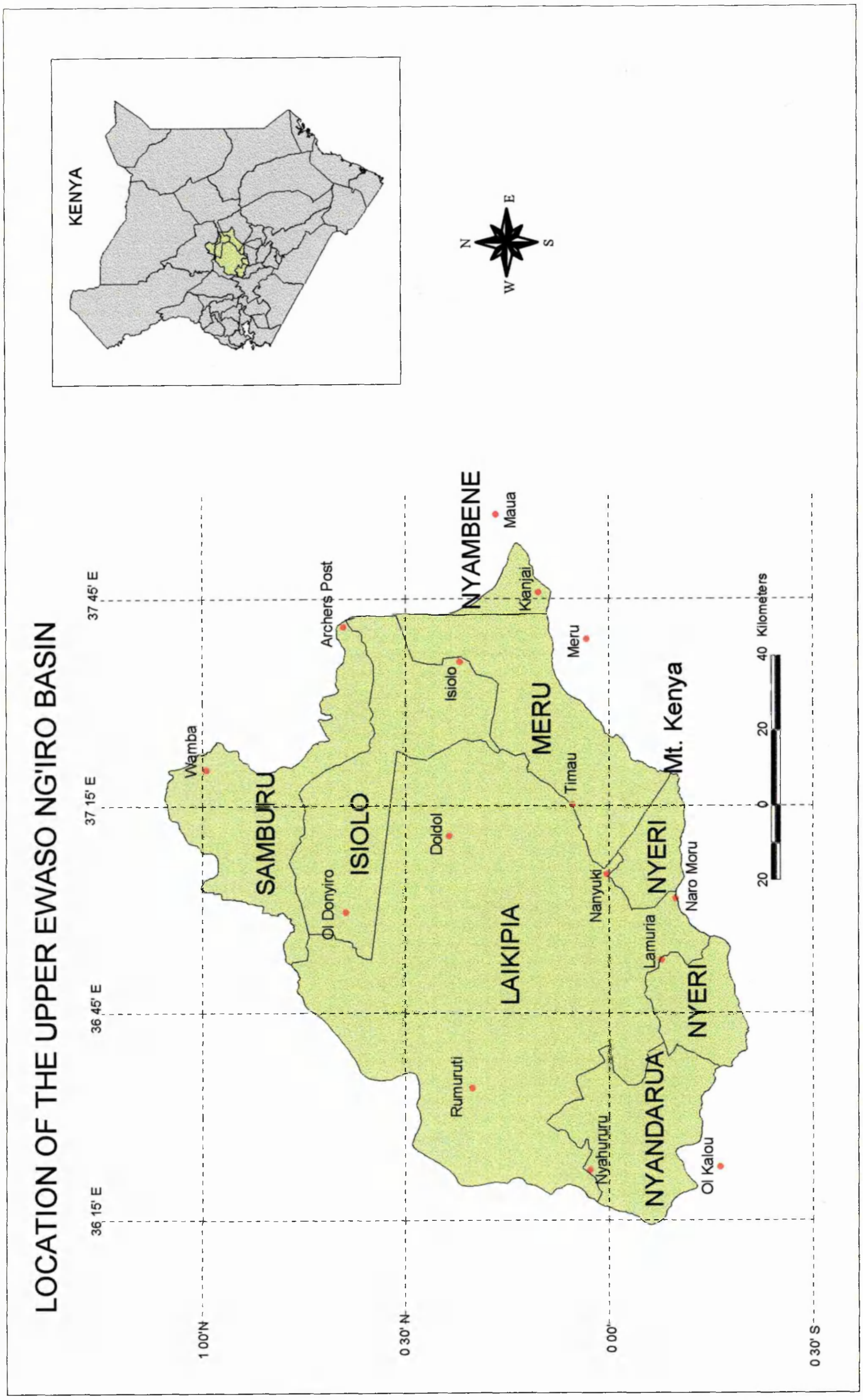

Figure 2.1 Location of the Upper Ewaso Ngi'ro basin

2.2 Topography

The topography (Figure 2.2) is dominated by Mt. Kenya and the Nyandarua Range in the south and the Nyambene Hills to the east of the basin. Altitudes range from 862 m above sea level at Archer's Post to 5199 m at the summit of Mt. Kenya (Sombroek et al 1980; Jaetzold and Schmidt 1983). The upper mountain slopes are undulating to rolling with deeply incised V-shaped valleys, where elevation ranges from about 2500 to over 4000 m, while the lower parts consist of broad ridges dissected by rivers and streams. Most of the central region is occupied by the extensive gently undulating Laikipia Plateau at an elevation of 1700-1800 m. The north and north-east of the basin is characterised by undulating to rolling topography comprising uplands, hills and minor scarps, with many of the latter having outcroppings of basement complex rocks at their tops. Here, altitudes drop rapidly from about 1700 m to less than 1000 m towards the extreme north-eastern region.

2.3 Climate

Due to its position on the lee slopes of Mt. Kenya and the Nyandarua Range, the Upper Ewaso Ng'iro Basin is predominantly an ASAL region (Figure 2.3). The rainfall amounts are low, tapering from over 2000 mm on the Nyandarua Range, to under 365 mm per annum in the drier northern eastern areas (Jaetzold and Schmidt 1983; Thomas and Liniger 1994). Mean annual rainfall averages about 700 mm in the basin. Despite this relatively high figure, rainfall distribution is such that the seasonal amounts are insufficient for proper crop growth in most parts of the basin (Thomas and Liniger 1994; Liniger 1995). In the western and north western areas, continental rains fall between April and August. The eastern region has a clear bimodal distribution, with rainfall maxima in April and October (Berger 1989). The central region is a transition zone, where the two patterns overlap. This is the driest zone. Rainfall intensities are usually high, averaging about 20 to 40 mm hr^{-1} and higher intensity storms of up to 96 mm hr^{-1} have been recorded (Liniger 1991).

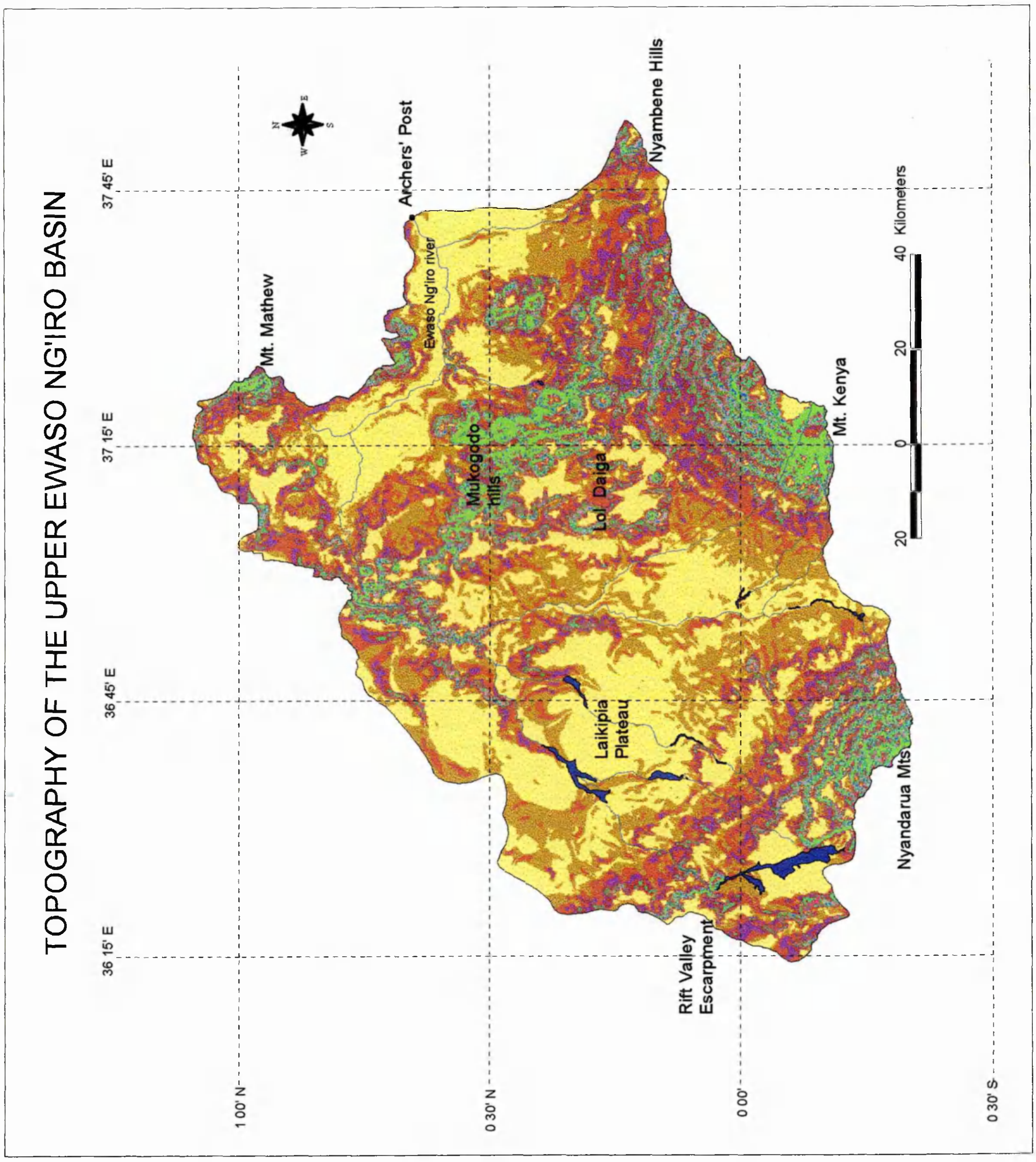

Figure 2.2 Topography of the Upper Ewaso Ngi'ro Basin

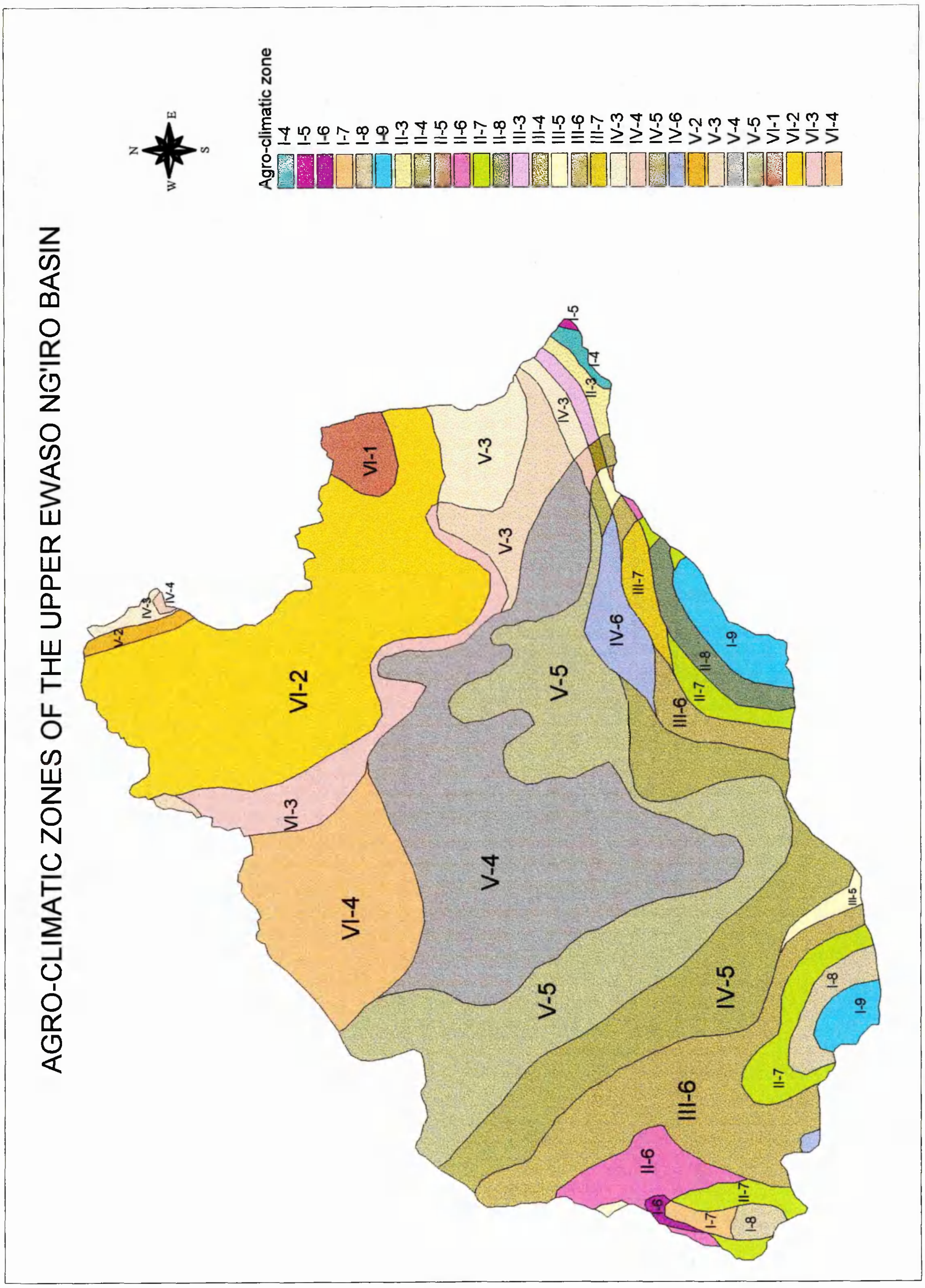

Figure 2.3 Agroclimatic zones of the Upper Ewaso Ng'iro basin (Source: Sombroek et al 1980)

Due to the differences in altitude, mean annual temperatures in the Upper Ewaso Ng'iro basin range from under 10° C at the top of Mt. Kenya to over 24°C at Archers Post. As a result, the basin has a wide climatic range, straddling agro-climatic zones I-VI (Sombroek et al 1980). In comparison to other ASAL regions of Kenya, temperatures are relatively low, with mean annual values averaging 18-20° C. This is due to the higher altitudes and the effects of the cool winds that descend from the mountains (Berger 1989).

2.4 Soils

2.4.1 Geology

The geology of the Upper Ewaso Ng'iro basin is related to relief and volcanic activity (Jaetzold and Schmidt 1983; Government of Kenya 1962). On Mt. Kenya, the Nyandarua mountains and the Nyambene hills, volcanic rocks of considerable thickness dominate. Complex Basement outcrops are found in the central highlands around the Lol Daiga and Mukogodo hills. Northwards, beyond these hills, around the Ewaso Ng'iro-Ewaso Narok junction, the Basement rocks are overlain by volcanic rocks consisting of phonolytes, trachytes and basalt lava flows. The volcanic rocks range in age from Tertiary to Pleistocene. Basalt lavas also form the caps of a number of small isolated plateaux around Ol Donyiro and Barsalinga in the north.

2.4.2 Soils and their distribution

The distribution of the soils in the Upper Ewaso Ng'iro basin (Figure 2.4; Appendix 1) is related to the relief, volcanic activity and climate, which have influenced their weathering and development (Sombroek et al 1980; Muchena 1982; Ahn and Geiger 1986; Speck 1983; Mainga and Mbuvi 1994; Mbuvi and Kironchi 1994; Mati, current study). The dominant soil types include the following:

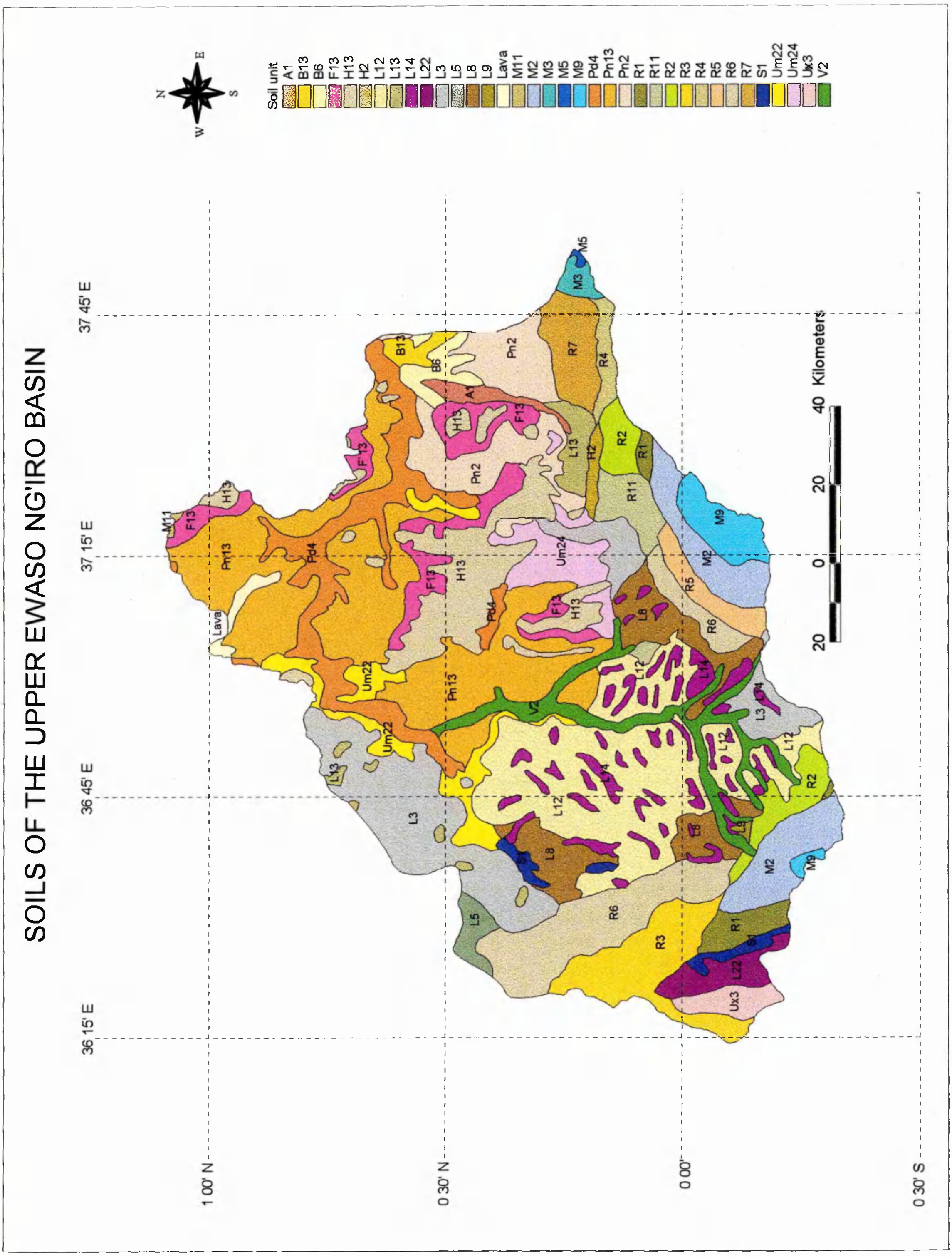

Figure 2.4 Soils of the Upper Ewaso Ng'iro Basin (Source: Sombroek et al 1980)

Soils of the mountains: On the Mt. Kenya and the Nyandarua Range, the higher altitudes exceeding 2000 m above sea level are dominated by deep clay loam soils on volcanic rocks, comprising of chromic-humic Cambisols and humic Andosols (FAO classification). These soils are formed from recent volcanic activity, therefore, they have a thick humic topsoil, with organic matter content ranging about 4.5 to over 13 percent. At lower altitudes, the rolling to undulating uplands of the mountain footridges and the Nyambene hills have very deep, dark red to red, or dark reddish-brown friable clays comprising of the eutric Nitisols and luvic Phaeozems. They usually have a moderate to strong subangular blocky topsoil, which is underlain by a moderate angular blocky subsoil. These soils have favourable moisture storage capacity and aeration conditions. They have good structural stability, which enables them to be cultivated even on steep slopes with minimum degradation hazards.

Soils of the plateaux: The middle parts of the Laikipia Plateau, around Ol Pejeta, Mutara and Mukenya comprise imperfectly drained, cracking clay soils (chromic-pellic Vertisols). These soils cover about 12 percent of the basin. They are fine in texture and contain montmorillonitic clay minerals. During the dry season, they shrink whilst during the wet season the soils swell up. Whereas the infiltration rate of the dry soil is very high due to the cracks, permeability drops to very low values once the soil is saturated. Under this condition, the soils are very susceptible to erosion. Appearing in pockets on parts of the plateaux are the eutric Planosols, comprising imperfectly drained, dark brown firm clay soils, with a pronounced abrupt transition between a relatively light textured topsoil and a heavy textured, compact and hard B-horizon. They are found on flat or slightly depressional old land surfaces, where actual erosion is quite minimum. The swamps that occur in the plateau have poorly drained, firm clay soils with poorly decomposed litter on the top (gleyic Solonchaks).

Soils of the hills and minor scarps: The hills and central uplands of the Mukogodo, Lol Daiga and the Mathews Range have well drained to excessively drained, shallow to deep, dark reddish brown gravely sandy loam to sandy clay soils. The gravely soils are found on the upper slopes (eutric Regosols), while on the lower slopes, where colluvial material has accumulated, chromic Luvisols dominate. Erosion has removed the topsoil in parts of the uplands.

Soils of the northern lowlands: These comprise mostly calcic-chromic Cambisols and ferric-chromic Luvisols, which cover about 24 percent of the basin. These soils are characterised by low organic matter (less than 1 percent) in the topsoil and illuviation of silicate clay minerals in the B-horizon. As the subsoils are often of low porosity and relatively high bulk densities, they have poor water storage capacity and a tendency to form a strong surface seal. Thus, the soils have high runoff producing properties.

2.5 Population and Land use

Population density in the Upper Ewaso Ng'iro basin averages about 60 persons/km^2, but the distribution ranges from 212 persons/km^2 on the highland small scale farming areas, to less than 24 persons/km^2 in the plateau areas (Huber and Opondo 1995). The differences in population densities relate to the land use systems, which are diverse. A large proportion of the basin area is taken up by large-scale commercial ranches for beef and dairy cattle. The drier northern regions of Mukogodo, Isiolo and Wamba are occupied by communal grazing lands and group ranches used by the pastoral communities who include the Maasai, Samburu, Boran, Turkana, Ndorobo and Somalis (Thurow and Herlocker 1993). Two game reserves, Samburu and Buffalo Springs are found within the basin and reserved exclusively for wildlife. Along with these, wildlife is to be found in most parts of the basin.

Cultivated land occupies a small proportion of the Upper Ewaso Ng'iro basin. The large scale wheat and barley farms are found in thin strips around Mt. Kenya and the Nyandarua Range. Adjacent to these are the small scale settlements operated as mixed farms. Here maize is the predominant crop, supplemented by beans, peas, potatoes and vegetables (Kohler 1987). Forests are found on higher altitudes of Mts. Kenya, Nyandarua and the Nyambene hills above the croplands. Forests having less canopy and bushlands are found on the Mukogodo and Engare Ndare highlands, Mathews Range, hills and minor scarps.

The diversity in land use and management practices ranges from highly mechanised and modern farming techniques on the large scale farms and vegetable/greenhouse irrigated farms of the Timau area, to the manual cultivation with low technological and material inputs of the adjacent small scale farms. There are contrasts in the grazing management between the large scale commercial ranches and the communal grazing areas, where overgrazing occurs and land degradation is quite evident. Tourism is an important economic activity, the main attraction being wildlife. There are different wildlife management practices which include county council owned game reserves, privately owned game ranches (with or without livestock), gazetted forests and communal grazing lands. The animal populations and diversity of species change with each management system (Thurow and Herlocker 1993).

Given the foregoing characteristics, identifying a suitable methodology to assess soil erosion hazard in the Upper Ewaso Ng'iro basin has to address the prevailing physical, climatic and social-economic structures described in this chapter. This requires some background knowledge of appropriate methods. Such information has been obtained from literature as described in the next chapter.

CHAPTER III:

EROSION HAZARD ASSESSMENT: A THEORETICAL BACKGROUND

This chapter reviews literature on methods of erosion hazard assessment and the use of remote sensing, Geographic Information Systems and soil loss models in erosion studies. It provides a conceptual background to the development of a methodology for the assessment of erosion hazard in the Upper Ewaso Ng'iro basin.

3.1 Assessment of erosion hazard

Erosion hazard has been defined (Bergsma 1980) as "the probability that soil erosion will start in the near future, or, in the case that erosion is already evident, erosion hazard expresses the intensity of the erosion processes, or the degree of soil loss expected". Erosion hazard, which is the combined effects of all the factors associated with soil loss, should be distinguished from erosion susceptibility, which is influenced by the relatively permanent factors of climate, relief and the soil. Thus, erosion susceptibility depicts a characteristic of an area, which is independent of land use and management. Therefore, for the current study, erosion hazard assessment is more relevant.

Assessment of soil erosion hazard is a difficult task particularly as erosion is an intermittent process. It is normally difficult to observe the erosion process in action, and in most cases, only its consequences are investigated. These can be seen as exposed subsoils and sediments removed by erosion. However, these indicators of erosion may not always be conspicuous and their traces are easily obliterated. In addition, erosion does not occur as an isolated phenomenon, but takes place with other processes such as deposition (Zachar 1982). In Africa there are other problems that discourage erosion assessments (Chakela 1992). These include, for instance, lack of long-term and continuous data collection, spatial sampling problems due to poor instrumentation, lack of well developed infrastructure to operate monitoring systems efficiently, manpower, availability of resources and shortage of funds to enable procurement of equipment and materials required for the monitoring system instrumentation and data analysis. The current study was faced with similar problems. There is also the question of scale which affects the type of data available and the methods to use for determining erosion hazard for large areas.

3.1.1 Scales in erosion hazard assessments

Changes of scales in time and space generally go together, and affect the level of detail to be included in an erosion hazard assessment exercise (Kirkby 1998). At each upward scale, there is a choice between computations for larger areas, as in the current study, or for longer periods. Upscaling goes together with loss of detail and the need to extrapolate data in the spatial domain. At scales from the erosion plot to the single hillslope, the timing and volume of overland flow hydrograph is critical, together with its distribution across interill and rill areas. At the regional or catchment scale, topography, soil and vegetation become dominant, while at the coarser national to global scales, climate and lithology are the dominant variables. Whereas individual study plots may be established so that variance in the erosion related parameters may be minimised, it is usually difficult to cater for the physical and environmental heterogeneity of large catchments. This is especially a problem in the mountain environments (Harden 1990) where landscapes can be extremely fragmented, not only in topography, but also in soil types, climate and land use patterns, as occurs in the Upper Ewaso Ng'iro basin. However, there are different techniques of assessing erosion hazard at each scale.

The assessment of soil erosion can be carried out at microscale (detailed scales), mesoscale (semi-detailed) or macroscale (reconnaissance), depending on the type of data required, the level of detail sought, and availability of resources including time (Morgan 1995; Lal 1998). The microscale involves studies of soil erosion from plots and hillslopes, at the scale of a few square metres to a few hundred square metres. At this scale, studies of the basic processes governing soil splash, detachability and transportability, initial overland flow and sediment transport by rills can be done with either direct observations and/or measurements. The mesoscale involves evaluation of sediment sources from small catchments and farm units measuring from a few hectares to hundreds of hectares. Measurements of erosion at this scale are needed to evaluate the effects of farming practices, land use systems and topographic factors on runoff and erosion. The macroscale involves assessment of erosion for large watersheds, which may be in hundreds to thousands of square kilometres. This is the scale used to assess the degradation of major river basins, mountain systems, ecological regions and countries. Erosion hazard assessment in the Upper Ewaso Ng'iro basin is basically a macroscale study, but there are interactions with the other scales as data collection was done at all three scales.

Erosion hazard assessment normally involves an evaluation of the land resources, aimed at dividing the land into regions, similar in their degree and type of soil erosion (Morgan 1995). It may include determining the actual or potential risk of soil erosion and loss in productivity of the land affected. The FAO (1979) has listed four general ways by which erosion assessments can be achieved, which include:

- Direct observation and measurements,
- Parametric methods,
- Remote sensing techniques, and
- Simulation models.

3.2 Observations and measurements

Direct observations and measurements are among the most commonly used erosion hazard assessment methods (West and Bosch 1998). However, the time and effort required for assessment of large areas are often beyond the resources available. One method at the detailed scales is to conduct direct measurement of soil loss from plots and small catchments. Plot studies can also provide the factors of erosion which are used in regression equations to determine soil loss from larger catchments. Both field measurements and laboratory studies can be used, but in the Upper Ewaso Ng'iro basin, only field plots were used.

3.2.1 Runoff plots

A runoff plot provides a physically isolated piece of land of known size, slope steepness, slope length and soil type, with areas ranging from one or two square metres to about a hectare for the quantification of runoff and soil loss (Hudson 1995). Plots have the advantage of isolating the amount of runoff and soil loss, where conditions can be controlled to study specific soil erosion processes. They are suitable for long-term observations on permanent stations requiring full-time monitoring. The standard plot (Morgan 1995) is normally taken as having the dimensions of the USLE unit plot (Wischmeier and Smith 1978) which is defined as 22.1 m long on a 9 percent slope, and is continuously maintained in a clean tilled fallow condition, with tillage performed up-and-down-hill. In their comparison of laboratory and field plots for erosion studies Mutchler et al (1988) suggested that other plot sizes should be wide enough to minimise errors due to edge effects and large enough to allow the development of rills downslope. Small plots are normally equipped with a collecting tank of known volume, where runoff can accumulate before it is measured, sampled and analysed. For larger plots, divisor units are usually included in the collector systems so that a known fraction of runoff can be sampled (Hudson 1995).

Runoff plots are important in erosion studies because they are used to demonstrate some known facts, or to make comparisons of different conservation options. They also provide data on the factors of erosion for use in prediction equations (Hudson 1995) as in the current study. However, data from runoff plots can be expensive, requiring trained staff and equipment, while backup facilities such as laboratories are also necessary. Zachar (1982) lists several studies in many parts of the world where runoff plots have been installed. In Kenya, runoff plots have been used (Kilewe 1978; Onstad et al 1984; Mati and Tsunoda 1990) for erosion assessments under diverse covers, and in the Upper Ewaso Ng'iro basin (Liniger 1991; NRM[3] 1997) several runoff plots have been set up for monitoring soil erosion and water balance dynamics. However, the high costs of setting up and maintaining the relevant infrastructure has resulted in their limited use in Kenya, including in the Upper Ewaso Ng'iro basin, where more plots were required for the current study, than could be set up with the available resources.

3.2.2 Measurements of rill and gully volume

At the catchment scale, slope lengths are usually long enough for development of rills and much of the sediment yield is the result of rill erosion. Rill measurements are therefore suitable for studying soil erosion over larger areas, especially when integrated into other field surveys (Hudson 1993). The most common methods of measuring rill erosion make use of rill meters (Mc Cool et al 1981) and photographic methods (Watson and Evans 1991). However, although rill erosion was observed in some parts of the Upper Ewaso Ng'iro basin during the current study, their measurement could not be included in the methodology due to time and logistical limitations.

Gullies are a major source of land degradation and their presence is an indicator that severe erosion is already taking place (Zachar 1982). Although ephemeral gullies usually form in the same location as previous ephemeral gullies, it is difficult to predict where and when new gullies will occur, how fast they will develop, and whether or not they will be a factor in soil degradation for a particular area. Gully erosion rates have been recorded of up to 3000 t $km^{-2}yr^{-1}$ (Laflen and Roose 1998). Measurements of gully erosion are therefore important in quantifying soil loss from small catchments, as they can be a source of huge quantities of sediments

In assessing gully erosion, volumetric methods are usually adopted, but they can be supplemented with photographic methods. Various methods of gully assessment have been described (Thorne and Zevenbergen 1990; Hudson 1993). They involve measuring gully dimensions, such as depth, width, local slope upstream area and distance downstream from gully head, over a given time to determine the rate of development. The assessment of gully erosion helps to determine the main causes of the problem so that rehabilitation as well as preventative measures can be applied. In Kenya, gully erosion has been studied at Longonot (Gathuru et al 1989), Kiambu (Mati 1989), Nyeri and Muranga (Mati 1993), showing that overgrazing, deforestation and road drainage are the main causes. Gully erosion is also a problem in the Upper Ewaso Ngiro basin, as was observed during reconnaissance surveys in the current study, but the scale and the available time and resources could not permit detailed gully measurements or their mapping. However there has been sediment monitoring from some small catchments in the basin (Ondieki 1993).

3.2.3 Measurement of runoff and sediment transport in rivers

Erosion rates at regional or national scales are often computed using techniques that include measurements of runoff and sediment transport in streams, rivers and large drainage basins. This may involve monitoring sediment transport rates past a river channel in the watershed over several years (Lal 1990). These measurements are usually made with water level recorders, discharge meters and flumes. Erosion rates over a delineated watershed can also be calculated by monitoring sediment yields in reservoirs. This technique has been used in many parts of the world, for instance in Tanzania (Rapp et al 1972), Lesotho (Chakela 1981) and in Kenya (Ogwenyi 1979).

Data on sediment deposition from reservoirs and stock ponds can be used to compute the sedimentation ratio over the watershed. The amount of sediment delivered to the watershed outlet is only a fraction of the gross soil erosion that occurs within a watershed. This fraction is determined by the sediment delivery ratio, defined as the ratio of sediment delivered at the catchment outlet to gross erosion within the catchment. If the information on trap efficiencies is known, the volume of sediment transported out of the watershed over a design period can be estimated (Stromquist 1981). Sediment delivery ratio is usually inversely related to catchment size (Lal 1990) ranging from about 5 percent for large watersheds over 100 km^2 to about 70 percent for small plots of 0.2 ha (Trimble 1977). Other studies have indicated an increase in sediment delivery ratio with watershed area (Heusch 1980). These anomalies have been attributed to the confounding effects of other geomorphologic and environmental factors (Walling 1983) such as the time lag and total sediment outputs for large watersheds, as sediment yield is a function of the runoff volume, which increases with size of the watershed. Edwards (1979) observed similar anomalies in comparing sediment yields from 97 river gauging stations in Kenya, 15 of which were within the Upper Ewaso Ng'iro basin.

3.2.4 Measurements of changes in surface level

Direct measurements of changes in surface level are used where soil erosion is localised and high erosion rates are expected (Hudson 1993). These types of measurements are usually suited to areas where the position of the erosion can be predicted such as on steeplands, deforested areas, cattle tracks and rangelands. The change in surface level can be measured at a point to give depth of soil loss, or in two dimensions to give a profile or cross-section, or in three dimensions as for volumetric measurements of rills or gullies. A limitation of quantifying soil loss by surface level changes is that measurements can include changes caused by factors other than erosion, such as those caused by humidity variations, freezing and thawing and cultivation (Zachar 1982).

One of the most common methods of point measurement is the use of erosion pins (Hudson 1993). These are metal pins, nails or stakes implanted on slopes, rills or gullies. The pins are slipped through washers and driven vertically into the ground so that the washer sits flush on the soil surface. Soil erosion is determined by the amount of surface lowering recorded (De Ploey and Gabriels 1980). Comparisons of soil erosion measurements using erosion pins with sediment assessments from reservoirs (Millington 1981) found that estimations with erosion pins tended to be higher. Another problem with erosion pins is that in some countries, iron or steel pins might be stolen (Hudson 1993). This happened in the current study where nearly all the erosion pins fixed at the beginning of the research work were stolen, thereby, forcing the method to be abandoned.

Detector methods, such as painting collars around rocks, tree roots or fence posts (Lal 1990) are sometimes used to deduce soil erosion. In the rangelands, the remnants of vegetation and tree root exposure can also be used as indicators of surface lowering by erosion. However, caution is required using such information and the results can be misleading. In a comprehensive study in Tanzania, Rapp et al (1972) observed that tree mounds were the result of the soil protected from splash erosion when the surrounding soil is eroded, resulting in a lowering of the surface of about 10 mm per year. Studies in Botswana (Biot 1990) in which soil erosion was calculated using tree mounds, obtained about ten to fifteen times greater soil loss estimates than by other methods. This exaggeration was attributed to a raising of the local surface due to the trapping of soil and organic matter, rather than a lowering of the surrounding surface. In addition, some tree species grow with their roots exposed even on undisturbed soil, while other trees with dominant tap roots may not show erosion even if 20 cm of the surrounding soil has been eroded. Although these types of raised tree mounds were observed in the Upper Ewaso Ng'iro basin, they were used only as indicators of soil erosion, and not used to quantify soil loss.

3.3 Parametric methods

Erosion hazard assessments are often based on small-scale reconnaissance surveys. These surveys are usually combined with information on topography and climate, to provide qualitative data that can be used to develop relative rankings of soil erosion (West and Bosch 1998). Parametric methods can be used in semi-detailed or reconnaissance erosion assessments, which may include land capability classifications, soil surveys, radioisotope techniques and factorial scoring methods. Parametric methods were of interest to the current study because they provide semi-detailed data, which can be used to complement plot data for the assessment of erosion at the basin scale.

3.3.1 Land capability classification

Land capability classification is used to rank land based on the severity of its limitations for agricultural use (Landon 1991). A land capability unit consists of a group of soil types of sufficiently similar conditions of profile form, slope and degree of erosion as to make them suitable for similar crops. Up to eight capability classes have been defined (Morgan 1995), whereby the dominant criteria is soil type and topography. The main problem with land capability classifications is that the quantified limits for distinguishing features of subclasses may not coincide with the measurable values in practice. This may be solved by modifying the limits for local use, or by redefining the standard limits to coincide with naturally occurring land features.

3.3.2 Soil surveys

Soil surveys have long been used to give qualitative estimates of erosion hazard over large areas (Lal 1990). In addition to indicating the location and extent of each kind of soil, interpretations of soil maps can be made to show the susceptibility of soils to erosion, and consequently the various conservation alternatives. Quantitative descriptions of the soil are made, which classify erosion risk into four classes as shown in Table 3.1.

Table 3.1 Classes of erosion (Lal 1990)

Class	Description
1	No apparent or slight erosion
2	Moderate erosion, moderate loss of topsoil generally and/or some dissection by runoff channels or gullies.
3	Severe erosion; Severe loss of topsoil generally and/or marked dissection by runoff channels or gullies
4	Very severe erosion: Complete truncation of the soil profile and exposure of subsoil (B horizon) and/or deep and intricate dissection by runoff channels or gullies

Various erosion assessments have been carried out using soil survey methods (Ritcher 1980; Muchena 1979). In most cases, the soils information is collated with basic inventories of vegetation, climate and other aspects of the land. The essential land characteristics are then developed which, together with ground truth studies, help to determine the ratings for erosion hazard of the area. One problem with soil surveys is with the soil classifications used to derive the data for parametric assessments of erosion. West and Bosch (1998) attributed this to the definitions of diagnostic horizons and taxa, which are based on limits rather than absolute values. These limits usually express the range for a property, rather than a mean value, and the mean of a range may not necessarily represent the mean of the population of the region of interest. Despite this, soil surveys provide vital information about soils and land characteristics. In the current study, soil surveys were used to derive factors of soil erodibility, which were subsequently used in erosion modelling.

3.3.3 Factorial scoring

Factorial scoring (Morgan 1995) is a simple method of erosion hazard assessment for large areas and country studies, which involves rating erosion risk by a scoring system. The region is divided into grids and each unit rated on a scale depending on erosivity, erodibility, slope, ground cover and land utilisation. The scores are added up to give a total score, which is compared with an arbitrary value set to classify the land into zones of low, moderate and high erosion risk. The problem with this technique is that each factor is treated independently, and they are combined by addition with each factor being accorded equal weighting. Multiplication of the factors is also possible, but there is the problem of some factors with zero values giving misleading results. Factorial scoring is easy to apply, especially with Arc/Info GIS to provide maps of erosion hazard at scales of 1:1,000,000. It was adopted for assessment of erosion hazard in the Mediterranean countries through the CORINE programme (Briggs and Giordano 1992). For finer resolutions, Herweg (1996) devised a similar scoring system, called Assessment of Current Erosion Damage (ACED) achieved through simple measurements and by checking erosional features on small fields. The detailed data obtained from the ACED can be used for conservation planning at catchment level.

There are other methods of rapidly estimating soil erosion at regional scales (Morgan 1995). One method involves the assessment of erosion intensity, which can be achieved by determining the length of stream per unit area (drainage density), or by determining the number of first-order streams (drainage texture). In addition, rainfall erosivity indices obtained through empirical models such as the Universal Soil Loss Equation (Wischmeier and Smith 1978) or the Soil Loss Estimator for Southern Africa (Elwell 1981) can be used to deduce erosion risk areas. However, these days, many erosion hazard assessments for large watersheds and country studies rely on data obtained by remote sensing.

3.4 Use of remote sensing

Until the 1950s, information on the nature and extent of erosion was collected mostly by conventional surveys (Dwivedi et al 1997). Since the 1960s and early 1970s, space-borne multispectral data has been extensively used in conjunction with aerial photographs and ground truth, for deriving information on eroded lands. Remotely sensed data offers some advantage over data obtained by conventional surveys (Pickup and Chewing 1994). It covers larger areas, allowing them to be analysed as a unit. In addition, remotely sensed data provides the ability to obtain repeated coverage of an area, showing temporal changes relatively economically and quickly. The data for land resource surveys is commonly obtained from satellite images such as the meteorological NOAA-AVHRR (National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer) which has a resolution of 1.1 km and is quite good for reconnaissance or country scales for weather and vegetation studies. The others include Landsat Multispectral Scanner (MSS) and the Thematic Mapper (TM), which have 79 m and 30 m ground resolutions respectively, the European Remote Sensing Satellite (ERS-1), the Japanese Earth Resources Satellite (JERS-1), the Indian Remote Sensing Satellite (IRS-1Aand 1B) and SPOT (Lillesand and Kieffer 1994). Land cover mapping in the Upper Ewaso Ngiro basin made use of SPOT imagery.

3.4.1 SPOT imagery

The SPOT satellite carries high resolution visible (HRV) sensors that acquire digital image data having either a 10 m spatial resolution for SPOT panchromatic or 20 m for SPOT multispectral image in three bands; the green, red and near infrared bands of the spectrum (Lillesand and Kieffer 1994). Due to its higher spatial resolution, the SPOT system can be used to map smaller areas than the other satellites and visual interpretation is much easier. Another advantage of SPOT data is that it has the possibilities of stereoscopic coverage of the scene (Stromquist et al 1988). In addition, the XS imagery is system corrected for radiometry and geometry of the earth's rotation, curvature and angle of registration, while the panchromatic image is precision corrected (geometric properties of the image are close to those of a topographic map). SPOT data is particularly useful for assessing vegetation.

3.4.2 Assessment of vegetation cover with remotely sensed data

Remote sensing has been especially useful in deriving indices of vegetation cover for degradation assessments. This is because vegetation cover has spectral reflectance properties that include leaf colour, texture and chlorophyll levels, which can be determined with the Normalised Difference Vegetation Index (NDVI), the soil background, and water (Barrett 1991). In dry areas, the general lack of cover allows direct observations of the land surface, and hence erosion. Identification of denuded areas is easier, as vegetation is sparse or absent, especially with gullying and mass movements. In some areas, the topsoil is removed, leaving a bright subsoil due to lack of organic matter (Millington 1981). Another problem is that in tropical climates, the rainy season scenes are usually difficult to interpret, as the whole area greens up, obscuring the surface conditions. In addition, plant species composition usually cannot be detected directly from reflectance characteristics. It is also not possible to recognise many types of erosional features such as rills, gullies or sheet flow because of inadequate spatial resolution. Land degradation, therefore, must be defined in terms of one or more of the vegetation indices (Pickup and Chewing 1994).

3.4.3 Assessing soil degradation with remote sensing

The determination of the extent, frequency and rates of soil degradation by remote sensing is based on spectral contrasts of reflectance values, measured from the upper few mm of soil the surface (Nizeyimana and Peterson 1997). However, direct assessments of soil degradation are preferable with nonimaging radiometers, because they can provide higher resolutions than satellite images. The chemical, physical and morphological soil properties detectable by remote sensing instruments are soil surfaces as a result of soil degradation, organic matter, iron oxide, moisture content, texture and roughness (Curran 1985). Other methods include visual interpretation and semi-quantitative means, for example, mapping soil erosion by radiances and calibrating soil erodibility with band ratios generated from raw radiances of satellite imagery (Pickup and Nelson 1984). Dubucq et al (1991) derived the Brightness Index (BI) from SPOT images, which could be used to distinguish erosion classes.

Remote sensing has been used for runoff prediction and soil erosion assessment in many parts of the world (DeJong 1994; Chen et al 1997). SPOT imagery has been used for land resources inventories in Lesotho (Stromquist et al 1988; Lunden and Nordstrom 1990) where the results were found to predict quite well the extent of erosion on the ground. Bocco et al (1990) created a map showing the distribution of gullies in Mexico using photo interpretation techniques of colour composites of enhanced SPOT stereo imagery. They found that gullies had a high reflectance in all bands and appeared as relatively shallow, irregularly shaped features. Adinarayana et al (1994) used Landsat TM combined with GIS to develop atlases of land use/land cover, drainage, soil type and erosion in India. In Kenya, aerial photographs have been used to compare the effects of land use on degradation in Machakos (Thomas 1974; Tiffen et al 1994). Land classification, its status and soil erosion have been assessed in Baringo District using Landsat (Wahome 1984). Remote sensing has also been used to assess land use dynamics, desertification and availability of resources in the Arid and Semi-Arid Lands (ASAL) of Kenya (Isavwa 1989). The use of remotely sensed data for erosion hazard assessments requires spatial modelling facilities, which can be provided by use of a GIS as in the current study.

3.5 GIS in erosion hazard assessment

A Geographic Information System (GIS) is set of tools for capturing, storing manipulating, analysing and displaying georeferenced data (Burrough 1986). GIS allows the development of spatial databases with associated attributes, that can be accessed and used by written algorithms or statistical analysis methods, to modify and combine data, and/or draw relationships (Petersen et al 1998). Recent developments in Global Positioning Systems (GPS) and Digital Orthophoto Quandrangles (DOQ) have greatly promoted GIS applications (Kelmelis 1993). This is because GPS allows the user to record accurately and rapidly the geographic coordinates of any location in the field, while DOQs, which are digital images of aerial photographs corrected to remove relief displacement and distortions, can be used quite easily.

The advantages of GIS (Petersen et al 1995) include the fact that data can be stored in a physically compact format, which can be retrieved quickly. Since spatial and attribute data are integrated into a single system, analyses by computer algorithms are now performed which would otherwise be impossible on analog map data. In addition, GIS is cost-effective for certain complex spatial modelling tasks (Bird 1989). On the other hand, the main limitations of using GIS include the high costs of the hardware and software, especially for complex modelling tasks. The conversion of existing analog and attribute data into digital formats can be laborious and quite costly. Also, a high level of technical expertise is required for successful GIS ventures. The current study made use of GIS for data acquisition, analysis and presentation. The use of GIS depends basically on reliable sources of data.

3.5.1 Sources of spatial data

Spatial data for erosion hazard assessments can be acquired by manually digitising soil and topographic maps, scanning aerial photographs and satellite imagery or by field surveys in which instruments such as a Global Positioning

System (GPS) are used. GIS data can be in various forms (Burrough and Mc Donnell 1998); vector data from surveys or digitised maps, attribute data (non-graphic data linked to points, lines, areas or objects for administrative records) or as images scanned into pixels in a raster format. GIS is scale dependent, it can be applied at global, regional or local level. It can also be used to provide information systems on land, networks, environment, planning and specialised information systems. The capture of existing information from analog maps into digital format requires consideration of the quality and characteristics of the mapping base (Petersen et al 1995). These maps must be spatially registered to a common controlled geographic coordinate system with similar scales, and with the relevant linkages as illustrated in Figure 3.1.

3.5.2 Digital Elevation Models

A Digital Elevation Model (DEM) is an ordered array of numbers that represents the spatial distribution of elevations above some arbitrary datum in a landscape (Moore et al 1991). DEMs are subsets of Digital Terrain Models (DTMs) which can be defined as ordered array of numbers that represent the spatial distribution of terrain attributes. The term DEM basically covers any digital representation of the continuous variation of relief over space, whereas DTM implies attributes of a landscape other than the altitude of the land surface (Burrough 1986).

A DEM can be structured in any of three ways; as a square-grid network, a Triangular Irregular Network (TIN) or a contour-based network. The most commonly used data structure is the square-grid network (Moore et al 1991). Topographic attributes such as slope, specific catchment area, aspect, plan and profile curvature can be derived from all three types of DEMs, but the most efficient DEM structure for estimating these attributes is generally the grid-based method.

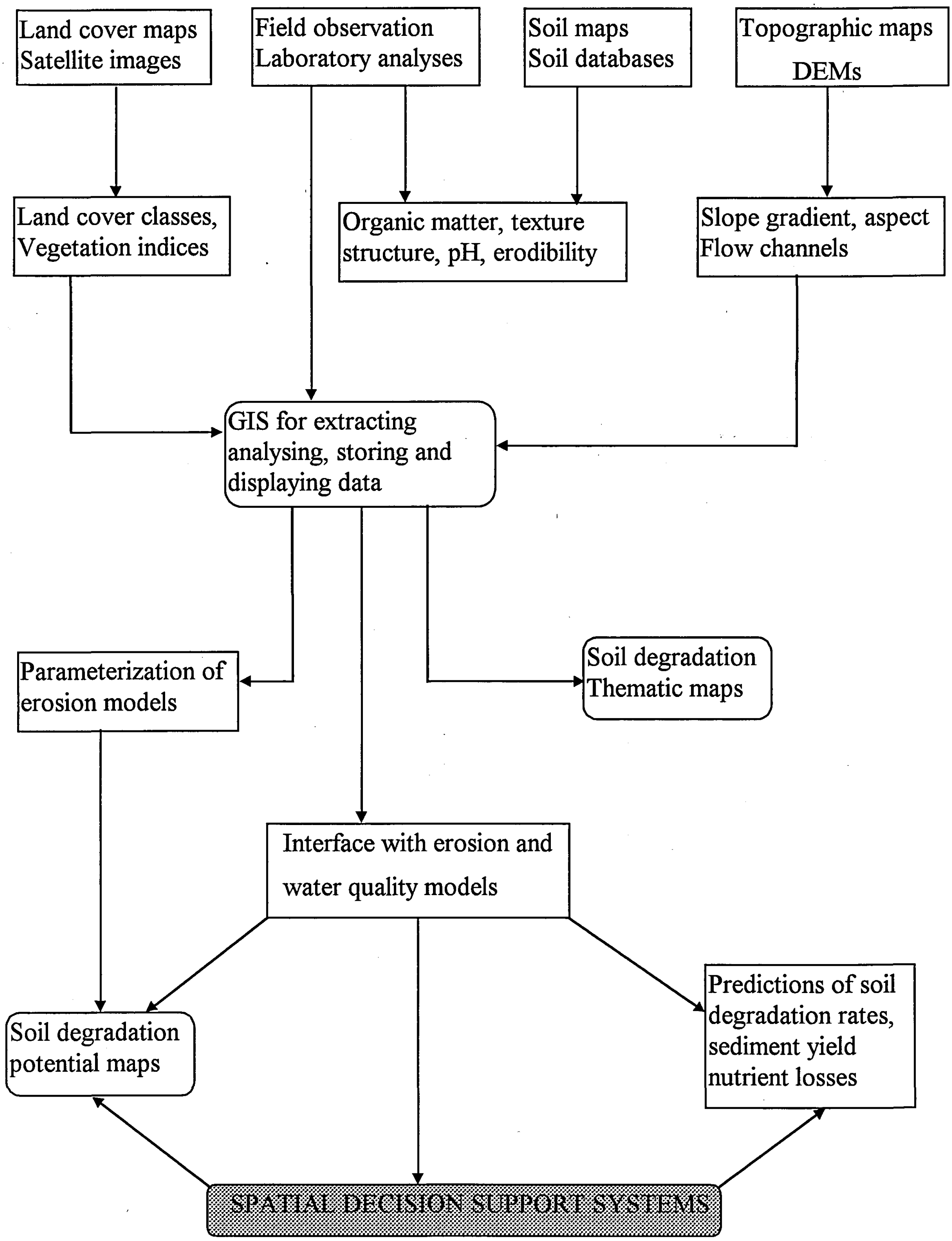

Figure 3.1 Flow diagram illustrating soil degradation data sources, and input and output of GIS analysis (Petersen et al 1998).

In comparison, the contour-based methods require a precise order of magnitude and do not provide any computational advantages, while the irregularity of the TIN makes the computations more difficult than for grid-based methods (Moore et al 1991; Petersen et al 1995). Therefore, based on these factors, this study made use of a grid-based DEM.

Several researchers (Moore et al 1993; Jensen and Domingue 1988) have developed algorithms to calculate primary terrain attributes such as slope gradient, aspect, curvature, specific catchment area, flow paths and watershed divide. For grid data, local interpolation methods are the simplest and easiest to implement (Zevenbergen and Thorne 1987). These terrain variables describe specific characteristics of the topographic surface, and can be displayed in three dimensions. In landscapes with natural depressions, the numerical filling of depressions in the DEM is used as a method of determining storage volumes, and to assign flow directions that approximate those occurring in the natural landscapes, once the depressions are filled by rainfall and runoff (Moore and Larson 1979). One problem with the analysis of digital elevation data for hydrologic applications is the definition of drainage paths when the DEM contains depressionless or flat areas. However, current developments in GIS have provisions for automatically generating flow sinks (ESRI 1997). The problem may now be the accuracy of the generated sinks as compared to their actual position on the ground.

A number of GIS software packages have been developed over the last few years. Some of the more popular ones include SPANS (Tydac 1997), GRASS (Geographical Resource Analysis Support System) and Arc/Info (ESRI 1997). Although most of these packages contain both vector and raster capabilities, each emphasises one or the other structure. For instance, GRASS is especially a raster-based and public domain software, while Arc/Info, which was used in this study, is primarily vector-oriented.

3.5.3 Arc/Info GIS

Arc/Info (ESRI 1997) is a vector-based GIS composed of two primary components; ARC, which stores coordinate data and performs all operations of the vector type of data, and INFO, which is a relational database management system (DBMS) to store and perform operations on attributes (the descriptive non-coordinate data). Arc/Info is one of the most widely used GIS softwares in the world and it is available to users on large mainframe computers, PCs and workstations (Peuquet and Marble 1989). Over the last decade, Arc/Info has undergone great technical evolution. It is now capable of rasterising vector data through modules such as the square GRID system or Triangular Irregular Networks (TIN), and performing interpolations and computations. In addition, the Librarian and Network modules permit the breakdown of large databases into smaller operational units which are added to the basic GIS. Arc/Info can be linked to image processing facilities such as ERDAS-IMAGINE (ERDAS 1997) thereby allowing more rapid and accurate data analysis. The Arc-View component of Arc/Info enables the viewing and querying of spatial data even by inexperienced users. New developments in Arc/Info are emerging every day and users have the advantage of upgrading old systems by downloading current packages from the Internet.

Despite these advantages, Arc/Info has limitations in that many of its programmes, especially for PCs users, still require typing commands at a DOS prompt. Much of the work with Arc/Info requires trained and experienced expertise. Arc/Info files usually require large computer memories which can be a disadvantage for portability of data, especially for use under field conditions, as was experienced in the current study. Like all GIS packages Arc/Info outputs can only be as good as the quality of data input in the first place, otherwise, it is quite a versatile software to use.

3.5.4 Integrating remote sensing with GIS

There are three main ways in which remote sensing and GIS technologies complement each other when used in erosion studies (Wilkinson 1996).

(i) Remote sensing can be used as a tool to gather datasets for use in the GIS, such as land cover mapping

(ii) GIS datasets can be used as an ancillary information to improve products derived from remote sensing

(iii) Remote sensing and GIS can be used together in environmental modelling and analysis, as in the current study.

Remote sensing products therefore form part of the graphics database, which makes it possible to overlay these data with GIS derived data. The current trend is to use softcopy photogrammetry to generate digital orthophotos, elevation data and feature extraction from scanned aerial photography (Petersen et al 1995). Integrating image processing techniques with conventional GIS provides possibilities for optimising the transformation of data into thematic information and improving the data quality for modelling and rule-based operations (Valenzuela 1991).

3.5.5 Integration of soil loss models with GIS

With advances in computer applications, the integration of GIS with erosion models has become quite popular in the 1990s (Petersen et al 1998; Fedra 1993) as illustrated in Figure 3.2. Grid cell-based models are easily interfaced with a GIS because of the high performance capabilities, such as the Arc/Info GRIDTOOL (ESRI 1997) used to rasterize vector data, as was used in the current study. Empirical models can be amended for GIS parameterization, since their coefficients and exponents can be easily applied to GIS layers. Integration of GIS with physically based models, however, requires detailed data inputs and is usually more demanding in resources and technology

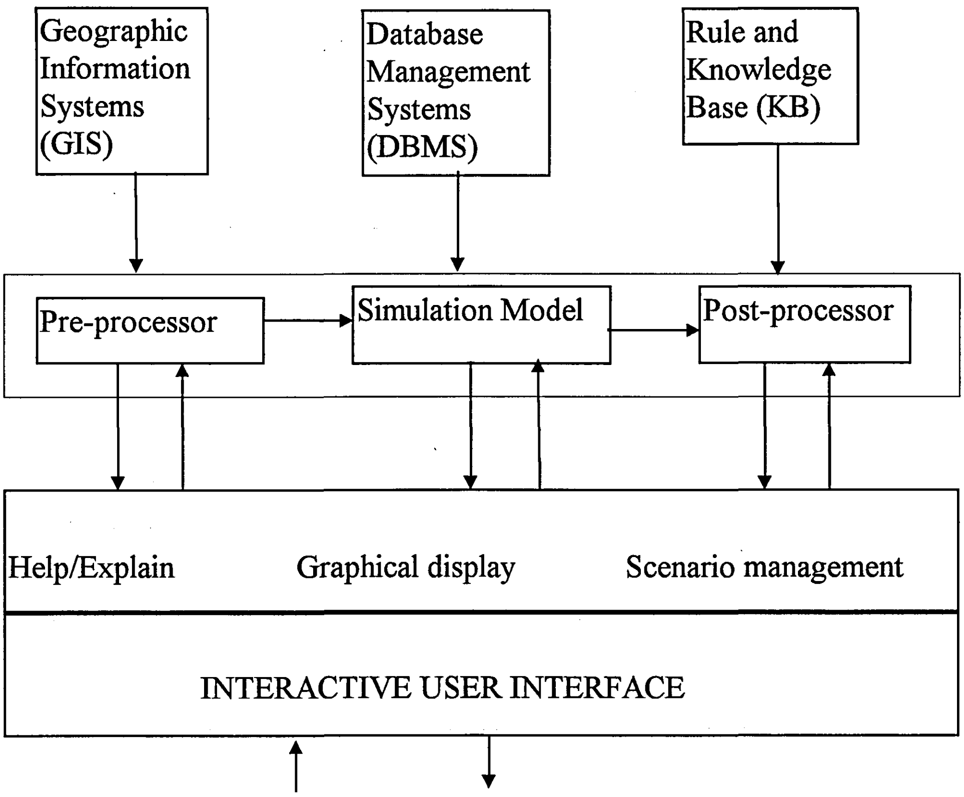

Figure 3.2 Integration of GIS with simulation models (Fedra, 1993)

(Sasowysky and Gradner 1991). In many cases, it is necessary to make use of interfaces, such as the Earth Resources Data Analysis System (ERDAS), that creates model input files from GIS databases, and performs the data processing required between the GIS and the model. For soil erosion studies, GIS has been used especially in association with remotely sensed data, to provide scenarios of the factors that affect erosion. Adinarayana et al (1994) used GIS to delineate land use patterns from spectrally inseparable classes, for a river catchment in India. Fedorowicz (1988) used a parametric approach to soil erosion modelling, and a raster type data base to increase the application and range of soil erosion surveys. One of the more popular soil loss models that has been used in a GIS environment is the Universal Soil Loss Equation (Wischmeier and Smith 1978). The simplicity of the USLE and the spatial variability of its parameters, makes it well suited for use in GIS. The variables of land cover, soil, slope gradient and length are first translated into classes of C, K, L, and S factors for each mapping unit or grid cell respectively. A digital map showing the distribution of long-term average soil loss in the watershed is then created by overlaying these GIS layers. A similar technique was adopted in this study.

The USLE has been used together with GIS in many soil erosion studies, such as in north-eastern Ghana (Folly 1997) in the Baden-Wurttemberg region of Germany (Jager 1994) and in the Black Brook watershed of Canada (Mellerrowicz at al 1994). In Kenya, Maingi (1997) used the USLE and Arc/Info GIS to estimate erosion in Kiambu. Other soil loss models have also been successfully applied in GIS. For instance, Savibi et al (1995) used the Water Erosion Prediction Project (Flanagan et al 1991) with GRASS and found that the model predicted runoff quite well. Similarly, GRASS has been used to simulate soil loss with the AGNPS model (Engel et al 1993) and also with the ANSWERS model (De Roo et al 1989). The choice of the GIS system to use also depends on the type of soil loss model applied.

3.6 Soil erosion models

Soil erosion models, like other models, are a representation of reality. They use equations, charts or diagrams which can simulate the response of a hydrological system to given inputs. Models can assist in the understanding of the system and therefore when used for hypothesis testing, they can provide a predictive tool for management (Beven 1989). According to Moore et al (1993) a good model should not be unnecessarily complex, and it should include the smallest number of parameters whose values must be obtained from data collection. It should not pretend to do too much, should be testable and accurate. Morgan et al (1987) state that models are of limited value until they have been validated with appropriate data. In addition, mathematical models of soil erosion are valuable for land use planning, if they can provide acceptable predictions of soil loss for a given set of conditions and simulate the role of soil conservation practices. The correct use of models requires an understanding of both the biophysical systems being studied and the operation of the model. A certain level of compatibility is required between the structure, spatial scale and the database needed to drive the model (Moore et al 1993). Soil erosion models may require climatic or weather input data and model parameters derived from measurements of topography, soil physical and chemical properties, geology, land use and land cover, hydrography and water quality data. These data can be of different temporal and spatial variability.

Soil erosion models can be used for farm planning, site specific assessments, project evaluation and planning, policy decisions or as research tools to study processes and the behaviour of hydrologic and erosion systems (Foster 1990). It is therefore important for the modeller to define the objectives and then consider the attributes of different models relative to the problem, in order to determine which model can provide the desired results. Some of the considerations include model purpose, representation, data requirements and availability, ease of parameter estimation, ease and cost of simulation (De Roo 1993). In addition, it is important to decide whether model results need be absolute values or relative comparisons between alternative scenarios. The current study aims to predict relative ranges of soil loss, for a watershed at reconnaissance scale, for resource planning and management at regional level. Therefore the model to be used should be applicable in a GIS environment, and flexible enough to allow easy parameter extrapolation from existing plot data and as cost effectively as possible. The next section reviews some of the commonly used soil erosion models.

3.6.1 Types of erosion prediction models

Soil erosion models can be grouped into physical, analogue and digital as described in Table 3.2 (Morgan 1995). With the advancements in computing capabilities, digital models have become the most common method of erosion modelling (De Roo 1993).

Table 3.2 Types of soil erosion models (Morgan 1995)

Type	Description
Physical	Scaled-down hardware models usually built in the laboratory; need to assume dynamic similitude between model and real world.
Analogue	Use of mechanical or electrical system under investigation, e.g. flow of electricity used to simulate flow of water.
Digital	Based on use of digital computers to process vast quantities of data.
(a) Physically-based	Based on mathematical equations to describe the processes involved in the model, taking account of the laws of conservation of mass and energy.
(b) Stochastic	Based on generating synthetic sequences of data from the statistical characteristics of existing sample data; useful for generating input sequences to physically-based and empirical models where data only available for short period of observation.
(c) Empirical	Based on identifying statistically significant relationships between assumed important variables where a reasonable database exists. Three types of analysis are recognised: *black-box:* where only main inputs and outputs are studied; grey-box: where some detail of how the system works is known; white box: where all details of how the system operates are known.

The types of models considered relevant to the current study are both the physically-based and the empirical models.

3.6.2 Physically-based models

Physically based (process-based) prediction models utilise a more deterministic (free from random variations) approach to simulate the transport and deposition of sediments over the landscape (Beven 1989). Process-based models predict erosion using mathematical representations of fundamental hydrologic and erosion processes, which are mainly detachment by raindrop impact, detachment by flow, transport by raindrop impact, and deposition by flow (Foster 1990) either as single events or continuous processes. Due to the greater demand for detailed data for process-based models, they usually apply to small areas the size of erosion plots, single slope planes or small catchments. Their value lies in extending process understanding knowledge through detailed field and laboratory experimentation, but they are generally too demanding in data requirements and often in computing time to be widely applicable as a management tool (Kirkby 1998). Some of the commonly used physically-based models are briefly described below.

The Areal Non-Point Source Watershed Environment Response Simulation (ANSWERS) (Beasley and Huggins 1980) estimates erosion and sediment yield for single events by representing the catchment as a square grid. Its primary application is in planning and evaluating various strategies for controlling surface runoff and sediment transport from intensively cropped areas. ANSWERS has the advantage of being easy to link with raster-based GIS (De Roo 1993) and it also considers runoff transmission losses. Its limitations are that it does not include erosion in the channel or gullies. In addition, it makes use of huge databases such as topographic maps, soil surveys and crop management surveys. The Small Watershed Model (SWAM) model was developed by the USDA (De Coursey and Seely 1988) to estimate the impact of alternative agricultural management on chemical, sediment and water losses from small catchments. It is designed to represent mixed land use watersheds of less than 25 km^2. The CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) model (Knisel 1980) was developed to predict non-point source pollution of agricultural chemicals due to erosion from small watersheds of up to a few hundred hectares. In comparison to the USLE which can be used directly in the field, CREAMS requires large computations in the office.

The Water Erosion Prediction Project (WEPP) is a physically based, deterministic, hydrologic, continuous simulation model (Flanagan et al 1991) that simulates the processes which are important to erosion prediction as a function of time, and as affected by management decisions and climatic conditions. WEPP estimates spatial and temporal distributions of soil loss for an entire hillslope on a daily, monthly or annual basis. In addition, erosion predictions are applicable to field-sized areas with uniform slope, profile and shape. For very dissected landscapes, it becomes difficult to apply the model unless several profile shapes are delineated. WEPP was one of the models considered for this study. However, it was not possible to acquire the level of detailed input data demanded by the model.

The Agricultural Non-Point Source Pollution Model (AGNPS) (Young et al 1989) provides a means for assessing watershed storm-based generation and transport of non-point source pollutants. AGNPS is an event-based model, applicable to watersheds of up to 800 ha. It accommodates sediments eroded from gullies and animal feedlots. However, it requires detailed nutrient analysis. EPIC (Erosion/Productivity Impact Calculator) developed by Williams et al (1990) also determines the relationship between soil erosion and soil productivity. The model uses a daily time step and a drainage area of about one hectare. Another process-based model is the Soil Erosion Model (SEM/SHE) (Styczen and Nielsen 1989) which was developed to improve on small catchment models like ANSWERS and is capable of predicting rill erosion. The Mediterranean Desertification And Land Use (MEDALUS) model (Kirkby 1995) can predict soil loss for catchments up to 2000 km^2. The European Soil Erosion Model (EUROSEM) is an event-based model designed to compute the sediment transport, erosion and deposition on fields and small catchments (Morgan et al 1992). As EUROSEM was chosen for use in the current study, it is discussed in greater detail in section 3.8.

3.6.3 Empirical models

Empirical prediction models are usually based on data from observations and experimentation (Morgan 1995). They can be used to predict mean annual erosion rates of an ungaged catchment, from a knowledge of the catchment characteristics and the local hydroclimatic conditions (Garde and Kathyari 1990). The introduction of GIS into erosion modelling has made empirical modelling more common especially at regional scale as exemplified by various studies (Mellerowicz 1994; Jager 1994; Maingi 1997; Folly 1997). Some of the commonly used empirical models are outlined below.

The GUELPH model for evaluating effects of Agricultural Management Systems on Erosion and Sedimentation (GAMES) (Madramootoo et al 1988) predicts water erosion and sediment delivery in agricultural fields, operating on a seasonal bases. GAMES can be run either as an analytical or predictive model, proving very efficient for identifying "hot spots" in selected watersheds, evaluating alternative soil and crop management practices and providing insights to the spatial variability of soil erosion and sediment yields (Dickinson et al 1990). However its application to the current study was limited by the scale, and the high data requirements.

The Soil Loss Estimator for Southern Africa (SLEMSA) (Elwell 1981) was developed using data from the Zimbabwe High Veldt. The model structure closely resembles that of the USLE as it also estimates long-term average annual soil loss. Though this model was developed for southern African conditions, it was not used in this study due to lack of the an adequate database or previous locally derived values for comparison of its factors, unlike the USLE. The Morgan, Morgan and Finney (MMF) model (Morgan et al 1984) was developed to predict annual soil loss from field sized hillslopes. It was developed to encompass the simplicity of the USLE, while retaining a stronger physical base like CREAMS. The MMF requires good information on rainfall and soils. However, it cannot be used for predicting sediment yields from basins or soil loss from individual storms.

The PERFECT (Productivity, Erosion, and Runoff Functions to Evaluate Conservation Techniques) model (Littleboy et al 1992) was developed for subtropical conditions in Australia to analyse the risks of soil erosion to long-term crop production. It simulates interactions between soil type, climate, fallow management strategy and crop sequence. Though PERFECT is a useful tool for modelling erosion on agricultural land, there are limitations on its use in rangelands and forest areas.

Perhaps the most commonly used empirical model is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). In attempting to expand its scope and improve its applicability or link it to GIS, some modifications have been made to the original USLE resulting in the Revised Universal soil Loss Equation (RUSLE) (Renard 1992) the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) and the Differential Universal Soil Loss Equation (DUSLE) (Flacke et al 1990). Compared to the USLE, MUSLE is applicable to individual storms, and eliminates the need for sediment delivery ratios, because the runoff factor represents the energy used in detaching and transporting the soil. The DUSLE is a version of the USLE, modified for mid-European conditions, combined with a digital elevation model, which has the structure of a triangular irregular network (TIN). The USLE, RUSLE and MUSLE were evaluated by Freebairn et al (1989) in Queensland, Australia, with the result that no single model was consistently superior to the others.

The current study was done using two models; process-based modelling with EUROSEM on two subcatchments in the basin and empirical modelling with the USLE. The USLE was chosen because compared to the other empirical models, it can utilise the relatively low number of input variables obtainable from the available data, while permitting easy extrapolation of its factors in a GIS. There has been extensive discussion as to whether the USLE is applicable to the tropics (Roose 1977; Vanelslade et al 1984) where the conditions differ from those under which the model was developed. However, the USLE is one of the few models in which several input parameters have been estimated under varying conditions, providing a reasonable background for further research and validation of the results obtained. In the Upper Ewaso Ng'iro basin, a number of plot and reconnaissance studies have been carried out providing data on soil loss and various factors of erosion. As this study was aimed at providing soil loss estimates for conservation planning at regional scale, the USLE was considered adequate for this purpose.

3.7 The Universal Soil Loss Equation

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) has evolved to become one of the most widely used models for predicting soil loss in many countries (Dissmeyer and Foster 1980). It estimates average annual soil erosion from rill and interill erosion, from the indices derived of rainfall, soil, topography and crop management. With the parameter values available, cropping and management alternatives can be determined to reduce the estimated soil loss to tolerable values for a given soil type.

According to Wischmeier (1976) the USLE may be properly used to:

- Predict average annual soil loss from a field with specific land use conditions
- Guide the selection of cropping and management systems and conservation practices for specific soils and slopes
- Predict the change in soil loss that would result from a change in cropping or conservation practices on a specific field
- Determine how conservation practices may be applied or altered to allow more intensive cultivation

• Estimate soil losses from other land use areas such as construction, rangelands, woodland, and recreational areas

• Provide soil loss estimates for land use planners, farmers and technicians to use for determining conservation needs.

Wischmeier (1976) warns that although applying the USLE to new geographic regions does not constitute a misuse, the model should be applied to situations for which its factor values can be determined from existing data with acceptable accuracy. However, for the USLE applications, some knowledge is required of the relationships that determine the derivation of each of its factors.

3.7.1 Components of the USLE

The USLE predicts soil loss for a given site as a product of six major factors, whose values at a particular location can be expressed numerically. Erosion variables reflected by these factors vary considerably about their means from storm to storm, but the effects of these fluctuations average out in the long run. That is why the USLE is preferable for predicting long-term averages (Mitchell and Bubenzer 1980) in which soil erosion is calculated as follows (Wischmeier and Smith 1978):

$$A = R \times K \times LS \times C \times P \qquad [3.1]$$

Where,

A = Is the computed soil loss per unit area, expressed in the units selected for K and for the rainfall return period used to calculate R. In practice these values are selected to provide the annual soil loss in units of $t\ ha^{-1}\ yr^{-1}$.

R = Rainfall erosivity factor ($J\ mm.m^{-2}\ hr^{-1}$)

K = Soil erodibility factor ($t\ J^{-1}\ mm^{-1}$)

LS = Factors of slope length (L) and slope steepness (S), which can be combined into a single topographic index (LS).

C = Crop and management factor

P = Conservation supporting practices factor

Each of these factors is determined as follows:

3.7.2 Rainfall erosivity factor (R)

The rainfall erosivity index (R) is defined as the product of rainstorm kinetic energy, and the maximum 30-minute intensity (Wischmeier and Smith 1978) which in SI units is calculated as follows:

$$R = EI_{30}/1000 \qquad [3.2]$$

Where,

E = Rainfall kinetic energy (J)

I_{30} = maximum 30-minute intensity (mm h^{-1})

This equation was derived from regression analysis of soil erosion with rainfall parameters in the USA (Wischmeier et al 1958). The rainfall erosivity indices for individual storms can be summed up for any time period to provide a numerical measure of the erosivity of the rainfall during that period. These rainfall factor values for a large area can be presented as curves of equal erosivity (iso-erodents) on a map of the affected area. The EI_{30} index, has been widely used as the standard USLE erosivity index. This index has been verified in many parts of the world (Bollinne 1980; Zanchi and Torri 1980; Lal et al 1980; Roose 1980; Foster et al 1982). In Kenya, soil erosion has been found to correlate with the EI index (Ulsaker and Onstad 1984; Kilewe 1987) showing that it can be used for estimation of erosion.

Several authors (Elwell and Stocking 1973; Hudson 1965; Lal 1976) have discussed the problems of determining an adequate rainfall erosivity index for areas outside of those for which the USLE was developed. Mitchell and Bubenzer (1980) found that the large variability in computed EI values between locales close together affected primarily the short duration storms. Moore (1979) observed that for East African conditions, the differences in the timing of erosive rains with respect to crop cover changes within a growing season affected the correlation between erosivity and soil erosion. However, for annual values in Kenya, erosivity has been found to correlate with soil loss quite well (Onstad et al 1984). Hudson (1995) cautions that in general, empirical indices should be treated with reserve, and comparisons involving the various erosivity indices need a backup of adequate database.

3.7.3 Soil erodibility factor (K)

The USLE erodibility factor (K) reflects the combined effect of the soil properties that significantly influence soil loss (Wischmeier and Smith 1978; Wischmeier et al 1971). It represents the rate of soil loss per rainfall erosion index (t $ha^{-1}yr^{-1}$) as measured from a unit plot. The K-factor describes the resistance of the soil to detachment by raindrops, and the subsequent transport of the detached soil particles by runoff. As K is an average value for a given soil, direct measurements of the factor require soil measurements for a representative range of storm sizes and antecedent soil conditions. Otherwise, the K-value can be estimated though indices derived either experimentally or empirically. The subject of soil erodibility has been well covered by various authors (Morgan 1995; Hudson 1995; Lal 1990; Wischmeier et al 1971) showing that it is an important factor in the process of soil erosion.

Direct measurement of erodibility is both costly and time consuming. It requires measurements from a unit plot over a sufficiently long period, to sample adequately the rainfall location. Wischmeier and Smith (1978) recommended a 22-year record because of the cyclical patterns of rainfall. In a study of the relationship between measured K values of 15 soil properties and their interactions, Wischmeier and Mannering (1969) developed a multiple regression equation of 24 terms which were considered valid for a broad range of medium textured soils. This was too cumbersome for general use. It was simplified to a relationship that calculates erodibility as a function of six soil properties, mainly the percentage silt, very fine sand, clay, and organic matter, soil structure and permeability. The relationships were expressed in the form of the USLE erodibility nomograph (Wischmeier et al 1971). This nomograph can be used to predict the soil erodibility factor, K, for soils for which the K value has not been previously determined.

There are contradictory reports concerning the applicability of the nomograph for estimating the erodibility of soils in the tropics (Hudson 1995). This diversity can be explained by the wide differences in tropical soils, and the still many soil types yet to be evaluated. The range of parameters used in the nomograph is rather wide. Thus, there is a need to develop adequate techniques for predicting the erodibility of the wide range of tropical soils, based on easily and routinely measurable properties. Finding a suitable erodibility index for soils under tropical conditions has its limitations because the majority of existing erodibility indices have been developed for soils in temperate regions. However, by using the USLE K-factor, it is possible to compare the erodibility factors obtained with those from other regions where the model has been widely applied (Vaneslade and Gabriels 1987; Onstad et al 1984; Jaiyeoba and Ologe 1990; Barber et al 1979). There have been suggestions that the USLE K-factor nomograph sometimes does not fit tropical soils (Vaneslade et al 1984). Studies by Roose (1977) indicated that the USLE was applicable to soils where kaolinite is the dominant clay mineral, whereas it may not be applied to Vertisols, characterised by expanding lattice clay minerals. This would suggest that in the current study, the K-factor determined by the USLE nomograph would predict erodibility well for some of the soils and not for others as the basin is comprised of a wide range of soil types.

3.7.4 Slope steepness and length factors (LS)

The factors of slope steepness (S) and length (L) can be calculated separately or they can be merged into a single index (LS), which expresses the ratio of soil loss under given slope steepness and length, to the soil loss from the standard USLE unit plot condition. The L and S-factors can be obtained from nomographs or calculated with the equations developed by Wischmeier and Smith (1978) as follows:

$$S = 65.41\ sin^2\theta + 4.56\ sin\theta + 0.065 \qquad [3.3]$$

$$L = (\lambda/22.13)^m \qquad [3.4]$$

Where,

θ = angle of the slope

λ = Slope length in m

m = an exponent that depends on slope steepness and n is 0.5 for slopes exceeding 0.5, 0.4 for 4 percent slopes and 0.3 for slopes less than 3 percent.

Equations 3.3 and 3.4 were developed for single uniform slopes. The topographic factor (LS) described by the equation will usually overestimate soil loss from concave slopes, and underestimate loss from convex slopes. To correct for irregular slopes, Foster and Wischmeier (1974) developed the following equation:

$$A = RKCP[\Sigma(S_jX_j^{1.5} - S_jX_{j-1}^{1.5})/X_e(22.13)^m] \qquad [3.5]$$

Where,

Xj = distance from the top of the slope to the lower end of the jth segment (m)

X_{j-1}=slope length from the top of the hill to the upper end of the j^{th} segment (m).

X_e = Overall slope length (m)

S_j = the value of the slope-gradient factor for the j segment and *A, R, K, C, P* and *m* are as defined previously.

For long slopes on which rill and interill erosion occurs, the LS factor was found (Mc Cool et al 1987) to consist of two linear relationships, with break-points at the 9 percent slope. These relationships predict less erosion on slopes steeper than 9 percent and also on slopes flatter than 1 percent than the original Wischmeier's equation. The two equations are given as follows:

$$S = 10.8\sin\theta + 0.03 \quad \text{for slopes} < 9\% \quad [3.6]$$

$$S = 16.8\sin\theta - 0.50 \quad \text{for slopes} > 9\% \quad [3.7]$$

These relationships describe the increase in soil erosion as the slope steepness increases due to the formation of larger rills at the steeper slope.

The application of the USLE in a GIS environment has greatly benefited from the possibilities of generating digital elevation models (DEMs) using contour maps (Burrough 1986). Thus, algorithms for automatically determining the USLE LS-factors in the GIS have been developed (Desmet and Govers 1996) which can run on IDRISI software. In a simplified form, Moore et al (1991) developed the following equation, for calculating the LS factor in the GIS:

$$LS = (m+1) \times (A_s/22.13)^m \times (\sin\theta/0.0896)^n \quad [3.8]$$

Where,

$n = 1.3$

A_s = the specific catchment area, while m and θ are as defined previously.

This equation was derived from the unit power theory by Moore and Burch (1986), and is better suited to landscapes with complex topographies than the original equation given by Wischmeier and Smith (1978), as it explicitly accounts for flow convergence and divergence through the A_s term in the equation. In applying the USLE for large catchments, the LS factor determination is very important. In the current study the choice of the equations to use in the LS-factor determination was guided by the presence of a wide range of slope gradients, as large areas of the Upper Ewaso Ng'iro basin have slopes in the two extremes, being less than 1 percent or exceeding 9 percent gradient. The Moore et al (1991) equation was found unsuitable as it requires very high resolution input DEMs which were not available. Therefore the Mc Cool et al (1987) equations were used.

3.7.5 Cover and management factor (C)

The cover and management factor (C) is defined as the ratio of soil loss from a specific cropping or cover condition, to the soil loss from a clean-tilled, continuous fallow condition (Wischmeier and Smith 1978). The C-factor is one of the most important parameters in the USLE as it measures the effects of all the interrelated cover and management variables (Renard et al 1991). The magnitude of the C-factor depends on the crop development and the rainfall distribution throughout the year. Values of C can vary from near zero for well-protected soil to 1.5 for finely tilled, ridged surface that is highly susceptible to rill erosion. In estimating the C-factor for other vegetation covers such as forests and rangelands, certain sub-factors are incorporated which include soil reconsolidation, depression storage and high organic matter content (Dissmeyer and Foster 1980).

C-factors can be determined from runoff plots in which there is a standard fallow treatment, and crop cover treatments in which the percentage cover may vary throughout the year with the stage of crop growth (Wischmeier and Smith 1978; Mutchler et al 1988). Crop-stage soil loss ratios and average annual EI_{30} indices for each crop-stage are used to compute the expected average annual soil loss. Six crop stage periods have been identified (Morgan 1995) which include fallow, seed-bed to 10 percent cover, establishment, development, maturity and residue or stubble harvest. The C-value is derived by dividing the year into the respective crop-stages, to obtain an initial C-factor for a crop at each stage. These C-factors are then weighted by the percentage of the R-factor associated with each stage. The sum of the weighted C-values for the different crop stages gives the average annual C-factor. This procedure is slow and it requires detailed experimental data taken over long periods. C-factors can therefore be estimated for different crops from studies done in various parts of the world. A comprehensive list of the USLE C-factors has been compiled by Morgan (1995).

Different approaches to C-factor mapping using remotely sensed data have been made. These range from automatic classification and principal component analysis to the use of spectral indices. One method is to use knowledge-based approaches which utilise additional geographical data besides satellite images (Hutchinson 1982). In these types of approaches, interrelationships are formalised into a set of rules and individual pixels are classified by determining the probability of a certain land cover type. Probabilities can be assigned using artificial intelligence or simply by applying a set of logistical decision rules. Such an approach was used by Folly et al (1996) to map C-factors in Spain. Since the C-factors cannot be obtained directly from remotely sensed data, a land cover map is first produced and the corresponding C-factors to the respective land cover types adopted from literature. This was the technique adopted in the current study.

There are problems associated with C-factor mapping from remotely sensed data. These include classification of land cover types for unhomogeneous areas such as the small scale-farms. In some cases, remotely sensed data does not correlate with the variables required by soil erosion models (De Jong 1994). The lack of correlation is mainly attributed to the fact that the low resolution of satellite imagery may not show information on canopy structure, litter layers or management practices. In addition, it is usually necessary to combine satellite image interpretation with ground truth data, which can be slow and expensive to undertake.

3.7.6 The conservation practice (P) factor

The conservation practice (P) factor is defined as the ratio of soil loss with a specific support practice to the corresponding loss with ploughed up-and-down hill culture. Values of P range from about 0.05 for reverse-slope bench terraces, to 1.0 where there are no erosion control practices (Wischmeier and Smith 1978). Values of P have been determined for terraces and cultural practices such as contouring, contour strip cropping, mulching and these vary with slope steepness.

Compared to the other factors of the USLE, research on the P factor has been rather limited. Thus, P-factors have to be adopted from the original values developed for the USA by Wischmeier and Smith (1978). However, these values do not include estimates of P for trash lines, grass strips, stone lines, fanya juu terraces or agroforestry practices adopted in other countries (Hudson 1995). Foster (1981) suggested that most of the mechanical properties represented by the P-factor, which are used to support protection provided by crop rotations, canopy cover and residue mulches, are probably transferable. Studies in Machakos, Kenya (Onstad et al 1984) found that P factors obtained using Wischmeier's tables could be transferred directly, and therefore, relevant to the current study.

3.7.7 Tolerable soil loss rates (T)

The tolerable soil loss (T) has been defined (McCormack and Young 1981) as the maximum level of soil erosion that will permit a high level of crop productivity to be maintained economically and indefinitely. The T-value is operationally defined in terms of the long-term average annual soil losses estimated with the USLE and is normally applicable to agricultural fields. It is a value based on soil renewal due to soil formation rates, as well as replenishment of fertility from added organic matter.

The cropping and management sub-factors to control soil erosion are determined using the value of T thus:

$$CP = T/RKLS \qquad [3.9]$$

Where *C, P, R, K L* and *S* are as defined in sections 3.7.1

Guide values of T have been developed in the USA (Hall et al 1985). These guide values have been adopted by many other researchers, including in Kenya (Kassam et al 1991; Kilewe 1987) for the assessment of erosion hazard.

A knowledge of the T value for a particular soil is important in the application of the USLE to help in selecting appropriate land use types and management practices. The maximum T value of 11.2 t ha^{-1} yr^{-1} (Mc Cormack and Young 1981) was adopted in the USA for permeable medium-textured soils in well managed cropland where the A horizon is estimated to develop at about this rate (Hall et al 1985). This rate of soil formation is much faster than the rate at which most parent materials weather to form soil. In the semi-arid and arid environments of Kenya, Dunne et al (1978) estimated soil formation rates of 0.125 t ha^{-1} yr^{-1} and 0.18 - 0.3 t ha^{-1} yr^{-1} for the humid areas. Barber (1982) observed that in Kenya, the T values have to be lower than those in the USA and that even with a T value of 6.7 t ha^{-1} yr^{-1} soil depth would still be lowered. Therefore, the application of T values in tropical regions, such as in the Upper Ewaso Ng'iro basin, where fertilizer application is limited by economic constraints requires further investigations. According to Lal (1984) higher concentrations of organic matter are selectively eroded in fine-textured soils, resulting in a loss in nutrients per tonne of eroded sediment that is greater than the nutrients in an equivalent mass of the original soil. He recommended that the nutrient enrichment ratios in the eroded soil should be used to set tolerance limits, as the maintenance of inherent soil fertility is the major factor determining soil productivity.

3.7.8 Limitations of the USLE

The simplicity of the USLE has many advantages that can lead to its application to conditions beyond its scope. To avoid this, Wischmeier (1976) suggested that the USLE should not be used to predict sediment deposition and delivery yields from a watershed, channels, gullies and rivers. In addition, the USLE should not be used to determine the processes of erosion or for predicting soil loss from a single storm, as all the factors are long-term averages which smooth out the large variations.

The empirical nature of the USLE implies that by multiplying the factor values which have been estimated individually, error propagation can be quite high. Burrough (1986) tested the error propagation of the USLE for soil loss calculated using a grid-based GIS and found serious error propagation problems of up to 50 percent. His recommendations for improvements included making use of a small number of predictive factors, avoiding multiplicative indices, and identifying the largest errors in an attempt to control them. In another study, Risse et al (1993) developed a set of statistics that would measure the performance of USLE. They obtained a model efficiency of 0.58 and found that in general, the USLE overpredicted soil loss on plots with low erosion rates, while the plots with higher rates were underpredicted. In addition, the cover and management and topographic factors had the most significant effect on the overall model efficiency, thus indicating that most of the research emphasis should continue to be placed on these factors.

In order to determine the factors associated with soil erosion from single storm events and complement the results of the empirical modelling obtained with the USLE in the current study, a process-based model, EUROSEM, was applied to two subcatchments, Embori and Mukogodo, in the Upper Ewaso Ng'iro basin. The model is briefly discussed below.

3.8 The EUROSEM model

The European Soil Erosion Model (EUROSEM) is a dynamic distributed (process-based) model designed to simulate the erosion transport and deposition of sediment over the land surface by interill and rill processes (Morgan et al 1992; Morgan et al 1998a). The model can be applied to individual storm events and to spatial scales ranging from a small field to a small catchment. It is designed particularly to predict soil loss from those storms which contribute most of the annual soil loss and therefore have return periods of six months or more. EUROSEM can also provide changes in surface elevation and rill geometry, as well as the dynamic effects of the interception process as the model separates leaf drip, direct throughfall, stemflow and interception storage.

EUROSEM operates by taking rainfall and runoff as inputs (Morgan et al 1992). The model then deals in turn with the interception of the rain by the plant cover, soil detachment by runoff and transport capacity, operating for short successive time steps within a storm. Compared to other erosion models, EUROSEM has explicit simulation of interrill and rill flow, plant cover effects on interception and rainfall energy; rock fragments or stoniness effects on infiltration, flow velocity and splash erosion and changes in the shape and size of rill channels as a result of erosion and deposition. EUROSEM can be applied to smooth slope planes without rills, rilled surfaces and surfaces with furrows. The dynamic nature of the simulation provides advantages over approximate flow methods commonly used (Morgan et al 1998b).

3.8.1 Components of EUROSEM

The components of EUROSEM are presented in the flow chart in Figure 3.3. EUROSEM is simulated with break-point rainfall data, ideally on a one-minute resolution for the storm, and computes in turn, the interception of the rain by plant cover, the generation of runoff as infiltration excess, soil detachment by runoff, transport capacity of the runoff and deposition of sediment (Morgan et al 1998a).

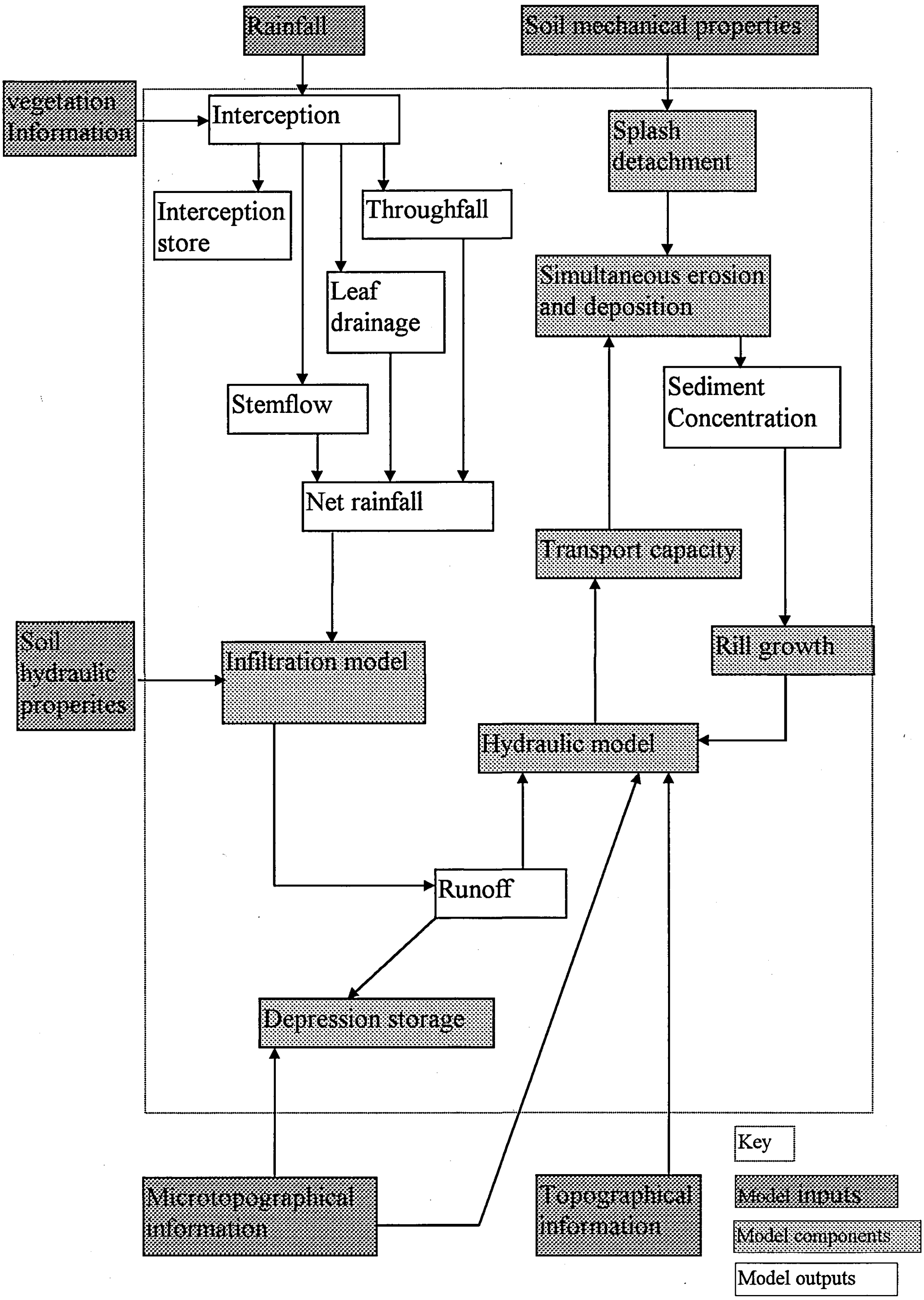

Figure 3.3 Components of EUROSEM (Morgan et al 1998b)

It uses the runoff generator and the water and sediment routines from KINEROS model (Woolhiser et al 1990). Both KINEROS and EUROSEM use an infiltration model based on unsaturated porous media physics, which models the onset of runoff and reduction in infiltration capacity during the storm (Smith et al 1995). The computation is based on the dynamic mass balance equation of erosion as presented in equation (7.1) (Morgan et al 1998b).

$$d(AC)/dt + d(QC)/dt - e(x,t) = q_s(x,t) \qquad [3.10]$$

Where,

A = Cross-sectional area of the flow (m^2)

C = Sediment concentration (m^3m^{-3})

Q = Discharge (m^3s^{-1})

e = Net detachment of rate of erosion of the bed per unit length of flow ($m^3s^{-1}m^{-1}$)

x = the horizontal distance (m)

t = time (s)

q_s = External input or extraction of sediment per unit length of flow ($m^3s^{-1}m^{-1}$).

Values of surface runoff Q(x,t) and A(x,t) are obtained by numerical solution of the dynamic mass balance equation for water.

$$dA/dt + dQ/dx = r(t) - f(t) \qquad [3.11]$$

Where

r(t) = The rainfall rate less the interception

f(t) = The local infiltration rate.

The term e in equation (1) is defined as:

$$e = DR + DF \qquad [3.12]$$

Where,

DR = The rate of soil particle detachment by raindrop impact ($m^3\ s^{-1}\ m^{-1}$)

DF = The balance between the rate of soil particle detachment by the flow and the particle deposition rate ($m^3\ s^{-1}\ m^{-1}$)

A detailed description of EUROSEM is presented in Morgan et al (1998a). However, three of the basic equations that describe the processes of soil particle detachment by raindrop impact, detachment and/or deposition by flow and the transport capacity of flow are described here to represent the major model processes.

3.8.2 Soil particle detachment by raindrop impact

The soil particle detachment by raindrop impact is modelled as a function of the kinetic energy of the rainfall at the ground surface, the detachability of the soil, and the water surface depth. This can be simplified into the following equation (Morgan et al 1998b).

$$DR = [(KE)e^{-bk}]/\rho_s \qquad [3.13]$$

Where,

k = an index of the detachability of the soil ($m^3\ J^{-1}$)

KE = the kinetic energy of the rainfall at the ground surface (Jm^{-2})

b = an exponent taken as equal to 2.0

h = the depth of water surface layer (m)

ρ_s = the sediment particle density (usually 2.65 $Mg\ m^{-3}$)

The kinetic energy of the rainfall represents the combined energy of the rain reaching the ground surface as direct throughfall, and that of leaf drainage.

3.8.3 Soil particle detachment by runoff

Soil detachment by runoff is modelled in terms of a generalised erosion-deposition theory (Smith et al 1995). This assumes that the transport capacity concentration of the runoff reflects a balance between the two counteracting processes of erosion and deposition. The general equation for particle detachment and/or deposition by flow is given as follows:

$$DF = \beta w v_s (TC - C) \qquad [3.14]$$

Where,

β = a flow detachment efficiency coefficient

w = width of the flow (m)

v_s = the settling velocity of the particles in the flow (m s^{-1})

TC = the sediment concentration in the flow at transport capacity and

C = the actual sediment concentration in the flow.

The term β in the equation is a function of the cohesion of the soil, usually measured with a torvane under saturated conditions. The cohesion of a soil has been found to be related to the detachment of soil particles by concentrated overland flow (Poesen and Govers 1990) which affects the possibility of rill initiation.

3.8.4 Transport capacity of the flow

The capacity of runoff to transport detached soil particles is expressed in EUROSEM in terms of a concentration. Two different relationships are used to predict interill and rill flows. For interill flow, the concentration is modelled as a function of the modified stream power, based on the experimental work of Everaert (1991) as follows (Morgan et al 1998a):

$$TC = b/(\rho_s q)[(\Omega - \Omega_c)^{0.7/n} - 1] \qquad [3.15]$$

Where,

b = a function of particle size,

Ω = Bagnold's modified stream power

Ω_c = a critical value of Bagnold's modified stream power

$n = 5$

For flow in rills, the transport capacity (TC) is modelled as a function of unit stream power, using a relationship based on the work of Govers (1990) which showed that the transporting capacity of overland flow could be predicted from simple hydraulic parameters. This is given in equation (7) as follows:

$$TC = c(w - w_c)^{\eta} \qquad [3.16]$$

Where,

w = unit stream power (the product of slope and flow velocity)

w_c = a critical value of unit stream power (0.4 cm s^{-1})

c and η are experimentally derived coefficients related to particle size.

Compared to other models that assume that all the sediment detached by raindrop impact and flow on interill areas is delivered into rills, EUROSEM computes delivery based on the transport capacity of the interill flow. For interill flow paths longer than 1 m, EUROSEM explicitly routes the flow, allowing deposition of sediment to occur within the interill areas.

3.8.5 Channel erosion

Channel flow and erosion are simulated in EUROSEM using the same general approach adopted for rill erosion, but soil detachment by raindrop impact within the channel is neglected. If there is no input of runoff at the upper end of the channel, the transport capacity at the first node is zero and the boundary condition is set as follows (Morgan et al 1998b):

$$C(O,t) = qs/(Qtv_sBW) \qquad [3.17]$$

Where,

BW = the bottom width of the channel (m)

Otherwise, procedures are precisely the same as for calculation of rill sediment transport, and bank collapse is not simulated.

3.8.6 Scope of the model

EUROSEM can be applied at a range of scales from single slope planes to small catchments (Morgan et al 1998a). A catchment is represented by a network of surfaces and channels of various complexity. Channels may receive distributed inputs from hillslopes on either side or both sides or as concentrated flow from one or two upstream channels. Hillslopes may be represented as heterogeneous flow paths.

Application of EUROSEM to catchments requires that the watershed be divided into homogenous slope elements, which are arranged in a cascading sequence to enable correct routing of water and sediments over the land surface (Morgan et al 1998b). Up to 60 elements can be used. The outputs from EUROSEM include total runoff, total soil loss, storm hydrograph and storm sedigraph for each slope element simulated. By interpreting the model outputs, it is possible to determine the timing of peak runoff, sediment delivery to the watercourses and the sediment sinks.

3.8.7 Limitations of EUROSEM

One of the limitations of EUROSEM is that it is not able to simulate erosion by ephemeral gullies or by saturation overland flow (Morgan et al 1998a). Erosion predictions are applicable to field-sized areas, with uniform slope profiles and shape. There are limitations to the application of EUROSEM for large watersheds because for very dissected landscapes, many cascading planes are required. Although EUROSEM has been applied to European conditions quite successfully, its applications to tropical conditions has not yet been thoroughly tested. Somba (1998) applied the results obtained from EUROSEM in SPANS GIS and found that the model requires cell sizes of at least 50 m in topographic raster-grid modelling. However, the model has yet to be incorporated in a GIS environment so that the processes it simulates can be assessed spatially and interactively. The model requires very detailed rainfall and catchment data inputs, which makes it difficult to adopt for modellers having no access to detailed data from a research station. There are still gaps in how to apply the model for mixed crops or non-agricultural fields. Applying the model to simulate rill erosion is especially difficult due to the huge volumes of data required for every rill in the hillslope. This is because rills are dynamic and their dimensions and position on the ground can change from day to day.

EUROSEM has been validated using plot data from Woburn, Bedfordshire, UK (Quinton 1994), in the Netherlands (Folly et al 1998), in Spain (Albaledejo et al 1994) and the C5 Watershed in Oklahoma, USA (Quinton and Morgan 1998). The model was found to simulate quite well the time to peak discharge, the peak discharge and the overall shape of the hydrograph, but it tends to overestimate sediment concentrations. Quinton (1994) found that apart from the overland flow hydraulic dynamic models, none of the other models are easily comparable with EUROSEM directly. He concluded that it was not possible to judge whether EUROSEM had performed better or worse than other models, but the general impression from validation results for the model was that EUROSEM performs to a similar standard as other process-based models.

Having discussed the theoretical background of the soil erosion hazard assessment, the next chapter presents the materials and methods used in this study.

CHAPTER IV

ASSESSING EROSION HAZARD WITH THE USLE AND GIS

This chapter describes the sources of baseline data, its acquisition and the methodology adopted in the assessment of erosion hazard in the Upper Ewaso Ng'iro basin, using the Universal Soil Loss Equation (USLE) and Geographic Information Systems (GIS). The chapter starts with consideration of the sources of baseline data and its acquisition. Then the steps taken in the derivation of the individual USLE factors from plot and reconnaissance data and their spatial interpolation with GIS are described as well as the prediction of erosion hazard in the Upper Ewaso Ng'iro basin. In addition, the limitations in scope and quality of the data and the implications for the results of the erosion hazard assessment are discussed.

4.1 Overall methodology

The assessment of erosion hazard in the Upper Ewaso Ng'iro basin relied on data from runoff plots and reconnaissance studies for spatial interpolation of soil loss in the basin, with the aim of obtaining results that can be used for reconnaissance conservation plans. The Universal Soil Loss Equation (Wischmeier and Smith 1978) was applied in a GIS environment to determine the average annual soil loss and its distribution in the basin. The USLE has been applied successfully in this manner in studies of soil erosion in other parts of the world (Kok et al 1995; Mellerowicz et al 1994; Jager 1994; Folly 1997). In this study, the procedure adopted involved creating GIS files for each factor in the equation (R, K, L, S, C, P). This was enhanced by interpolation of data obtained from weather stations, reconnaissance surveys, runoff plots and topographic maps. The files were then combined by cell-grid modelling procedures in Arc/Info GIS (ESRI 1997) to predict soil loss in the spatial domain. The grid-cells were set to 100 by 100 m, which was the resolution possible with the available data and computer facilities. Although the USLE is recommended for small plots and fields (Wischmeier and Smith 1978) the 1 hectare cell sizes used in this study were considered to give adequate detail as this study was of reconnaissance scale (Goodchild 1993). Each pixel was viewed as a single slope plane for which the USLE could be applied individually. It was not possible to route runoff and soil loss within a given subcatchment in the basin. Therefore, the soil loss values predicted in this exercise represent sediment yields per hectare of land area within each pixel, but they do not indicate sediment yields in small catchments or over hillslope units of a larger area. The data used in this exercise was acquired as follows.

4.1.1 Sources of baseline data

One of the greatest challenges of this study was the development of a research methodology that would combine the limited amount of erosion plot data available, with reconnaissance surveys to provide reliable estimates of erosion hazard in the Upper Ewaso Ng'iro basin. The first task was to identify the potential sources of data and assess its viability for use in the study. The second task was to identify gaps in the database and the extent to which they could be filled by field surveys. These activities took up the first six months of the research time, beginning November 1995. During this period, reconnaissance surveys were made of the study area to identify the potential for obtaining measurable variables. Since the basin is very extensive in area, the catchment and climatic characteristics vary widely. As the available plot data was insufficient in both spatial and temporal coverage for estimating erosion hazard, alternative methods and/or sources of data were necessary. The data to be collected had to be within the financial and time resources available.

It was found that some of this data had to be collected during the course of the study period, while the rest could be obtained from various institutions and published reports. The other sources of data were the Natural Resources Monitoring Modelling and Management (NRM^3) project of Nanyuki (NRM^3 1997), published reports (Jaetzold and Schmidt 1983; Sombroek et al 1980;

Ahn and Geiger 1986; Speck 1983; Kironchi et al 1992; Mainga and Mbuvi 1994; Mbuvi and Kironchi 1994) and government institutions such as the Soil Conservation Branch of the Ministry of Agriculture, Nairobi and the Department of Resource Surveys and Remote Sensing, Nairobi. Table 4.1 summarises the baseline data types and their sources for this study.

4.1.2 Data acquisition from reconnaissance surveys

Reconnaissance data were collected by the author from field surveys during the course of the study, to bridge the gap in the data obtained from other sources. Due to limitations of time and financial resources, it was not possible to set up new equipment for measuring soil erosion, or even to expand the existing facilities in the basin. Thus, data collection was planned to be extensive in both scope and spatial coverage. It was aimed at estimating easily measurable factors of erosion that could not be obtained from the available data, such as the soil erodibility and vegetation cover. As the data from other sources were of generally coarse resolution, the field data from reconnaissance surveys were meant to improve on the interpolation of parameters that were to be derived from maps in the GIS. These reconnaissance surveys were also used to ground truth the land cover mapping from the satellite imagery and to get a qualitative estimate of erosion hazard in the basin.

For the reconnaissance data collection, the first task was to design a suitable methodology that would allow the gathering of data quickly and cheaply, and yet provide relatively reliable results. It involved selecting subcatchments that were representative of the major land use, cover, soils, relief and apparent erosion hazard. Their location was stratified to include as wide a geographical

Table 4.1 Baseline data types and their sources

Data type	Source
Soil types	Soil sampling from 83 test site
Soil texture	Laboratory soil analysis
Organic matter content,	Laboratory soil analysis
Stone cover	Reconnaissance and laboratory studies
Soils map	Sombroek et al (1980)
Soil structure and permeability	Sombroek et al (1980); Ahn and Geiger (1986) Mainga and Mbuvi (1994)
Vegetation cover	Satellite imagery and reconnaissance surveys
Catchment vegetation cover types	Ground-truth studies
Land use and management	Reconnaissance surveys
Plot vegetation covers	NRM^3 database
Satellite imagery	Department of Resource Surveys and Remote Sensing, Nairobi
Rainfall characteristics and climate	
Annual rainfall amount	NRM^3 database
Daily rainfall amount, storm intensities and energy	NRM^3 database
Exploratory isohyetal map of Kenya	Jaetzold and Schmidt (1983)
Agroclimatic zones map	Sombroek et al (1980)
Topography	
Slope steepness at test sites	Estimated with a clinometer
Topographic maps	Survey of Kenya (1976)
Conservation practice	
District maps of the conserved areas	Soil Conservation Branch, Ministry of Agriculture, Nairobi.
Soil erosion	
Qualitative erosion hazard assessment	Reconnaissance surveys
Plot runoff and soil loss	NRM^3 database

NRM^3 = Natural Resources Monitoring Modelling and Management project; Nanyuki, Kenya coverage as possible in the basin. It was found that the sampling of strictly true hydrological subcatchments would be difficult, and would concentrate the selected areas in the highlands and hills. Thus, for better representation, especially of the plateau and lowland areas, the selected subcatchments were not necessarily defined by a definite hydrological boundary. For that reason, they have been referred to simply as "test sites". A total of 83 test sites were sampled (Figure 4.1). To maintain consistency in the evaluation, a data form was designed (Appendix 2) which was first tested in the field before adopting it. Each of the test sites was visited and the data form completed. The actual location of each test site was made in the field using a Trimble Scout^M Global Positioning System (GPS). At each test site, data were collected on physiography, land use and vegetation cover, soils and indicators of erosion and soil samples were also taken.

4.1.3 Data from plot studies

The data from erosion plot studies were obtained from nine NRM³ research stations. These stations were set up on diverse dates between 1984 and 1994 (NRM³ 1997). Site selection for each station had been stratified to include the major agro-climatic and land use systems in the Upper Ewaso Ng'iro basin, concentrating on the slopes of Mt. Kenya (Table 4.2). In an attempt to standardise results, each station was equipped with a weather station, which included a recording rain gauge and runoff plots. The plots are all identical (Plates 4.1-4.4) each measuring 10 m long by 2 m wide and having a collector tank of 0.2 m^3 for the inner tank and 1.15 m^3 for the outer tank.

The runoff plots were in most cases located on slopes of 4 to 5 percent, which are representative of the average slope gradients in the cultivated areas. However, some plots at Karuri (potatoes) and Naro Moru Met (bamboo forest) were on steeper slopes. As most of the runoff plots with neutron probes, and there are no control plots.

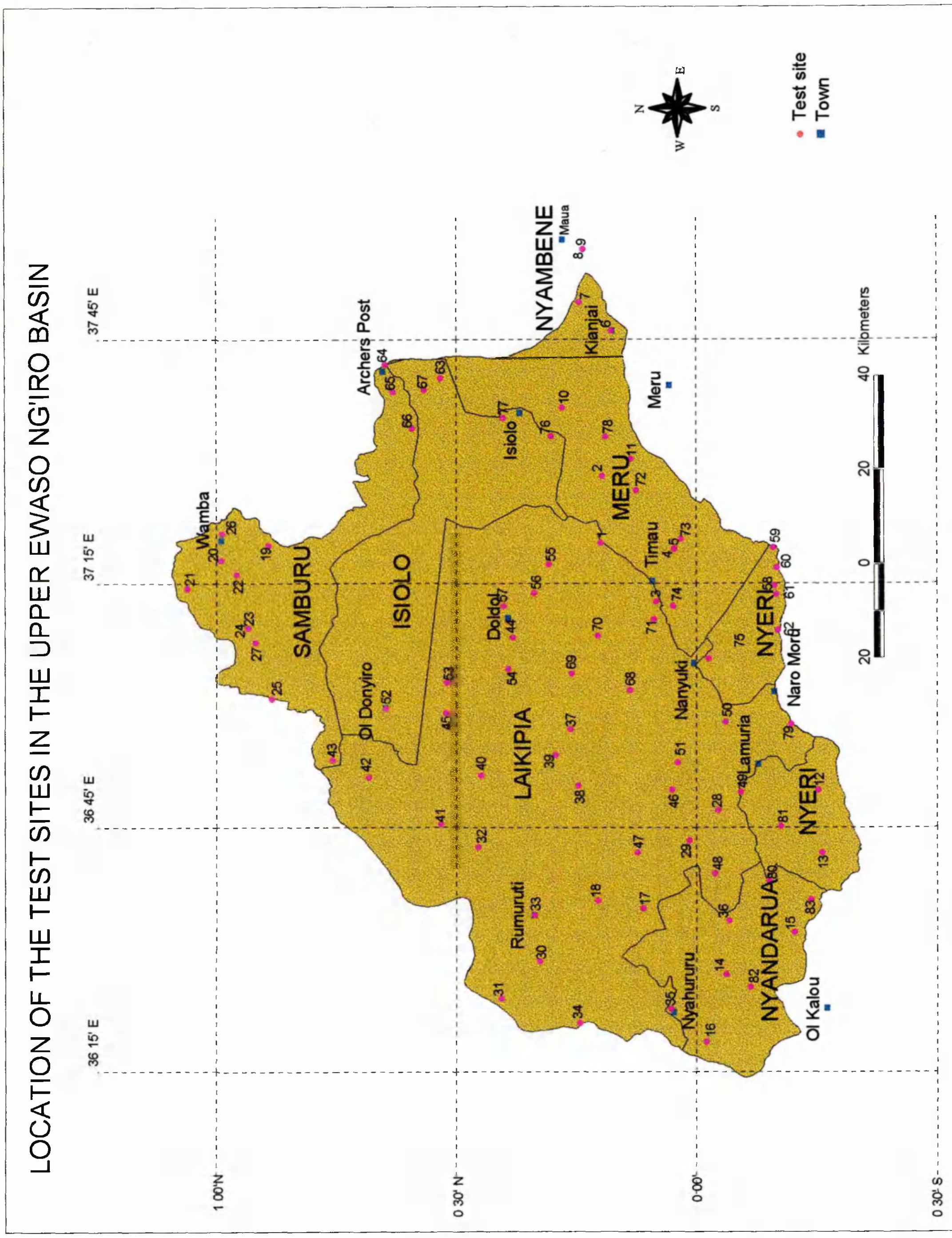

Figure 4.1 Location of the test sites in the Upper Ewaso Ng'iro basin

Table 4.2 General characteristics of the erosion plots

Station ID	Station name	Agro-climatic zone	Annual rainfall (mm)	Slope (%)	Soil type	Predominant Vegetation	Years with soil loss data
13	Embori	III-7	735	13	chromo-luvic Phaeozem	Barley	1994-95
28	Kalalu	IV-5	724	5	verto-luvic Phaeozem	Maize, grass	1990-95
31	Karuri	II-8	831	4 - 11	humic Andosol	Potatoes, grass	1993-95
44	Matanya	V-4	787	4	pellic Vertisol	Maize, grass	1986-92
52	Mukogodo	V-4	362	5	ferro-chromic Luvisol	Shrubland	1994-95
61	Naro Moru Gate	II-7	1059	5	humic Andosol	Grass, forest	1994-95
62	Naro Moru Met.	II-8	1470	5 - 12	humic Andosol	Grass, forest	1995
86	Sirima	IV-5	828	4	eutric Planosol	Bush, grass, potatoes	1993-95
91	Teleswani	II-8	812	4 - 9	humic Andosol	Grass, forest	1993-95


Plate 4.1 Runoff plots at Kalalu


Plate 4.2 Runoff plots at Sirima


Plate 4.3 Runoff plots at Teleswani


Plate 4.4 Runoff plots at Karuri

The data from the erosion plots used in this study were collected between 1993 and 1995. This was because that period contained the most comprehensive records of the relevant data. At each erosion plot station, weather data were collected as per standard procedure (Liniger 1991) but runoff and soil loss data were collected (or not collected) according to the requirements of the researcher using the plots that season. Thus, there are gaps in the available data on crop cover, runoff and soil loss from the various stations for some years. In compiling the annual data for use in the USLE in this study, these gaps were a major problem because in some stations, soil loss data were available for part of a year, and not for the full year, or rainfall data were available for a year when soil loss data were not available, and vice versa. Again depending on the individual researcher's requirements, there were data on mulching and various levels of grazing management on grasslands. These data were useful as indicators of the effects of the various management practices on soil erosion, but were too scant to be used for interpolation in prediction of soil loss at the basin scale. Therefore, this study made use of the data obtained only under conventional land use and management practices. The data used in this study had been quality controlled at NRM[3] and provided three basic parameters; rainfall, vegetation cover, runoff and soil loss. These data, together with that from reconnaissance studies, were used to determine the respective USLE factors.

The thematic maps relating to the USLE factors and erosion hazard are presented in chapter V, as they constitute the results of the study as well.

4.2 Determining rainfall erosivity

The general procedures followed in developing a rainfall erosivity map for the Upper Ewaso Ng'iro basin are illustrated in Figure 4.2. They involved calculation of erosivity indices using storm data from six stations (Embori, Kalalu, Karuri, Mukogodo, Sirima and Teleswani) for which comprehensive autographic records were available (Appendix 3), determining the annual rainfall-erosivity relationship and the spatial interpolation of erosivity from annual rainfall data in the GIS.

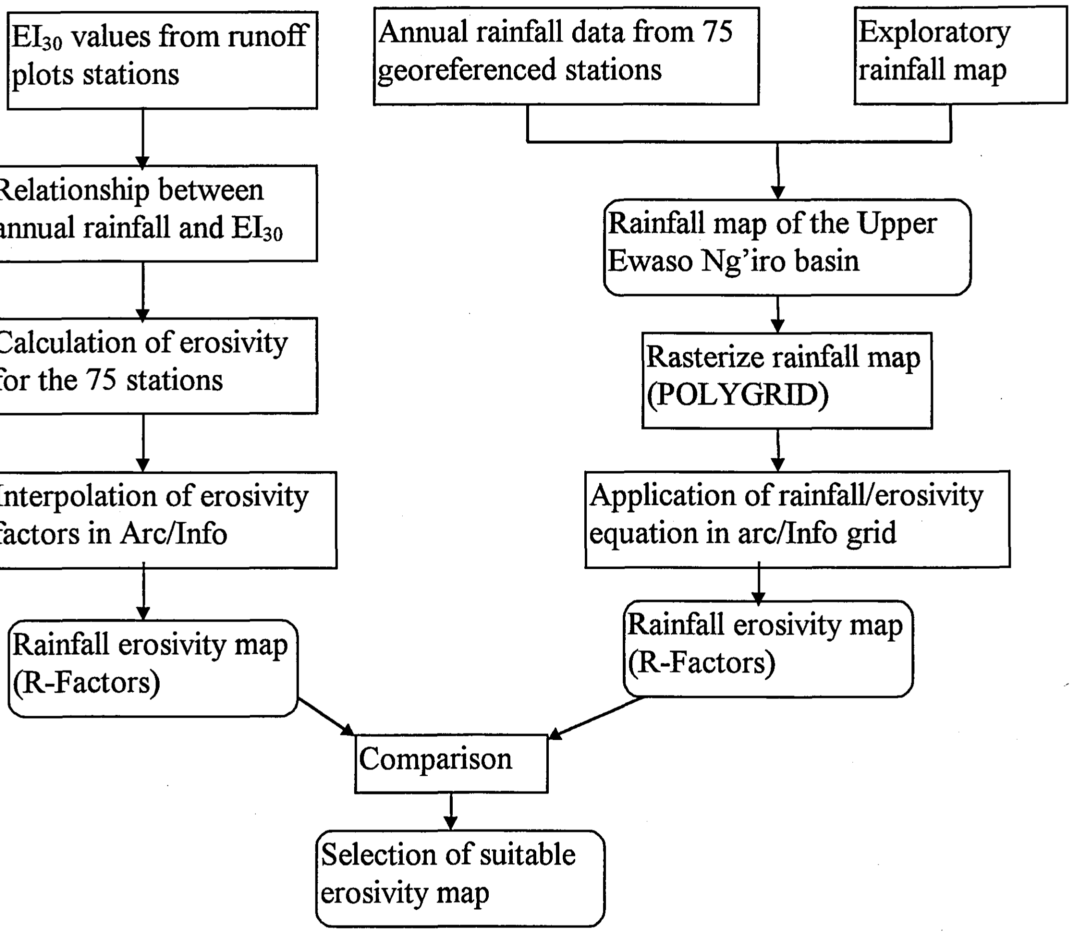

Figure 4.2 Determining rainfall erosivity in the Upper Ewaso Ng'iro basin

4.2.1 Calculation of erosivity indices

Storm erosivity values were calculated as the product of the rainfall energy and its maximum 30-minute intensity (Wischmeier and Smith 1978) as illustrated in equation 3.2. The rainfall energy term, E ($J\ m^{-2}\ mm^{-1}$), in the equation was calculated with Wischmeier's (1978) equation as follows:

$$E = 11.9 + 8.7 \log_{10} I \qquad [4.1]$$

The storm erosivities obtained were accumulated for each year per station to give the USLE rainfall erosivity index, the R-factor. In total, 17 plot years of rainfall erosivity data were obtained for the six stations (Appendix 3). The 17 plot years provide only a small amount of data in comparison to the size of the watershed, but that was all that was available as a result of the limitations in data discussed earlier.

4.2.2 Determining the rainfall-erosivity relationship

Annual rainfall data was obtained for 75 georeferenced manual gauging stations, spread in and around the Upper Ewaso Ng'iro basin (Figure 5.1; Appendix 4). These were the records of rainfall collected by government institutions, individual farmers, researchers and the NRM[3] stations, over diverse periods of time. Some records are over 30 years long, while others are less than five. Details regarding the sources of this data, its analysis and general characteristics can be obtained from published reports by Berger (1989) and Thomas and Liniger (1994).

The relationship between annual rainfall amount and its erosivity was determined by regression analysis. At first, all the 17 plot years were used in a single linear regression. This produced a poor relationship between annual rainfall and erosivity. However, when the data were split into two groups according to the respective agro-climatic zone of the stations (Sombroek et al 1980), improved correlation coefficients were obtained (Table 4.3). The regression equations (1 and 2 in Table 4.3) corresponding to the two groups of agro-climatic zones were used to calculate R-factors for the other 75 gauging stations in the basin, obtaining the values shown in Appendix 4.

Table 4.3 Regression equations relating annual rainfall with erosivity

	Agro-climatic zone	Stations	Erosivity/rainfall relationship	R^2	e	n
1	I – III	Embori, Karuri, Teleswani	EI = 0.649R - 94.2	0.695	85	8
2	IV – VI	Kalalu, Sirima, Mukogodo	EI = 1.17R - 258.5	0.706	124	9
3	All	All	EI = 0.574R - 18.4	0.457	134	17

R^2 = Coefficient of linear regression; n = Number of observations; e = Standard error of estimate, EI = Average annual rainfall erosivity (J m^{-2} mm h^{-1}); R = Annual rainfall amount (mm)

4.2.3 Preparation of rainfall map

The aim of preparing a rainfall map was to update the exploratory scale rainfall map obtained from the Farm Management Handbook of Kenya (Jaetzold and Schmidt 1983). It was necessary to update the existing map because more recent data were now available at a reconnaissance scale, while the available map was of exploratory scale. To do this, numerical values of annual rainfall from the 75 gauging stations (Appendix 4) were spatially interpolated as points with the Arc/Info GRID module. The main problem with this procedure was that the 75 points were too few for a good interpolation, in addition to being unevenly distributed in the basin. Most of them are located in the Mt. Kenya region (Figure 5.1) leaving the northern, eastern, and western parts of the basin with very few stations. To improve on the interpolation, corrections were made to rainfall class boundaries in areas with scant data using the class boundaries from the isohyetal map obtained from Jaetzold and Schmidt (1983), resulting in the rainfall map of the Upper Ewaso Ng'iro basin. Whereas the map obtained in this exercise is suitable for reconnaissance studies, its use for more detailed work needs further refinement. This rainfall map was used to determine rainfall erosivity in the basin.

4.2.4 Spatial interpolation of rainfall erosivity

Two methods of spatially interpolating rainfall erosivity in the GIS were used. The first method involved the direct interpolation of the calculated rainfall erosivity data comprising the 75 stations (Appendix 4) in Arc/Info GRID. The erosivity map obtained (Appendix 5) was found to contain unrealistic distribution of R-values, especially in the south-western region, in comparison with the rainfall distribution and agro-climatic zones, and local knowledge of the area. This was because the poor distribution of the interpolation points in the north, south-west and eastern parts of the basin. It was therefore necessary to improve on the erosivity map by inclusion of extra data beyond the 75 gauging stations. Therefore this map (Appendix 5), was set aside and another one prepared.

The second method involved calculating rainfall erosivity directly from the updated rainfall map. As the calculations had to use the two equations (Table 4.3) representing the two agro-climatic groups, the erosivity data (Appendix 4) for the 75 stations was split into the respective groups (zones I-III and IV-VI). A break-point was found at around the 750 mm level, with the majority of the stations with higher rainfall in zones I-III and those with lower rainfall in zones IV-VI. This break-point was used interactively to apply the two equations (1 and 2 in Table 4.3) to the rainfall map in Arc/Info GRID, obtaining the erosivity map of the basin. The advantage of this map over the one obtained by direct interpolation is that it is more representative of the conditions on the ground, since the poor spatial distribution of the gauging stations in the north, south-west and east of the basin has been evened out by the incorporation of the Jaetzold and Schmidt (1983) map into the original rainfall map.

4.3 Determining soil erodibility

The aim of soil erodibility assessment for the Upper Ewaso Ng'iro basin was to provide erodibility factors, K, which are spatially interpolated for the whole basin, for calculation of soil loss with the USLE. Figure 4.3 shows a flow diagram of the steps taken in determining the K-factor of the soils in the basin.

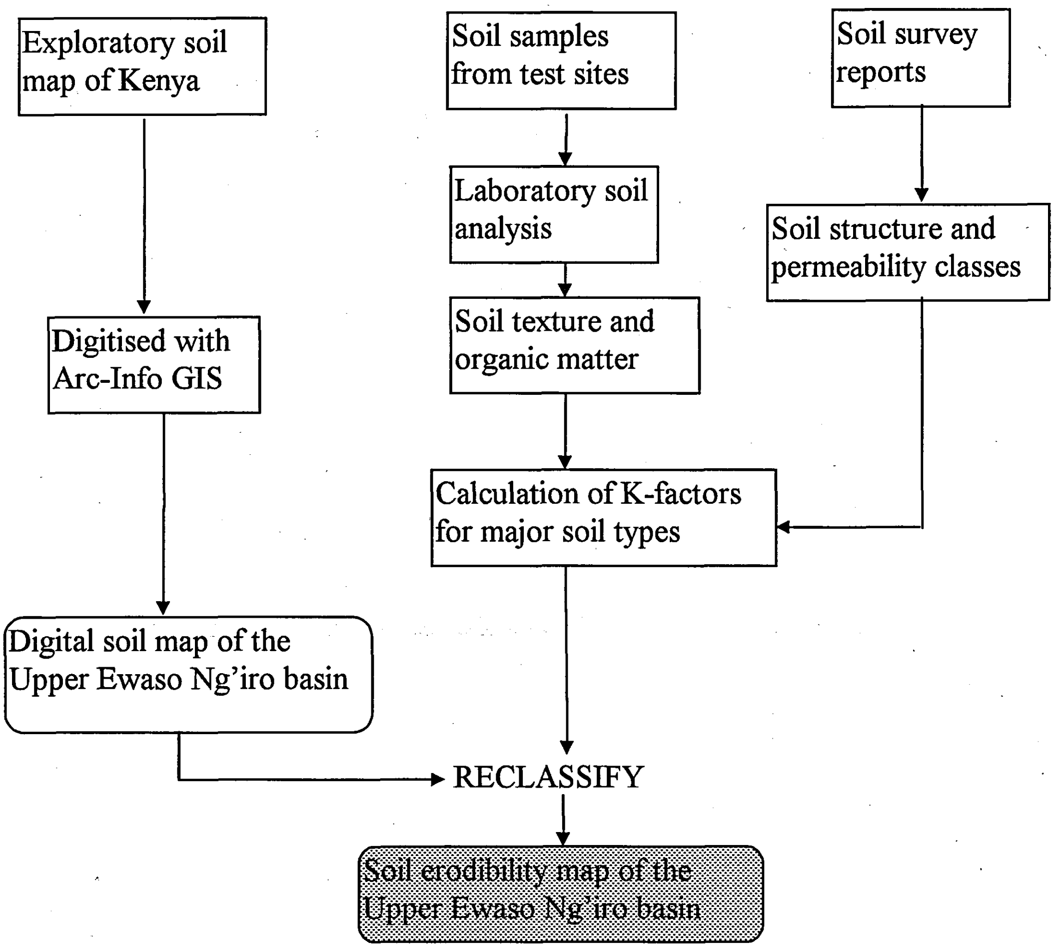

Figure 4.3 Determining soil erodibility in the Upper Ewaso Ng'iro basin

4.3.1 Preparation of the soil map of the Upper Ewaso Ng'iro Basin

Preparation of the soil map of the Upper Ewaso Ng'iro basin was aimed at providing soil mapping units that could be used for the interpolation of the soil erodibility map of the basin. Several soil survey reports have been made (Mainga and Mbuvi 1994; Mbuvi and Kironchi 1994), covering some subcatchments within the basin, including a soil map of the Laikipia District (Ahn and Geiger 1986; Speck 1983), providing soil maps at reconnaissance, semi-detailed and detailed scales. However, these maps cover individual sections of the basin which were of interest to the surveyors at the time of their preparation. Thus, for the current study, the Exploratory Soil Map of Kenya (Sombroek et al 1980) which offered a complete basin coverage was used.

The soil map of the Upper Ewaso Ng'iro basin (Figure 2.4) was prepared by digitising the Exploratory Soil Map of Kenya (scale 1:1 000 000) with Arc/Info GIS (ESRI 1994). The resulting soil map contains 36 major soil types as defined by the FAO classification (FAO 1978). According to Kok et al (1995), soil types can be described adequately in GIS for cells of 1 km by 1 km with Arc/Info. Goodchild (1993) states that maps at a scale 1 million have a 500 m effective resolution. Therefore, the exploratory scale soil map used in this case was within these limits. However, El-Swaify (1982) has shown that K-values have such a wide range within each FAO soil class, that a single value may be misleading. It was thus necessary to supplement this data with soil sampling in the field.

4.3.2 Soil sampling from test sites

Soil sampling was done to provide a spatially comprehensive database on soil properties, for the determination of soil erodibility factors. The samples were collected from 83 test sites (Figure 4.1; Appendix 6) selected at random (Yates 1985) but stratified to include major soil mapping units in the basin. At each test site, a general description of the soil surface characteristics was made (Kenya Soil Survey 1987; McKeague et al 1986). The amounts of stones and gravel on the soil surface were estimated using a meter rule. Large rock cover was estimated visually, by considering 100 by 100 m transects and signs of rill, interill and gully erosion were recorded by a score as indicated in Table 4.4.

From each test site, soil samples were collected with an auger from the top 30 cm and put into polythene bags which were tightly closed. Three replicate samples were taken from each site. At sites with different land use, such as at the forest/cropland transition at Nyambene hills, six samples were taken. A total of 270 soil samples were collected from the 83 test sites. These samples were taken to the laboratory for textural and organic matter analysis.

Table 4.4 Qualitative classification of soil erosion at the test sites

Class	Description
1	No apparent erosion
2	Slight to moderate erosion
3	Moderate loss of topsoil generally and/or some dissection by runoff channels or gullies.
4	Severe loss of topsoil generally and/or marked dissection by runoff channels or gullies
5	Very severe erosion with exposed subsoil and intricate dissection by runoff channels or gullies

4.3.3 Laboratory soil analysis

Soil texture analysis was done in the laboratory to determine the percentage sand, silt and clay, and also for the sand fractionation to determine the percentage of fine sand (< 0.1 mm) in each sample. The determination of the percentage silt and clay was done by the hydrometer method, while the percentage sand, the percentage fine sand and percentage gravel were determined by wet sieving following the procedures described by Bouyoucos (1951), Davidson (1955) and Kenya Soil Survey (1987). The organic matter content was determined by the Walkey-Black method (Page et al 1982). The results of the laboratory soil analysis, including soil texture and organic matter contents for each of the test sites are presented in Appendix 6.

4.3.4 Determining soil erodibility

Soil erodibility (Appendix 6) for each sampled site was calculated using the USLE soil erodibility nomograph (Wischmeier et al 1971). The nomograph has been converted into a regression equation which is more versatile to apply. According to Wischmeier and Smith (1978) this equation applies to soils having less than 70 percent silt plus very fine sand contents. For such soils, erodibility varies approximately as the 1.14 power of this parameter. The soils sampled in this study were within these limits. Therefore, the K factor was calculated as follows (Wischmeier and Smith 1978).

$$100K = 2.1\, M^{1.14}(10^{-4}) \times (12-a) + 3.25 \times (b-2) + 2.5 \times (c-3) \qquad [4.2]$$

Where,

$\boldsymbol{M}$ = (percent silt + very fine sand) × (100 - percent clay)

$\boldsymbol{a}$ = percent organic matter

$\boldsymbol{b}$ = the soil structure code used in soil classification

$\boldsymbol{c}$ = the profile permeability class.

Values for the terms $\boldsymbol{M}$ and $\boldsymbol{a}$ were obtained from the laboratory analysis of the soil samples from the 83 test sites. The parameters $\boldsymbol{b}$ and $\boldsymbol{c}$ were derived from soil survey reports (Mainga and Mbuvi 1994; Ahn and Geiger 1986; Mbuvi and Kironchi 1994), and by reference to the legend of the original soil map (Sombroek et al 1980; Muchena 1982).

4.3.5 Correction for rocky/stony soils

As 36 of the sampled sites had soils containing various amounts of stones and gravel, it was necessary to include a correction factor for this effect on soil loss. The following equation (Berg 1992) was used:

$$K_{stony} = KF_{COAR} \qquad [4.3]$$

Where

K_{stony} = Soil erodibility on stony areas

F_{COAR} = Correction factor, and

$$F_{COAR}=COAR(1.026-0.025)+COAR^2(2.534\times10^{-4})-COAR^3(1.026\times10^{-6})$$
[4.5]

Where,

COAR = Maximum percentage coarse fragments in the upper soil layer. The soil erodibility factors obtained from these equations are given in Appendix 6.

4.3.6 Preparation of the soil erodibility map

Mean soil erodibility values were calculated for each soil type represented in the soils map. These mean K factors for each soil type were used to reclassify the mapping units of the soil map of the basin in the GIS (ESRI 1994). By using this type of classification, it was assumed that the average K factors were representative of each soil type regardless of its geographical location. This type of classification is accepted as a common and necessary process of data reduction, as it helps to make complex observations understandable (Burrough, 1989). In addition, the resolution of K values matches the resolution of 'best available' soils data.

4.4 Determining the topographic factors (LS)

The USLE slope length (L) and steepness (S) factors were determined as illustrated in Figure 4.4. The procedure involved the preparation of digital topographic maps, creation of the DEM and determination of the slope steepness and length factors respectively.

4.4.1 Preparation of topographic coverages of the basin

Digital topographic data for the Upper Ewaso Ng'iro basin were obtained by digitizing 32 sheets (Appendix 7) of topographic maps of scale 1:50 000 obtained from the Survey of Kenya (1976). The contours and the drainage system were digitized separately. This work was done with PC Arc/Info (ESRI 1994) in Kenya where due to limitations of time, computer memory and the

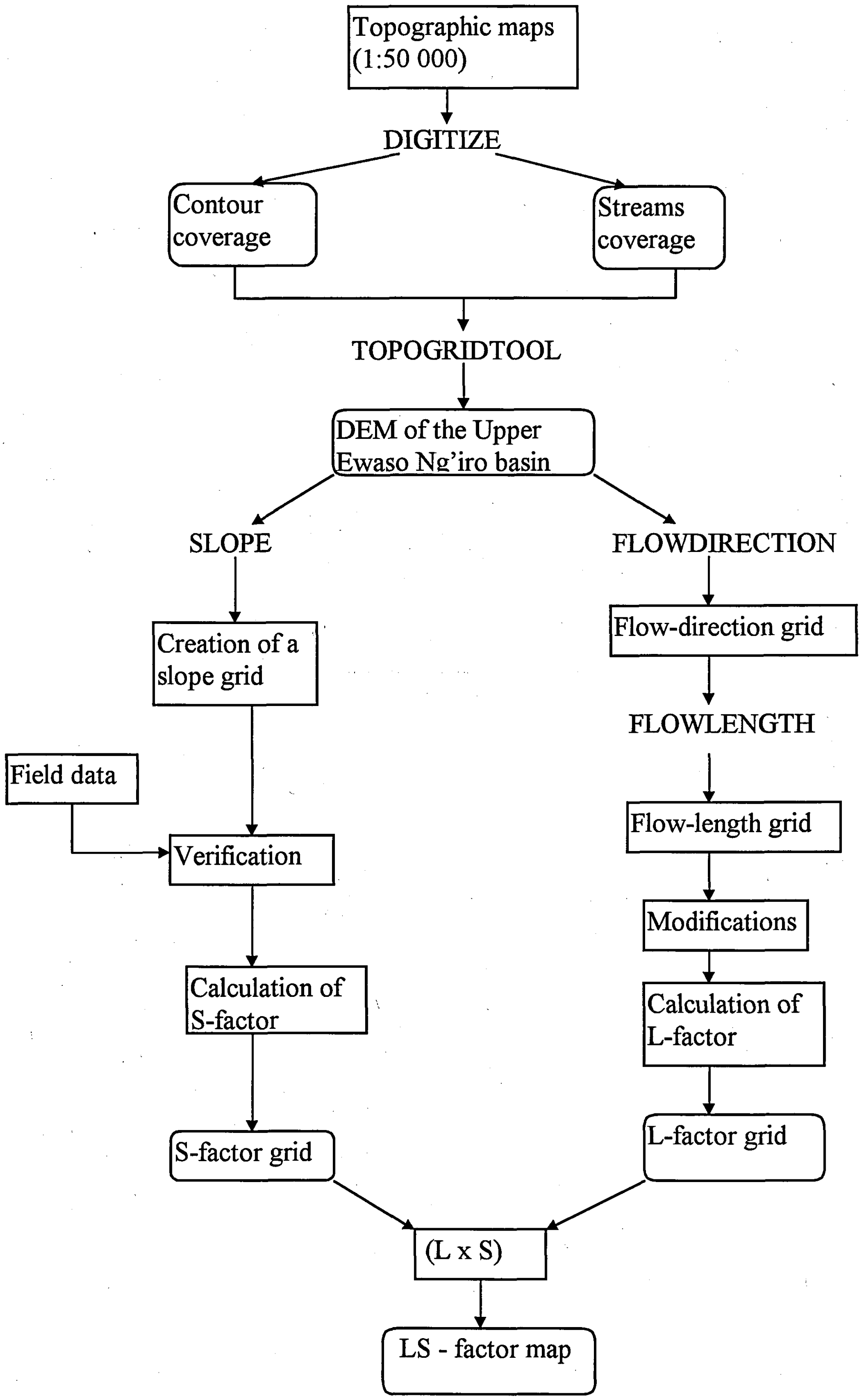

Figure 4.4 Procedures in the preparation of the DEM and the LS-factor maps

high labour requirements, only the 200 m contours were digitized. The resulting contour map was therefore of coarse spatial resolution, especially in the flatter plateau areas. In preparing the drainage coverage, care was taken to ensure that each stream channel was digitized in the direction of flow. All the watercourses shown on the 1:50 000 maps were digitized giving a detailed stream coverage, which, when used alongside the coarse contour coverage improved the interpolation of the DEM. The contour and stream coverages obtained are shown in Appendices 8 and 9 respectively. The two coverages were subsequently used to build the DEM of the basin.

4.4.2 Creation of the DEM

The Digital Elevation Model (DEM) of the Upper Ewaso Ng'iro basin was generated using the TOPOGRIDTOOL of Arc/Info NT (ESRI 1997). The TOPOGRIDTOOL generates a hydrologically correct grid of elevation data points from stream and elevation coverages. A grid cell size of 100 m was used. According to Moore et al (1993) the grid cell size should not exceed the slope break points. In this case, the 100 m pixel sizes were considered to be less than the minimum distance between any two stream channels. A higher resolution caused computational memory problems and even with the 100 m pixels, the basin had to be split into 4 subcatchments before running TOPOGRIDTOOL, so that the computer memory could cope. The resulting DEM contained sinks automatically generated from the stream coverage and it was used to calculate slope steepness and length factors.

4.4.3 Determining slope steepness factor (S)

Slope steepness was determined from the DEM of the basin using the SLOPE function of Arc/Info GRID (ESRI 1997). The slope gradients predicted for the low and medium steepness areas were comparable to observed values at test sites. However, in the mountain regions, some of the slopes were overestimated and in the flatter areas, slopes were underestimated. This was attributed to the coarse resolution of the input contour coverage. Thus a correction was used to set maximum slopes at 45 degrees. The USLE S-factor was then calculated from the slope grid file with the equations 3.6 and 3.7. These equations by Mc Cool et al (1987) have been developed from the original Wischmeier's equation (Wischmeier and Smith 1978). They were found to predict soil loss for steeper slopes better as they are more suited to complex topographies as described in section 3.7.4.

4.4.4 Determining slope length factor (L)

Determining the USLE L-factor from a DEM is a difficult exercise and several methods have been developed mostly to calculate the combined LS-factors. Moore et al (1991) developed algorithms (equation 3.8) that calculate the LS-factor using the slope steepness from the slope plane areas created by the DEM. This methodology was at first attempted for the Upper Ewaso Ng'iro basin, but the LS-factors obtained in this exercise were excessively high, as compared to field data. This was attributed to the coarse resolution of the input contour coverage, which created very large areas and the method was therefore abandoned. Another method developed by Desmet and Govers (1996) uses algorithms that calculate the LS-factors automatically from the DEM, but it runs on IDRISI software and requires a high resolution DEM, facilities that were not available for this study. A direct approach was therefore adopted.

Determining the L-factors from the DEM of the Upper Ewaso Ng'iro basin relied on the fact that the GRID module of Arc/Info can automatically generate flow lengths, if it has well defined sinks (ESRI 1997). Arc/Info GRID can also create sinks given a contour coverage input, but in this study, the sinks were provided by the stream coverage. Thus, the following procedure was adopted.

(i) From the basic DEM, the flow direction was determined using the FLOWDIRECTION grid function.

(ii) The flow lengths were next determined using the FLOWLENGTH grid function. This function calculates the length of slope from the top of the hill to the sink or stream. The resulting flow lengths file contained some slope lengths that were too long in comparison to observed lengths in the field. As above, this was attributed to the coarse resolution of the contour input file. Thus corrections were made to set the maximum slope length to 200 m, which corresponds to the maximum slope length allowed for the USLE (Wischmeier and Smith 1978). This flow length therefore describes the length of slope over which runoff is expected to occur until it enters a drainage channel or slope gradient decreases enough to allow deposition to begin.

(iii) The USLE slope length factor (L) was now calculated using equation 3.4.

(iv) The LS-factor was subsequently obtained by multiplying the S and L-factors in Arc/Info GRID.

4.5 Land cover types and C-factor determination

Mapping of the land cover types and the subsequent determination of the USLE C-factor in the Upper Ewaso Ng'iro basin were based on the interpretation of SPOT 1 HRV imagery, land cover data obtained from 83 test sites in the basin and crop cover data from 9 runoff plots stations as illustrated in Figure 4.5.

4.5.1 Satellite image interpretation

Satellite image interpretation, ground truthing and digitizing of the imagery to create GIS coverages were done in Kenya. The financial and infrastructural facilities could only permit the purchase of locally available satellite imagery (Figure 4.6) and visual image interpretation. In all, 10 prints of multispectral SPOT 1 HRV (1987-88) images and one Landsat (1976) which adequately cover the Upper Ewaso Ng'iro basin were used. The inclusion of the Landsat scene was necessitated by lack of SPOT image cover in part of the south western region. In addition, topographic maps of scale 1:50 000 (Appendix 7) were used both during the image interpretation and the ground truthing exercises to identify and locate relevant features on the image.

The image interpretation exercise was complemented by ground-truthing work in the field. This involved visits to various parts of the basin, which also included the 83 test sites (Appendix 10) where a known or unknown feature marked on the image would be verified on the ground and any necessary corrections made to the image interpretation. A Trimble Scout^{M} GPS instrument was used for the correct geopositioning of the relevant features in the field. The instrument uses signals from four satellites to provide position fixes in three dimensions, including altitude. It gives the position in both UTM and geographic units to within 100 meters accuracy. The ground-truthing work was done during the dry season (January - April 1997), to coincide with the conditions when the imagery had been taken.

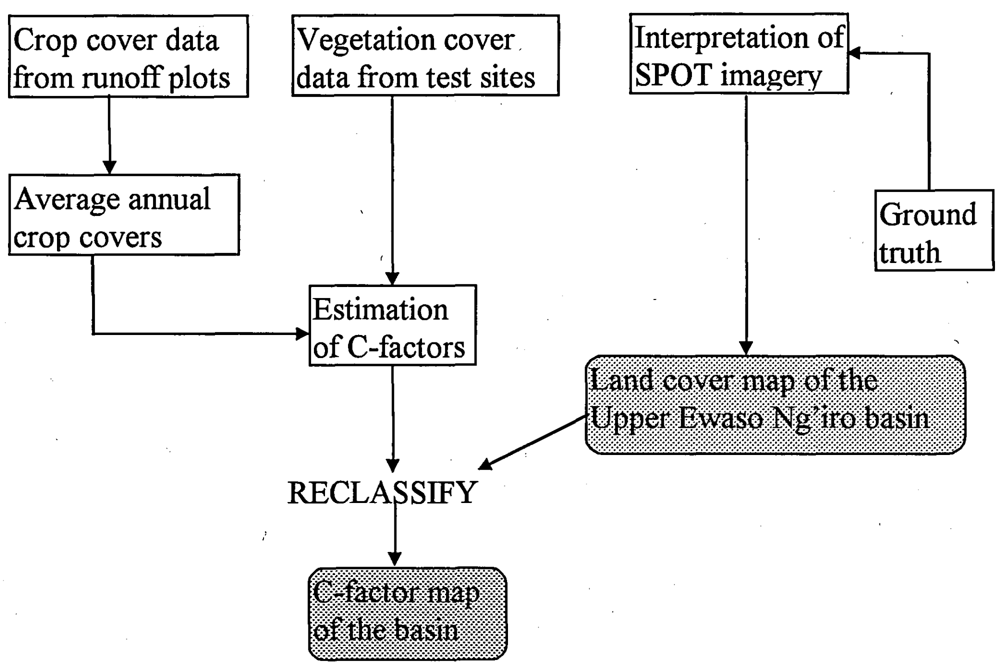

Figure 4.5 Preparation of the land cover and C-factor maps

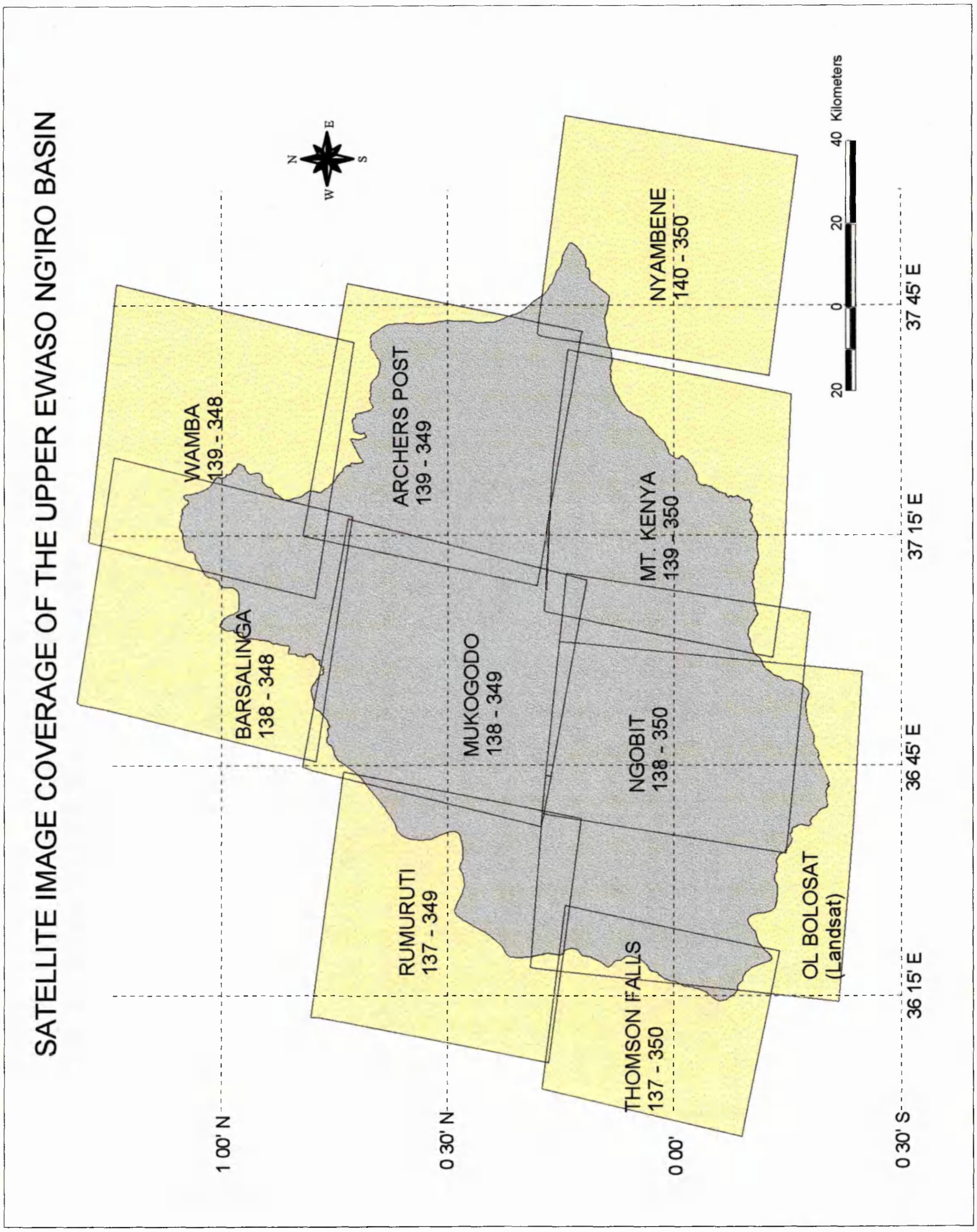

Figure 4.6 Coverage of Spot 1 HRV imagery over the Upper Ewaso Ng'iro basin

The visual image interpretation involved matching the colours and textures on the image with the observed vegetation and land use conditions on the ground. These were then delineated on a transparency overlaying the image. One interesting observation was that in the Ngobit and Ol Pejeta areas, white patches observed on the image represented a grass (*Themeda Triandra*) when it was dry. In the Isiolo and Wamba areas, white and yellow patches on the image were found to represent soils with high amounts of sand and limestone on the surface, but the texture was quite different from that derived from the dry grass condition. In these dry zones, vegetation cover during the dry season is so sparse (Plate 4.11) that the satellite imagery was found to show predominantly soil colours which are more pronounced than the scattered shrub cover. Large scale farms and forests were easily identifiable as the fields are large enough to appear distinct on the image. Small scale farms were identifiable by the mixed pixel characteristics (Isavwa 1989) associated with mixed cropping, and the iron-roofed houses close to each other. This has the effect of increasing the noise (or rough texture) in the image due to the many shiny/white colours mixed with the reds and browns of the crop cover. The fact that dry-season imagery was used in the interpretation helped to delineate small scale farms from the surrounding bushlands and shrublands, where darker tones having a more uniform colour texture were observed on the image.

As more than 70 percent of the Upper Ewaso Ng'iro basin lies in the rangelands, a vegetation classification scheme that is sensitive to these conditions was necessary for the image interpretation and GIS work. Thus, vegetation cover classification relied heavily on the system used to classify rangelands in Kenya (Thurow and Herlocker 1993). This system is based on the broad classification scheme developed for East African conditions by Pratt and Gwynne (1977). Appendix 11 shows sketch diagrams of the major vegetation types in the basin. For this study, some modifications were made to the classification scheme to include such classes as small-scale cropland (all crops), large scale croplands, swamps and urban settlements. Eleven major land cover types (Plates 4.5-4.14) were identified as follows:

Moorland: Moorland is the afro-Alpine vegetation found at altitudes exceeding 3,500 m above sea level. This consist mainly of grasses and moorland shrubs such as *Lobelia keniensis, Dendrosenecio brassica, Carex monostachya* and *Alchemilla johnstonii.*

Forest: Most trees are 7-40 m or taller with crowns often interlocking. Evergreen forests are characterised by individual trees that may shed leaves, but the canopy as a whole remains green throughout the year (e.g. composed of trees such as *Olea africana).* Deciduous forests are characterised by trees that lose their leaves during the dry season (e.g. *Acacia* and *Combretun spp*).

***Bushland*:** Bushlands consist of woody plants which often have multiple stems, most of which grow to not more than 10 m. Crowns are often interlocking and canopy cover is over 20%. Trees are scattered but conspicuous. The herbaceous understorey is usually sparse. Dominant species include *Lannea commiphora, Carissa-acokanthera, Euclea* and *Copporis.*

***Bush Grassland*:** Bush grassland consists of grassland with scattered trees and shrubs having a combined canopy cover less than 20%, dominated by *Chrysopogon plumulosus, Pennisetum mezianum* and *Acacia mellifera.*

***Grassland*:** Grasses or sedges dominate these communities. Woody plants are either lacking or are dwarfed and inconspicuous and comprise less than 2% of the canopy cover. Dominant grass species include *Themeda triandra, Cenchrus ciliaris* and *Portulaca-eragrostis.*

***Shrub Grassland*:** Shrub grasslands are grassland with scattered shrubs which have a canopy cover less than 20%, dominated by *Acacia mellifera, Euclea divinorum* and *Acacia dreponolobium.*

***Shrubland*:** Shrubland consists of woody plants about 6 m tall without a significant presence of trees. Canopy cover can be more than 20% consisting mainly of *Acacia nilotica, Acacia tortilis, Acacia reficiens, Commiphora spp* or *Fansavieria intermedia*. The herbaceous understorey is usually sparse.

***Scarpline vegetation*:** Vegetation of the minor scarps is characterised by scattered shrubs less than 6 m tall, sparse or no herbaceous vegetation and rocky ground cover. Dominant species include *Acacia brevispica and Acacia tortilis.*

Small Scale cropland: Small scale cultivated lands and mixed farms with varying levels of grass, trees, shrubs, fallow and crop covers.

***Large scale cropland*:** Mechanised large scale farms mostly growing wheat and/or barley.

***Swamps*:** Land covered by permanent standing water and supporting various plant communities including reeds, sedges, rushes, sometimes trees or shrubs and aquatic species.


Plate 4.5 Moorland on Mt. Kenya


Plate 4.6 Forest on Mt. Kenya


Plate 4.7 Bushland at Karama in Meru


Plate 4.8 Bush grassland at Lol Daiga


Plate 4.9 Grassland at Nyakinyua Ranching


Plate 4.10 Shrub grassland in Samburu Game Reserve


Plate 4.11 Shrubland at Garba, Isiolo


Plate 4.12 Scarpline vegetation at Luissie Gap, Samburu

Plate 4.13 Small scale farms in the Nyambene Hills

Plate 4.14 Large scale farm at Embori, Timau

4.5.2 Assessment of vegetation cover from test sites

Vegetation cover was assessed on 83 test sites selected to represent the major land cover types and stratified to include the major geographic zones of the Upper Ewaso Ng'iro basin. At each test site, the vegetation cover was evaluated as catchment cover. This involved pacing quadrants of 20 x 20 m, then counting the number of trees, estimating the percentage canopy cover, height of trees, percentage grass or forbs and vegetation types, including tree names wherever possible. Crop cover from farmlands was recorded as per the field conditions at the time of visit. The overall land cover type was then deduced based on the Pratt and Gwynne (1977) classification scheme.

4.5.3 Mapping land cover types

The land cover data from the interpreted satellite imagery and field surveys was put in the GIS by digitizing the transparency overlays, using PC Arc/Info (ESRI 1994). This provided coverages for each image, which were consequently merged to provide the land cover map of the basin.

4.5.4 Determining C-factors from plot data

The data on crop cover from erosion plots were obtained from the NRM[3]. These data provided diverse crop covers, based on the type of crop grown at each station (Appendix 12). It was established that in all the stations, vegetation cover had been measured on a weekly basis. The methodology used was an adaptation of the string and bead method (Slonecker and Moldenhauer 1977). The string used in the cover assessments was ink-marked at spacings of 40 cm and then pulled diagonally across the plot. The number of times a marking touched a piece of vegetation was counted, and the procedure repeated for the other diagonal. Vegetation cover was then calculated as:

$$Cover\ (\%) = (n/N) \times 100 \qquad [4.5]$$

Where,

n = Number of hits achieved at markings,

N = Total number of markings across the diagonal.

The mean annual crop cover was then calculated for each crop type and at each station. Some of the crop cover data from cultivated plots contained such details as mulching, agroforestry and minimum tillage treatments and various grazing management levels. However, for the purpose of interpolating C-factors, only the data from conventional management plots was used.

The USLE cover and management factors (C-factors) corresponding to each crop/vegetation condition were estimated using guide tables (Morgan 1995; Wischmeier and Smith 1978; Lal 1990). At first it was difficult to decide on a specific C-factor for a crop, due to the wide range in the choice of the crop C-factors allowed by the guide tables. This problem was solved by using plot soil loss data to validate the C-factors, by assuming that the other components of the USLE (R, K, LS, P) had been determined as accurately as possible. It involved calculating soil loss with the USLE, and adjusting the C-factor (within the limits allowable in the tables) until the model produced soil loss as close to observed values as possible. The C-factors obtained (Appendix 12) were adopted as the mean annual values for each respective crop type. They were used to estimate the C-factors for the same types of crop, for other areas represented by the test sites. C-factors for vegetation types not represented by the plot data were directly estimated from USLE guide tables.

4.5.5 Creating the C-factor map

The C-factor values determined for the test sites (Appendix 10) were used to re-classify the land cover map. The reclassification was done such that the differences in C-factors obtained from plot and test site data for the same crop type in different geographical regions could be depicted. The resulting C-factor map was divided into four subcatchments (to correspond with the DEM) and rasterized with the POLYGRID module of Arc/Info NT (ESRI 1997), so that actual values of C-factors could be ready for later use in the USLE.

4.6 Preparation of the conservation practice factor (P) map

The data for the conservation practice factor was obtained from district maps of the catchments conserved through the "Catchment Approach" program of the Soil and Water Conservation Branch, Ministry of Agriculture (1988-97). These maps were obtained from the District Soil Conservation Officers of Nyandarua, Nyeri, Meru, Laikipia, Nyambene and Isiolo Districts. Data on the types and amounts of conservation activities were obtained from annual reports of the Soil and Water Conservation Branch of the Ministry of Agriculture in Nairobi.

The district soil conservation maps were digitized and joined to provide a GIS layer showing the location of the conserved catchments in the basin. Annual reports from the Ministry of Agriculture (Republic of Kenya 1996) provided summarised information on the types of structures found in each district. However, it was not possible to tell from the annual reports what structure had been installed in which catchment as the annual reports give only the total lengths of terraces in metres or number of gullies rehabilitated in a district. However, the commonly used structures are fanya juu terraces, stone lines, contour bunds and grass strips. As P values for these types of structures were not available from literature (Wischmeier and Smith 1978; Morgan 1995) an average P-factor of 0.18 was adopted for all conserved catchments, assuming that the available soil conservation structures perform like outward sloping bench terraces. This constant P-factor was used to classify the conservation practices map in Arc/Info GRID.

4. 7 Determining soil erosion hazard

The calculation of soil loss for the erosion hazard map was done directly in Arc/Info GRID (Figure 4.7), by multiplying the respective USLE grid files.

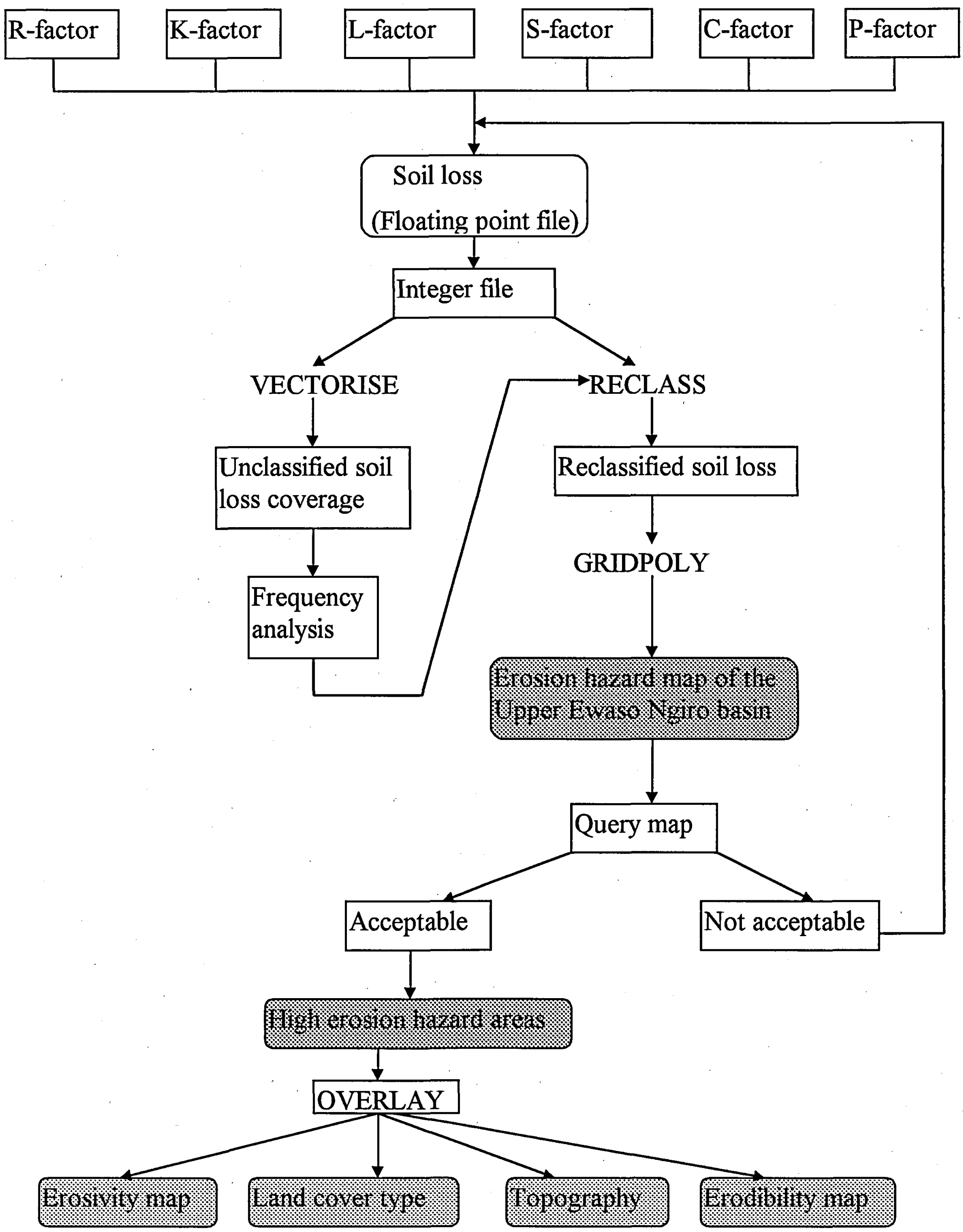

Figure 4.7 Applying the USLE to predict erosion hazard with GIS

$$Sloss = (RG) \times (KG) \times (CG) \times (SF) \times (LF) \times (PF) \qquad [4.6]$$

Where,

Sloss = Soil loss calculated for each grid cell in t ha^{-1} yr^{-1}

RG = Rainfall erosivity value for grid cell

KG = Soil erodibility grid file

CG = Cover and management file

SF = Slope steepness factor calculated for each cell

LF = Slope length factor file

PF = Conservation practices factor grid file.

The resulting output grid file (Sloss) contained actual calculated values of soil loss (floating point file). To permit the conversion of the grid (raster) file to arc (vector) files, the decimal values were first converted into integer values (integer grid file). The resulting file contained discrete values of soil loss, which were grouped into six erosion hazard classes based on a frequency distribution analysis.

4.7.1 Validating the USLE with plot data

The validation of the USLE for the Upper Ewaso Ng'iro basin was performed with plot data. At first, linear regression analysis was done with the combined 45 plot years of data (Appendix 12). This obtained a correlation coefficient of 0.645 (95 percent confidence interval), while the standard error of estimate (5.475 t ha^{-1} yr^{-1}) was high. In order to obtain better results, the regression analysis was done again after separating the data into four groups according to similarities in type and climatic conditions of each erosion plot station. It was found that in general, the USLE underestimated soil loss in areas with poor vegetation while it overestimated erosion in areas with good cover, otherwise the model could be applied to the basin bearing in mind the limitations in the data.

4.7.2 Querying the erosion hazard map

The mean annual soil loss estimated from the nine runoff plot stations was used to query the erosion hazard map. This involved overlaying the GPS of each station on the map and comparing the observed versus predicted soil loss values. In addition the values predicted by the USLE with plot data outside of the GIS were compared. However, as the regression equations obtained from plot data represented only a small proportion of the land cover types, they were not used to calibrate the soil erosion hazard map. Therefore the soil loss values obtained directly with the USLE and GIS have been presented in chapter V.

4.7.3 Evaluating the factors associated with soil loss

By consideration of the soil depth and the fact that most of the study area is uncultivated, a soil loss tolerance (Morgan 1995; McCormack and Young 1981; Hall et al 1985) of 9.0 t $ha^{-1}yr^{-1}$ was adopted for the of the Upper Ewaso Ng'iro basin. This T-value was used to delineate two classes of erosion hazard showing the areas of respective low and high erosion risk. The map obtained, was subsequently overlaid on the respective coverages of the land cover, LS-factor, rainfall erosivity and the soil erodibility to determine the effects of these factors on erosion hazard in the basin.

Since the methodology adopted in determining erosion hazard in the Upper Ewaso Ng'iro basin with the USLE was empirical and with scarce data resources, it was not possible to conduct a sensitivity analysis of the model. The results obtained from the whole exercise are discussed in chapter 5.

CHAPTER V

EROSION HAZARD IN THE UPPER EWASO NG'IRO BASIN

Soil erosion hazard in the Upper Ewaso Ng'iro basin has been assessed with the Universal Soil Loss Equation (USLE), using remote sensing and Geographic Information Systems (GIS) techniques to yield quantitative data and an erosion hazard map of the basin. In addition, thematic data on rainfall erosivity, soil erodibility, topographic factors, land cover and management factors and conservation practice factor have been determined, all of which were necessary for the derivation of the final soil loss hazard map of the basin. These results are presented in this chapter, along with a discussion of their implications to the problem of soil erosion in the basin.

5.1 Rainfall erosivity

5.1.1 Rainfall distribution

The map of rainfall distribution in the Upper Ewaso Ng'iro basin (Figure 5.1) obtained in this study shows that precipitation is strongly influenced by the relief and aspect of the major mountains in the region, with high spatial variations. The Mt. Kenya, the Nyandarua Range, the Nyambene hills and the edge of the Rift Valley receive over 1000 mm per year, these being the wettest parts of the basin. The Laikipia Plateau shows little horizontal differentiation of rainfall, averaging between 600 to 800 mm, but total precipitation decreases towards the north to less than 500 mm. Aspect plays an important role in rainfall distribution because the basin lies on the lee slopes (northern) of the mountains. Thus, though altitudes are high, rainfall amounts are much lower than for equivalent altitudes on the windward (southern) side of the mountain (Jaetzold and Schmidt 1983). Annual rainfall distribution, seasonality and the storm characteristics vary highly in the study area (Berger 1989).

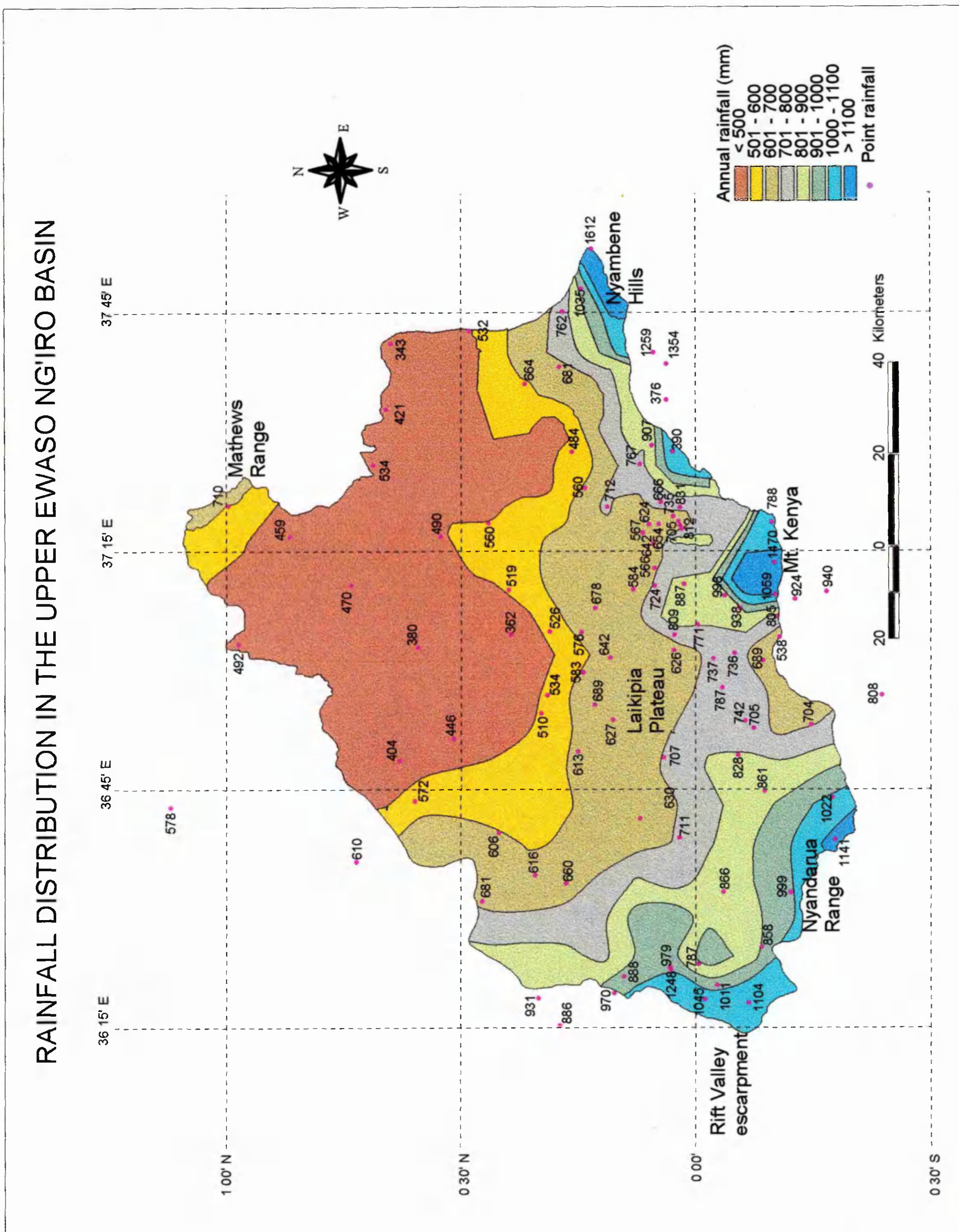

Figure 5.1 Rainfall distribution and the position of the gauging stations in the Upper Ewaso Ng'iro basin

Whereas in some parts of the world, an annual rainfall of 700 mm would be adequate for rainfed crop growth, in the Upper Ewaso Ng'iro basin, rainfall intensities and the seasonal separation means that most of the rains come within a few heavy storms, and sometimes, the seasonal total may fall within one or two months stopping before the crops reach maturity so that crop failures are common in the region. In addition, annual rainfall fluctuations are high and droughts quite common (Berger 1989). The fluctuations in rainfall erosivity are similarly high (Appendix 3).

5.1.2 Derivation of rainfall erosivity factors

In determining rainfall erosivity for this study, the EI_{30} method (Wischmeier and Smith 1978) was used. Ideally, erosivity is best estimated directly by measurements of storm energy load (Wischmeier 1976). However, this can be slow and expensive, necessitating the use of empirical equations and short-term data for estimation of erosivity. The choice of a suitable erosivity index is critical in erosion modelling with the USLE. The most common method is to use the USLE R-factor calculated by the EI_{30} method. Though originally developed for the USA, the EI_{30} method has been validated for many parts of the world (Foster et al 1982; Thomas and Coutinho 1994; Roose 1977). The rainfall erosivity map of the Upper Ewaso Ng'iro basin (Figure 5.2) was determined with the EI_{30} method.

There has been a growing body of evidence that for tropical rainstorms, other indices relate rainfall erosivity with soil loss much better. Lal (1976) suggested a relationship that relates the maximum 7.5 minute intensity with rainfall amount, while the KE>25 index was found to predict soil loss in southern Africa (Elwell and Stocking 1973). In general, the basic rainfall parameter affecting soil erosion is its energy. Wischmeier and Smith (1958) found that the kinetic energy explained most of the measured soil loss from the field plots. Morgan (1995) lists several values of energy for storms in various parts of the world, showing that kinetic energy of rainfall varies with each part of the world. In addition, the choice of a different index would require that K-factors be recalculated since these are expressed in the units of R.

In Kenya, little has been done to develop erosivity indices for the region, as most of the researchers have normally adopted the existing indices. The EI index has consequently been validated for various parts of Kenya. Onstad et al (1984) observed that erosivity as expressed in the EI_{30} function was satisfactory for predicting soil loss on an alfisol in Machakos. Similarly, Rowntree (1982) used the EI_{30} equation to evaluate seasonal erosivities in Kenya, with the result that the highest erosivities were in the long rains in April. Mati (1995) found that splash detachment correlated highly with both the EI_{30} and the EI_{45} at Kabete. According to Wischmeier (1976) the EI_{30} index can be used reliably for a wide range of climatic conditions if the intensity-energy data for the region are available. However, there are limitations of data and facilities in a developing country such as Kenya. Wischmeier and Smith (1978) recommended at least 20 to 25 years of data to adequately develop erosivity indices for a region. As the available intensity data is still limited, there is a need for long-term planning to include research into the rainfall erosivity indices suitable for Kenya, and specifically for the Upper Ewaso Ng'iro basin.

5.1.3 Distribution of rainfall erosivity in the basin

The highest rainfall erosivities in the Upper Ewaso Ng'iro basin (Figure 5.2) were predicted around Mt. Kenya, the Nyandarua Range and the Nyambene hills. Conversely, the lowest values were in the dry northern regions. In general, rainfall erosivity increased with amount of rainfall, but in the intermediate areas comprising agro-climatic zone IV, for a given rainfall amount, erosivities were higher than in the cooler areas. The relationships between annual rainfall and its erosivity in the Upper Ewaso Ng'iro basin (Table 4.3) show that better correlations were obtained

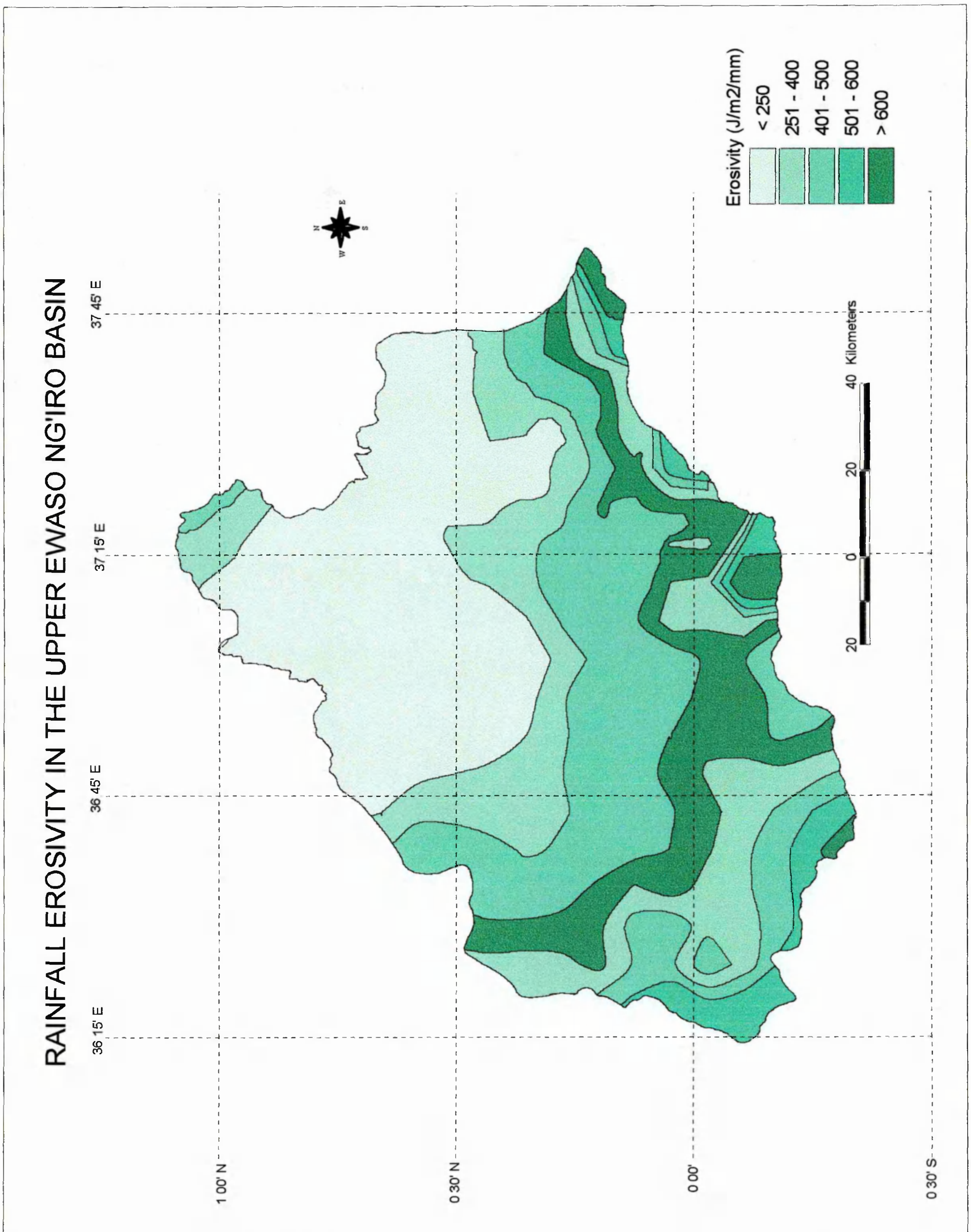

Figure 5.2 Rainfall erosivity in the Upper Ewaso Ng'iro basin

between rainfall and erosivity when the data were grouped according to the agro-climatic zones (Sombroek et al 1980) of the region, though the standard errors of estimate were still high. The agro-climatic zones represent the influence of relief on storm characteristics much better than annual rainfall on its own (Jaetzold and Schmidt 1983). From the daily records as well as annual erosivities (Appendix 3) Karuri, Teleswani and Embori have higher annual rainfalls than Kalalu and Sirima, yet for similar rainfall amounts, the latter have higher erosivities. Therefore, for equivalent amounts of annual rainfall, higher erosivities are observed in the dry areas than in the cool high altitude areas.

It was noted from the storm intensity data that in the dry Mukogodo areas, threshold rainfall amounts of 2.2 mm hr^{-1} (3 mm rainfall) are capable of producing runoff as compared to 5 mm hr^{-1} in the wet areas. Though the reasons for this go beyond the rainfall erosivity factor alone, it was concluded that a bigger proportion of the total rainfall contributes to soil loss in the dry areas than in the wet areas. This brings out the danger of generalising assumptions about erosivity in tropical regions. For instance, Folly (1997) obtained threshold values of 10 mm hr^{-1} for a Savannah region in Upper East Ghana. In Kenya, Othieno and Laycock (1977) observed threshold values of 20 mm hr^{-1} in tea fields in Kericho. Setting rainfall thresholds is also a question of scale. On small plots of 10 m length as in this study, lower thresholds are observed while higher thresholds are expected for sediment loss from larger catchments due to deposition. In the same Mukogodo area, Ondieki (1993) observed rainfall thresholds of between 8 and 18 mm from records of sediment yield at the catchment outlet, which was 2 km^2.

The spatial interpolation of rainfall erosivity relied on putting regression equations in a raster GIS to calculate erosivity automatically. The resulting map can be evaluated or used in other equations. Jager (1994) used this type of interpolation to obtain isoerosivity maps of the Baden-Wurttemberg area of Germany. This type of interpolation assumes that storm patterns of similar nature occur in the ungaged areas. However, rarely, if ever, is a natural storm exactly duplicated. Different values of storm intensities, duration and amount may occur in any one of numerous possible combinations. The most useful rainfall erosivity factor is one whose magnitude represents a composite measurement of the effect of the various rainstorm characteristics, which influence the effect of the rate of erosion. As this is difficult to measure, using annual average values becomes more realistic.

Appendix 4 shows in more detail the values of erosivity obtained for the 75 gauging stations used in the interpolation of rainfall erosivity. Annual erosivity values in the Upper Ewaso Ng'iro basin were found to range between 145 and 990 J mm m^{-2} h^{-1} at Archers Post and on Mt. Kenya respectively. Relief and climatic zone have been associated with this wide diversity. It was noted that about 68 percent of the basin experiences rainfall erosivities in excess of 400 J mm m^{-2} h^{-1}, mostly in the highlands of Mt. Kenya, the Nyandarua Range and the Nyambene hills. Similar results were obtained by Moore (1979) who examined rainfall erosivity parameters for East Africa and observed that the highest erosivities were in the highland areas. He obtained a value of 163 at Nanyuki, compared to the 477 J m^{-2} obtained in this study. The big difference can be attributed to the fact that he used the KE>25 method (Elwell and Stocking 1973) as compared to the EI_{30} method adopted in this study. This type of difference is expected as indicated by Elwell and Stocking (1973) who observed that the EI_{30} and the KE>25 indices yield vastly different values, because of the inclusion of the I_{30} in the former. They suggested that the two indices could not be substituted for each other. It was observed from the runoff and soil loss data in the current study that storms of intensities as low as 3 mm hr^{-1} produced runoff and soil loss. This was particularly common in Mukogodo, where the soils are subject to surface sealing (Mainga and Mbuvi 1994). In addition, runoff and soil loss are influenced by antecedent soil moisture, thus a relatively high intensity on a dry soil may not yield runoff whereas a smaller storm the next day would. This calls to question two issues, (i) that the KE>25 method ignores small intensity storms, which were found to contribute erosion under certain circumstances, and (ii) the empirical nature of the USLE does not take account of the initial conditions of the catchment, which would help to separate storms of high erosion risk from those having a low risk, and therefore reduce the uncertainty in the predictions. It was also observed that although low erosivity values were obtained for the dry areas, the storms in these regions are highly erosive. Mutunga (1994) observed that a few single storms were responsible for most of the soil loss in Mukogodo.

From Appendix 3, it appears that an increase in annual rainfall does not necessarily result in an increase in total erosivity. Although the data used in this work is rather limited, it still puts to question the generalising of relationships between annual rainfall and its erosivity in regional soil erosion studies. Hudson (1995) warns that the tendency to use empirical indices should be treated with reserve, as many years of data are needed to validate them. Thus, in the Upper Ewaso Ng'iro basin and indeed in Kenya, more data and further studies are required to determine how rainfall erosivity relates to agro-climatic zones.

5.2 Soil erodibility

The soil erodibility factors determined in this study were the USLE (Wischmeier and Smith 1978) K-factors calculated as the mean value for each soil type. Figure 5.3 shows the spatial distribution of soil erodibilities in the basin. The actual K-factors obtained for each soil mapping unit (Appendix 6) were used in the calculation of soil loss with the USLE. The interpretation of the soil erodibility data should take into consideration that about 70 percent of the Upper Ewaso Ng'iro basin is rangeland and only about 14 percent is cultivated. Therefore, the relatively low K-factors obtained for most of the basin can be explained by the fact that the soils are mostly under natural vegetation, having appreciable amounts of organic matter and a structure that is not seriously disturbed. In general, K-factors ranged from 0.02 to 0.47 (Appendix 6), obtaining an overall mean value of 0.19 and a standard deviation of 0.078. In addition, 84 percent of the basin has K-factors in the medium range between 0.10 and 0.25. The relatively low standard deviation indicates that soil erodibility did not vary greatly within the basin. This range of erodibilities compares well with K-factors from other tropical regions. (Roose 1977; Vaneslade et al 1984; Ngatunga et al 1984; Barber et al 1979). However, many of these studies show that the nomograph has a tendency to underestimate erodibility for tropical soils, especially those found in arid conditions. This may explain why in the dry areas of the basin, soil erodibility values estimated with the USLE nomograph in this study do not seem to explain the apparent land degradation observed during reconnaissance surveys.

Soils having the lowest erodibility were found on the upper slopes of Mt. Kenya and the Nyandarua Range at altitudes exceeding 3000 m above sea level. They comprise the dystic Histosols (Sombroek et al 1980) and they were predicted to have a mean K-factor of 0.03 (Figure 5.3). They are organic soils and although the silt contents were quite high, the high organic matter reduces erodibility to very low values. The soils lying immediately below these altitudes are the humic Andosols (Figure 2.4). Despite their high silt contents, these soils were found to have low erodibility factors averaging about 0.10. Comparative measured K-factors for both Histosols and Andosols in the region were not available. However, Lal (1990) cites studies by Utomo and Mahmud (1984) who obtained values of 0.18 and 0.08 as compared to nomograph values of 0.22 to 0.18 respectively. They observed that the nomograph estimated values were usually less than the field estimated ones. The low erodibility values obtained in this study are considered realistic due to the abundance of bogs and vegetative cover, which protect the soil in the respective moorlands and forests.

Close to half of the basin (45 percent) has soils of moderately high erodibilities, with K-factors ranging from 0.21 to 0.25. The dominant soil type in this group, are the ferric-chromic Luvisols (Figure 2.4), which cover 15 percent of the total basin area. These soils were found to have K-factors of about 0.22. Luvisols are found in the northern regions of Mukogodo, Barsalinga and Wamba. Data on the erodibility of Luvisols in Kenya has been scarce. Barber et al (1979) obtained K-values of

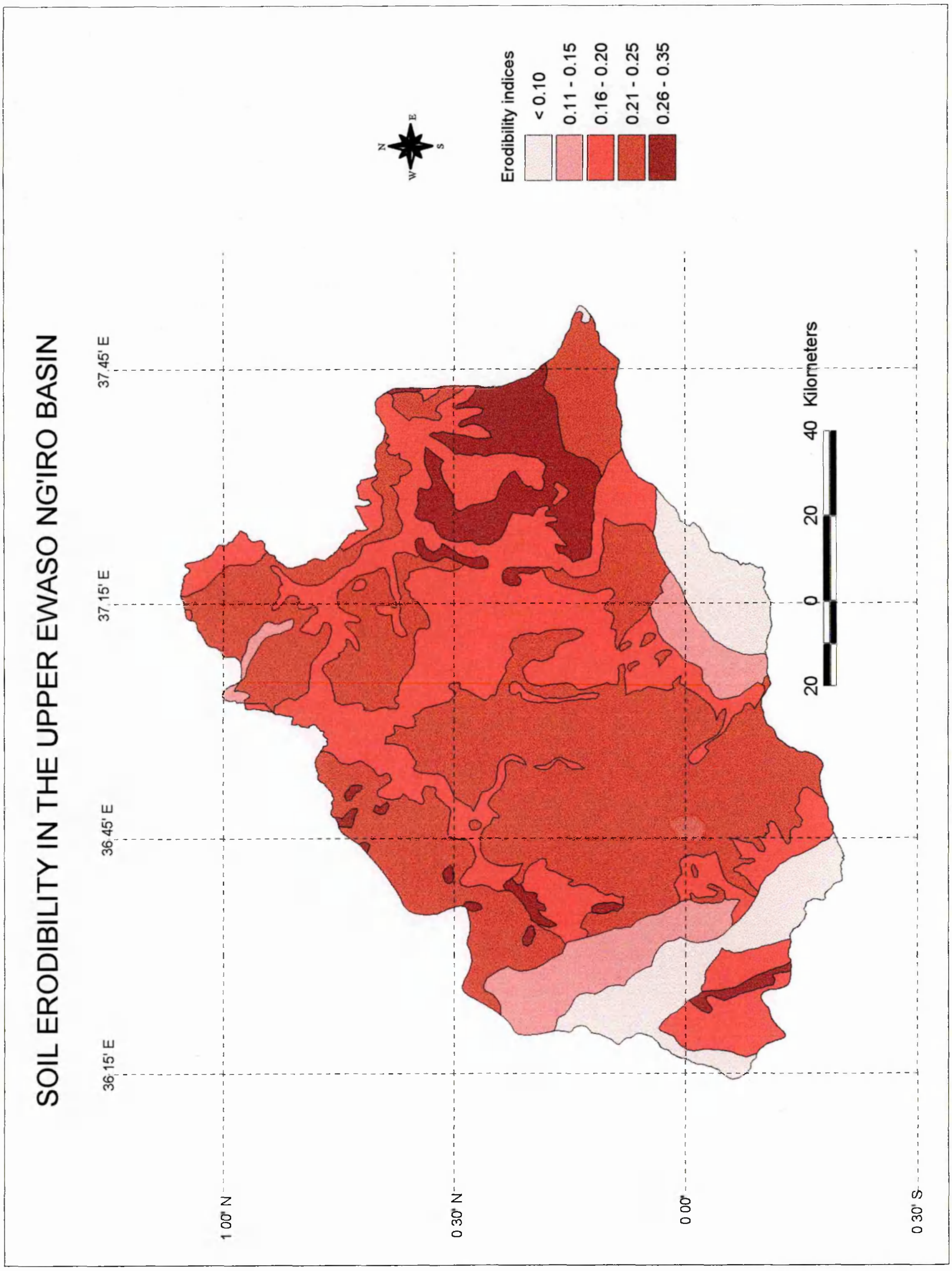

Figure 5.3 Soil erodibility map of the Upper Ewaso Ng'iro Basin

0.52 for a ferral-chromic Luvisol in Machakos, Kenya. Their value was much higher than the one obtained in this study. However, in west Africa, Folly (1997) quotes values of 0.36 (estimated) and 0.19 (measured) for Luvisols. The two comparisons give vastly different results. Either the K-factor obtained by the USLE method does not fully explain soil erodibility, or factors other than soil erodibility are responsible for the apparent degradation. One reason could be the low fertility of these soils, since the organic matter contents obtained in the current study were less than 1 percent. There being little fertility to sustain vegetation cover, less protection is provided for the soil, and high rates of degradation occur. Alternatively, the erodibility factor may be much higher than estimated by the USLE nomograph, because of the sealing properties of the Luvisols (Mainga and Mbuvi 1994) which have not been accounted for by the equation.

According to Muchena (1982) Luvisols have poor structural stability of the topsoil resulting in a tendency to form a strong surface seal. This leads to low infiltration rates and high runoff generating properties. As a result, the soils are highly erodible. A similar observation was made by Folly (1997) who found that due to low aggregate stability in the soils of northern Ghana, crusting and excessive generation of runoff occurred, and these factors could not be related to the soil erodibility factors calculated. It would therefore appear that in this case, although other factors are responsible for the degradation of the Luvisols in the Upper Ewaso Ng'iro basin, the soil erodibility factor does not fully describe soil erosion hazard. Thus, further studies including direct measurements of erodibility are needed in order to obtain better relationships. This is especially important because Luvisols cover large parts of the semi-arid regions of Kenya.

The erodibility values predicted for Vertisols and Planosols (Figure 5.3) ranged 0.24 to 0.27. These soils occupy a significant proportion of the total basin area (26 percent), covering the large sections of the Laikipia Plateau used for commercial ranching (Figure 2.4). The K-factors obtained are higher than the values of 0.10 obtained for a Vertisols in West Africa (Roose 1977). However, the erodibility values obtained by the nomograph do not account for the effects of the montimorrillonitic clay minerals of the Vertisols, which causes the soil to shrink and crack when dry, and the subsequent swelling when wet, thereby drastically reducing infiltration. Even on a gentle slope, runoff and rill erosion can occur. According to Roose (1977) the USLE nomograph does not adequately predict erodibility of Vertisols. The Planosols, found in pockets in the low lying area occupied by the Vertisols are subjected to less actual erosion than the Luvisols. However, the topsoil is underlain by a heavy textured, compact and hard B-horizon, which inhibits permeability. Hence their susceptibility to erosion is higher.

The soils of the valleys and minor scarps, consisting of chromic Cambisols and eutric Regosols were found to have moderate erodibility values ranging from 0.18 to 0.21. These soils have a stony and gravelly surface, a factor that was predicted to reduce erodibility. Studies in other regions have shown that stones and gravel reduce erosion (Savat 1982; Collinet and Valentin 1984; Lamb et al 1950). However, Poesen and Ingelmo-Sanchez (1992) suggest that rock fragments increase erosion when embedded, while they decrease erosion when partly embedded or resting on the surface. The soils sampled in the current study were in most cases partly embedded and partly on the surface. It was therefore difficult to decide whether the stones reduce or increase erosion. This is because the areas in the basin having large amounts of stone cover, as observed in Rumuruti, Lodungukwe, Mukogodo and Lussie Gap, were also sources of large volumes of runoff. Although soil erosion would not be apparent on the rocky ground itself, the lowlands below, which normally have little stone cover, were found to be scarred by rill and gully erosion, some of which was quite severe (Appendix 13.3). It would appear that the overall effect of the stone cover at the sub-catchment level would be to increase soil erosion. Mutunga (1994) assessed soil erosion in Mukogodo from runoff plots located at the lower reaches of the subcatchment, where stone cover was limited, and interill and rill erosion are prevalent. In the current study, the coarse resolution of the basin scale could not accommodate the fine differences within a subcatchment. Thus further studies are required at a more detailed level than the current study, and covering a broader spatial resolution than Mutunga's work, to establish the role of stone cover on soil erosion in the basin.

The slopes of the mountain footridges are covered by eutric Nitisols, which have a relatively good permeability but their low organic matter contents yield a relatively high predicted erodibility factor of 0.23. This is much higher than the value of 0.05 obtained by Barber et al (1979) for a humic Nitisol at Kabete in Kenya, although regional differences and management may be the reason. On the other hand, the eutric Regosols of the Mukogodo forest and Lol Daiga hills were predicted to have an erodibility index of 0.17 which is much lower than the 0.47 obtained for calcaric Regosols in Spain by Albaladejo et al (1995). Apart from regional differences, there were rock outcrops and stones at Mukogodo forest, which may contribute to the lower K-factors. In addition, less degradation has been observed than that from Luvisols in the same region, due to better vegetation cover and organic matter contents.

Only a small part of the Upper Ewaso Ng'iro basin is covered by Alfisols. However, this area, near Isiolo (Figure 2.4), was significant because it had the highest erodibility values averaging 0.39. Erodibility assessments on Alfisols in other tropical regions show comparable results. Mtakwa et al (1987) obtained measured values ranging 0.147 to 0.245 as compared to USLE estimated values ranging 0.136 to 0.160. Compared to other local values, Onstad et al (1984) obtained K-factors of 0.24 from plots on Alfisols at Katumani in Machakos, Kenya. Later studies on the same plots by Kilewe (1987), after the plots had been degraded gave values of 0.47. It would appear that the K-factor is dynamic and dependent on land management. In the Machakos case, the measured values were on cultivated land. For instance, in the current study, the soil from a cultivated field in the Nyambene hills having 4.7 percent organic matter had a K-factor of 0.17 as compared to a value of 0.03 obtained for the forest soil bordering the farm, whose organic matter was 11 percent. Similar observations were made by Ekwue et al

(1993) who found that soil detachment by raindrop impact decreased exponentially with organic matter. Roose and Sarrailh (1989) noted that the K-factor of tropical soils increases when soils are cultivated and that it varies with the soil type, seasons and cultural practices. It is therefore possible to relate land degradation to erodibility resulting from cultivation. In the current study, the land has been degraded due to overgrazing. As there were no records of K-factors prior to the current degradation, further studies are needed to relate the effects of overgrazing on erodibility.

Overall, comparison of soil erodibility values obtained in this study with earlier estimates (Mati et al 1998) using the FAO texture classification methodology (FAO 1978; Kassam et al 1991) show that the USLE methodology used here produces better results. The FAO classification methodology was too lumped, allowing only four classes as all the factors had been estimated from the Exploratory soil map (Sombroek et al 1980) making it difficult to account for even regional scale variability. Both methods agree about the low erodibility risk for soils with high organic matter. There are major differences for the soils in the dry areas, especially those with high percentage sand contents like the Luvisols, for which the FAO methodology overestimated erodibility. In general, the results obtained with the USLE K-factor method in this study were found to represent soil erodibility reliably for reconnaissance scale studies. For more detailed work, further studies would be required to determine soil erodibility at a finer resolution.

5.3 Topographic factors

The LS factor component of the USLE accounts for the effect of topography on soil erosion. The results of the slope steepness, slope lengths and the combined derived LS factors for the Upper Ewaso Ng'iro basin, are presented in this section.

5.3.1 Slope steepness

Slope steepness in the Upper Ewaso Ng'iro basin (Figure 5.4) is related to the incidence of mountains and hills that dominate the area, as well as stream density (Appendix 9). The steepest slopes are found on the upper parts of Mt. Kenya, the Nyandarua Range and the Mukogodo hills. Slope steepness gradually decreases as altitude declines from undulating to gently undulating footslopes, culminating in the flat plateau areas. The slope steepness values obtained by GIS (Figure 5.4) compare well with the values obtained from field measurements.

On the Laikipia Plateau, slope steepness averages about 1.0 to 1.5 percent. On the steep-sided valleys of Mt. Kenya, the Nyandarua Range and the Nyambene hills steeper slopes were found some exceeding 30 percent. However, there were some exceptions, for instance, the flat to gently undulating slopes at altitudes above 2400 m on the upper areas of the Nyandarua Range. In general, about 77 percent of the basin is flat to gently undulating. This serves as an indicator that topographic factors may not be responsible for much of the soil erosion in the basin.

The importance of slope steepness to soil erosion has been well documented (Moore and Burch 1986; Gao et al 1996; Hudson 1995). Overland flow on complex hillslopes produced by rainfall excess has been observed to erode more soil from certain points in the landscape than others. The erosion processes are made complicated by the likelihood of convergence and divergence of flow, as well as the possibilities of deposition. Rill erosion is more likely to occur on long slopes than on short ones. Mc Cool et al (1987) observed that there is a threshold length at which rilling starts to occur. They found that runoff varied more with steepness on the low slopes than on the steep slopes and that above a slope of about 8 percent, runoff did not vary significantly with steepness. The 9 percent slope was used as a breakpoint because it represents an S factor of 1.0. They developed two regression equations for determining the S factor based on the fact that erosion increases at a slower rate for the low slopes than for steeper slopes. The use of the two equations (3.6 and 3.7) in the

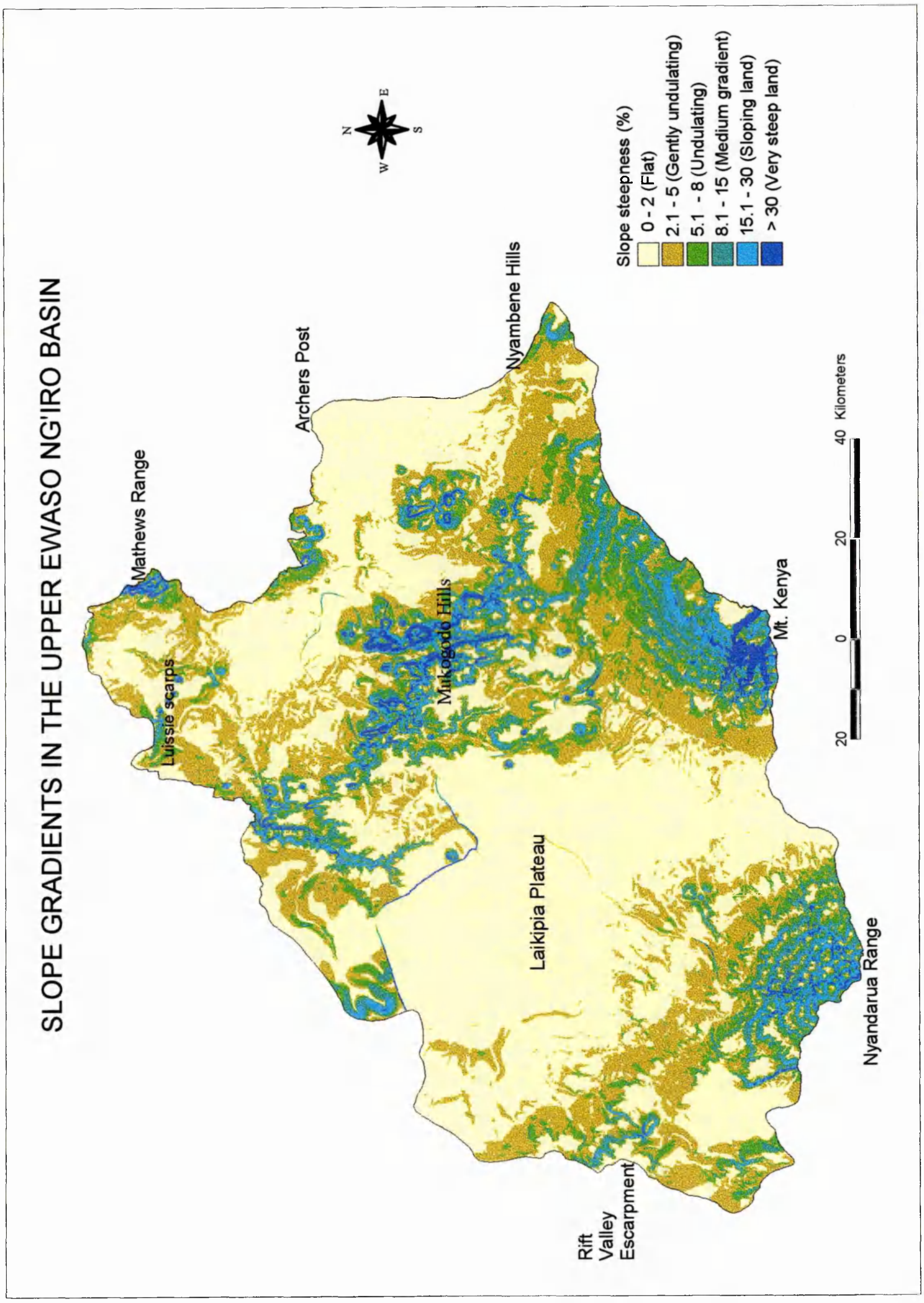

Figure 5.4 Slope steepness map of the Upper Ewaso Ng'iro basin

current study was found to predict soil loss better that the original Wischmeier (1978) equation.

Square raster modelling, as used in the current study, has been one of the most common methods of deriving slope steepness from maps and other data (Burrough 1986; Jenson 1991). This is because the heterogeneity of a slope is a sensitive parameter in terms of contributing to area dynamics (Beven 1991). Research has shown that the slope shape, as the interaction of angle and distance determined by element size, has important effects on the total magnitude of erosion or deposition (Renard et al 1996; Mitasova et al 1996). The USLE does not take into account catchment convergence or divergence explicitly. Moore and Burch (1986) observed that for catchments of equal area, a converging catchment will produce more sediment than a diverging catchment. The implications of this are not easily incorporated in a grid model. Jenson (1991) noted that slopes calculated from raster elevation data vary significantly depending on cell size and data source. Since independent data for particular cell sizes are not usually available, it becomes necessary to use representative values or generalisation approaches. Moore et al (1993) suggest that the grid size for slope modelling should not exceed slope break lengths. The current study used 100 m grid cells which were considered to be within these limits, as observed from field surveys and topographic maps.

Some of the limitations of preparing the DEM of the Upper Ewaso Ng'iro basin have been discussed in chapter 4. With the available facilities in Kenya, it was necessary to split the basin into 19 subcatchments in order to create DEMs of the basin at 200 m resolution. Later work at Silsoe College, England with more powerful software and Windows NT computer facilities still required the basin to be split into 4 subcatchments, in order to create DEMs with a 100 m resolution. Given the facilities and time constraints, the DEM used in this study has been considered adequate for the resolution of the work. Even so, the importance of a higher resolution input coverage cannot be understated. Weibel and Heller (1991) state that contours are mainly a form of terrain visualisation, and are not particularly useful as a scheme for numerical surface representation. They observed that contour data yields DEMs of only limited accuracy, but they also pointed out that since large area coverage is achieved relatively cost effectively, contour coverages provide a compromise method of obtaining topographic data for use at medium to regional scales, as was the case with the current study. Further work, to produce a higher resolution DEM is recommended. This calls for more powerful computer facilities, or splitting the basin into many small subcatchments.

5.3.2 Slope length

Slope length in the Upper Ewaso Ng'iro basin follows the drainage density and altitude. With the exception of the cultivated areas, where slope length may have been reduced by terracing or field boundaries, much of the basin consists of natural rangelands and forests, where the natural slope lengths still remain. Comparison with manually estimated slope lengths showed that very long slopes were prevalent in the Laikipia Plateau, and in the northern plains, between Isiolo and Archers' Post. Due to the reconnaissance nature of the DEM used, it was not possible to account for changes in micro-topographic relief.

The slope lengths determined from the DEM of the basin in some cases exceeded 200 m. This was comparable to the long slopes observed on the Laikipia plateau, and on river valleys at higher mountain altitudes in the reconnaissance surveys. Wischmeier and Smith (1978) recommend the calculation of the LS factor for slopes not exceeding 200 m. This is because in reality, long slopes are expected to consist of segments of several lengths, with those at their base declining in gradient and encouraging deposition. However, this maximum slope length is valid for the east of the Rocky Mountains in the USA, so the implications may be quite different in other regions. Thus, the use of a maximum slope length of 200 m is rather artificial, as it does not completely correspond with the real field conditions. It was considered realistic because soil erosion without deposition is unlikely beyond such a length. Since the topography of the Upper Ewaso Ng'iro basin is generally flat to gently undulating, which corresponds to the conditions under which the USLE was developed, limiting all slope lengths to 200 m seemed reasonable in the absence of better information.

5.3.3 The LS factor

Figure 5.5 shows the combined effect of the USLE slope steepness and length (LS) factors in the Upper Ewaso Ng'iro basin. It shows that about 75 percent of the basin has LS factors less than 1.0. The relatively low values obtained are realistic because much of the basin is flat to undulating topography, where slopes less than 9 percent are predominant. Even then, it is worth noting that some of the areas with high LS factors are located on the mountain slopes and regions most subject to cultivation and deforestation. These are the same areas that have relatively high rainfall erosivities.

The advantages of GIS capabilities for terrain and hydrological modelling include the fact that for the determination of USLE LS factors, the map algebra processor can be used to evaluate the equation at each cell in the spatial domain (Petersen at al 1995; Gao et al 1996). Even so, determining the LS factor from grid-based DEM has its limitations. Other than the resolution of the input data, slope lengths as generated by TOPOGRID (ESRI 1997) were based on the assumption that each slope plane consists of a homogeneous vegetation cover. In reality, this may not be the case. Ideally, the LS factor should be relevant for the runoff-producing sections of the hillslope. According to Desmet and Govers (1996) if a land use that does not contribute runoff (e.g. forest) is upslope of another that does (e.g. cropland), the LS factor generated from the DEM is overestimated. In addition, corrections may be required to take care of concavity and convexity of slopes. Such corrections may be possible for a small catchment, but for the current study, the scale of the work could not permit such details as separating slopes according to covers or slope shapes.

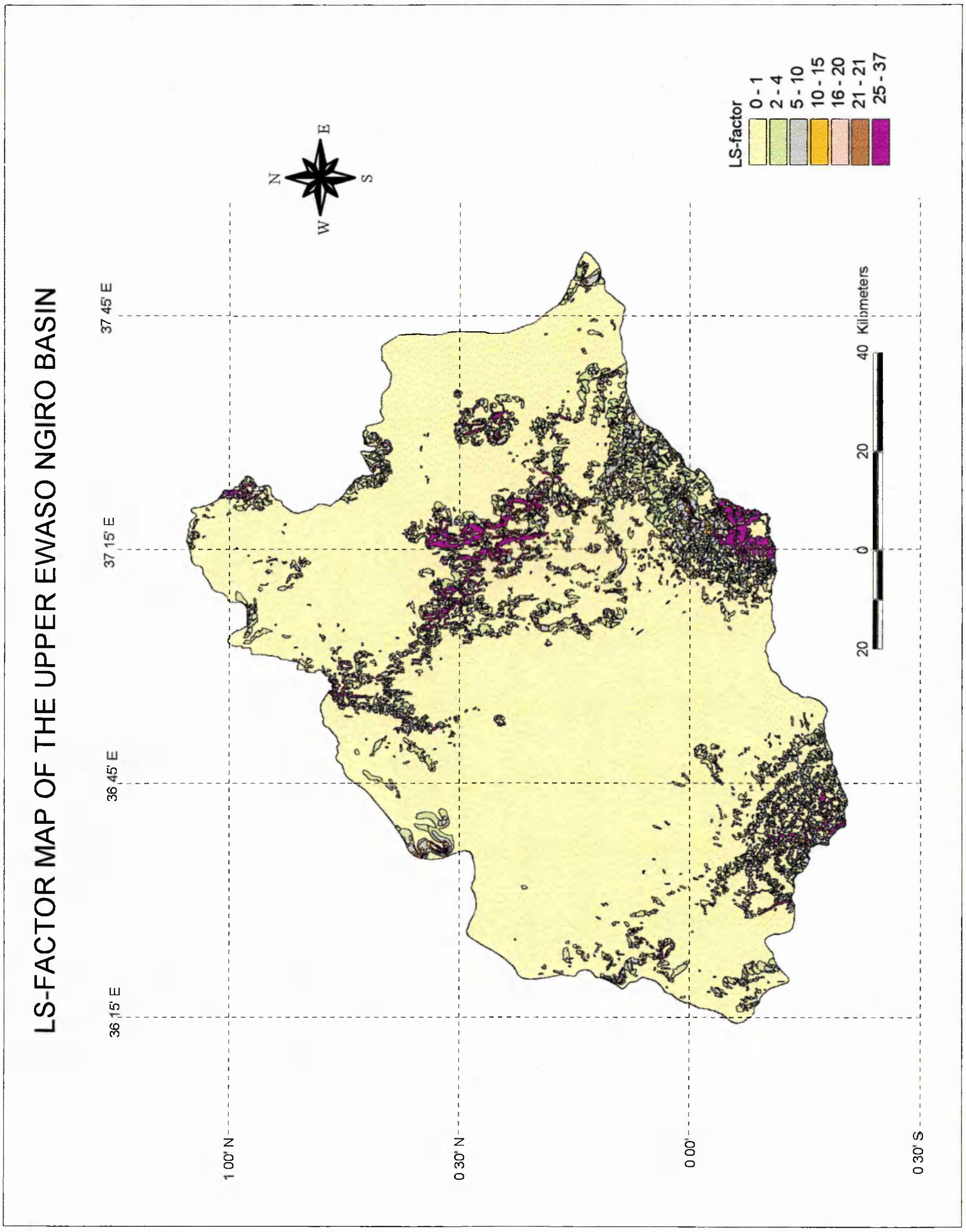

Figure 5.5 USLE LS-factor distribution in the Upper Ewaso Ng'iro basin

The LS factor is important as a measure of the sediment transport capacity of runoff from the landscape. However, it fails to account fully for the hydrological processes that affect runoff and erosion (Moore and Burch 1986). As the LS factor increases, overland flow concentrates into rills, increasing flow depth and velocity, which increase the stream power. Wischmeier and Smith (1978) noted that on long steep slopes susceptible to rill formation, the exponent 'm' in the USLE L-factor (equation 3.4) is likely to be greater than 0.5. Recent advances in GIS have seen the development of computer algorithms that can automatically calculate the LS factor from the DEM (Desmet and Govers 1996; Moore et al 1991). However, these algorithms require high resolution DEMs, which compared with manual methods, offer quicker solutions. Jager (1994) noted that the LS factor has the highest influence on the results of a GIS simulation of the USLE. Such algorithms could not be used in the current study due to limitations in software and data resolution. Nevertheless, the LS factors obtained by GIS modelling in this study compared well with calculated values from plot data (Appendix 12) and therefore were considered adequate for this work. Otherwise, for detailed applications, a finer resolution DEM and input data would be advisable.

5.4 Land cover and management factors

The determination of the major land cover types and the factors associated with cover that affect soil erosion were very important in this study. This section presents the results of the land cover mapping using remotely-sensed data and GIS, and the respective C-factors obtained for the Upper Ewaso Ng'iro basin.

5.4.1 Land cover types in the Upper Ewaso Ng'iro basin

The distribution of the major land cover types in the Upper Ewaso Ng'iro basin (Figure 5.6) shows that most of the basin is still covered by natural vegetation and only about 14 percent of the basin is cultivated in both large scale and small scale (Table 5.1). Forests cover about 11 percent of the total area. Over 70 percent of the basin is covered by the combination of grasslands, bushlands, shrublands, shrub

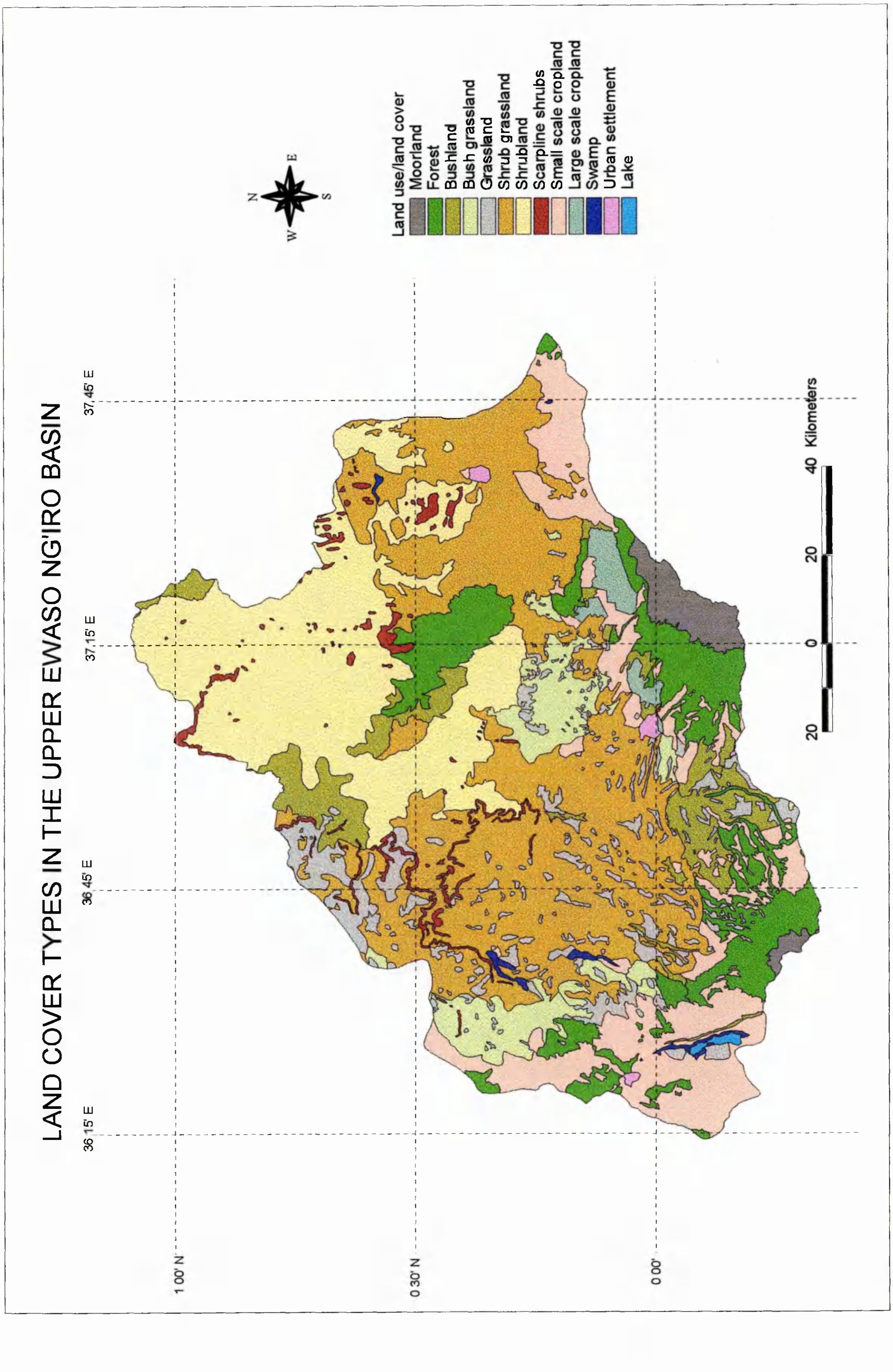

Figure 5.6 Land cover types in the Upper Ewaso Ng'iro basin

grasslands and bush grasslands which can be described as 'rangelands' (Thurow and Herlocker 1993). The rangelands are home to a wide diversity of livestock and wildlife, where management systems are quite varied depending on land ownership, financial status and social structures.

Table 5.1 Areal coverage of the land cover types in the Upper Ewaso Ng'iro basin

Land cover type	Area (km^2)	Percentage area
Moorland	306	2.0
Forest	1689	11.1
Bushland	911	6.0
Bush grassland	843	5.5
Grassland	1012	6.6
Shrub grassland	4667	30.6
Shrubland	3228	21.1
Scarpline shrubs	295	1.9
Small scale cropland	1987	13.0
Large scale cropland	194	1.3
Swamp	59	0.4
Urban settlement	43	0.3
Lake	21	0.1
TOTAL	15251	100

In the central region of the basin, the areas comprising grasslands and shrub grasslands in the Laikipia Plateau are occupied by large scale commercial cattle ranches, such as Ol Pejeta, Mutara, Mukenya, Suguroi and Solio (Appendix 10). Some of the ranches have in addition privately owned wildlife sanctuaries or the livestock share the grazing grounds with controlled amounts of wildlife. In the ranches, stocking rates are low and management of high standard with electric fencing to keep out unwanted livestock and wildlife. Therefore, grass cover and overall vegetative cover in the region is over 60 percent, while the predicted C factors were low. Some of the shrub grasslands were not in such a good condition, as observed in the north and south eastern parts of the basin such as Kirimun and Isiolo Quarantine Area. These areas previously used to be protected, as they were the government livestock holding grounds (Herlocker et al 1993) but are now open to communal grazing. In addition, the climate is drier and therefore grass cover is poorer even in the well managed game reserves of Buffalo Springs and the Samburu Game Reserve, resulting in higher C factors.

The shrublands (Figure 5.6; Plate 4.11) form the part of the rangelands that has been most subjected to communal grazing (Herlocker et al 1993; Thurow and Herlocker 1993). They are found in the north and north east of the basin, around Mukogodo, Makurian, Lengusuka, Wamba and Longopito. Grass cover is low, mixed with unpalatable forbes or simply lacking and bare surface occupies 40 to 70 percent of the area (Appendix 10). Wildlife and livestock compete for the available fodder, which is usually inadequate especially for cattle (Herlocker et al 1993). From reconnaissance surveys, it was found that the area is visibly degraded. This could be attributed to overgrazing on land that had once been shrub grassland as described in section 1.1.3. This was evident even on the satellite images, whereby the fence, separating the large scale commercial ranches from the communal grazing areas around Il Polei, was also the line of abrupt transition from shrub grassland to shrubland, although the soils and climate are the same. This implies that the loss of grass cover in the shrublands may be a result of human influence or poor management. As these regions are easily identifiable, the biggest challenge now is their rehabilitation. As soil erosion in this region is associated with historical land tenure issues, social and demographic trends (Herren 1987) a multi-disciplinary approach to land rehabilitation would be necessary.

There are indications that deforestation in the Upper Ewaso Ng'iro basin is on the increase. From the reconnaissance field surveys, it was observed that bushlands in such areas as Ndaragwa, Naromoru and the fringes of Mukogodo forest contained remnants of forest tree species such as cedar, indicating that they were former forests that had been decimated for timber, charcoal burning or fuelwood. Thus, the forest cover in the Upper Ewaso Ng'iro basin should be more in view of the mountainous nature of the basin. Kilewe and Thomas (1992) reported that forest cover is diminishing in Kenya due to overpopulation, cultivation and deforestation. In the study area, small scale farms are encroaching the forests of the Nyandarua Range, the Mt. Kenya and the Nyambene hills (Figure 5.6). The Rift Valley escarpment, once a major forest area, has been converted into farmlands. As these were qualitative observations, further studies are necessary to quantify the levels of deforestation in the basin and the possible remedies for it.

5.4.2 C-factors

The C factors determined for the Upper Ewaso Ng'iro basin (Figure 5.7; Appendix 10) were found to decrease exponentially with cover. Forest cover had the lowest C factors, with a mean of 0.007. This agrees with the findings of Dissmeyer and Foster (1980) who suggest that several subfactors such as canopy, reconsolidation and high organic matter content should be included. They showed that the USLE can be used to estimate interill and rill erosion for forest conditions.

Although the cultivated croplands occupy only about 15 percent of the total basin area, they are significant as they contribute much of the soil loss in the basin. The relatively small proportion of cultivated land may be attributed to the arid conditions in the basin, as most of the farms are concentrated around the mountains (Figure 5.6). However, recent studies (Kohler 1987; Flurry 1987; Huber and Opondo 1995) raise the issue of rapid population growth and increase in the number of small scale farms. Population pressure and immigration has resulted in the subdivision of the ranches even in dry marginal areas such as Nyakinyua, Rumuruti and Isiolo. The removal of the natural vegetation in such fragile environments for small scale farming will enhance the risks of soil erosion. As depicted in Figure 5.7 the C factors for cropland are the highest, ranging between

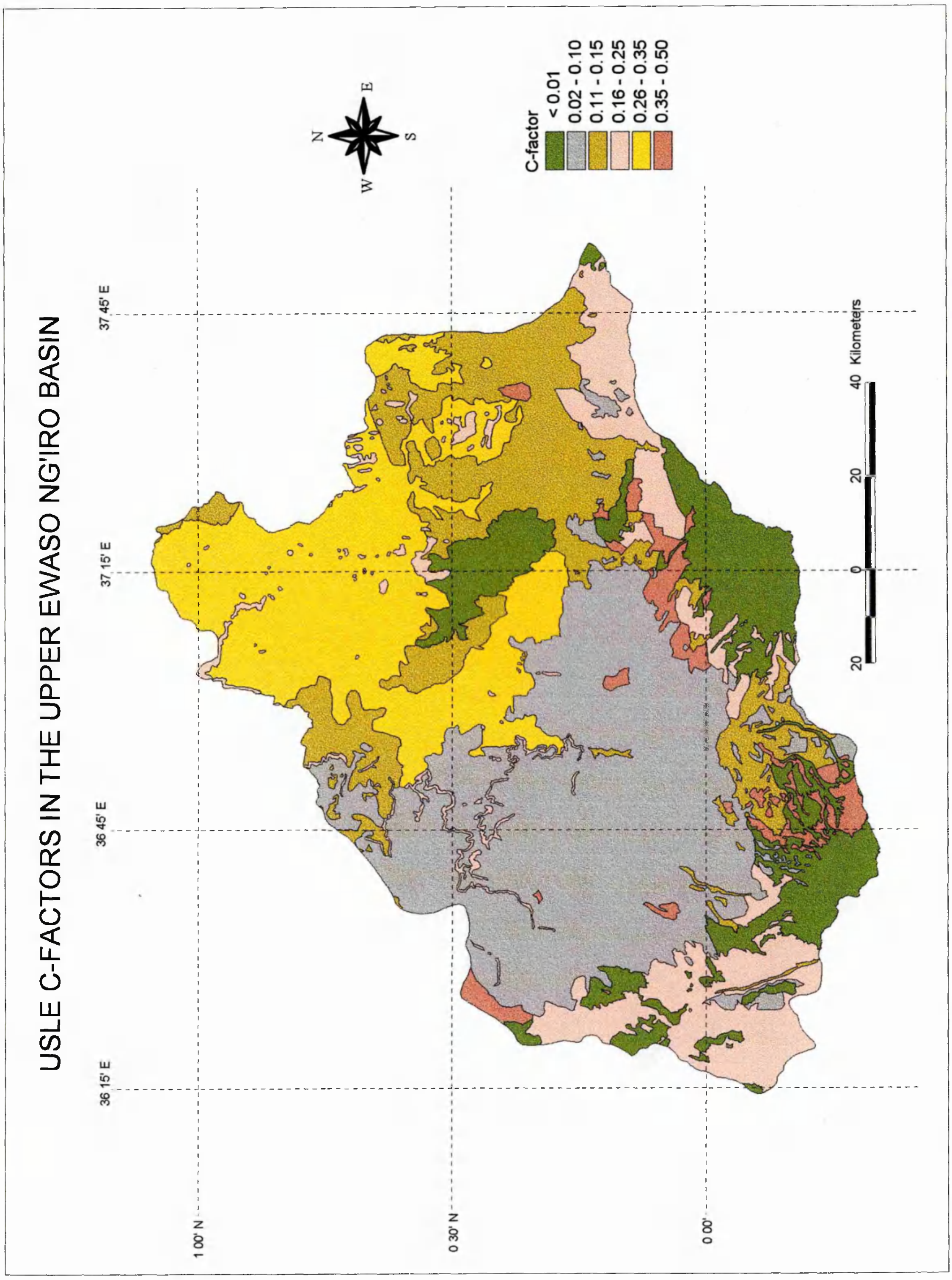

Figure 5.7 USLE C-factor map of the Upper Ewaso Ng'iro basin

0.2 and 0.49. These values compare favourably with the findings of Onstad et al (1984) who obtained a C factor of 0.24 in Machakos. The relatively high C factors obtained here can be linked to the fact that the land is left bare during the beginning of the rainy season, which has been associated with the most erosive storms (Liniger 1991).

The average C-factors derived for the rangelands from the USLE guide tables (Wischmeier and Smith 1978) were found to range from 0.18 to 0.4. Compared to observed soil loss values at Mukogodo on runoff plots, these factors do not explain the high soil erosion rates recorded under shrublands, as C factors in excess of unity would have been required. This may be partly related to the estimation of C-factors for heterogeneous conditions or to other unknown factors. Therefore further studies are required to provide improvements in USLE C-factor estimation for this region.

According to Wischmeier and Smith (1978) the cropping and management factors include the interrelated effect of cover, crop sequence, cultural practices and length of growing season. This makes the evaluation of the C factor difficult due to the many effects. When other types of cover such as forest and grassland are included, several assumptions are necessary to make the estimation possible. In this study, the C factors were estimated using the USLE guide tables (Wischmeier and Smith 1978) for all vegetation types. Some improvements in the predictions were obtained by separating ground cover from canopy cover during field assessments. Therefore, the C factors obtained are considered adequate for this work.

Most of the literature on the derivation of C factors refers to field crops (Elwell and Stocking 1976). The values of C factors obtained in this study for small scale farms were based on maize and beans, potatoes and wheat or barley in each respective region. They are rough estimates as in most of the small scale farms, crops are usually intercropped, often with more than two or three crop types, including trees and vegetables (Huber and Opondo 1995). In addition most farms have a part of the land reserved as grassland for the animals. It was not possible at the resolution of this study to delineate the grazing areas within the small scale farms, therefore, relatively lower C factors for cropland were derived to account for this. Regional differences in crop cover were derived by obtaining higher C factors for the drier areas, where crop covers are generally poorer. Conversely, lower C-values were predicted for the wetter areas, as in the Nyambene hills and the Nyandarua region, where crop covers are higher, while the maize crop when grown takes longer to mature (Jaetzold and Schmidt 1983). The C-factors derived in this study are comparable to those obtained by Kassam et al (1991) for Kenya in general, and by Kilewe (1987) for Machakos. However, further studies are required with controlled experimentation to derive C-factors at finer resolutions and for multiple vegetation covers, especially in the rangelands.

5.5 Conservation practices

The spatial distribution of the documented soil conservation catchments in the Upper Ewaso Ng'iro basin is shown in Figure 5.8. The map relates to areas where physical soil conservation structures have been installed. As explained in section 4.6, a uniform P-factor of 0.18 was estimated for all the conserved catchments. Whereas the actual value of P may be different, it was not possible at the resolution of this study to determine the individual farm values. The choice of a suitable average value was compounded by the heterogeneity of the topography, since P-factors increase with slope. That left the choice of either ignoring the conservation practices completely, or using a median value, which roughly represents the conditions. The latter option was adopted in this study, as it was important to get an indication of the influence of soil conservation activities in the study area. The effects of cultural conservation measures have been incorporated in the derivation of the C-factors presented in the preceding section.

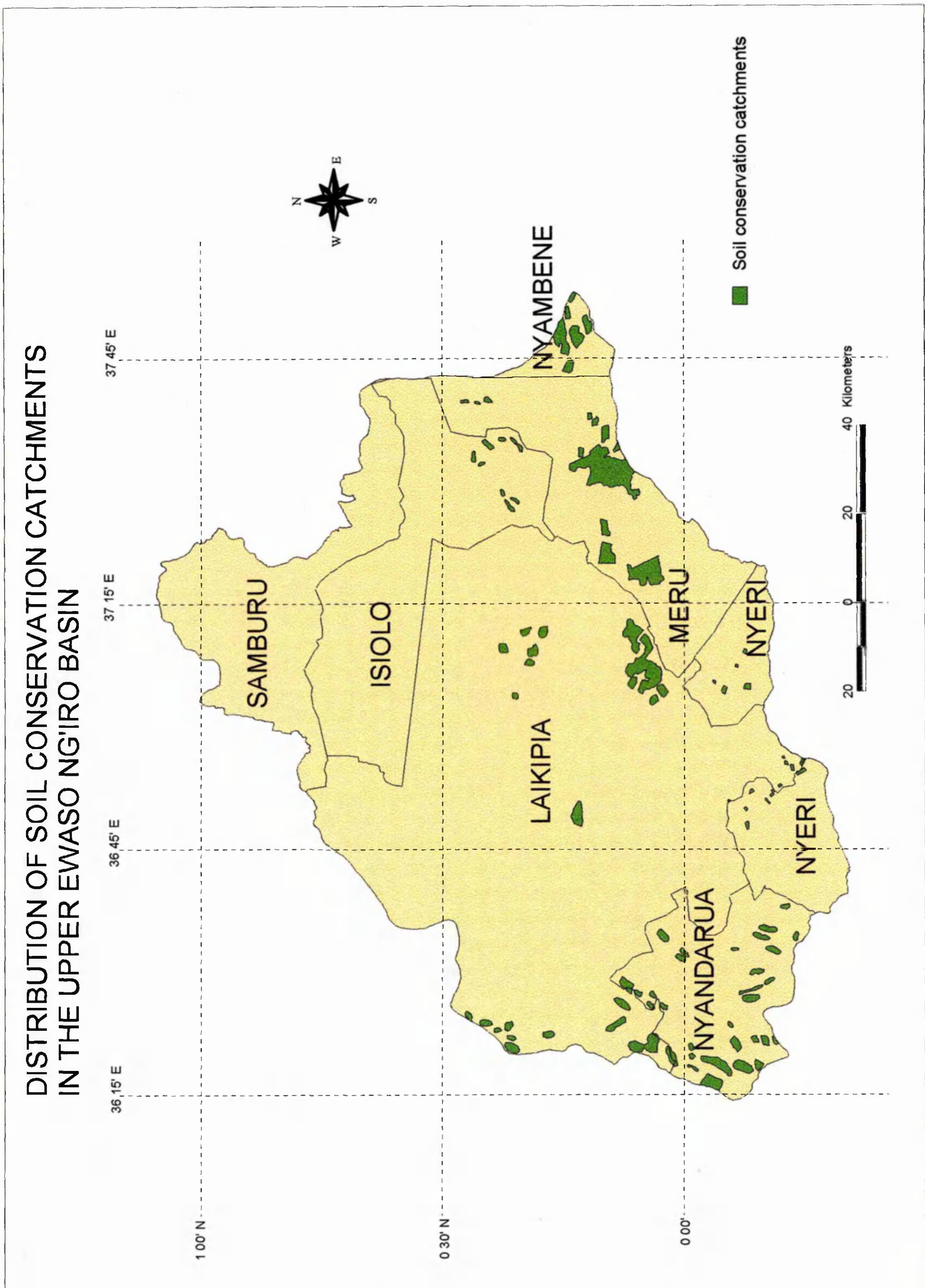

Figure 5.8 Distribution of soil conservation catchments in the Upper Ewaso Ngi'ro basin

The prediction of the USLE conservation practice factor (P) normally relates to cultivated fields, where specified soil conservation measures are operational, and is also related to the slope. The USLE guide tables (Wischmeier and Smith 1978) provide estimates that can be used for similar conditions. In addition, Mitchell and Bubenzer (1980) point out that the P-factor is most effective for slopes in the range of 3 to 8 percent, and that it increases as slope increases. According to Foster et al (1982) most of the P factors for mechanical practices used in the USA such as contouring, strip cropping and terracing, are transferable to other parts of the world. However, there are no values for some of the soil conservation practices used in Kenya such as trash lines, stone lines and fanya juu terraces. In the current study, this was made more complicated by the presence of different types of structures in the same subcatchment. Therefore, there is a need to develop local values of conservation practice factors.

Only relatively small areas are covered by soil conservation activities in the Upper Ewaso Ng'iro basin. This may be explained by the fact, already noted, that soil conservation extension usually relates to small-scale croplands, which form only a small proportion of the basin area. Another reason was that much of the basin, including the small scale farming areas, lies on relatively flat to gently undulating slopes, which may not be considered priority areas for soil conservation. Even then, it is worth noting that little effort has been put into conserving the rangelands, especially in the north of the basin, which were found to be severely degraded. The reasons for this are varied, and include harsh environmental conditions, social economic constraints, pastoral grazing habits, insecurity and low population (Herlocker et al 1993). The conditions in the Upper Ewaso Ng'iro basin differ from Machakos, where the increase in population has resulted in improvements conservation activities (Tiffen et al 1994). Unlike on cropland, where terraces can be seen, conservation activities in dry rangelands normally take longer and require more resources and sometimes, there is little evidence of success. As Figure 5.8 shows little soil conservation activity in the rangelands. Therefore, future conservation efforts should focus on these areas.

5.6: Soil erosion hazard

The soil erosion hazard in the Upper Ewaso Ng'iro basin (Figure 5.9) as predicted with the USLE and GIS, is described using six broad classes. Erosion risk ranges from areas experiencing soil loss of less than 1.0 t ha^{-1} yr^{-1} to medium hazard areas experiencing between 2 and 9.0 t ha^{-1} yr^{-1} and then to high hazard areas with over 50 t ha^{-1} yr^{-1}. These results are discussed in this section with reference to the applicability of the USLE to the basin, the use of tolerable soil loss values and the factors associated with the low and high erosion hazard, as well as the limitations experienced.

5.6.1 USLE applicability in the Upper Ewaso Ng'iro basin

The applicability of the USLE for this study was tested by validation of the model using plot data (Appendix 12). The linear relationships presented in Table 5.2 show that in general, the USLE predicted soil loss quite well, with an overall correlation of linear coefficient value of 0.645 between predicted and observed soil loss. Better correlation coefficients were obtained when the data were split into four groups of vegetation cover. The fit of the 45° line (ASCE 1996) showed that the model overestimated soil loss under forest conditions, while it underestimated for the other covers. Similar results were obtained by Risse et al (1993) who observed that the USLE overpredicted soil loss on plots with low erosion rates, while on plots with higher erosion rates, erosion was underpredicted. This means that there are factors in the erosion process that may not have been accounted for by the USLE.

From Table 5.2, the standard errors of estimate and the intercepts of the regression equations are relatively high indicating some degree of uncertainty in the model performance. This may not be unusual considering that the number of observations were not so many and the high variations in the observed data from year to year, as well as the empirical nature of the model since it uses average values. In a similar

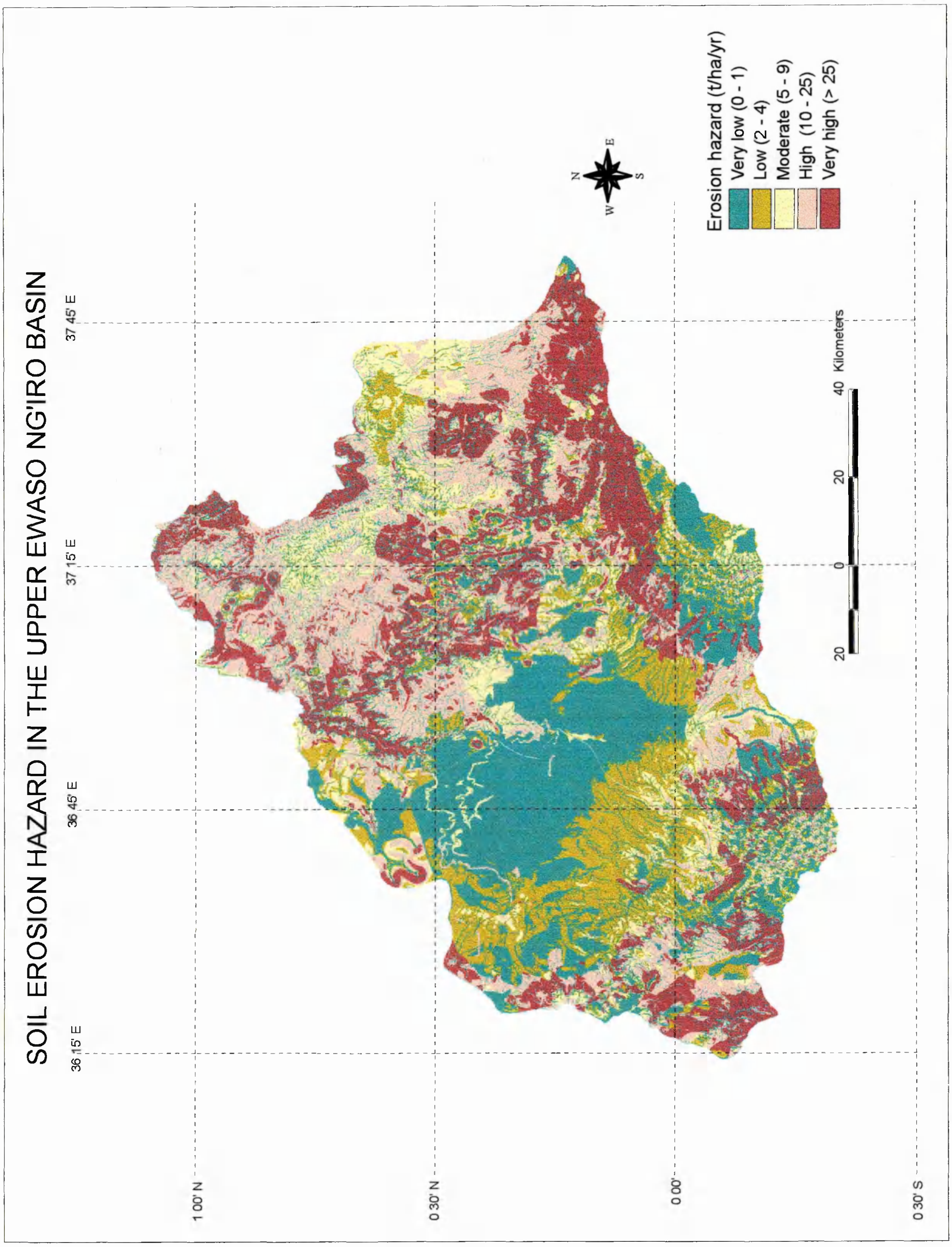

Figure 5.9 Soil erosion hazard in the Upper Ewaso Ng'iro basin

study with the USLE in Portugal, Thomas and Coutinho (1994) observed that the USLE adjustment to observed data was not fully satisfactory, due to variations of the data from year to year.

Table 5.2 Results of linear regression for the validation of USLE with plot data

Station name	Cover	Regression equation	N	(R^2)	e
Naro Moru Gate, Teleswani	Forest	$S_u = 1.389S_o + 0.109$	6	0.991	0.079
Kalalu, Teleswani Naro Moru Met, Naro Moru Gate,	Grass	$S_u = 0.693S_o + 0.883$	14	0.690	3.679
Kalalu, Karuri Sirima	Maize, potatoes	$S_u = 0.411S_o + 8.673$	12	0.526	8.102
Mukogodo, Sirima	Shrubland Bushland	$S_u = 0.427S_o + 4.695$	13	0.708	3.342
Combined data	All	$S_u = 0.535S_o + 2.947$	45	0.645	5.475

Where, S_u = Predicted soil loss (t ha^{-1} yr^{-1}); S_o = Observed soil loss (t ha^{-1} yr^{-1}); N = Number of observations; R^2 = Coefficient of linear regression; e = Standard error of estimate

Table 5.3 shows the maximum and minimum soil loss predicted at plot (USLE- plot) and regional scales (USLE-GIS), as compared to measured values from the available runoff plot data. The use of class ranges has been recommended (Wischmeier and Smith 1978) as a better method of checking the applicability of the USLE than comparing absolute values. These results show that the model predicted soil loss with similar ranges that were comparable to observed values, and therefore, it can be applied to the Upper Ewaso Ng'iro basin. However, the range from minimum to maximum values in all three data groups (predicted and observed) are high and the predictions less certain at the extremes of the ranges in soil loss.

5.6.2 Extent of erosion hazard

The spatial distribution of the areas predicted to have high rates of soil loss are presented in Figure 5.10. This was achieved by setting an upper limit of soil loss, 9.0 t ha^{-1}yr^{-1}, separating areas of high from low erosion risks respectively. The choice of

Table 5.3 Comparison of USLE predicted and observed soil loss values

Station	Treatment	Soil loss rates (t ha^{-1} yr^{-1})								
		Soil loss predicted with the USLE using plot data			Soil loss predicted with the USLE and GIS			Soil loss measured from plots		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Embori	Barley	15.0	18.2	32.4	21.4	31.3	39.7	0	51.3	102.6
Kalalu	Maize	5.7	22.2	48.5	1.6	8.2	18.1	1.1	14.8	25.4
Karuri	Potatoes	5.7	14.8	15.2	19.7	35.4	49.9	0.5	24.5	69.4
Mukogodo	Shrubland	8.9	12.2	14.0	24.2	38.2	52.4	2.2	18.3	35.2
Naro Moru Gate	Bamboo forest	0	0.1	0.1	0	0.8	1.2	0	0	1.0
Naro Moru Met.	Bamboo forest	0	0	0.3	0	0.9	1.5	0	0	1.3
Sirima	Potatoes	13.3	9.5	23.1	16.2	5.2	27.3	0.9	3.7	8.3
Teleswani	Forest	0.1	0.1	0.1	0	0.4	0.7	0	0.1	1.0

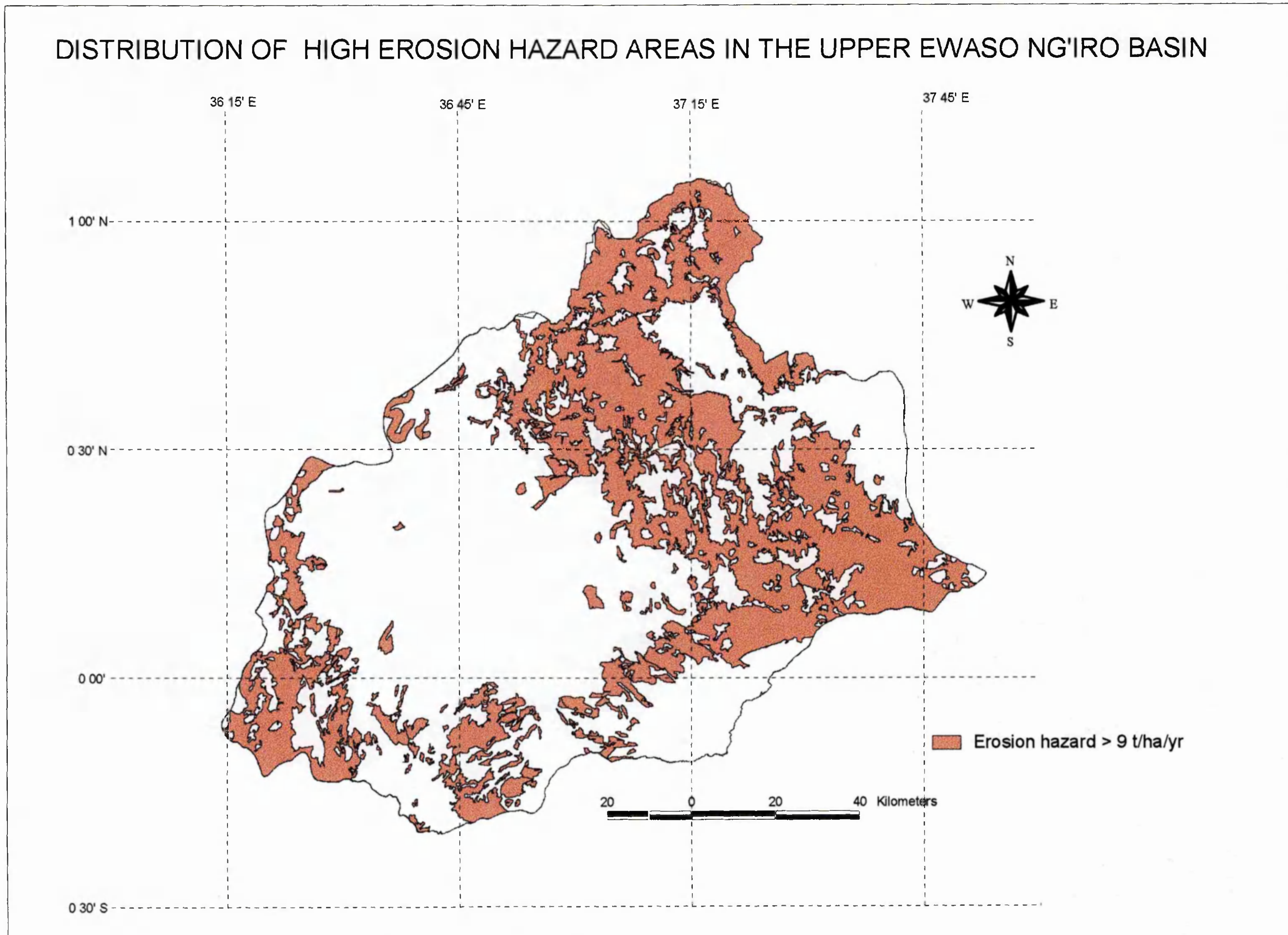

Figure 5.10 Spatial extent of areas predicted to exceed tolerable soil loss in the Upper Ewaso Ng'iro basin

9.0 t $ha^{-1}yr^{-1}$ as an appropriate tolerable soil loss value (T) (McCormack and Young 1981) for the Upper Ewaso Ng'iro basin, was based on values of average soil depth and the fact that most of the study area is uncultivated, therefore, soil renewal by leaf litter is expected to be higher than on cultivated lands.

Although the generally accepted tolerable soil loss (Table 5.4) values for renewable and non-renewable soils were originally derived for the USA, east of the Rocky Mountains, they have been adopted by many researchers (Lal 1993; Hall et al 1985; Barber 1982). They apply to areas where rill and interill erosion are the dominant erosion processes. A knowledge of the T value for a particular soil is intended to help in selecting appropriate land use types and management practices, to ensure that soil loss does not exceed a critical value, based on slope, soil and climatic attributes of specific catchment areas.

The selection of appropriate T values for Kenyan conditions has raised concern because there is limited data on soil formation rates. Dunne et al (1978) estimated soil formation rates from consolidated material ranging from 0.18 to 0.30 t ha^{-1} in the humid areas, and rates less than 0.13 t ha^{-1} in the semi-arid areas. Since these estimates do not include soil renewal by organic matter, researchers in Kenya (Barber 1982; Kilewe 1987; Dunne 1979) have continued to use the guide values listed in Table 5.4, as was done in the current study.

Table 5.4 Guide values of soil loss tolerance (McCormack and Young 1981)

Rooting depth (cm)	Soil loss tolerance values (t ha^{-1} yr^{-1})	
	Renewable soils	Non-renewable soils
0 - 25	2.2	2.2
25 - 50	4.5	2.2
50 - 100	6.7	4.5
100 - 150	9.0	6.7
> 150	11.2	11.2

In order to determine the factors responsible for the various levels of erosion hazard in the Upper Ewaso Ng'iro basin, Figure 5.10 was overlaid on the respective thematic maps of land cover, LS factor, rainfall erosivity and soil erodibility, obtaining Figures 5.11, 5.12, 5.13, and 5.14 respectively. Figure 5.11 shows that high erosion hazard in the Upper Ewaso Ng'iro basin is associated with the land cover types having high C-factors. This illustrates the major impact land cover and management has on soil erosion in the basin. Figure 5.12 shows that in the drier parts of the basin high erosion hazard is associated with increasing LS factors, but elsewhere, on slopes covered by forest and bushlands, high LS factors did not result in extreme erosion risks. Figure 5.13 shows that erosion hazard cannot be explained by rainfall erosivity because some of the areas with the highest R factors were predicted to have low erosion risk while large areas with low R factors were predicted to have high erosion risk. Similar results were obtained in relating erosion hazard with soil erodibility (Figure 5.14). High risk areas were found to traverse soils of high erodibility as well as soils with very low erodibilities. Therefore, it appears that soil erosion in the basin is affected primarily by land cover and management and secondly by topographic factors.

5.6.3 Factors associated with low erosion hazard

The low erosion hazard areas (Figure 5.10) are defined as the regions where erosion risk was predicted to be less that 9.0 t ha^{-1} yr^{-1}. Notable in this group are areas predicted to lose less than 1.0 t ha^{-1} yr^{-1}. They cover the forests of the mountains, and the well managed commercial ranches of the Laikipia Plateau. In general, erosion hazard was low under vegetation covers exceeding 70 percent (Appendix 10). However, in these regions, rainfall amounts are also higher ensuring better covers. It is evident that low erosion risks were predicted (Figures 5.13 and 5.14) even on areas with high rainfall erosivity factors and soils of relatively high erodibility so long as a well maintained natural vegetation cover, or flat terrain were present. This is supported by plot data (Table 5.3; Appendix 12), whereby soil loss rates rarely exceed 0.5 t ha^{-1} under forest cover at Naro Moru

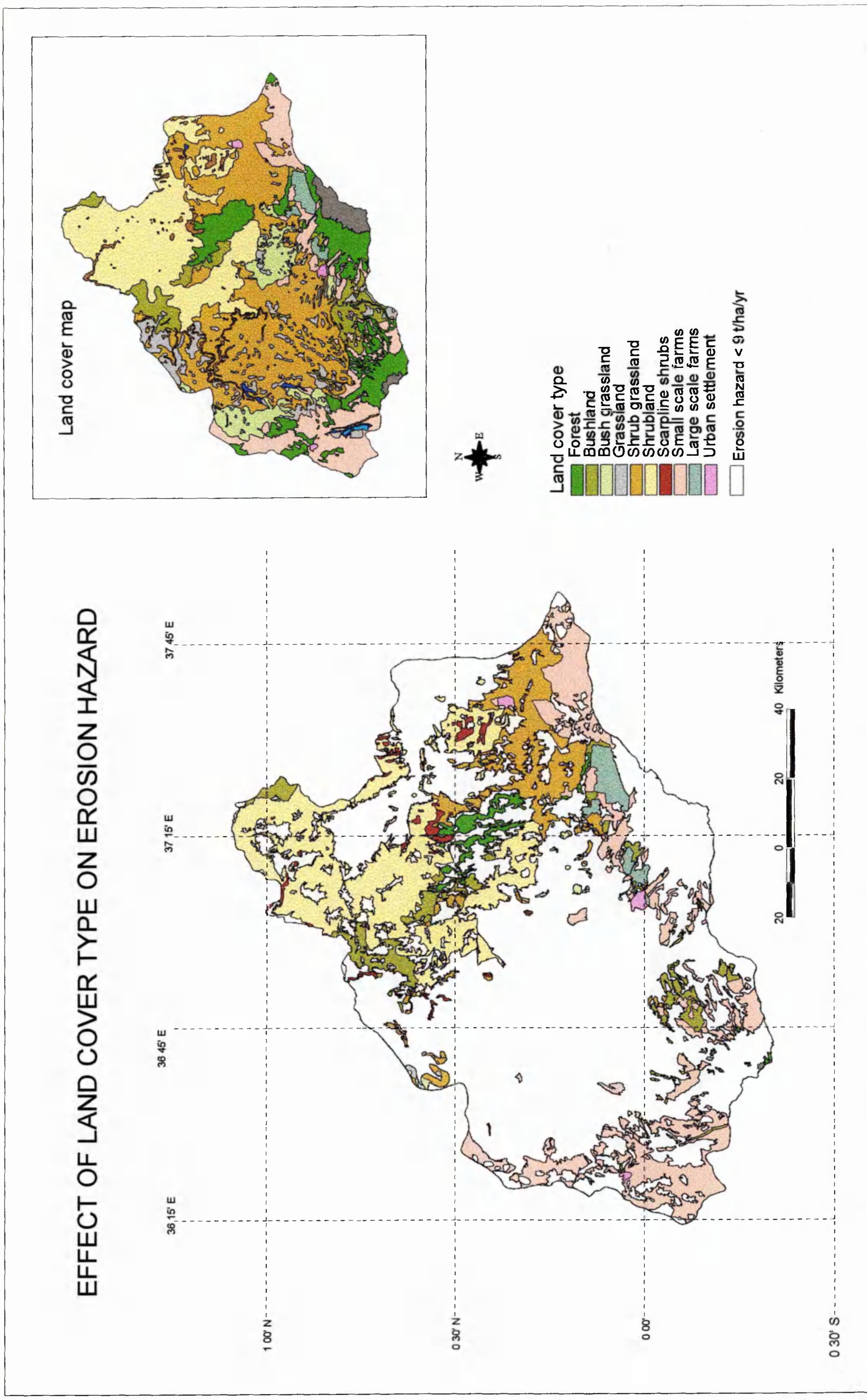

Figure 5.11 Land cover types associated with high erosion hazard in the Upper Ewaso Ngiro basin

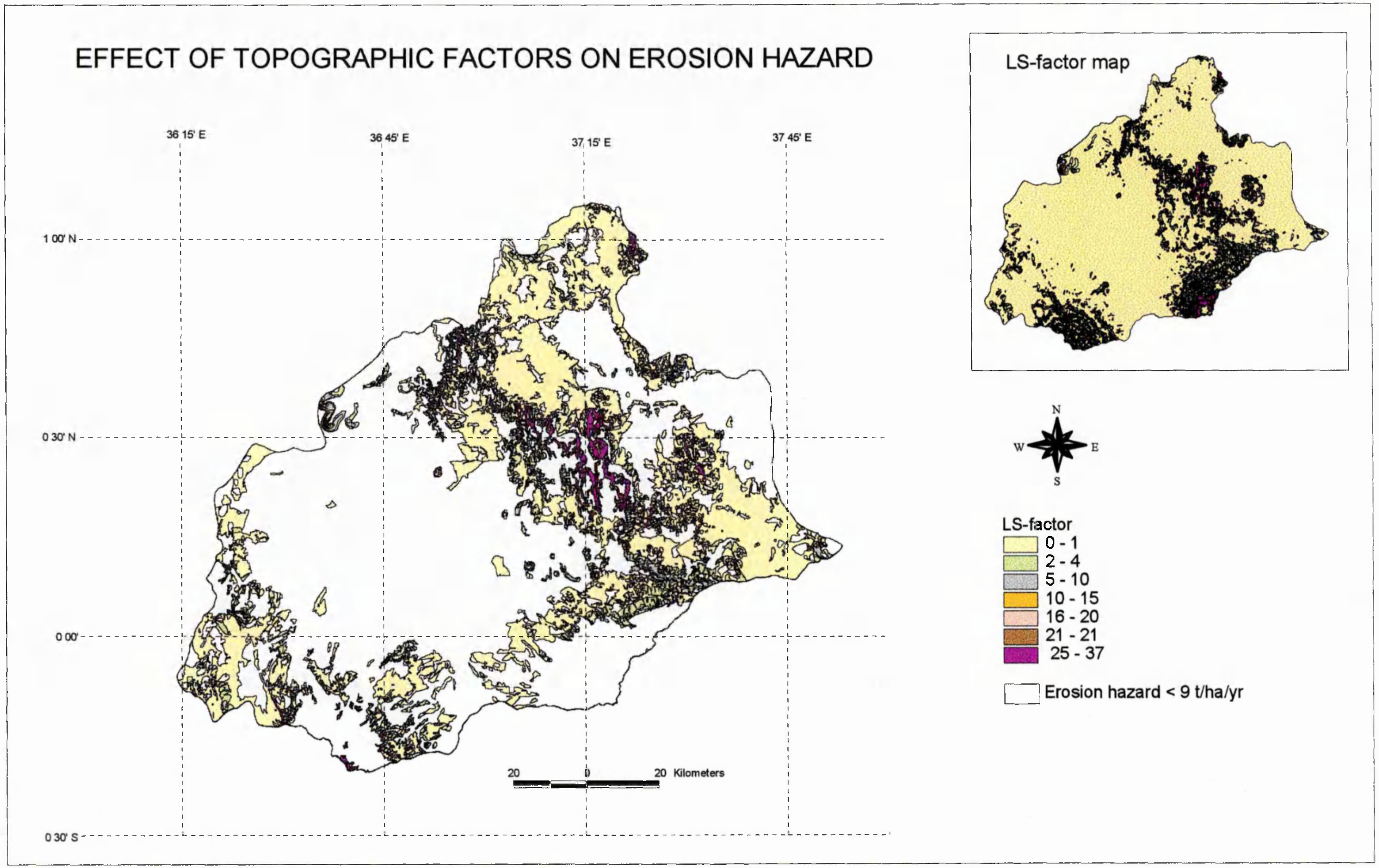

Figure 5.12 Effects of topographic factors on erosion hazard in the Upper Ewaso Ng'iro basin

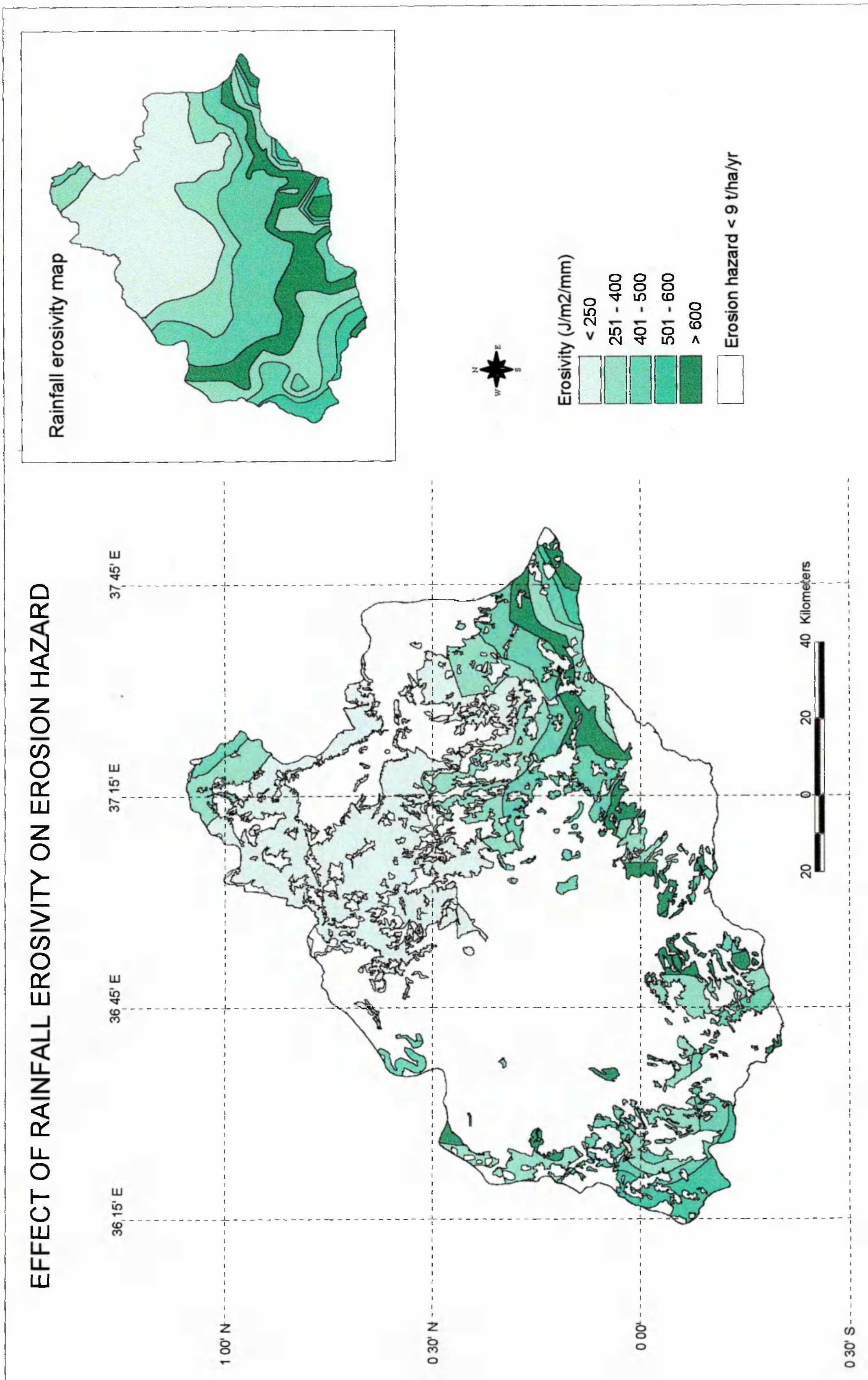

Figure 5.13 Rainfall erosivity effects on erosion hazard in the Upper Ewaso Ng'iro basin

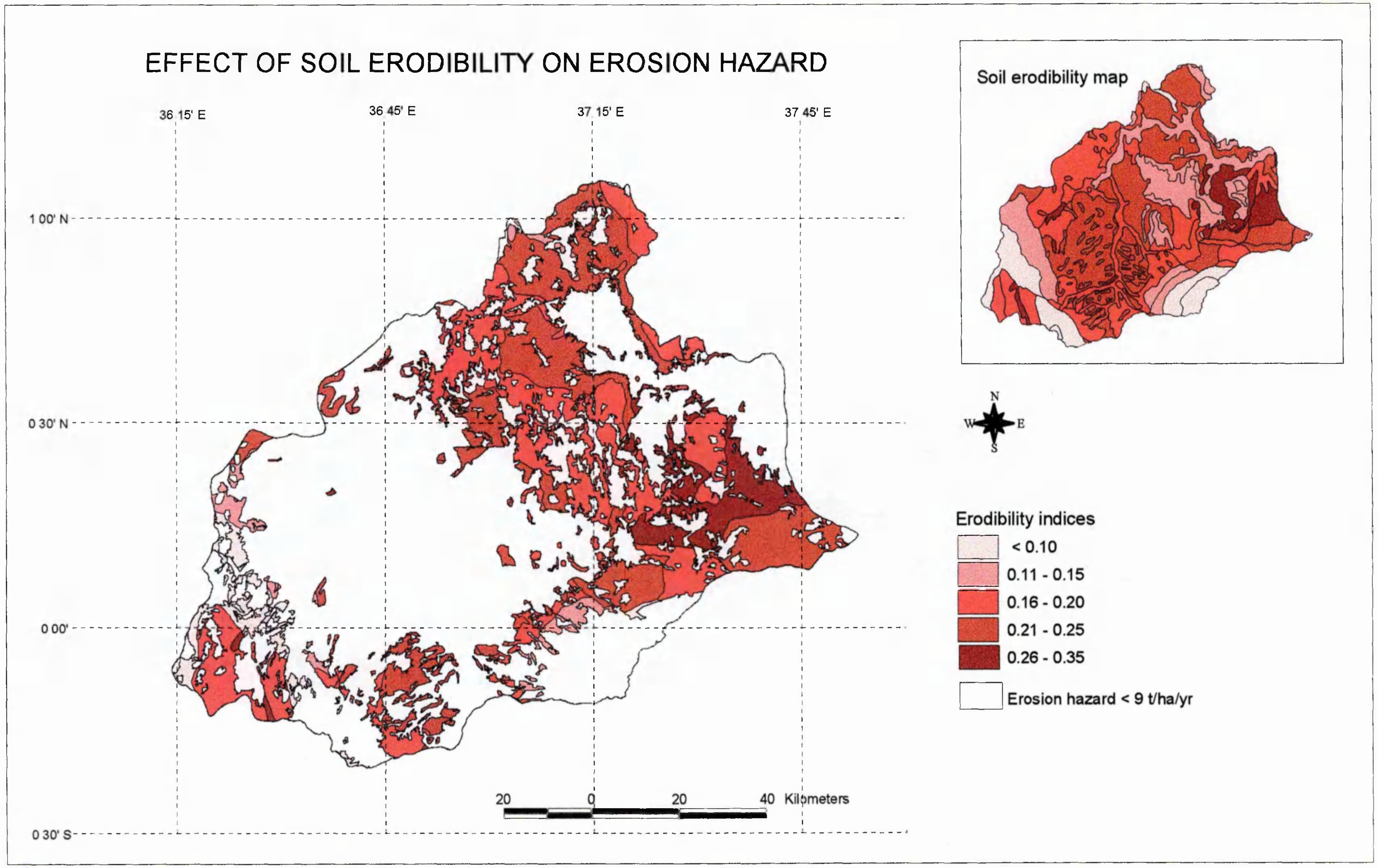

Figure 5.14 Soil erodibility effects on erosion hazard in the Upper Ewaso Ng'iro Basin

Met, Naro Moru Gate and Teleswani. Dunne (1979) observed that sediment yields in Kenyan catchments that have suffered little or no disturbance are low throughout the range of climates. He noted that the most dramatic differences in basin sediment yield result from differences in land use. Sediment yields become more sensitive to variations in runoff and topography as the vegetation thins from forest through agricultural cropland to rangeland. During this study, similar observations were made from reconnaissance surveys.

The low erosion hazard predicted for the Laikipia Plateau is associated with the combination of relatively good cover (Figure 5.6; Appendix 13.2) and the flat-gently undulating topography as described (Figure 5.4). Unfortunately, there was no plot data from large scale commercial ranching areas, with which to compare. Sediment yields from river gauging stations in the basin (Table 5.5) point to this fact. The mean annual sediment load of 33 t km^{-2} yr^{-1} recorded at the Ewaso Ng'iro Hulme's Bridge station, which is within the Laikipia Plateau is one of the lowest in the basin. Other rangelands on similar topographic conditions (e.g. Isiolo) obtained higher soil loss values, indicating the overriding effect of cover on soil erosion.

5.6.4 Factors associated with high erosion hazard

High erosion risk areas in the Upper Ewaso Ng'iro basin (Figure 5.10) cover 36.2 percent of the total basin area. It is evident that these areas occupy much of the northern, north eastern and south western parts of the basin, in the areas covered by shrublands, shrub grasslands and croplands. The areas predicted to have a high erosion hazard agree with observations made during reconnaissance surveys with a few exceptions. The differences occur in areas depicted as low hazard, which were observed to be degraded (e.g. the northern rangelands around the Ewaso Ng'iro and Archers Post). Conversely, the large scale farms around Timau, and the small scale farms in parts of the Nyandarua highlands which were predicted to be in the high risk category, were observed from reconnaissance surveys to be relatively stable. These inconsistencies can be related in part to the scale of data extrapolation. In the case of the underpredicted values in the north around the

Ewaso Ng'iro, it was observed that the predicted LS factor was low, which is realistic as these areas lie on land with relatively flat-gently undulating terrain. However, very low LS factors may not be the only problem because soil erosion is a complex phenomenon in the dry semi-arid areas. For instance, in the dry shrublands of Isiolo and Samburu, rill and gully erosion were observed on slopes

Table 5.5 Sediment yields of some river gauging stations in the Upper Ewaso Ng'iro basin (Kihara 1997).

Code	Catchment name	Catchment Area (km^2)	Sediment yield ($t\ yr^{-1}$)	Sediment discharge ($t\ km^{-2}\ yr^{-1}$)
AL	Upper Logilado	1	250	200
AM	Lower Logilado	3	567	220
AN	Upper Teleswani	2	23	12
AP	Lower Teleswani	3	373	124
AQ	Mid-Ituuri	4	330	86
AR	Lower Ituuri	6	1,126	182
A5	Upper Naromoru	87	11,312	130
A6	Mid Naromoru	174	10,091	58
A9	Nanyuki	68	8,264	121
AA	Likii	174	39,071	225
AC	Sirimon	60	9,654	161
AD	Teleswani	39	9,138	234
AE	Timau	59	6,920	118
AF	Nanyuki/Timau junction	855	21,780	25
AG	Ewaso-Ng'iro Hulmes Bridge	1,839	61,196	33
AJ	Ewaso-Ng'iro (Junction)	4,640	266,084	57
B1	Mukogodo	2	260	119
B2	Ngenia	1	82	76
B4	Sirima	3	437	138
A0	Archer's Post	15,364	9,371,986	610

less than 3 percent. Other than the USLE factors used to determine soil erosion, in the semi-arid environments, factors such as the long term effects of the overgrazing and burning of rangelands (Thurow and Herlocker 1993) and soils with sodic or surface sealing properties (Muchena, 1982) can cause more erosion than can be predicted (Appendix 13).

The USLE predicted that croplands are exposed to soil loss in excess of tolerable rates (Figure 5.11). Qualitative assessments during the reconnaissance surveys would suggest that the USLE values were overpredicted as there was little evidence of severe interill, rill or gully erosion on most farms. The results obtained from erosion plot studies (Appendix 12) show that the values predicted by the USLE were realistic. For instance, runoff plot data at Karuri shows that soil loss of 69.4 t ha^{-1} was recorded from a potato crop in 1994 and at Embori, a total of 102.6 t ha^{-1} was recorded from a barley field in the same year, while at Kalalu, soil loss values exceeding 25 t km^{-2} yr^{-1} have been recorded in a maize field. Conversely, negligible soil loss values were obtained from the same plots in years with lower rainfall erosivities. In addition, from the Timau gauging station, which serves as the catchment boundary for some of the large scale farms in the area, relatively high amounts of sediment loss (118 t km^{-2} yr^{-1}) have been recorded (Table 5.5). Therefore, it would appear that depending on rainfall characteristics, many croplands are at a high risk of soil erosion. This illustrates the advantages of quantitative measurements over qualitative assessments in erosion studies.

Land management is evident as the main factor influencing soil erosion because the shrub grasslands in the well managed ranching areas have low erosion risk while those in the communal grazing areas around Isiolo are in the high risk category. By spatial extent, the highest soil losses in the Upper Ewaso Ng'iro basin were predicted in the communal grazing lands comprising the shrubland, and shrub grasslands in the north of the basin. These high erosion rates are attributed to the poor cover found in the shrublands as a result of overgrazing and poor management. Similar observations were made by Liniger (1991) who observed that on grazing land, 50 percent of the rainfall was lost as runoff. Comparisons of soil loss from grazing lands in Machakos (Zobisch 1993) obtained a critical cover of 40 percent, below which slight reductions in cover had serious effects on soil loss. A similar scenario was applicable to the Upper Ewaso Ng'iro basin where the degraded areas had less than 30 percent grass covers (Appendix 10). Records of sediment yields at Archers Post (Table 5.5) where the highest sediment yields in the basin of 610 t km^{-2} yr^{-1} have been recorded attest to this. This value can be compared with the next station upstream, the Ewaso Ng'iro Junction station, which marks the lower end of the commercial ranching area, where sediment yields of 57 t km^{-2} yr^{-1} were recorded. Although there are many tributaries between these two stations, the big difference in the sediment yields give an indication of the proportion of total sediment contributed from the communal grazing areas occupying the land north and east of the Junction station.

The results of this study compare well with observations from other parts of Kenya. Dunne (1977) observed that soil erosion rates even on gentle slopes in Kenyan rangelands were extremely high. He estimated average values ranging from 40 to 120 t ha^{-1} yr^{-1} for northern Kenya. Barber (1982) observed that in the semi-arid areas of Kenya, data on catchment sediment yields is much more limited, partly reflecting the difficulties of taking regular samples from seasonal streams. He estimated losses ranging 535 to 20000 t km^{-2} yr^{-1} and observed that degraded grazing land is the major source of eroded sediments in most catchments. Similar observations have been made in other parts of the tropical Africa. Stocking (1984) obtained soil loss values ranging from 20 to 62 t ha^{-1} from a rangeland at Shinyanga in Tanzania. He observed that high erosion rates were associated with poor vegetation cover, whether, crop, pasture or natural bush, but high rainfall erosivities exacerbated the problem. Lal (1993) estimates that in Africa, the Savannah can lose between 10-200 t $ha^{-1}yr^{-1}$ while cropland can lose 5-50 t $ha^{-1}yr^{-1}$, which is comparable to the values obtained in this study. He suggests that high erosion rates are linked to social factors like communal land rights, subsistence farming, lack of technical know-how and insufficient extension services. Similar problems have been documented in relating land use problems in the Upper Ewaso Ng'iro basin (Kohler 1987; Huber and Opondo 1995; Thurow and Herlocker 1993) although they were not directly related to soil erosion in the region.

5.6.5 Limitations of modelling with the USLE and GIS

In modelling with the USLE, it is important to note that each of the six erosion factors in the equation is a function of numerous secondary variables and their interactions. These must be considered when computing local values of the factors. In addition, each factor is derived independently, while in reality, the factors interact in a dynamic system and several assumptions have to be made to adapt the model to a given set of conditions. The capabilities and limitations of the USLE have been well documented by Wischmeier (1976). In this study, the 45 observations (Table 5.2) used in the regression equations were considered too few to be used for correction of the erosion hazard map, or for a thorough error assessment. However, in general, the USLE was found to underpredict soil loss in the Upper Ewaso Ng'iro basin, albeit with high standard errors of estimate. According to Risse et al (1993) the model efficiency is most affected by the LS and C factors and is more accurate the higher the total soil loss. Similar observations were made in the current study.

Modelling with the USLE in conditions of multiple land covers requires extrapolation of the C-factors to very different conditions and the model may not always give satisfactory predictions because other long-term factors may be operative. In addition, the application of the USLE in a GIS environment can lead to other problems, which may propagate errors in the results. The majority of GIS type errors were kept to a minimum this study. However, likely sources of inevitable errors include geometric classification of the remotely sensed data, which was visually done, raster interpolation as with the rainfall erosivity map, the use of averages as with the classification of soil erodibility using the soil mapping units, and the use of a low resolution contour coverage input for the preparation of the basin DEM. Scale can also affect the results. According to Kirkby (1998) the scale jump from plot to basin level requires using longer duration and more average variables, which inevitably increases the chances for errors. The USLE predicted values with GIS (Table 5.3) provided a narrower range between minimum and maximum, while the mean values were in most cases higher. Similar results were obtained by Somba (1998) who observed that for a regional study with the USLE, changing the scale affected the results at each of the two extremes of very high erosion risk and very low erosion risk.

Reducing errors in modelling and GIS is difficult and it starts with the use of accurate data sources, methodologies and exercising care in data handling and processing. Several methods have been suggested of reducing error propagation. Ralphs (1993) suggested the use of metadata or 'data about data' as a solution to the problem of documentation and analysis. Burrough (1989) offers the fuzzy set theory, a set of GIS algorithms which allows users to define class memberships that match practical experience, and can be used for unions and intersections of coverages. In applying the USLE to regional scales, Somba (1998) suggests the use of composite map classification (in which each pixel is given the proportionate weighting for multiple cover classes), rather than dominant (in which the cover type occupying the largest proportion of the pixel is used to classify the entire cell) for separating mixed vegetation classes in a pixel. Wischmeier (1976) suggested that the use of interpolated values guided by judgement and knowledge of the situation can be more accurate than values selected directly from guide tables for the USLE. This type of approach was adopted in the current study, whereby error reduction relied on using runoff plot data and reconnaissance surveys, and exercising care in data handling and processing. However, there is still room for improvement, but with the available facilities, the results obtained provide an indication of the extent of soil erosion in the Upper Ewaso Ng'iro basin. The next chapter presents the results of the process-based modelling with EUROSEM.

CHAPTER VI

EROSION PREDICTION WITH EUROSEM: A CASE STUDY OF EMBORI AND MUKOGODO CATCHMENTS

6.1 Introduction

In this chapter, the prediction of soil erosion using a process-based model, the European Soil Loss Model (EUROSEM) (Morgan et al 1998a) for the Upper Ewaso Ng'iro basin is presented. This work was done in an effort to complement the results of empirical modelling with the USLE, which gives mean annual averages, while EUROSEM can predict soil loss on a storm basis. Due to the large spatial extent of the basin, the model could not be applied to the full basin coverage. Thus, two subcatchments, Embori and Mukogodo (Table 4.2) were selected for this purpose. This was because both Embori and Mukogodo had records of high erosion losses from runoff plots, while they represent different, climate, soils, land cover and management practices. It was necessary to use data from an area with relatively high records of soil loss because that would help to test model applicability better than validating for sites with negligible soil loss values. EUROSEM was applied without GIS as time and logistical constraints did not allow for its incorporation within a GIS environment. In this study, the model has been used to predict interill erosion from single slope planes without channels.

6.1.1 Characteristics of the Embori catchment

The Embori catchment is a large-scale wheat/barley farming region on the slopes of Mt. Kenya. Although the catchment lies at altitudes of 2000-2800 m above sea level, it is situated on the leeward side of the mountain and receives a mean annual rainfall of 735 mm (Appendix 4). The seasonal distribution of rainfall is such that the amounts are insufficient for proper crop growth (Flurry 1987) as the catchment lies in the transition zones discussed in section 2.3. However, the relatively cool temperatures allow the growing of wheat and barley, but the farmers sometimes practice water conservation techniques. The soils are loams and well managed. Soil erosion is not evident except in the areas affected by mass wasting. However, plot studies have showed that in seasons of heavy rainfall (Appendix 12) soil erosion rates on cropland can be quite high. The farms are mechanised and both conventional and minimum tillage are practised. In this study, only data from the conventional tillage plots has been used in simulating EUROSEM because it represents more broadly the farming conditions in the catchment.

6.1.2 Characteristics of the Mukogodo catchment

The Mukogodo catchment is located in the dry central highlands region at an altitude of 1750 m above sea level. The area is hot and dry, receiving on average 362 mm of rain per annum (Berger 1989). The soils are sandy loams, classified as chromic Luvisols, developed on Basement system rock (Sombroek et al 1980). The predominant vegetation is shrubland. Land use is mainly communal grazing of livestock, but wildlife also share the grazing lands without any formal management. Reconnaissance surveys done during this study indicated that the land is denuded, recording vegetation covers less than 40 percent (Appendix 10). In the current study, evidence of soil erosion in the form of interill, rill and even gullies on the steeper slopes, was noted in the catchment, and the area was predicted (Figure 5.9) to experience high soil erosion hazard.

6.2 Applying EUROSEM to Embori and Mukogodo catchments

This section describes the steps followed in the calibration and validation of EUROSEM for Embori and Mukogodo catchments and its application to predict soil loss from simulated vegetation covers of barley, maize, grass and forest.

6.2.1 Availability of data for EUROSEM

The same procedures were followed in applying EUROSEM to the two catchments of Embori and Mukogodo. In both catchments, available runoff and soil loss data had been collected from runoff plots, which measured 10 m long and 2 m wide, with three replications. Data for Embori included the period 1994-96, although the 1995 year had been dry without any appreciable soil loss on record.

For Mukogodo, rainfall and soil loss data were available for the period 1994-95. In each case, EUROSEM was simulated as a single-plane catchment model to predict interill erosion.

The plots at Embori (Plate 6.1) had been set up primarily to study soil moisture dynamics in the catchment. They were therefore fitted with neutron probe access tubes and did not have a bare plot (control). Instead two treatments consisting of barley crop, grown under conventional and minimum tillage practices were under investigation. In this study only the data from the conventional tillage plots has been used as it was more representative of the general land use conditions in the catchment.

For the Mukogodo catchment, three treatments that represent the general land cover conditions were used (Plates 6.2, 6.3 and 6.4). These were bare (naturally bare land from overgrazing), perennial grass (open grazing land with some remnants of grass and forbes) and shrub (like bare, but also including a shrub in the plot).

In each case, the data were first statistically analysed by the t-test method, to determine that the replications belonged to the same populations. The results obtained indicated that there was no significant difference between the treatment replicates in both data sets (95 percent confidence interval). Therefore, the mean runoff and soil loss were calculated and have been used in the respective model simulations. From an analysis of rainfall hyetographs, it was found that the storm characteristics for each catchment could be grouped into four classes as follows; single storm one peak rainfall; multiple storms, peak at the beginning of the storm; multiple storms, peak at the middle of the storm and multiple storms, peak at the end of the storm. The rainfall data for each catchment was divided into two groups, one half for calibration and the other validation of the model, making sure to include each storm type in both sets of data. This type of sample-splitting was recommended by Klemes (1986) as it makes use of the same dataset, whereby

Plate 6.1 Erosion plot at Embori for barley

Plate 6.2 Bare plot at Mukogodo

Plate 6.3 Grass plot at Mukogodo

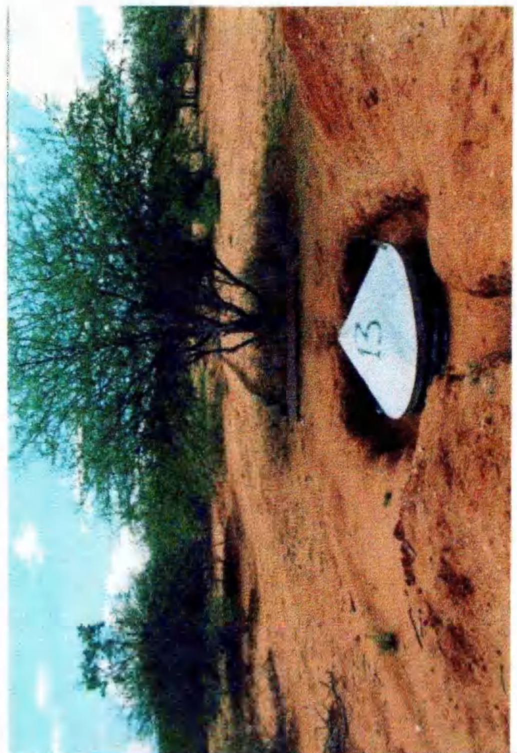

Plate 6.4 Shrub plot at Mukogodo

half of the data is used for calibration and the rest for validation. In this study, data grouping also included stratification according to the time of season. Thus, for Embori, 10 storm events were selected for calibration and 12 for validation, while for Mukogodo each group had 12 events. The simulation of EUROSEM requires two input files; the rainfall parameter file (PCP) and the catchment parameter file (PAR). Details regarding EUROSEM input variables and parameters are presented in Appendix 14.

6.2.2 Preparation of rainfall parameter files

The rainfall input parameter files (PCP) were prepared in the format used by EUROSEM for each storm event (Morgan et al 1998a). The rainfall and runoff/soil loss data used with EUROSEM in this study consisted of a total of 22 storm-events for Embori and 24 for Mukogodo respectively. In each case, the storm data were obtained from a Helman autographic rain gauge, from which rainfall amounts every 15 minutes within a storm was recorded. These were used to calculate cumulative durations and rainfall amounts for each storm, creating the EUROSEM PCP files (e.g. Appendix 15).

6.2.3 Preparation of catchment parameter files

The EUROSEM catchment input file (PAR) (e.g. Appendix 16), requires data from several sources. In this study, these data were obtained from erosion plot studies (Section 4.1.3) while the parameters for unknown factors were estimated using the EUROSEM guide tables (Morgan et al 1998a) as shown in Table 6.1.

EUROSEM runs by combining both the PCP and PAR to produce outputs in three files; the dynamic output file, the auxiliary file and the static output file (Morgan et al 1998b). In the current study, hydrograph and sedigraph data were not available. Therefore, both the calibration and validation of the model was rather limited as it was not possible to validate the dynamic file outputs and only the static output files were used (e.g. Appendix 17).

Table 6.1 Data requirements for EUROSEM

Available data	Embori	Mukogodo
Plot length (m)	10	10
Width (m)	2	2
Slope (%)	13	5
Soil texture	Loam	Loamy sand
Cohesion (bare land)	2.0	2.8
D50	300	350
Cover	-	-
Porosity (calculated)	0.31	0.419
DERO (m)	2.0	1.26
RFR (bare land)	4.0	0.5
ROC	0	0
TFIN	-	-
Cumulative storm data	-	-
Estimated from EUROSEM guide tables		
DINTR	-	-
EROD	2.0	3.0
FMIN	1.8	1.7
G	375	147
IRMANN	0.3	0.01
PANGLE	-	-
PLANTH	-	-
SHAPE	-	-
THMAX	0.25	0.38

The (-) represents parameters which vary from day to day on the plot (Appendix 16).

6.2.4 Calibration of EUROSEM

It was necessary to calibrate some of the parameters in EUROSEM so that it could simulate runoff and soil loss as close to observed values as possible. First, trial runs of EUROSEM were made using the measurable parameters, to determine the optimal values. This helped to obtain parameter values for variables which had invoked a sensitive response in previous studies (Quinton 1994) such as effective net capillary drive (G), maximum volumetric moisture content of the soil

(THMAX) and detachability of the soil (EROD). Dynamic parameters such as infiltration recession factor (RECS), cohesion of the soil (COH), maximum interception storage (DINTR), initial volumetric moisture content (THI), and percentage basal area of vegetation (PBASE) were thereafter determined by running the model several times (trial and error) until their optimal values were achieved. However, any of these factors would require adjustments in running the model according to the rainfall and catchment conditions of the day. Of the other factors, crop cover (COV) was obtained from records. Surface roughness (RFR) was measured with a straight rule and tape. Although the soil cohesion (COH) had been measured with a torvane on bare land, it required to be estimated for each simulation since it is a dynamic factor.

The median particle size (D50) was estimated using the soil texture data from laboratory analysis of the soils (Terzaghi 1967) while the duration of model simulation (TFIN) was obtained from the storm data. The available data on the saturated hydraulic conductivity (FMIN) from soil survey reports (Mainga and Mbuvi 1994) gave rather high values, which when used in trial runs of EUROSEM failed to produce runoff for all storms. Therefore, it was necessary to obtain optimum values for these factors. All the parameters were normally held within physically realistic limits during the calibrations.

Determining the optimum values for FMIN, COH and IRMANN involved first running the model for several values of FMIN until it yielded runoff equivalent to observed amounts for a particular event. Then the best value of FMIN would be used to simulate the model once again for several values of IRMANN and COH until predicted soil loss would be nearly equivalent to observed values. To simplify the procedure, the values of FMIN and IRMAN obtained during each test run would be tabulated against the respective predicted runoff and soil loss for that event. The percentage difference between the observed and simulated runoff/soil loss was then calculated. The values of FMIN and IRMANN producing the least percentage difference between the observed and simulated runoff/soil loss were consequently adopted.

6.2.5 Validation of EUROSEM

To validate EUROSEM for each respective catchment, the rainfall and cover data set aside for this purpose was used. The model was simulated with baseline parameters (Table 6.1) while some adjustments were made in the values of COH, DINTR, IRMANN, COV, PBASE, and THI as per the prevailing catchment conditions for each event. The values of simulated runoff and soil loss (Appendices 18 and 19) were correlated with observed values by linear regression to obtain the results shown in Figures 6.1 to 6.5. The scattergrams obtained (Figures 6.1 to 6.5) were tested for goodness-of-fit (Chatfield 1983) obtaining a good fit for soil loss at Embori (5 percent), but the fit was poor for the other treatments. The fit of the 45^0 line (ASCE 1996) showed that both runoff and soil loss were underpredicted by the model in all the treatments.

The validation of EUROSEM for Embori was done for barley crop under conventional tillage, while for Mukogodo, it was done for the bare and perennial grass conditions. EUROSEM predicted runoff and soil loss from Embori quite well (Figures 6.1 and 6.2). For Mukogodo, the model predicted runoff from bare plots quite well obtaining a correlation coefficient of 0.895 (Figure 6.3). However, poorer correlation coefficients of 0.557 and 0.570, were respectively obtained for soil loss from bare plots (Figure 6.4) and runoff from grass plots (Figure 6.5), while the model failed to predict soil loss under grass plots. High standard errors of estimate were obtained in all the cases.

Application of EUROSEM to the data from the shrub plots was hampered by the fact that observed soil loss values were mostly zeros or values very close to zero. As the model was usually under-predicting soil loss, simulated values of zero or near-zero values obtained for shrub cover would not necessarily be a

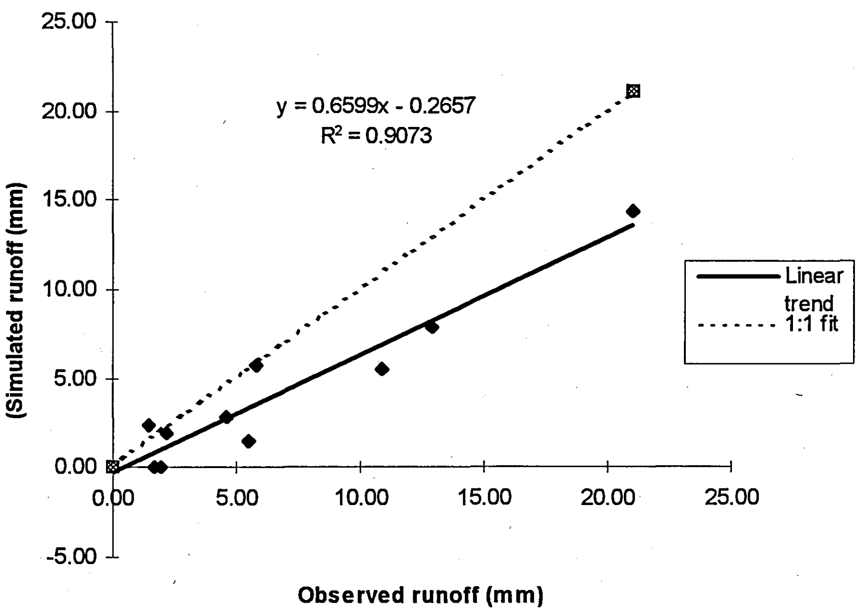

Figure 6.1 Linear regression between observed and simulated runoff for Embori

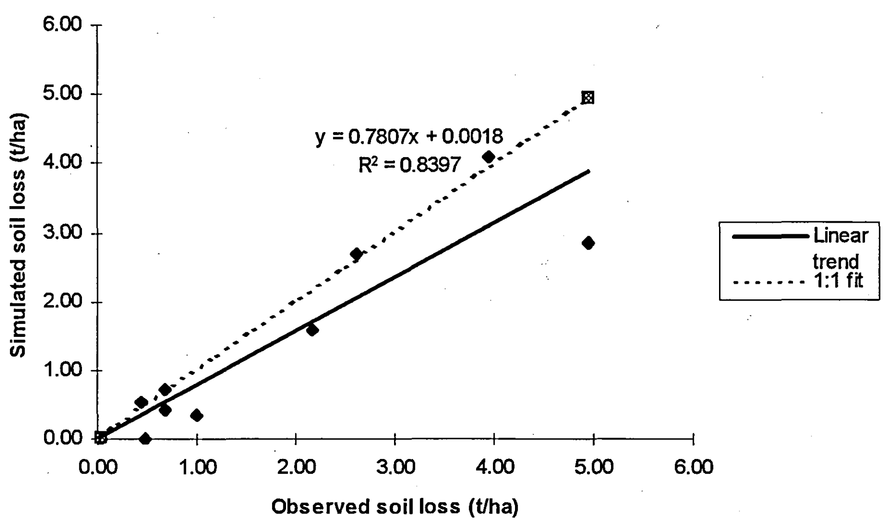

Figure 6.2 Linear regression between observed and simulated soil loss for Embori

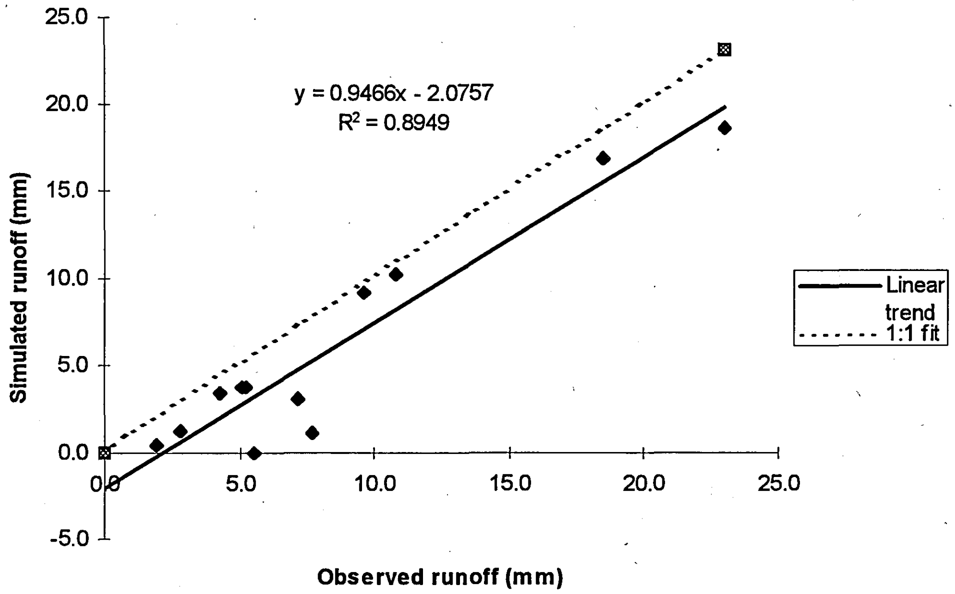

Figure 6.3 Linear regression between observed and simulated runoff from bare plots at Mukogodo

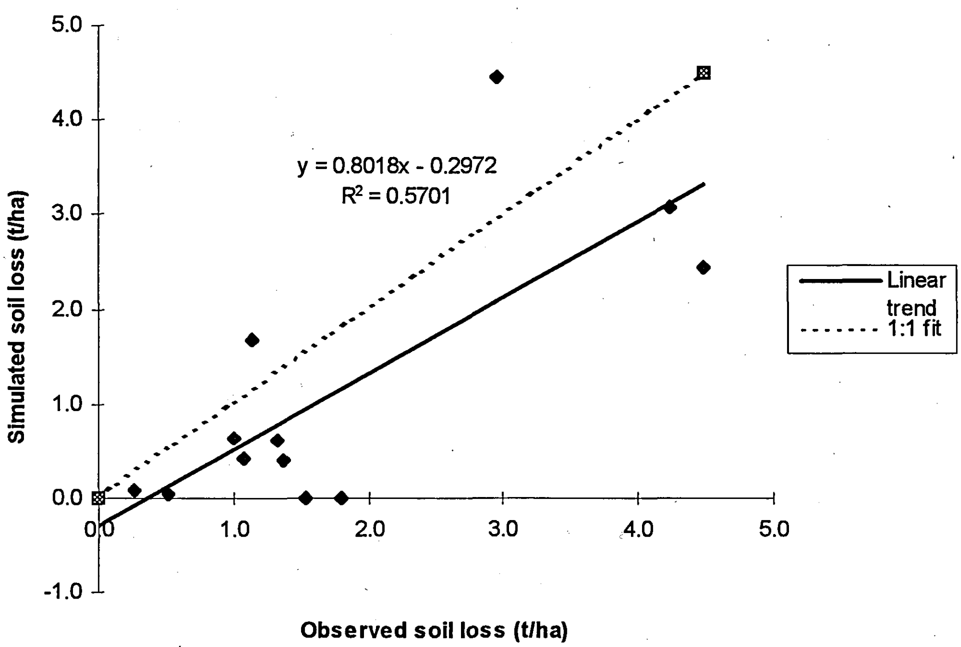

Figure 6.4 Linear regression between observed and simulated soil loss from bare plots at Mukogodo

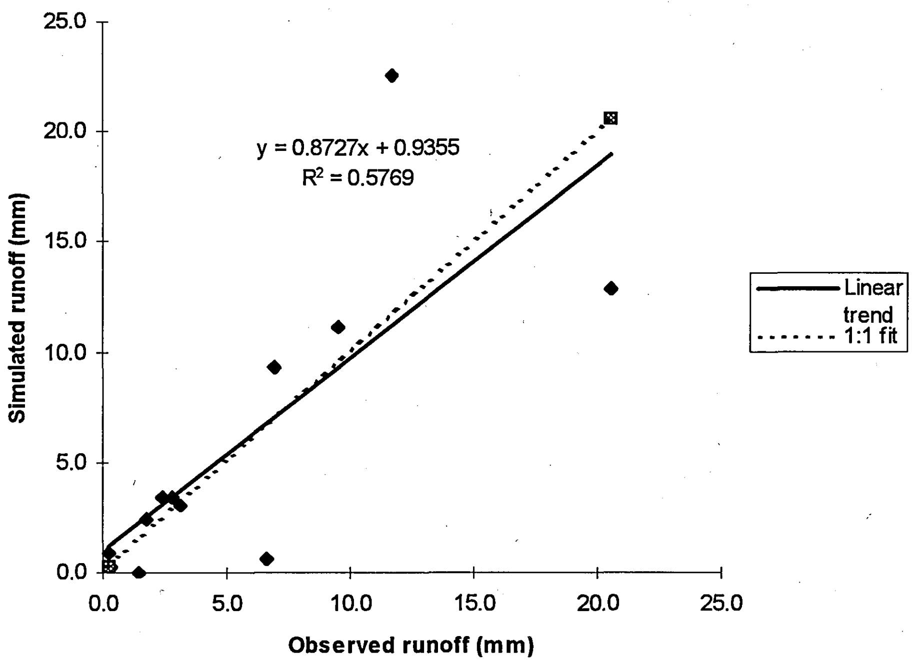

Figure 6.3 Linear regression between observed and simulated runoff from grass plots at Mukogodo

representation of model performance. In addition, it was difficult to estimate reliable cover parameters for the vegetation cover in the shrub plot, since the model assumes that a given cover is spread over the area, whereas the shrub is only at the lower end of the plot (Plate 6.4), while soil loss is collected from the entire plot. Since the model had failed to predict soil loss for the grass plots (containing a cover of grass and forbs) it was therefore not possible to use EUROSEM to predict the impact of cover on soil loss under the conditions of Mukogodo catchment.

6.3 Applicability of EUROSEM to the Upper Ewaso Ng'iro basin

During the model calibration, it was found that the most sensitive variables of EUROSEM were THI, FMIN, IRRMAN, COH, and G for both Embori and Mukogodo. Similar results were obtained by Folly et al (1998) for catchments in the Netherlands. Although FMIN and G can be estimated in the field, for a catchment, sedigraphs are needed to calibrate EROD, which is responsible for splash detachment. Most of the calibrated model input variables were derived from the EUROSEM user guide tables, which have been developed for European conditions. There were little local data for comparison to determine how reliable these values were. However for the saturated hydraulic conductivity, available data from soil survey reports (Kironchi at al 1992; Mainga and Mbuvi 1994) indicated values ranging 5.2 to 338 mm h^{-1} for Embori and 11.8 to 175 mm h^{-1} for Mukogodo respectively. Trial runs of EUROSEM with these values failed to produce runoff. It was therefore necessary to calibrate new FMIN values because the soil surveys had been done at catchment level, and FMIN values can vary within the same locality (Morgan et al 1998b) as is evident from the soil survey reports. In addition, there have been changes in land management, such as tillage in Embori, for which different FMIN values would be relevant, and even these are likely to change from time to time as the soil settles due to consolidation.

For the Embori plots, the calibrated optimum FMIN of 2.0 mm hr^{-1} for the loam soils was within the limits of the EUROSEM user guide tables (Morgan et al 1998a) while the 1.7 mm hr^{-1} obtained for Mukogodo was below the 7 mm hr^{-1} recommended minimum for loamy sands. As the calibrated FMIN values greatly improved the model performance, they were assumed to be relevant for the time and conditions of the model simulations.

The validation of EUROSEM for Embori catchment showed that the model can predict runoff and soil loss quite well (Figures 6.1 and 6.2). However, the standard errors obtained were rather high as the values relate to storm events. The gradients of the regression line show that both runoff and soil loss were underpredicted. By comparison, EUROSEM has been found to overpredict soil loss in England (Quinton 1994) and in the Netherlands (Folly et al 1998). The opposite results obtained under the Kenyan conditions can be the attributed to several differences in the climate, soils, land use and management. For instance, the rainfall characteristics are quite different in the tropical regions, where rainstorms have bigger drop sizes (Lal 1976) capable of higher rates of splash erosion. This would lead to higher erosion rates than those predicted by the detachment component of EUROSEM.

Although EUROSEM predicted both runoff and soil loss quite well for Embori, in evaluating the model performance, it should be noted that the crop, topography, land preparation and cultural practices in the Embori catchment, have similarities with the European conditions for which the model was developed. At Embori, tillage is fully mechanised, the crop is barley, and the climate is cool with lower rainfall intensities. Quinton (1994) evaluated the performance of EUROSEM for Woburn in England and found that it performed reasonably well in simulating both runoff and soil loss, but that the simulation results were subject to considerable uncertainty as a result of difficulties in model parameterisation. He points out the lack of routines in EUROSEM to model saturated overland flow and crusting and that it is difficult to simulate the hierarchical nature of erosion processes and the dynamic nature of many of the parameters used in the model. Thus, the results obtained for Embori should be interpreted with caution because of the number of uncertainties associated with some of the model parameters used in the simulation. For instance, the values of FMIN, COH, THI, THMAX, IRRMAN, PBASE, which are sensitive to model performance have all been estimated or calibrated.

The suitability of EUROSEM for application to Mukogodo is questionable. Whereas relatively good model performance was obtained for simulation of runoff (Figure 6.3) for the bare plots, the model poorly predicted soil loss from bare and runoff from grass plots (Figure 6.4 and 6.5), while it could not predict soil loss under grass. The slopes of the regression curves obtained indicate that EUROSEM underpredicted runoff and soil loss, and higher errors were recorded in all the cases. The poor model performance in Mukogodo may be attributed to physical and climatic conditions. The storm characteristics are quite different to those of

Embori. In Mukogodo, storms of 4 mm and rainfall intensities of 3 mm hr^{-1} have recorded runoff on bare land. In addition, the soils are prone to surface sealing, which and therefore, more likely to produce runoff, since saturated hydraulic conductivity is achieved over the top few mm depth of the soil, which is contrary to model routines. Folly et al (1998) recommended improvements for model conditions where crusting is wide spread. They illustrated the difficulties associated with trying to evaluate a dynamic distributed model and to calibrate and use it in new locations. These included differences in storm characteristics, inadequate calibration data and difficulties in selecting a unique and correct parameter set to characterise the entire catchment. They recommended that future applications of the model should at least include a minimum and maximum output value of the output in order to give a reflection of the effect of the parameter uncertainty on model simulation results.

The simulation of EUROSEM for multiple vegetation covers in Mukogodo was complicated by lack of sufficient guidance in parameter calibration. The fact that the model failed to predict soil loss under vegetation in Mukogodo suggests that there are effects of vegetation variables in the erosion process that may not be explained by the routines used by EUROSEM. For instance, the guide tables do not separate between grasses and forbs, which are more prevalent in Mukogodo. The tree covers simulated by EUROSEM may not be comparable to the shrubs in the catchment. The impact of excessive compaction from years of overgrazing and denudation are difficult to simulate without actual measurements. Thus, it is necessary to expand the scope of the model to include the diverse soil, climatic and land cover conditions prevalent in dry rangelands.

EUROSEM needs high resolution data on rainfall, soil hydrology, detailed surface geometry, soil mechanical properties and vegetation characteristics (Quinton and Morgan 1998). Detailed data for the current study were limited, and therefore, the model performed well within the range of data available (section 6.2.1). Folly et al

(1997) observed that the model performed well for storms with characteristics similar to the calibration characteristics, whereas it did not perform too well for storms which were significantly different. According to Quinton (1997) one of the major difficulties faced by those wishing to use predictions from physically-based models is the level of uncertainty surrounding the model output. The uncertainty arises from a variety of sources including numerical errors, conceptual errors and those errors associated with the measurement of parameter values. In the current study, error assessment was limited by inadequate data. Therefore the results obtained from the validation of the model are subject to uncertainty.

As EUROSEM was found to predict runoff and soil loss for the barley crop under conventional tillage in the Embori catchment quite well (Figures 6.1 and 6.2), this was an indication that the model could be used to predict the impact of other covers on soil loss from storm data under similar conditions.

6.4 Predicting the impact of cover on soil loss

To determine the impact of vegetation cover on soil loss per storm event at Embori, EUROSEM was simulated for four vegetation types; barley, maize, grass and forest. These are the land cover types prevalent within a radius of 10 km of the Embori plots. The maximum storm event recorded at Embori in 1994 of 36.7 mm falling in multiple peaks (typical of the area) in about 4 hours was used in the simulations. This would ensure that the simulated runoff and soil loss were for optimum rainfall conditions. The model was consequently simulated with this storm by varying simulated vegetation covers from zero to 100 percent, and the respective soil parameters (COH, DINTR, IRMANN) accordingly.

The EUROSEM parameter values that are not sensitive to changes in crop cover were set to base values (Table 6.1) as derived from field measurements, the calibration exercise done earlier and from the EUROSEM User Guide (Morgan et al 1998a). A minor calibration was done by simulating the model with the 36.7 mm storm for barley crop at 18 percent cover (observed on day of this storm) to yield soil loss close to the 3.95 t/ha that had been recorded. This helped to set threshold values for the other parameters. The remaining parameters (COV, PBASE, PHEIGHT, COH, DINTR and IRMANN) were derived from the EUROSEM user Guide. Other parameters such as for the maize crop cover were estimated based on values obtained from Morgan (1996).

The soil loss values obtained in these simulations (Appendix 20) were plotted against the respective percentage vegetation cover, obtaining the exponential curves shown in Figure 6.6. It should be noted that nearly all the parameters used in these simulations were estimated, giving hypothetical results, which have to be treated with caution. As there were no available data to validate these results, they were evaluated by comparison with observed values from neighbouring runoff plot stations at Karuri, Kalalu and Teleswani and found to be within reasonable limits.

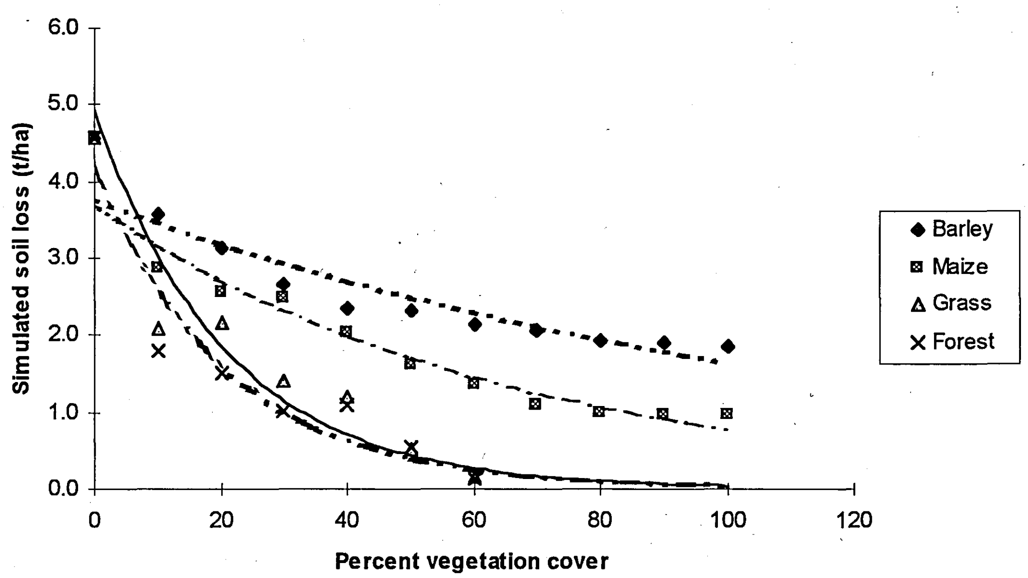

Figure 6.6 Simulation of soil loss with EUROSEM from four vegetation types

6.5 The impact of vegetation cover on soil loss

The results of the EUROSEM simulation, from hypothetical covers of barley, maize, grass and forest respectively at Embori, are presented in Figure 6.6. The model predicted an exponential decay of soil loss with increase in cover in all the four simulations. Table 6.2 shows the regression equations obtained.

Table 6.2 Regression equations of simulated soil loss for barley, maize, grass and forest with their respective covers

Vegetation Type	Regression equation
Barley	$S_l = 3.755e^{-0.008c}$
Maize	$S_l = 3.711e^{-0.015c}$
Grass	$S_l = .477e^{-0.068c}$
Forest	$S_l = 4.175e^{-0.048c}$

S_l = Simulated soil loss (t ha^{-1}), c = Simulated vegetation cover (percent)

The trends of the curves (Figure 6.6) show that high erosion rates are predicted from the maize and barley crops as compared to grass and forest. The curves for the maize crop indicate that soil loss drastically drops from 4.5 t ha^{-1} on bare ground and stabilises to about 2.5 t ha^{-1} at 50 percent cover. Morgan (1996) observed that for maize cover, in its early stages of growth, canopy is close to the ground and the slope of the curve is relatively steep. At higher canopy covers, a linear relationship with lower slope is obtained.

The grass and forest covers were predicted to control soil erosion completely at the 70 percent vegetation cover, while for the cultivated crops, maize and barley, there is little change in soil loss with increase in cover after the 70 percent cover. The exponential decline of soil loss with increasing cover was predicted for maize, but with a higher exponent value than for barley. Steeper exponents were obtained for grass and forest, indicating the rapid decrease in soil loss with cover. These results are typical of soil loss under vegetation covers obtained by other researchers (Elwell and Stocking 1976; Morgan 1996). The exponents of the curves are close to those obtained in many studies (Elwell 1978; Brown et al 1989). The results obtained in this study indicate that natural vegetation such as grass and forest are the optimum covers for controlling soil erosion in the catchment. This agrees with the earlier results of the USLE simulation.

6.6 Comparison of USLE and EUROSEM

The results of the USLE and EUROSEM simulations are not easily comparable (Quinton 1994) as each model predicts different processes of erosion. However, it would be interesting to assess the results from both models to find out if they provide similar or different messages for conservation planners. In the case of Mukogodo catchment, a comparison was not possible because EUROSEM could not predict soil loss under vegetation. For the Embori catchment, the USLE predicted high erosion hazard, which can be supported by plot data. High soil losses were also predicted for a single event at Embori for barley cover, suggesting a level of complementarity between the two models. However, EUROSEM simulations were based on too many estimated conditions to make a conclusive judgement. The exponential decrease in soil loss with increase in cover could be demonstrated easily with EUROSEM, while this was difficult with the USLE where the processes were not simulated.

As the USLE could be simulated in a GIS environment, it was better suited for the prediction of erosion hazard in spatial scales, and showing how the factors interact in the different geographic regions. The results obtained can be used for catchment soil conservation planning. EUROSEM is not currently available in a GIS mode and it would have required specific programming of the model to apply it as such. The large amounts of data required by the model and the fact that it routes both runoff and soil loss from cell to cell would require a process-based GIS software. This is a time-consuming task which could not be included in the present study. However, the demand for applying models in a GIS environment is growing and this should be the challenge in the development of EUROSEM to improve its versatility.

EUROSEM is more suited to predicting single events at plot and small catchment level, and for identifying the factors of erosion at that scale, while the USLE predicts annual averages. In addition, EUROSEM has the capability to predict runoff rates, which can be used to design the type and size of conservation structures. From both methods, it was observed that natural covers, especially grass and forest are very effective in reducing soil erosion. Both models also predicted that at vegetation covers exceeding 70 percent, soil loss diminishes under forest condition, while it reduces to a minimum under croplands. The use of erosion models in this study has demonstrated that there are advantages in applying both empirical and physically-based models for erosion modelling in large watersheds such as the Upper Ewaso Ng'iro basin of Kenya.

The conclusions and recommendations made from the results of both the USLE and EUROSEM models are presented in the next chapter.

CHAPTER VII
CONCLUSIONS AND RECOMMENDATIONS

This chapter summarises the general achievements obtained from the assessment of erosion hazard in the Upper Ewaso Ng'iro basin, as well as the recommendations that can be made from the research work.

7.1 General Achievements

The contribution of this study to the advancement of scientific knowledge can be summarised as follows:

1. Providing new thematic information regarding the Upper Ewaso Ng'iro basin of Kenya, that had not been previously available, which includes rainfall erosivity, soil types and erodibility, slope steepness, vegetation cover and the spatial distribution of soil conservation achievements.

2. Providing an erosion hazard map of the Upper Ewaso Ng'iro basin,

3. Quantifying soil loss rates to provide results which can be used for deciding priorities for conservation planning

4. Identifying the main factors associated with soil loss in the basin and using GIS to show the impact of the factors on soil erosion in the spatial domain

5. Showing that the relationship between annual rainfall erosivity with rainfall amount is a function of agro-climatic zones in the study area.

6. Developing a methodology that combines plot data, reconnaissance studies and GIS to put together the main factors and produce an erosion hazard map.

7. Showing that the USLE can be used in a GIS environment to determine erosion hazard in a large watershed.

8. Showing that EUROSEM is applicable to the sub-humid barley cropland conditions of the Embori catchment but not in the semi-arid rangelands of Mukogodo.

This study set out to determine the extent of soil erosion hazard in the Upper Ewaso Ng'iro North basin, and to identify the main factors associated with soil loss in the basin. A methodology has been developed for the assessment of erosion hazard with the USLE and GIS, using data obtained at plot and reconnaissance scales. In addition, it has highlighted the problems of soil erosion in the Upper Ewaso Ng'iro basin of Kenya. Unlike the other major drainage basins in Kenya, research has been scant on the Ewaso Ng'iro, especially in relation to soil resources and management. This study has succeeded in presenting such data both in the spatial domain and in quantitative forms. The results can be used by the various stake-holders, particularly land use planners of different technical backgrounds.

7.2 Specific conclusions

7.2.1 Rainfall erosivity

In general, rainfall erosivities in the Upper Ewaso Ng'iro basin were moderate, but with a wide margin ranging from 145 to 990 J m^{-2}. However, two groups of rainfall amount-erosivity relationship were obtained; the agro-climatic zones I-III of the mountain highlands, where erosivities are low per unit of rainfall and agro-climatic zones IV-VI, where high erosivities per unit of rainfall are dominant. Within each group, rainfall erosivity increased with amount. However, for areas within zone IV, a given amount of rainfall, obtained higher erosivities than in the rest of the basin. In addition, threshold rainfall intensities required to produce runoff were lower in the dry areas, where relatively low intensities (< 5 mm hr^{-1}) had recorded soil erosion.

7.2.2 Soils and soil erodibility

A soil map of the Upper Ewaso Ng'iro basin has been produced which shows that there are 36 major soil types (FAO classification). Laboratory analysis of the soil samples showed that most of the soils are loamy in texture, but with high sand contents. Organic matter is low in most of the soils, except those derived from forest conditions.

The soil erodibility indices obtained for the Upper Ewaso Ng'iro basin were comparable with those of similar soils under tropical conditions. It was found that about 84 percent of the basin has soils of medium erodibility, in the range of 0.10 to 0.25. Therefore, high erosion hazard in many areas could not be explained by the apparently low erodibility of the soils. Erodibility was found to vary greatly with organic matter content of the soils. Stone cover was predicted to reduce soil erodibility since it was found to be partly embedded and partly on the surface. However, land adjacent stony soils was observed to be severely eroded suggesting offsite effects of stone cover.

7.2.3 Topographic factors

About 77 percent of the Upper Ewaso Ng'iro basin comprises flat to gently undulating topography. The use of DEMs in topographic modelling was found to be a useful tool in this study, especially for the determination of the slope steepness and lengths. By setting the maximum slope length at 200 m, it was found that realistic values of the LS factor were obtained. Calculation of the LS-factor by the Mc Cool et al (1987) equation was found to yield better correlation with soil loss, than when the Wischmeier and Smith (1978) equation was used. Topographic factors were found to significantly influence the extent of erosion hazard on land with poor vegetation cover. However, on well vegetated land such as under forests and bushlands, soil loss was at a minimum regardless of slope gradient and length. Thus, vegetation cover was found to have an overriding effect over topographic factors, in influencing soil erosion in the basin.

7.2.4 Land cover and management

Thirteen major land cover types were identified in the Upper Ewaso Ng'iro basin, of which about 70 percent are rangelands, comprising bushes, shrubs and grass covers in various combinations. Percentage vegetation cover was poorest in the shrublands, where covers less than 40 percent were recorded and high erosion hazard was predicted and confirmed by ground truth studies. Field surveys showed that percentage vegetation cover was highest under forests and moorlands, followed by bushlands and bush grasslands respectively. Land management was identified as the main factor associated with the various levels of vegetation cover. Thus, communal grazing lands were more denuded than large-scale commercial ranches under similar topographic, soils and climatic zones. There were indications that deforestation has occurred on the fringes of the forest areas.

The crop and management factors obtained were generally low to moderate (0.007 to 0.449) as most of the basin is covered by natural vegetation. The C-factors derived for the rangelands showed that for the same canopy cover, lower C-Factors are obtained when the percentage grass cover was higher. High C-factors were obtained for croplands since bare soil is exposed completely between the growing seasons, and partially during the crop season. This had the effect of predicting high erosion hazard for cultivated areas, which was confirmed by plot data.

7.2.5 Conservation practices

About 25 percent of the small scale farms in the Upper Ewaso Ng'iro basin have been covered by soil conservation activities through the Ministry of Agriculture's Catchment Approach Soil Conservation Project (1988 to 1997) and were predicted to have a low erosion risk averaging 0.18. It was noted that nearly all the conserved catchments were on cultivated land, while there was little evidence of soil conservation activities on degraded grazing lands.

7.2.6 Erosion hazard in the basin

Over 36 percent of the Upper Ewaso Ng'iro basin was predicted to experience soil erosion in excess of an estimated tolerable soil loss rate of 9.0 t ha^{-1} yr^{-1}. The main factors associated with the various erosion hazard rates were land cover type and secondly the topography. Rainfall erosivity and soil erodibility were found to influence erosion risk only marginally, as both factors were overshadowed by the effects of vegetation cover.

The lowest erosion hazard rates in the basin were predicted for the forest, moorland and the flatter plateau areas, where less than 1 t ha^{-1} yr^{-1} was obtained. By spatial extent, the highest erosion hazard was predicted in the semi-arid rangelands associated with communal grazing occupying the northern and eastern parts of the basin. Land management was found to influence the different levels of erosion hazard, since the shrub grasslands in the well managed commercial ranches were predicted to be in the low erosion category as compared to the high erosion hazard in the shrub grasslands under communal grazing. It was noted that in certain parts of the basin, soil erosion rates predicted with the USLE did not explain the apparent land degradation. This was the case on flat and gently undulating lands lying adjacent to hills and minor scarps which are a source of large volumes of runoff. Soil loss from the croplands was predicted to be high, but it was observed that the rates were highly sensitive to changes in rainfall characteristics from year to year.

7.2.7 USLE

The USLE was found to predict soil loss from erosion plots in the Upper Ewaso Ng'iro basin quite well, obtaining an overall coefficient of linear regression of 0.645 with observed data. However, the model overestimated soil loss from forest, while it underestimated erosion from the other covers. In general, the soil loss values estimated by the USLE were considered realistic by comparing with plot data, reconnaissance surveys and sediment yields from the major rivers in the basin. Modelling with the USLE in a GIS environment provided a useful tool for the spatial extrapolation of data, while permitting calculations to determine the distribution of erosion hazard in the basin and to show the impact of the factors of erosion on the spatial distribution of erosion hazard. However, as the USLE does not predict deposition, the results obtained in this study only predict the susceptibility of a given area to yield sediment.

7.2.8 EUROSEM

The calibration of EUROSEM for Embori and Mukogodo catchments indicated that the model was sensitive to changes in THI, FMIN, IRMANN, COH and G. The model was found to predict both runoff and soil loss for Embori quite well, recording high correlation coefficients (0.907 and 0.840 respectively) between observed and simulated values. For Mukogodo, high correlation coefficients were obtained for runoff from bare plots (0.895), while soil loss from bare and runoff from grass plots had poor correlation coefficients of 0.577 and 0.570 respectively. However, EUROSEM failed to predict soil loss under grass and shrub covers. In all the treatments, the model underpredicted both runoff and soil loss and the standard errors of estimate were relatively high.

The application of EUROSEM was hampered by too many estimated model inputs such as saturated hydraulic conductivity, initial moisture content, splash detachability, soil cohesion and roughness coefficients. Thus, model performance would be improved by experimental determination of these factors in the actual field conditions. The model requires many input variables some of which are difficult to measure regularly. Its scope requires application to fields and small catchments, which would require more resources. In addition, it was difficult to determine the relevant factors for multiple vegetation covers and soils subject to surface sealing as in Mukogodo.

The storm-based soil loss values predicted by EUROSEM for four simulated types of covers; barley, maize, grass and forest obtained results that are comparable to values obtained in literature. Exponential decay of soil loss with cover was predicted for all the cover types. Higher soil loss was predicted for the maize and barley than under the forest and grass covers. At threshold grass and canopy covers of 70 percent, soil loss was predicted to diminish under both grass and forest, while in the maize and barley, it assumes a certain minimum value. There was a big gradient between soil loss from land under natural covers and that from cultivated land.

7.2.9 Comparison of USLE and EUROSEM results

The USLE predicted high erosion hazard for the Embori catchment and similar results were obtained in event-based simulation of soil loss using EUROSEM for barley cover at Embori. EUROSEM was more suited to predicting single events at plot and small catchment level, and for identifying the factors of erosion at that scale. The USLE could be simulated in a GIS environment, and it was better suited for the prediction of erosion hazard in spatial scales, showing how the factors interact in the different geographic regions, while EUROSEM is not currently available in a GIS mode and it would have required specific programming of the model to apply it as such. Both models predicted that vegetation covers exceeding 70 percent reduce soil erosion completely under natural covers, such as grass and forest, while under croplands, erosion is reduced to a minimum. The use of erosion models in this study indicates that there are advantages in applying both empirical and physically-based models for erosion modelling in large watersheds such as the Upper Ewaso Ng'iro basin of Kenya.

7.2.10 Concluding remarks

This study has shown that the USLE can be applied to determine field scale erosion hazard quantitatively and spatially over large watersheds, in a GIS environment. A simple methodology has been developed and used to collect representative data quickly and simply, with easy transferability of the knowns to the unknowns, especially in a GIS environment. It has been found that better correlation coefficients in the rainfall amount-intensity relationship were obtained, by incorporating the effects of the agro-climatic zones of the region. The results obtained in this study have established that cultivation of forest and grasslands for annual crops, and the overgrazing of rangelands are the main sources of eroded sediments. In the spatial domain, the areas covering the largest and most severe erosion hazard are the overgrazed rangelands in the semi-arid areas.

6.3 Recommendations for further work.

The use of the USLE in a GIS environment provides a useful tool for diagnostic studies as was illustrated with this study. However, conservation strategies are usually planned at field level, making it difficult to isolate the contribution of the various factors, and their interactions at the watershed level. This calls for further research into systems that utilise GIS techniques, for conservation planning at the basin level.

The rainfall amount-erosivity relationship has been investigated by many researchers for single storms. However, there has been little research into the same relationship, as applied to annual rainfall data, which is more relevant for modelling at reconnaissance scales. Although in the current study, annual rainfall erosivity was obtained to be a function of agro-climatic zones, the data available could only allow the grouping of erosivities into two class zones. It is recommended that further studies on this relationship be investigated, with larger data bases, and encompassing a wider range of agro-climatic zones, so that reliable relationships can be developed to predict erosivity indices for the various zones.

As the soil erodibility values produced in this study relied on estimates from the USLE nomograph, there is a need to correlate the values obtained by direct measurements. There are contradictory opinions as to whether stone cover increases or decreases soil erodibility. Based on the assumptions made in the current study, stone cover was predicted to decrease erodibility of the soil in situ, while it was suspected that erodibility of affected soils offsite may have been increased. This observation needs further investigation, especially with field studies under prevailing local conditions.

The topographic factors investigated in this study made use of a low resolution DEM. It is recommended that a higher resolution DEM of the Upper Ewaso Ng'iro basin be prepared for improved results of any work with topographic factors.

Land use and management issues in the study area have been associated with historical and socio-economic changes in the region. Most of the previous studies have been diagnostic, concentrating on small areas the size of tens to a few hundred square kilometres. As the problem of soil erosion is extensive in the region, a multi-disciplinary approach is required with problem-solving goals to identify solutions that are applicable at a reconnaissance scale for the rehabilitation of degraded lands in the Upper Ewaso Ng'iro basin.

The available guide values from USLE tables on conservation practice factors do not include certain conservation structures found in tropical countries like Kenya, such as trash lines, fanya juu terraces and stone lines. Therefore, there is a need for research to determine appropriate indices for these types of measures.

There is a need to determine the relevant rates of tolerable soil loss for local conditions, as the values obtained from McCormack and Young (1981) which were used in this study, are for temperate countries, where soil renewal rates can be quite different.

The validation of EUROSEM with plot data for Embori, and its poor performance for Mukogodo indicated that the model can be applicable to regions with similar crop, land management and cool climatic conditions to the temperate regions for which it was developed. As these were only two case studies, further research is required with longer-term experimentation under local conditions to validate the model for other conditions and crops such as maize, which are commonly grown in tropical conditions.

The cover and management routines required by EUROSEM utilise single crops whose growth conditions are monitored regularly. In addition, the poor performance of the model at Mukogodo was associated with, among others, the surface sealing properties of the soil. Thus, further studies are necessary to incorporate into the model routines for simulating multiple cropping systems, rangeland conditions and soils with surface sealing properties.

The requirements for rill erosion prediction with EUROSEM are rigorous, demanding measurements of the rill profiles regularly. Under tropical conditions, it is common to find that the land subjected to this form of erosion has multiple rills, whose shape and size are dynamic. The resources in time and labour demanded by this type of monitoring would therefore be daunting. Thus, further studies are required to simplify the model or the procedures for data estimation, so that it can be more adaptable to a wider range of users, physical and climatic conditions and to put the model in a GIS compatible mode.

CHAPTER VIII

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APPENDICES

Appendix 1 Legend of the soil map of the Upper Ewaso Ng'iro basin (Figure 2.4)

A1 - Imperfectly drained, very deep, dark brown to dark-reddish brown , firm moderately to strongly calcareous, stratified clay loam to clay, with varying salinity and sodicity in the deeper subsoil (calcic LUVISOLS, saline-sodic phase

B13 - Poorly drained, deep, very dark grey to very dark brown, firm, moderately calcareous, clay loam to clay, with humic topsoil (haplic CHERNOZEM)

B6 - Poorly drained, deep, very dark greyish brown, firm, moderately to strongly calcareous, slightly sodic clay, with a humic topsoil (calcic CHERNOZEMS, sodic phase)

F13 - Well drained, very deep, yellowish red, to dark reddish brown, loose, loamy coarse sand to friable sandy clay loam (chromic LUVISOLS, with rhodic FERRALSOLS and luvic/ferralic ARENOSOLS

H13 - Somewhat excessively drained, shallow, reddish brown, friable, rocky or stony, sandyclay loam (eutric REGOSOLS, lithic phase and Rock Outcrops)

H2 - Well drained, shallow, dark reddish brown, friable, rocky and stony, clay loam (chromic CAMBISOLS, lithic phase, and Rock Outcrops)

L12 - Imperfectly drained, deep, black to dark grey, very firm, cracking clay (pellic VERTISOLS and verto-luvic PHAEOZEMS)

L13 - Imperfectly drained, deep, very dark greyish brown, very firm, cracking clay (chromic VERTISOLS)

L14 - Imperfectly drained, deep, dark greyish brown, firm clay (hardpan), abruptly underlying a topsoil of sandy clay loam (eutric PLANOSOLS)

L22 - Complex of:- Well drained, deep to very deep, very dark greyish brown, friable and slightly smearly, clay loam (ando-luvic PHAEOZEMS) - Imperfectly drained, deep, very dark greyish brown to black, firm, moderately calcareous, cracking clay verto-luvic PHAEOZEMS)

L3 - Well drained, moderatelt deep to deep, dark brown, firm clay, with a thick humic topsoil (ortho-luvic PHAEOZEMS)

L5 - Well drained, shallow to moderately deep, reddish brown, firm clayloam, with a humic topsoil (chromo-luvic Phaeozems, partly lithic phase)

L8 - Well drained to moderately well drained, deep, very dark greyish brown, firm, cracking clay, with a thick humic topsoil (verto-luvic PHAEOZEMS)

L9 - Moderately well drained, very deep, dark greyish brown, firm clay (verto-luvic PLANOSOLS)

Lava - Excessively drained, exceedingly boulderly, extremely rocky land (boulders and Rock Outcrops)

M11 - Somewhat excessively drained, shallow to moderately deep, reddish brown, friable, rocky and stony, sandyclay loam (eutric CAMBISOLS partly Lithic phase with LITHOSOLS, eutric REGOSOLS and Rock Outcrops)

M2 - Well drained, very deep, dark reddish brown to dark brown, very friable and smeary, clay loam to clay, with a thick, acid humic topsoil, in places shallow to moderately deep and rocky (humic ANDOSOLS, partly lithic phase)

M3 - Well drained, very deep, dusky red to reddish brown, friable clay (eutric NITISOLS)

Lengend of soil map continued

M5 - Well drained, shallow to moderately deep, dark reddish brown, friable, humic, rockyand stony, clay loam (humic CAMBISOLS, rocky and partly lithic phase)

M9 - Imperfectly drained, shallow to moderately deep, dark red to yellowish brown, non to moderately calcareous, friable to firm, stony sandy clay with rock outcrops and ice in the highest parts (dystic HISTOSOLS, lithic phase, with LITHOSOLS, Rock Outcrops and ice)

Pd4 - Complex of well drained, shallow to moderately deep, dark red to yellowish brown, non to moderately calcareous friable to firm, stony, sandy clay loam,over petro-claci material or quartz gravel (calcic CAMBISOLS, lithic or petro-clacic phase; with chromic LUVISOLS)

Pn13 - Well drained, moderately deep to deep, dark red to strong brwon, friable to firm, sandy clay loam to clay (ferric and chromic LUVISOLS)

R1 - Well drained, extremely deep, dark reddish brown to dark brown, friable and slightly smeary clay, with and acid humc topsoil (ando-humic NITISOLS; with humic ANDOSOLS)

Pn2 - Well drained, shallow, very darkreddish brown, friable, slightly clacareous, stony and boulderly, clay loam to clay (chromic CAMBISOLS, lithic and boulderly phase)

R11 - Well drained, very deep, dark reddish brown, friable to firm clay with a humic topsoil (chromo-luvic PHAEOZEMS; over burried NITISOLS)

R2 - Well drained, extremely deep, dusky red to dark reddish brown, friable clay with and acid humic topsoil (humic NITISOLS)

R3 - Well drained, extremely deep, dusky red to dark reddish brown, friable caly; with inclusions of well drained, moderately deep, dark red to dark reddish brown, friable clay over rock, pisoferric or petroferric material (eutric NITISOLS; with nito-chromic CAMBISOLS and chromic ACRISOLS, partly pisoferric or petroferric phase)

R4 - Well drained, deep to extremely deep, dark reddish brown to dark brown, friable to firm, clay; in places gravely (eutric NITISOLS and nito-chromic CAMBISOLS; with chromo-luvic PHAEOZEMS)

R5 - Well drained, moderately deep to very deep, dark reddish brown, friable to firm, clay (nito-ferric LUVISOLS; with humic NITISOLS)

R6 - Well drained, moderately deep to deep, dark reddish brown, friable to firm, clay, with a humic topsoil (chromo-luvic PHAEOZEMS)

R7 - Well drained, modeately deep, dark reddish brown, firm, cracking clay, witha humic topsoil (verto-luvic PHAEOZEMS)

S1 - Poorly drained to very poorly drained, very deep, dark greyish brown to dark olive gery, firm to very firm, strongly saline, strongly sodic clay, in places with frangipanis at various ~~depths~~ (gleyic SOLONCHACKS, sodic phase and partly frangipani phase)

Um22 - Well drained, shallow to moderately deep, strong brown to brown, firm, gravelly to stony, sandy clay to clay loam, over soft rock (orthic LUVISOLS, partly paralithic phase)

Um24 - Complex of well drained, shallow to deep, red to dark red, friable to firm, sandy clay loam to clay, in places rocky (chromic and ferralo-chromic LUVISOLS; with chromic CAMBISOLS)

Ux3 - Well drained, deep to very deep, dark redidish brown to dark red, firm clay; with inclusions of imperfectly drained, moderately deep, dark greyish brown (nito-ferric/chromic LUVISOLS; with gleyic LUVISOLS)

V2 - Complex of well drained to imperfectly drained, shallow to moderately deep, dark reddish brown to very dark reddish brown, firm, slightly to moderately calcareous, rocky, stony or gravelly clay

Appendix 2 Field data sheet

ASSESSMENT OF SOIL EROSION IN THE UPPER EWASO NGIRO BASIN
FIELD DATA SHEET

CATCHMENT NAME____________________ DATE______________

ITEM	DESCRIPTION
Map location	
GPS	
Altitude	
Total area (ha)	
Area of each slope plane (ha) A, B, C, D…….	

PHYSIOGRAPHY	
Slope direction (facing uphill)	
No. of slope planes	
No. of channel elements	
Slope steepness (%) A, B, C……	
Slope lengths (m) A, B, C……	
Slope widths (m) A, B, C……..	

Agro-climatic zone	
Major land use type	
Land utilization	
Vegetation type	
No. of vegetation layers	
Type of layers	
Vegetation covers (%) A, B, C, D……	
Plant heights (m) A, B, C, D…..	

SOILS	
Soil surface condition	
Downslope roughness (m/2 m)	
Stone cover (%)	
Rock cover (%)	
Soil cohesion (kg/cm^2)	

Indicators of erosion	
Type of erosion	
Severity of erosion (score 0-5)	
Conservation Practice?	
Remarks	

Appendix 3 Annual rainfall and erosivity data from autographic records Upper Ewaso Ng'iro basin

Station ID	Station name	Agro-clim zone	Year	Rainfall (mm)	EI30 Index (J mm^{-1} m^{-2})
13	Embori	III - 7	1994	949	503
			1995	611	233
28	Kalalu	IV -5	1992	354	168
			1993	587	394
			1994	633	349
31	Karuri	II - 8	1993	771	562
			1994	896	438
			1995	521	212
52	Mukogodo	V - 4	1993	359	168
			1994	411	182
			1995	450	263
86	Sirima	IV - 5	1993	688	820
			1994	747	527
			1995	700	471
91	Teleswani	II -7	1993	805	426
			1994	1087	547
			1995	906	576

Appendix 4 Gauging stations, their location in the basin, rainfall amount and erosivitiy in the Upper Ewaso Ng'iro basin

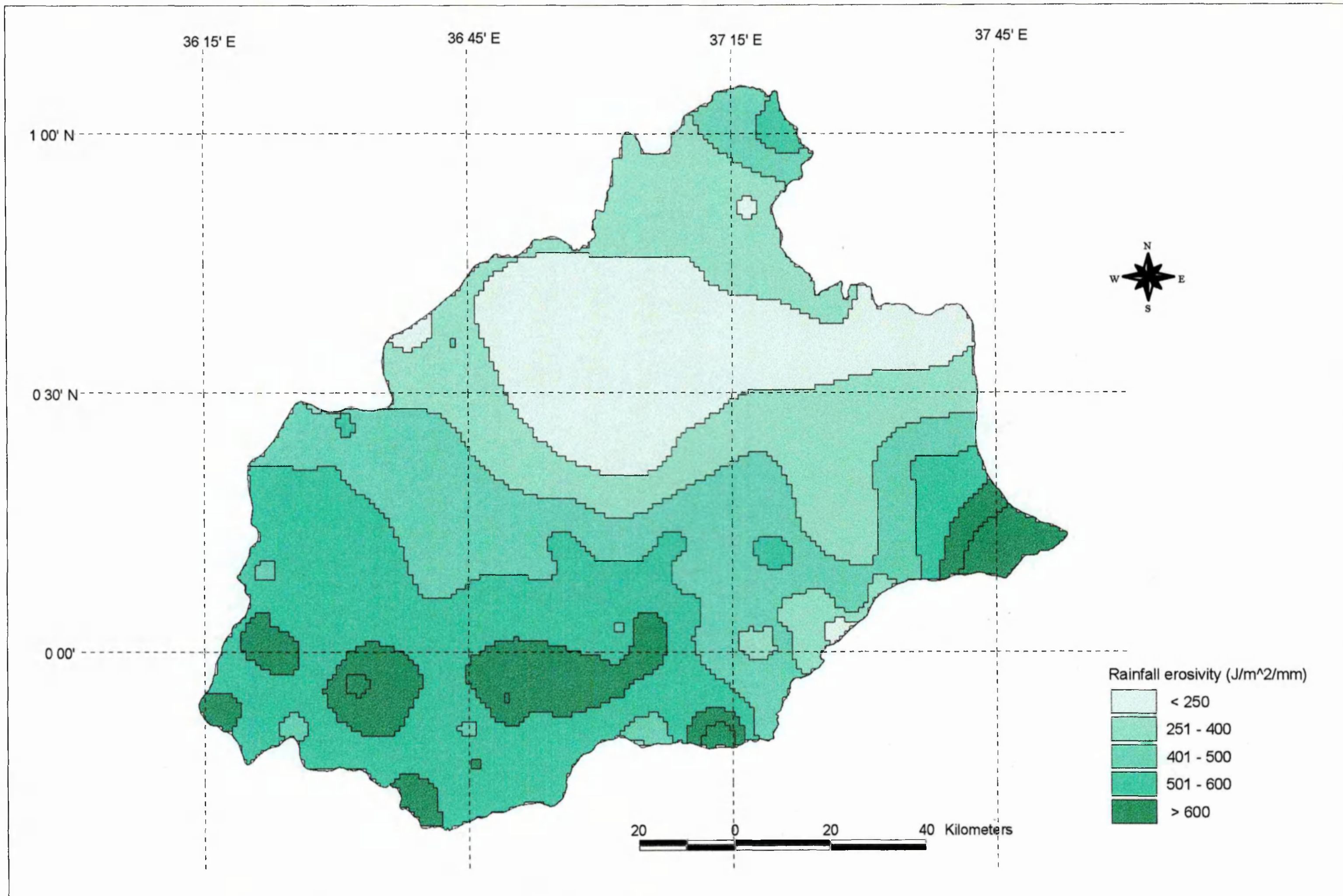
Agro-climatic zones I - III

Station ID	Station Name	Easting	Northing	Altitude (m)	Rainfall (mm)	Erosivity (J mm^{-1} m-^{2})
12	Embori Farm	37.339	0.067	2610	666	338
3	North Marmanet Forest	36.354	0.146	2120	888	482
11	Lariak Forest STN	36.309	0.325	2005	931	510
13	Embori (NRM)	37.309	0.041	2690	735	383
17	Gathiuru Forest STN	37.119	-0.099	2300	938	514
19	Gitundaga Forest STN	36.320	0.166	2280	970	535
31	Karuri (NRM)	37.328	0.027	2870	831	445
32	Kisima Farm	37.418	0.112	2410	767	404
35	Logilado (NRM)	37.299	0.030		705	363
40	Marania Forest STN	37.421	0.059	2880	998	554
40	Nanyuki Forest STN	37.145	-0.067	2270	998	554
41	Timau Marania	37.457	0.086	2500	907	495
41	Mariene CRS	37.534	-0.12	1620	1670	990
45	Meru Forest STN	37.626	0.055		1354	785
49	Nyahururu	36.368	0.047	2354	1248	716
54	Muringato Forest STN	36.938	-0.399	2130	808	430
59	Naro Moru FG Post	37.102	-0.176	2230	805	428
60	Naro Moru Forest STN	37.138	-0.215	2340	924	506
61	Naro Moru Gate STN	37.148	-0.174	2420	1059	593
62	Naro Moru Met STN	37.214	-0.171	2990	1470	860
63	Ndaragwa FST STN	36.530	-0.065	2280	866	759
67	Nyeri MoW	36.948	-0.413	1790	912	498
68	Ol Arabel FST STN	36.252	0.280	2060	886	481
74	Ol Bolosat FST STN	36.336	-0.052	2420	1011	562
75	Ontulili FST STN	37.169	0.019	2100	887	481
84	Shamata	36.529	-0.206	2800	999	554
88	South Marmanet Forest	36.373	0.048	2310	979	541
90	Teleki (Mt. Kenya)	37.298	-0.167	4300	788	417
91	Teleswani (NRM)	37.290	0.027	2680	812	433

Appendix 4 continued

Agro-climatic zones IV to VI

Station ID	Station Name	Easting	Northing	Altitude (m)	Rainfall (mm)	Erosivity (J mm^{-1} m^{-2})
1	Archers Post	37.668	0.637	830	343	145
2	Ardencaple Farm	37.253	0.083	2190	642	495
4	Borana	37.283	0.023	1980	585	285
9	Colcheccio	36.803	0.619	1740	404	216
10	Doldol DAO	37.157	0.388	1920	519	350
15	Enasoit Farm	37.070	0.235	1810	576	418
22	Isiolo DAO	37.585	0.354	1200	664	522
23	Jacobson Farm	37.014	-0.043	1800	737	607
24	Junction (Ewaso Narok)	36.848	0.505	1620	446	265
28	Kalalu (NRM)	37.165	0.081	2000	724	592
29	Kamwaki Farm	37.158	0.126	2040	584	428
33	Lamuria Met STN	36.870	-0.129	1850	705	569
34	Loldaiga Farm	37.119	0.207	2130	678	538
36	Loldoto Farm	37.017	0.175	1770	642	495
37	Lolmarik Farm	37.275	0.106	2280	567	408
38	Loruku Farm	37.085	-0.010	2100	771	647
39	Maralal DC	36.706	1.103	1945	578	421
44	Matanya (NRM)	36.954	-0.062	1840	787	665
46	Pyramid Ol Jogi	37.071	0.302	1870	526	359
47	Mogwoni Ranch	36.986	0.232	1740	583	426
48	Mpala Farm	36.901	0.320	1680	510	340
50	Mugie Ranch	36.592	0.711	1930	610	458
51	Mukenya Farm	36.821	0.242	1800	613	461
52	Mukogodo (NRM)	37.065	0.384	1750	362	166
53	Munyaka (NRM)	37.059	-0.184	2055	538	374
55	Mutara ADC Farm	36.682	0.111	1920	630	481
57	Nanyuki KAF	37.032	0.040	1860	626	477
65	Ngenia (NRM)	37.202	0.081	2120	566	406
66	Nicolson Farm	37.026	-0.088	1890	736	605
69	Ol Donyo Farm	37.293	0.092	2320	624	474
70	Ol Jogi Farm	36.938	0.306	1710	534	369
71	Ol Joro Orok FTC	36.380	-0.012	2380	787	666
72	Ol Mysor Farm	36.653	0.409	1790	606	453
73	Ol Pejeta Farm	36.809	0.061	1880	707	572
79	Rumuruti (NRM)	36.564	0.333	1820	616	465
80	Rumuruti MoW	36.548	0.267	1845	660	517
82	Satima Farm	37.010	-0.148	1920	689	551
83	Segera Plantations	36.888	0.169	1650	627	477
85	Siraji (NRM)	37.293	0.072	2460	654	509
86	Sirima (NRM)	36.815	-0.096	1970	828	714
87	Solio Ranch	36.877	-0.250	1910	704	568
89	Suguroi Estate	36.642	0.028	2040	711	576
92	Tharua Farm	36.885	-0.111	1790	742	613
93	Trench Farm	37.064	0.039	1890	809	692
94	Wamba DO	37.332	0.982	1500	710	575
95	El Karama	36.918	0.206	1720	689	550



Appendix 5: Rainfall erosivity in the Upper Ewaso Ngiro basin by extrapolation of point data

Appendix 6 Soil properties and erodibility data for the Upper Ewaso Ng'iro basin

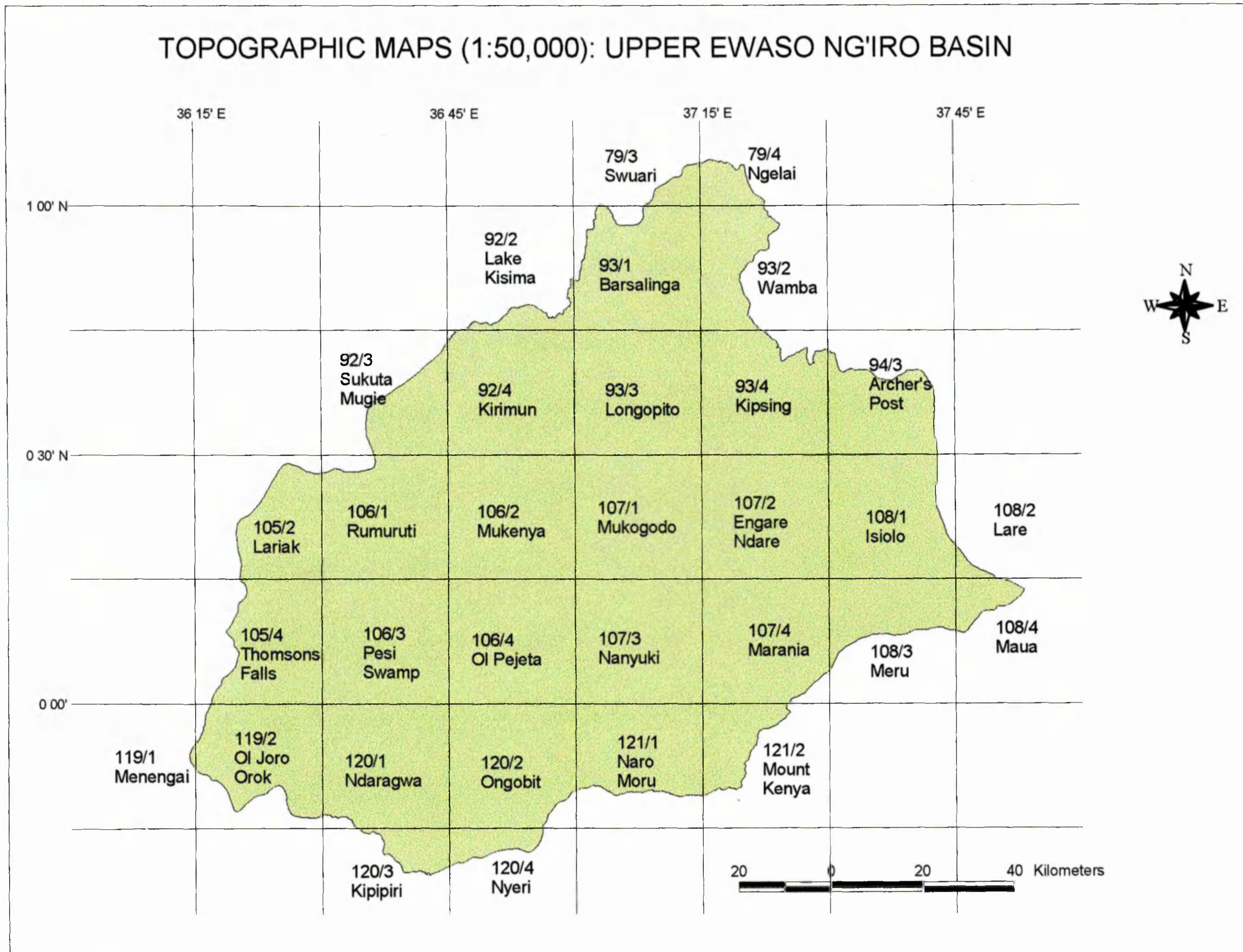
Site No	Sampled test site	Soil unit	Very fine sand (%)	Total sand (%)	Silt (%)	Clay (%)	Texture class	Structure class	Permeability class	O.M (%)	Stones FCOAR	K-Factor	Mean K-factor
58	Moorland (cave)	M9	9	49	31	20	L	2	5	12.95	1	0.03	0.03
59	Tophut	M9	8	80	12	8	LS	2	5	0.21	0.11	0.02	0.03
60	Teleki Valley (Lobelia forest)	M9	6	52	38	10	LS/L	2	5	13.12	1	0.02	0.03
83	Wuthering Heights	M9	5	45	28	27	SCL	2	3	8.93	1	0.05	0.03
34	Muhutetu	R3	11	45	16	39	CL	3	3	3.53	1	0.11	0.08
35	Nyahururu Tower	R3	9	66	25	9	SL	3	3	11.57	1	0.04	0.08
5	Teleswani	M2	7	53	46	1	SL	2	3	6.30	1	0.21	0.10
13	Baringo (Aberdares)	M2	8	56	31	13	SL	2	3	10.71	1	0.03	0.10
15	Shimata	M2	9	68	25	7	SL	2	3	11.39	1	0.01	0.10
61	Naro Moru Met. Station	M2	9	47	30	23	L	2	3	8.28	1	0.07	0.10
62	Naro Moru Gate	M2	9	46	31	23	L	2	3	4.43	1	0.15	0.10
73	Karuri	M2	9	44	29	27	CL/L	2	3	4.49	1	0.13	0.10
8	Kyegoi	M5	10	70	20	10	SL	3	3	10.95	1	0.05	0.12
9	Isaiah's Farm.	M5	9	63	28	9	SL	3	3	4.69	1	0.19	0.12
53	Kijabe (Tura)	H13	9	65	16	19	SL	3	3	1.38	0.68	0.11	0.14
55	Mukogodo Forest	H13	5	47	25	28	SCL	3	3	5.30	0.92	0.11	0.14
57	Doldol Forest stn	H13	10	73	14	13	SL	3	3	1.43	0.98	0.17	0.14
70	Lol Daiga	H13	7	60	20	20	SCL/SL	3	3	2.82	0.99	0.15	0.14
1	Simangua (Engare Ndare)	H2	7	53	27	20	SCL/SL	3	3	4.65	1	0.16	0.16
36	Ihigiani	R6	5	48	27	25	SCL	4	3	5.68	1	0.16	0.17
74	Angaine's farm (Sirimon)	R6	10	44	20	36	CL	4	3	2.85	1	0.17	0.17
24	Luisie Gap (scarps)	Lava	8	85	11	4	LS	4	5	1.77	0.87	0.20	0.17
25	Lodungukwe	Lava	8	84	10	6	LS	4	5	2.00	0.67	0.14	0.17
26	Mt. Mathew	F13	11	77	13	10	SL	4	3	2.47	0.81	0.15	0.18
69	Enasoit	F13	5	46	27	27	SCL	4	3	2.88	1	0.20	0.18
19	Lengusuka	Pd4	8	82	8	10	LS	4	5	0.46	0.79	0.17	0.18
44	Mukurian	Pd4	10	70	13	17	SL	4	5	0.90	0.78	0.19	0.18
65	Rangers Post (old gate)	Pd4	11	90	3	7	S	4	5	1.42	0.91	0.17	0.18
66	Koitongorr	Pd4	11	89	4	7	S	4	5	0.72	0.95	0.20	0.18

Appendix 6 continued

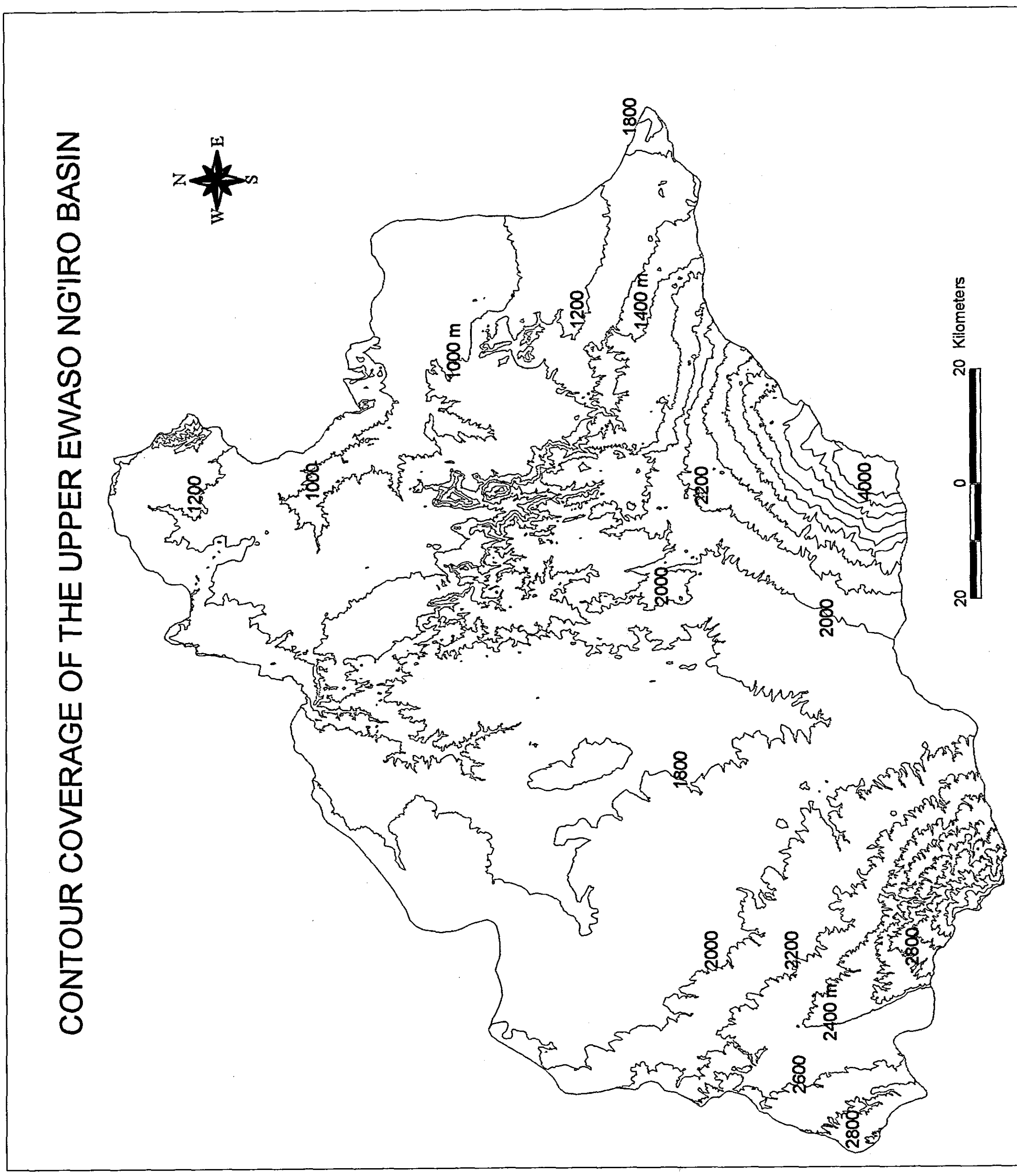
Site No	Sampled test site	Soil unit	Very fine sand (%)	Total sand (%)	Silt (%)	Clay (%)	Texture class	Structure class	Perme-ability class	O.M (%)	Stones FCOAR	K-Factor	Mean K-factor
30	Mataxi	L3	10	44	19	37	CL	3	3	2.43	1	0.14	0.18
41	Kisima	L3	8	56	26	18	SL	3	3	2.17	1	0.20	0.18
43	Kirimun	L3	8	57	24	19	SL	3	3	0.84	0.69	0.15	0.18
79	Solio Ranch	L3	8	44	38	18	L	3	3	3.77	1	0.24	0.18
11	Lower Ntirimiti	R2	9	46	39	15	L	3	2	4.11	0.94	0.21	0.19
12	Ol-orasha	R2	11	45	26	29	CL	3	3	2.60	1	0.19	0.19
72	Kisima (Timau)	R2	10	44	19	37	CL	3	3	4.20	1	0.12	0.19
80	Kaariki	R2	8	44	39	17	L	3	3	4.30	1	0.23	0.19
81	South Laikipia Forest	R2	9	47	40	13	L	3	3	4.13	1	0.26	0.19
56	Esipayo	Um24	9	65	17	18	SL	4	4	2.08	1	0.22	0.20
16	Maj. Kuria's farm (Podo)	Ux3	6	52	29	19	LS/L	4	3	4.48	1	0.20	0.20
32	Samburumbur (Sosian)	Um22	5	46	23	31	SCL	4	4	1.35	0.98	0.21	0.20
39	Mpala Research Centre	Um22	10	70	13	17	SL	4	4	1.27	0.60	0.13	0.20
42	Murijo Estate	Um22	8	54	28	18	SL	4	4	1.60	0.95	0.27	0.20
52	Ol Donyiro	Um22	10	73	14	13	SL	4	4	0.81	0.82	0.19	0.20
63	Ngare Mara	B6	5	49	23	28	SCL	4	6	1.69	0.76	0.20	0.20
3	Ngenia	L8	11	52	30	18	SL/L	4	3	5.05	0.68	0.15	0.20
18	Kifuku Farm	L8	9	50	35	15	L	4	4	3.16	1	0.31	0.20
48	Suguroi Ranch	L8	10	44	18	38	CL	4	4	2.43	1	0.19	0.20
71	Kalalu	L8	10	44	17	39	CL	4	3	3.01	1	0.15	0.20
75	Kwa Huku (Muita's farm)	L8	10	44	27	29	CL	3	4	2.66	1	0.21	0.20
14	Kanyagia	R1	9	46	41	13	L	3	3	5.83	1	0.21	0.21
7	Karama	M3	9	52	28	20	SCL/L	3	3	1.71	0.95	0.21	0.21
20	Matakweni	Pn13	9	88	5	7	LS/S	4	5	0.88	0.90	0.18	0.22
21	Lodumei	Pn13	8	87	6	7	LS	4	5	0.39	0.98	0.20	0.22
22	Maralal road	Pn13	8	84	8	8	LS	4	5	0.84	0.99	0.21	0.22
23	Luisie Gap (gullies)	Pn13	10	70	15	15	SL	4	5	0.54	0.98	0.26	0.22
27	Barsalinga Laga	Pn13	11	76	10	14	SL	4	5	0.93	0.92	0.21	0.22
37	Ol-Jogi	Pn13	10	75	15	10	SL	4	5	1.06	1	0.27	0.22

Appendix 6 continued

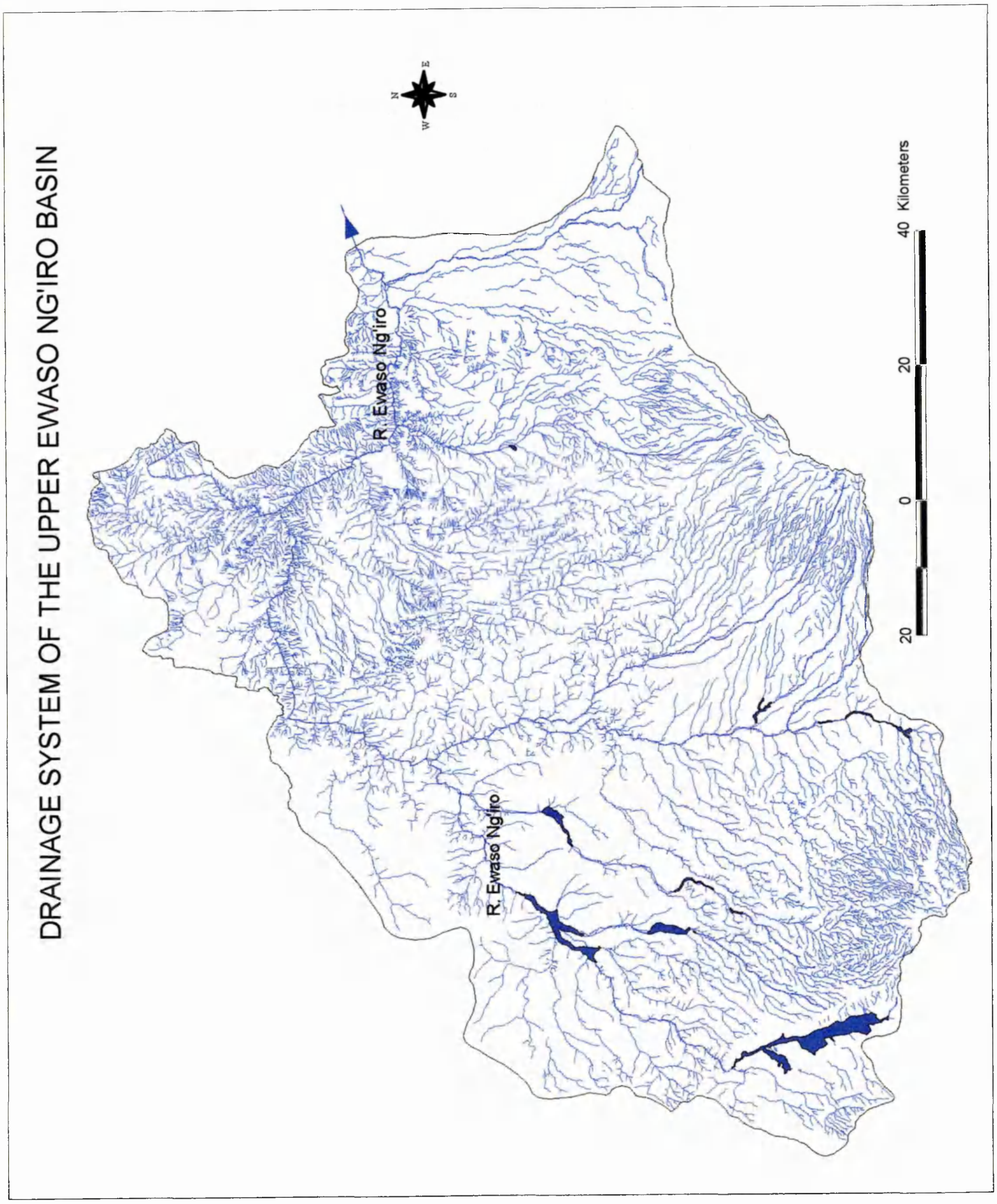
Site No	Sampled test site	Soil unit	Very fine sand (%)	Total sand (%)	Silt (%)	Clay (%)	Texture class	Structure class	Permeability class	O.M (%)	Stones FCOAR	K-Factor	Mean K-factor
40	Mpala Junction	Pn13	10	70	16	14	SL	4	5	3.48	1	0.23	0.22
45	Loborsoit	Pn13	8	80	11	9	LS	4	5	0.88	0.97	0.22	0.22
54	Il Polei	Pn13	8	83	8	9	LS	4	5	0.73	0.96	0.20	0.22
49	Sirima	L14	10	44	18	38	CL	4	5	2.19	1	0.22	0.22
6	Kianjai	R4	9	51	32	17	L	3	3	3.46	1	0.22	0.22
4	Embori	R11	9	49	33	18	L	3	3	3.56	1	0.22	0.22
78	Ntumbiri	R7	8	44	38	18	L	3	3	2.48	0.84	0.23	0.23
31	Sipili	L5	5	47	26	27	SCL	4	4	1.75	1	0.23	0.23
28	Ngobit	V2	10	44	28	28	CL	4	4	4.01	1	0.23	0.23
50	Matanya	V2	8	47	28	25	SCL/L	4	4	3.37	1	0.24	0.23
29	Withare	L12	10	44	24	32	CL	4	5	5.16	1	0.22	0.24
38	Mukenya Ranch	L12	10	51	31	18	L	4	5	2.71	1	0.32	0.24
46	Ol-Pejeta	L12	8	45	20	35	SCL/CL	4	5	3.76	1	0.20	0.24
47	Mutara Ranch	L12	10	44	24	32	CL	4	5	4.17	1	0.23	0.24
51	Sweetwaters	L12	8	46	27	27	SCL/L	4	5	3.00	1	0.26	0.24
68	Lairagwan	L12	10	44	17	39	CL	4	5	3.03	1	0.20	0.24
10	Karuiro	Pn2	8	45	39	16	L	3	3	2.95	0.95	0.26	0.26
64	Archers Post (old NYS)	B13	9	46	32	22	L	4	6	1.70	0.87	0.31	0.26
67	Buffalo Springs	B13	6	58	21	21	SCL	4	6	2.96	0.85	0.22	0.26
2	Lewa Downs	L13	9	47	35	18	L	4	5	2.41	0.92	0.32	0.27
33	Rumuruti	L13	5	49	26	25	SCL	4	5	2.38	0.87	0.22	0.27
17	Pesi swamp	S1	9	47	35	18	L	4	5	4.25	1	0.30	0.29
82	Weru settlement	S1	8	44	39	17	L	4	5	3.97	1	0.29	0.29
76	Isiolo Quarantine Area	A1	8	44	31	25	L	4	7	1.95	0.90	0.32	0.39
77	Garba	A1	7	47	45	9	SL	4	7	1.94	0.96	0.47	0.39



Appendix 7: Topographic maps (1: 50,000) coverage of the Upper Ewaso Ng'iro basin



Appendix 8 Contour coverage of the Upper Ewaso Ng'iro basin



Appendix 9 Streams coverage of the Upper Ewaso Ng'iro basin

Appendix 10 Land cover types and predicted C-factors in the Upper Ewaso Ng'iro basin

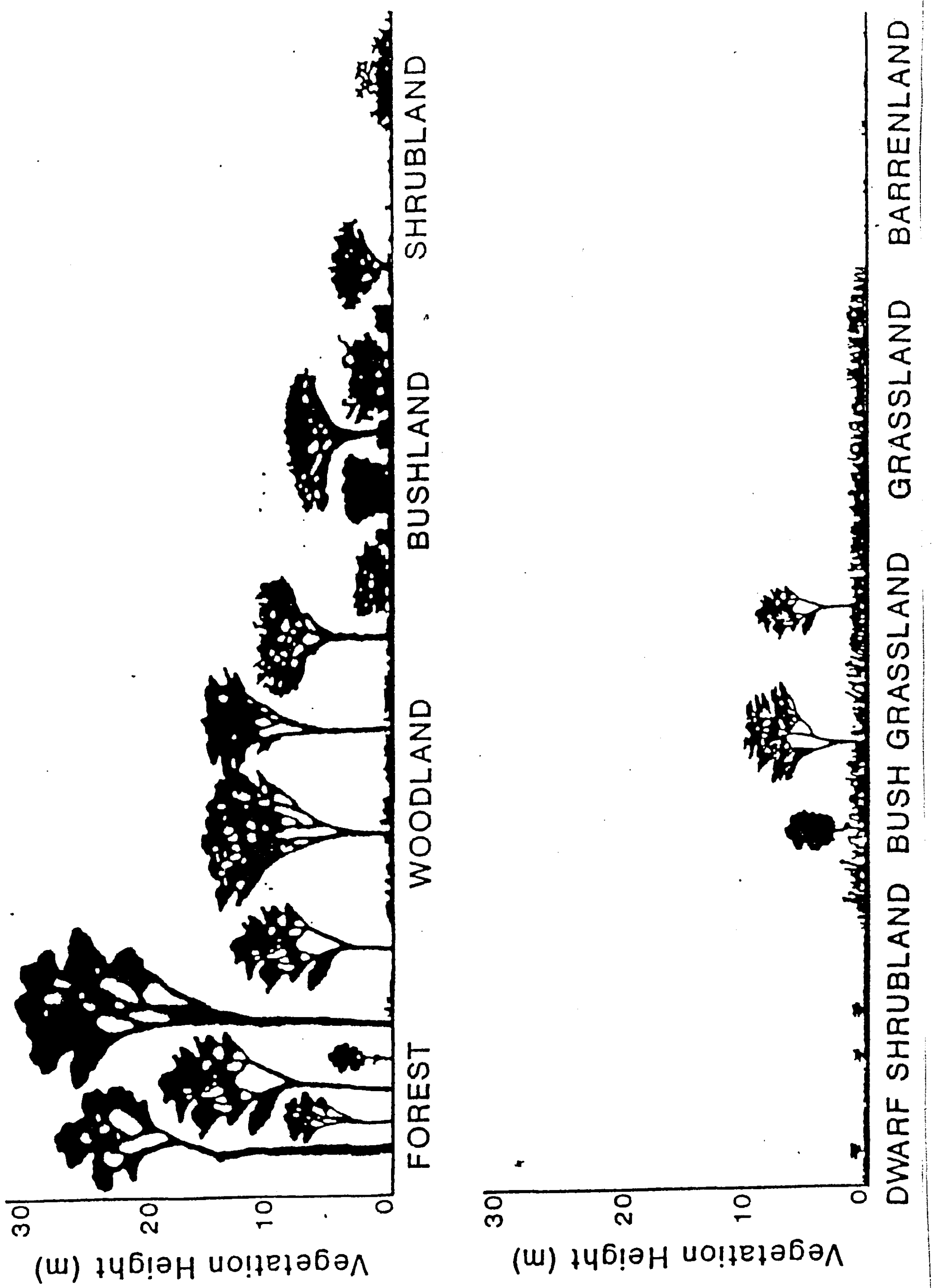
Site ID	Sampled test site	Easting	Northing	Altitude (m)	Land cover type	Overall cover (%)	Canopy cover (%)	Grass/forbes Cover (%)	Site C-factor	Mean C-factor
13	Aberdares forest (Baringo)	36.691	-0.265	2720	Forest	95	90	10	0.006	0.007
15	Aberdares forest (Shimata)	36.530	-0.208	2742	Forest	95	80	20	0.006	0.007
61	Met Station	37.215	-0.170	3040	Forest	95	75	20	0.007	0.007
62	Naro Moru Gate	37.143	-0.174	2490	Forest	95	75	20	0.007	0.007
8	Nyambene Hills (Kyegoi)	37.916	0.228	1750	Forest	95	90	10	0.006	0.007
5	Teleswani	37.309	0.041	2670	Forest	95	70	20	0.010	0.007
58	Mt. Kenya moorland (Cave)	37.233	-0.167	3660	Moorland	95	0	95	0.009	0.009
60	Lobelia forest	37.270	-0.171	4110	Moorland	95	0	95	0.009	0.009
83	Wuthering Heights	36.596	-0.241	3210	Moorland	95	0	95	0.009	0.009
35	Nyahururu Tower	36.375	0.048	2400	Forest	95	80	70	0.016	0.018
55	Mukogodo forest (Soisambu)	37.276	0.299	1900	Forest	90	70	70	0.018	0.018
1	Engare Ndare forest (Simangua)	37.320	0.192	1980	Forest	80	60	60	0.020	0.018
30	Mataxi	36.472	0.317	1890	Bush grassland	90	30	65	0.040	0.034
70	Lol Daiga	37.132	0.198	2100	Bush grassland	90	20	90	0.010	0.034
17	Pesi Swamp	36.579	0.104	2460	Bush grassland	80	20	70	0.030	0.034
37	Ol Jogi Ranch	36.942	0.255	1860	Bush grassland	80	30	60	0.038	0.034
42	Morijo Estate	36.845	0.670	1720	Bush grassland	80	30	60	0.038	0.034
10	Karuiro	37.594	0.271	1300	Bush grassland	70	30	50	0.050	0.034
69	Enasoit	37.056	0.253	1820	Shrub grassland	90	30	60	0.048	0.036
29	Withare	36.717	0.009	1920	Shrub grassland	85	25	60	0.032	0.036
46	Ol Pejeta	36.819	0.045	1890	Shrub grassland	85	15	75	0.019	0.036
51	Sweetwaters	36.875	0.033	1780	Shrub grassland	85	15	75	0.019	0.036
32	Sosian Ranch (Samburmbur)	36.703	0.444	1740	Shrub grassland	80	35	45	0.050	0.036
38	Mukenya Ranch	36.828	0.238	1690	Shrub grassland	80	30	55	0.049	0.036
47	Mutara Ranch	36.692	0.116	1920	Shrub grassland	80	20	60	0.036	0.036
2	Lewa Downs	37.456	0.189	1640	Grassland	90	10	80	0.038	0.039
18	Kifuku farm	36.594	0.198	1820	Grassland	90	10	80	0.038	0.039
41	Kisima	36.750	0.521	1830	Grassland	80	5	75	0.039	0.039
48	Suguroi Estates	36.650	-0.043	2010	Grassland	80	2	80	0.038	0.039
79	Solio Ranch	36.952	-0.200	1980	Grassland	80	2	80	0.038	0.039
40	Mpala Junction	36.848	0.439	1680	Grassland	65	5	60	0.042	0.039
56	Esipayo	37.219	0.329	1940	Grassland	65	5	60	0.042	0.039

Appendix 10 continued

Site ID	Sampled test site	Easting	Northing	Altitude (m)	Land cover type	Overall cover %	Canopy cover (%)	Grass/forbes Cover (%)	Site C-factor	Mean C-factor
28	Ngobit	36.778	-0.050	1930	Bushland	90	60	30	0.120	0.129
36	Ihigaini (near Pr.Sch.)	36.553	-0.072	2310	Bushland	85	60	30	0.120	0.129
7	Karama	37.808	0.236	1470	Bushland	80	60	20	0.140	0.129
81	South Laikipia Forest	36.745	-0.180	2370	Bushland	80	30	50	0.075	0.129
57	Doldol Forest Station	37.192	0.392	1950	Bushland	70	40	30	0.190	0.129
68	Lairagwan	37.022	0.131	1790	Shrub grassland	80	30	55	0.095	0.132
66	Koitogorr	37.553	0.581	810	Shrub grassland	70	30	40	0.129	0.132
67	Buffalo Springs	37.630	0.556	840	Shrub grassland	70	20	50	0.125	0.132
26	Mt. Mathew	37.340	0.973	1340	Shrub grassland	70	40	30	0.170	0.138
65	Rangers Post	37.627	0.620	860	Shrub grassland	65	25	40	0.140	0.132
43	Kirimun Market	36.881	0.746	1710	Shrub grassland	60	20	40	0.129	0.132
76	Isiolo Qarantine Area	37.537	0.295	1290	Shrub grassland	60	25	35	0.130	0.138
77	Garba	37.574	0.394	1100	Shrub grassland	60	30	30	0.140	0.138
53	Kijabe (Tura)	37.037	0.510	1840	Shrub grassland	50	15	35	0.140	0.138
63	Ngare Mara	37.655	0.523	900	Shrub grassland	50	20	30	0.150	0.138
4	Embori	37.308	0.041	2760	Large scale cropland	51			0.20	0.200
72	Kisima - Timau	37.427	0.118	2430	Large scale cropland	51			0.20	0.200
74	Angaine's farm	37.192	0.043	2160	Large scale cropland	51			0.20	0.200
39	Mpala Research Centre	36.890	0.285	1680	Scarpline shrubs	50	30	20	0.220	0.233
24	Luisie Gap (scarp)	37.148	0.920	1260	Scarpline shrubs	35	20	20	0.240	0.233
33	Rumuruti (Maundu ni meri)	36.565	0.328	1740	Scarpline shrubs	35	15	20	0.230	0.233
25	Lodungukwe hill	37.004	0.871	1290	Scarpline shrubs	30	10	20	0.240	0.233
9	Kyegoi (Isaiah's farm)	37.916	0.228	1720	Small scale cropland	50			0.21	0.259
11	Lower Ntirimiti	37.490	0.130	1955	Small scale cropland	41			0.28	0.259
14	Kanyagia (Muti-umwe)	36.445	-0.067	2490	Small scale cropland	53			0.24	0.259
16	Podo (Major Kuria's farm)	36.309	-0.026	2400	Small scale cropland	47			0.30	0.259
34	Muhutetu Settlement	36.347	0.235	1830	Small scale cropland	48			0.28	0.259
75	Kwa Huku	37.085	-0.031	2220	Small scale cropland	40			0.25	0.259
82	Weru Settlement	36.420	-0.117	2400	Small scale cropland	50			0.25	0.259

Appendix 10 continued

Site ID	Sampled test site	Easting	Northing	Altitude (m)	Land cover type	Overall cover %	Canopy cover (%)	Grass/forbes Cover (%)	Site C-factor	Mean C-factor
52	Ol Donyiro	36.985	0.636	1480	Shrubland	60	30	30	0.180	0.271
27	Barsalinga Laga	37.119	0.905	1200	Shrubland	50	20	20	0.240	0.271
19	Lengusuka Hill	37.315	0.878	1215	Shrubland	40	10	30	0.210	0.271
20	Matakweni Hills	37.285	0.976	1280	Shrubland	40	20	20	0.240	0.271
21	Lodumei	37.229	1.046	1440	Shrubland	40	20	20	0.240	0.271
22	Matakweni (Maralal road)	37.257	0.943	1290	Shrubland	40	20	20	0.240	0.271
45	Loborsoit	36.976	0.511	1830	Shrubland	40	25	15	0.310	0.271
23	Luisie Gap (gullies)	37.148	0.920	1260	Shrubland	35	15	15	0.400	0.271
64	Archers Post	37.682	0.637	750	Shrubland	35	15	20	0.320	0.271
44	Makurian	37.128	0.373	1760	Shrubland	30	15	15	0.400	0.271
54	Mukogodo NRM	37.065	0.383	1830	Shrubland	30	10	30	0.200	0.271
3	Ngenia	37.201	0.078	1920	Small scale cropland	46			0.47	0.449
6	Kianjai	37.751	0.170	1380	Small scale cropland	49			0.45	0.449
12	OL Doinyo Orasha Hill	36.818	-0.256	2040	Small scale cropland	39			0.42	0.449
31	Sipili	36.396	0.397	2070	Small scale cropland	49			0.45	0.449
49	Sirima	36.815	-0.097	1890	Small scale cropland	44			0.46	0.449
50	Matanya	36.957	-0.065	1820	Small scale cropland	55			0.41	0.449
71	Kalalu	37.165	0.082	2070	Small scale cropland	46			0.47	0.449
73	Karuri	37.328	0.027	2920	Small scale cropland	35			0.43	0.449
78	Ntumbiri	37.535	0.181	1620	Small scale cropland	40			0.49	0.449
80	Kaariki	36.633	-0.156	2430	Small scale cropland	42			0.48	0.449
59	Tophut	37.310	-0.165	4560	Moorland	0	0	0	1	1

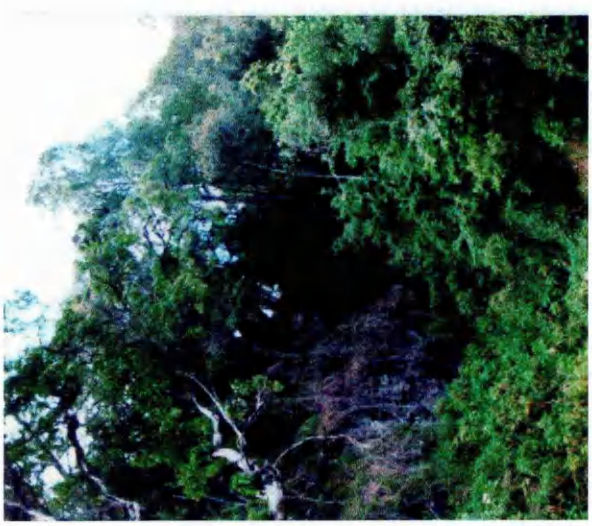


Appendix 11 Schematic representation of physiognomic vegetation types in Kenya (Herlocker et al 1993)

Appendix 12 Plot data for validation of the USLE

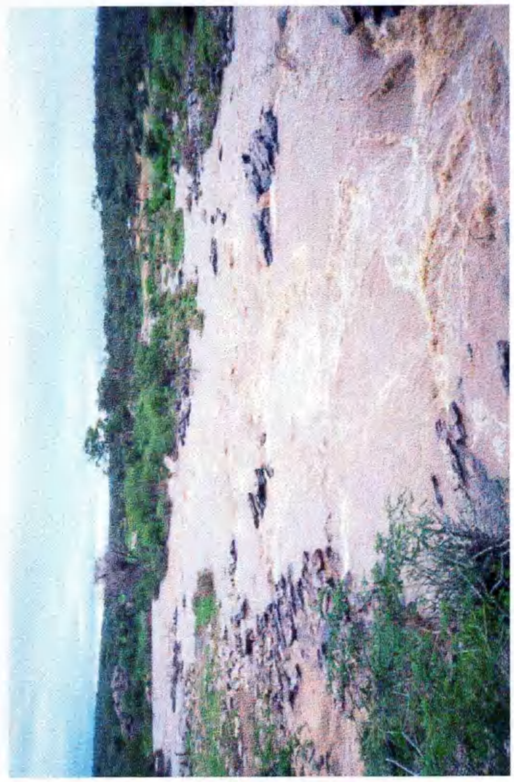
Year	Treatment	Catchment	R-Factor	K-factor	LS-Factor	C- Factor	Soil loss (t ha^{-1}) USLE	Soil loss (t ha^{-1}) Observed
1994	Barley	Embori	503	0.23	1.12	0.25	32.4	102.6
1995	Barley	Embori	233	0.23	1.12	0.20	4.1	0.0
1993	CG	Kalalu	394	0.19	0.383	0.40	11.5	25.4
1994	CG	Kalalu	349	0.19	0.383	0.20	5.1	5.2
1995	CG	Kalalu	1420	0.19	0.383	0.003	0.3	0.0
1993	Maize	Kalalu	394	0.19	0.383	0.80	22.9	25.4
1994	Maize	Kalalu	349	0.19	0.383	0.30	7.6	5.2
1995	Maize	Kalalu	1420	0.19	0.383	0.35	36.1	13.8
1993	Grass	Karuri	562	0.10	0.336	0.003	0.1	0.0
1994	Grass	Karuri	438	0.10	0.336	0.003	0.0	0.0
1995	Grass	Karuri	212	0.10	0.336	0.003	0.0	0.0
1993	Potatoes	Karuri	562	0.10	0.899	0.10	5.1	0.5
1994	Potatoes	Karuri	438	0.10	0.899	0.90	35.4	69.4
1995	Potatoes	Karuri	212	0.10	0.899	0.29	5.5	3.8
1994	Range (BE)	Mukogodo	182	0.22	0.383	1.00	15.3	31.0
1994	Range (BO)	Mukogodo	182	0.22	0.383	1.00	15.3	28.3
1994	Range (PE)	Mukogodo	182	0.22	0.383	0.40	6.1	9.4
1994	Range (PO)	Mukogodo	182	0.22	0.383	0.45	6.9	14.0
1994	Range (RO)	Mukogodo	182	0.22	0.383	0.40	6.1	11.5
1995	Range (BE)	Mukogodo	263	0.22	0.383	1.00	22.2	24.0
1995	Range (BO)	Mukogodo	263	0.22	0.383	1.00	22.2	35.2
1995	Range (PE)	Mukogodo	263	0.22	0.383	0.40	8.9	2.2
1995	Range (PO)	Mukogodo	263	0.22	0.383	0.45	10.0	16.1
1995	Range (RO)	Mukogodo	263	0.22	0.383	0.40	8.9	11.5
1994	Forest	NM Gate	580	0.10	0.383	0.003	0.1	0.0
1995	Forest	NM Gate	580	0.10	0.383	0.003	0.1	0.0
1994	Grass	NM Gate	580	0.10	0.383	0.003	0.1	0.1
1995	Grass	NM Gate	580	0.10	0.383	0.003	0.1	0.1
1995	Forest	NM Met	861	0.10	1.009	0.02	1.9	1.3
1995	Grass	NM Met	861	0.10	0.383	0.003	0.1	0.0
1993	Bush	Sirima	820	0.24	0.336	0.12	7.9	0.6
1994	Bush	Sirima	527	0.24	0.336	0.19	8.1	6.6
1995	Bush	Sirima	471	0.24	0.336	0.12	4.6	0.4
1993	Grass	Sirima	820	0.24	0.336	0.300	19.8	14.6
1994	Grass	Sirima	527	0.24	0.336	0.290	12.3	8.8
1995	Grass	Sirima	471	0.24	0.336	0.011	0.4	0.2
1993	Potatoes	Sirima	820	0.24	0.336	0.150	9.9	2.0
1994	Potatoes	Sirima	527	0.24	0.336	0.300	12.7	8.3
1995	Potatoes	Sirima	471	0.24	0.336	0.150	5.7	0.9
1993	Forest	Teleswani	426	0.10	0.676	0.008	0.2	0.1
1994	Forest	Teleswani	547	0.10	0.676	0.008	0.3	0.1
1995	Forest	Teleswani	576	0.10	0.676	0.003	0.1	0.1
1993	Grass	Teleswani	426	0.10	0.676	0.003	0.1	0.0
1994	Grass	Teleswani	547	0.10	0.676	0.004	0.1	0.1
1995	Grass	Teleswani	576	0.10	0.676	0.003	0.1	0.0

Appendix 13 Plates showing various levels of erosion hazard in the Upper Ewaso Ng'iro basin


13.1 A stable steep slope under forest; Nyandarua Range


13.2 Well managed grass cover in the Laikipia Plateau (Enasoit)


13.3 Severe erosion at Luisie Gap, below a stone covered hill


13.4 High sediment loads in the Ewaso Ng'iro at Crocodile Jaws

Appendix 14 Definitions of input variables and parameters required for EUROSEM catchment characteristics (Morgan et al 1998a)

Variable	Description	Units
BW	Width of channel bottom	m
CLEN	Characteristic length of catchment. Use maximum lengths of cascading planes or longest channel	m
COH	Cohesion of soil-root matrix as measured at saturation using a torvane	kPa
COV	Percentage canopy cover	
D50	Median particle diameter of the soil	µm
DELT	Time increment number used in calculations, usually 1 minute	
DEPNO	Average number of concentrated flow paths (rills) across the width of the plane	
DERO	Maximum depth to which erosion can occur because of a non-erodible horizon in the soil	m
DINTR	Maximum interception storage	mm
EROD	Detachability of the soil by raindrop impact	G/J
FMIN	Saturated hydraulic conductivity	mm/h
G	Effective capillary drive	mm
IRMANN	Value of Manning's n in the interill area, allowing for roughness effects of soil particles rock fragments, surface microtopography and vegetation cover (also used for non-rilled elements)	$m^{1/6}$
J	Element number	
MCODE	Governs selection of interill sediment transport equation (0 = Govers; 1 = Everaert)	
NC1	Element number of first channel contributing at upstream boundary	
NC2	Element number of second channel contributing at upstream boundary	
NELE	Total number of plane and channel elements	
NEROS	Not used – set to 2	
NL	Element number contributing flow to left-hand side of channel (when facing downstream)	
NPART	Number of sediment size classes for pond settling (not used in current version)	
NPRINT	1 suppresses print-out of auxiliary file; 2 gives auxiliary information	
NR	Element number contributing flow to right-hand side of channel (when facing downstream)	
NTIME	Code for time units, usually set to 2 for minutes	
NU	Element number contributing to upstream boundary	
PAVE	Proportion of surface covered by impermeable materials	
PBASE	Percentage basal area of the vegetation	

Variable	Description	Units
PLANGLE	Average acute angle of the plant stems to the soil surface	degrees
PLANTH	Effective canopy height	m
POR	Soil porosity	% v/v
RAS	Across-slope roughness	cm/m
RECS	Infiltration recession factor	mm
RFR	Downslope roughness	cm/m
RHOS	Specific gravity of the sediment particles	Mg/m^3
RILLD	Average depth of concentrated flow paths (rills)	m
RLMANN	Value of Manning's n for the rills, allowing for roughness effects of soil particles rock fragments, surface microtopography and vegetation cover	$m^{1/6}$
RILLW	Average width of concentrated flow paths (rills)	M
ROC	Proportion of rock in the surface soil by volume	
RS	Rill slope	M/m
SIR	Interill slope (also used for non-rilled elements)	
SHAPE	Plant leaf shape factor, 1 = bladed leaves, 2 = broad leaves	
SIGMAS	Standard deviation of sediment diameter	μm
SPLTEX	Water exponent affecting soil detachment by raindrop impact – set to 2 in current version	
TEMP	Air temperature at time of rainfall	°C
TFIN	Duration of model simulation	min
THETA	Weighting factor in finite difference equations, usually 0.7	
THI	Initial volumetric moisture content of the soil	v/v
THMAX	Initial volumetric moisture content of the soil	v/v
W	Width of plane element (set to 0 for channels)	m
XL	Length of plane or channel element	m
ZL	Side slope of left side of trapezoidal channel	1:x
ZLR	Side slope of concentrated flow paths (rills)	1:x
ZR	Side slope of right side of trapezoidal channel	1:x

Appendix 15 An example of a rainfall parameter file for EUROSEM used

```
 EUROSEM   Rainfall Input Data V3.5 7/96
#
****************************
   Gage Network Data
****************************
#
 NUM. OF RAINGAGES   MAX. NUM. OF TIME-DEPTH DATA PAIRS FOR ALL GAGES
   (NGAGES)          (MAXND)
1                     20
#
 There must be NELE  pairs of (GAGE  WEIGHT) data
*
 ELE. NUM. (J)   RAINGAGE    WEIGHT
     1              1          1.0
#
*****************************
   Rainfall Data
*****************************
 There must be NGAGES sets of rainfall data. Repeat lines from * to *
 for each gage inserting a variable number of TIME-DEPTH data pairs
 (see example in User Manual).
#
* ALPHA-NUMERIC GAGE ID: eurosem data for Embori on 22/05/94
#
 GAGE NUM.    NUM. OF DATA PAIRS (ND)
 ---------    ----------------------
   1                  20
#
 There must be ND pairs of time-depth (T D) data: NOTE: The last time
 must be greater than TFIN (the total computational time).
#
TIME(min)   ACCUM. DEPTH(mm)
 ------      ------------
0              0.0
15             0.6
45             2.5
60             5.0
75             8.6
90             3.1
105           16.6
120           22.2
135           22.9
165           23.2
195           24.5
210           25.1
225           28.1
240           28.7
255           32.3
270           34.3
285           35.3
300           36.3
315           36.7
320           36.7
321           *
```

Appendix 16 EUROSEM catchment parameter file

```
 EUROSEM V. 3.5/96 Parameter Input File EMBORI plot4 on 22/05/94
#
**********************************
*********** S Y S T E M ********
**********************************
* NELE  NPART  CLEN(M)  TFIN(min) DELT(min)  THETA  TEMP
   1       0       100.      315.        0.5          0.7      16.
#
***********************************
********* O P T I O N S ***********
***********************************
 NTIME  NEROS
   2       2
#
**********************************************
**** C O M P U T A T I O N   O R D E R ****
**********************************************
 There must be NELE elements in the list. NLOG
 must be sequential. ELEMENT NUM. need not be.
#
 COMP. ORDER   ELEMENT
   (NLOG)     NUM. (J)
   ------        --------
     1              1
#
**********************************************
****** E L E M E N T - W I S E   I N F O ***
**********************************************
  There must be NELE sets of the ELEMENT-WISE prompts and data
  records; duplicate records from * to * for each element. The
  elements may be entered in any order.
*
J  NU      NR     NL     NC1     NC2    NPRINT
1   0        0      0      0         0       1
----------------------------------------------------------------
   XL(M)   W(M)   S    ZR    ZL   BW(M)  MANN(Rilll) Mann(IR)
   10.0     2.0   0.13  0.0   0.0   0.0        0.0             0.25
----------------------------------------------------------------
   FMIN(mm/h) G(mm)  POR  ThI   ThMX   ROC  RECS(mm) DINT(mm)
    2.0          375.0   0.31  0.20  0.25   0.0   3.0          0.1
----------------------------------------------------------------
   DEPNO   RILLW(m)  RILLD(m)  ZLR   RS      RFR   SIR
   0.0       0.0          0.0         0.     0.       4.0   0.13
----------------------------------------------------------------
   COVER  SHAPE PLANGLE  PLANTBASE  PLANTH(cm)  DERO(m)  ISTONE(+/-)
    0.18    1        80.0        0.12            25.0            2.0          -1
----------------------------------------------------------------
   D50(u)   EROD   SPLTEX  COH    RHOS   PAVE   SIGMAS  MCODE
   300.0     2.0     2.0        2.40   2.65    0.0     1.00         1
*
```

Appendix 17 Example of a EUROSEM static output file obtained

```
   ----------------------------------------------
*   EUROSEM 3 STATIC SUMMARY FILE      *
----------------------------------------------

     RUN TITLE:g

   INPUT DATA FOR ELEMENT  1
   ========================
   NU:   0
    W:     2.00 M     XL:      10.00 M      S:   0.13
  MANN:    0.000    FMIN:      2.00 MM/HR  G:  375.00 MM
   POR:    0.31     THI:      0.20    THMX:    0.25
   ROC:    0.00     RECS:     3.00 MM DINTR:    0.10 MM
 DEPNO:     0.00       RS:      0.0      RFR:   4.000 %
   ZLR:    0.00    RILLW:      0.00 M  RILLD:    0.00 M
 COVER:     0.18    SHAPE:      1      PANG:   80.00 o
 PBASE:     0.12    PHEIG:     0.25 M   D50:  300.00 um
  EROD:    2.00 G/J SPLTX:     2.00     COH:    2.40 KPA
  RHOS:    2.65kgm3 PAVE:      0.00    SIGMA:    1.00
   SIR:    0.130    DERO:     2.00 m
 Derived parameters:  MN(IR):     0.248  SurfStor:  0.000004 mm

  EROSION SUMMARY
  --------------
  GROSS INTERRILL EROSION       8.204 kg   4.102 t/ha

  NET EROSION/DEPOSITION       8.204 kg   4.102 t/ha
  (a minus denotes deposition)

  HYDROLOGY SUMMARY, ELEMENT  1
  ==============================

  NET RAINFALL                   = 36.682    (MM)
  PEAK RAINFALL RATE                = 22.400    (MM/H)

  TIME TO RUNOFF                   =  60.500    (MIN)
  DURATION OF RUNOFF                  =  75.000    (MIN)
  TIME TO PEAK FLOW RATE               =  120.00    (MIN)
  PEAK FLOW RATE                  =  17.352    (MM/H)

  TIME TO PEAK SEDIMENT DISCHARGE        =  120.00    (MIN)
  PEAK SEDIMENT DISCHARGE             = 0.20198    (kg/MIN)

  GLOBAL VOLUME BALANCE
  ====================
  TOTAL RAINFALL DEPTH                 =   36.682 (MM)

  STORAGE REMAINING ON ALL PLANES        =  0.00088 (MM)
  STORAGE REMAINING IN CHANNELS+CONDUITS  =  0.00000 (MM)
  STORAGE REMAINING IN PONDS            =  0.00000 (MM)
  TOTAL INFILTRATION FROM ALL PLANES     =  22.28908 (MM)
  TOTAL INFILTRATION FROM ALL CHANNELS    =  0.00000 (MM)
  TOTAL BASIN RUNOFF                = 14.36625 (MM)       0.2873 CU.M.
TOTAL OF STOR., INFIL. AND RUNOFF TERMS =  36.65620 (MM)
*** GLOBAL VOL. ERROR =    0.0703 PERCENT ***
```

Appendix 18 EUROSEM basic parameters; measured and simulated values of runoff and soil for Embori plots

Date	Rainfall (mm)	Cover (%)	Cohesion kPa	Thi v/v	Surface runoff (mm) Observed	Surface runoff (mm) Simulated	Soil loss (t/ha) Observed	Soil loss (t/ha) Simulated
15/05/94	8.6	8	2.2	0.20	5.49	1.45	0.99	0.34
16/05/94	18.9	9	2.3	0.21	12.90	7.92	4.95	2.85
18/05/94	8.7	12	2.4	0.22	4.58	2.89	0.69	0.74
22/05/94	36.7	18	2.5	0.20	21.03	14.37	3.95	4.10
09/06/94	21.8	37	2.7	0.10	5.83	5.77	2.62	2.69
23/06/94	19.0	25	2.6	0.05	2.20	1.89	0.68	0.43
02/07/94	4.9	42	2.7	0.23	1.68	0.00	0.48	0.00
07/11/94	23.6	65	2.8	0.23	1.92	0.00	0.03	0.00
12/07/96	14.9	10	2.4	0.07	1.47	2.40	0.45	0.54
16/07/96	20.3	13	2.4	0.15	10.91	5.52	2.16	1.60

Appendix 19 Measured and EUROSEM simulated values of runoff and soil loss for Mukogodo

			BARE PLOTS				GRASS PLOTS				
Date	Rainfall mm	THI v/v	Runoff (mm) Observed	Runoff (mm) Simulated	Soil loss (t/ha) Observed	Soil loss (t/ha) Simulated	Cover (%)	Runoff (mm) Observed	Runoff (mm) Simulated	Soil loss t/ha) Observed	Soil loss t/ha) Simulated
05/05/94	15.6	0.34	10.8	10.2	4.5	2.4	7	9.5	11.2	2.4	0.8
16/05/94	16.7	0.30	9.6	9.1	1.1	1.7	9	7.0	9.4	1.1	1.4
18/08/94	9.6	0.28	5.3	3.7	1.3	0.6	9	2.8	3.5	0.3	0.5
03/10/94	9.4	0.30	1.9	0.5	0.5	0.0	6	0.3	0.3	0.0	0.0
11/11/94	11.1	0.34	7.7	2.1	1.5	0.1	21	6.6	1.6	1.0	0.0
08/02/95	34.5	0.10	18.5	16.9	3.0	4.4	26	11.7	22.5	1.3	3.6
13/02/95	8.8	0.15	4.3	3.4	1.0	0.6	28	3.2	3.1	0.6	0.4
02/03/95	35.2	0.20	23.0	18.6	4.2	3.1	11	20.6	12.9	2.5	1.4
10/05/95	9.8	0.19	5.1	3.7	1.1	0.4	41	2.4	3.4	0.5	0.4
14/07/95	7.0	0.15	2.8	1.2	0.3	0.1	20	0.3	0.9	0.0	0.1
04/09/95	13.7	0.20	7.1	3.0	1.4	0.4	22	1.8	2.5	0.4	0.2
19/09/95	10.5	0.20	5.6	0.0	1.8	0.0	24	1.4	0.0	1.0	0.0

Cohesion was 2.8 kPa for bare and 4.20 kPa for greass respectively

Appendix 20 Simulation of soil loss with EUROSEM from four vegetation types

	Soil loss (t ha^{-1})			
Cover	Barley	Maize	Grass	Forest
0	4.55	4.553	4.55	4.553
10	3.58	2.878	2.09	1.803
20	3.12	2.561	2.17	1.517
30	2.67	2.480	1.40	1.009
40	2.34	2.023	1.19	1.101
50	2.32	1.608	0.51	0.559
60	2.13	1.356	0.16	0.130
70	2.07	1.096	0.04	0
80	1.92	0.986	0.02	0
90	1.89	0.973	0.00	0
100	1.85	0.959	0.00	0