A Hierarchical Method for Soil Erosion Assessment and Spatial Risk Modelling

A Case Study of Kiambu District in Kenya

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Peter F. Okoth

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Dedicated to my late parents Mr. George Onyango and Mrs Marcella Onyango, my wife Elizabeth Adhiambo and to our two children, Newton Ochieng' and Marcella Anyango.

"One's perspective, whether as a scientist, villager or bureaucrat, determines the 'part' of reality one considers worthy of attention"

T.P Murray, J.J. Kay, D. Walter-Toews, E. Raez-Luna (1999)

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Glossary of definitions

The definitions presented herein are gleaned from literature (e.g. Lal, 1990) while some are coined by the author to meet their specific use and application in this thesis.

Catchment

A water-catchment in normal definition refers to an elementary hydrographic surface where rainwater falls before it drains into the drainage network or river-flow stream (Martínez-Casasnovas and Stuiver, 1998). A catchment is therefore a land segment within a watershed and is inclined in the direction of the river flow. Many people use the terms, watershed, catchment, and basins interchangeably, which in the context of this thesis is inappropriate and discouraged.

Drivers of erosion

Any feature or landscape property that influence the occurrence of soil erosion is referred to in this thesis as a driver of erosion.

Disrupters of erosion

Any feature or landscape property that creates a barrier or hinders soil erosion is referred to as a disrupter of soil erosion.

Erosion risk

Results from field experiments or field observations can be extrapolated to other regions via empirical or physical models (Lal, 1990). Models help to create an understanding of the cause-effect relationships involving major soil erosion agents and factors. There are a wide variety of erosion prediction models each developed to provide an answer to a specific question. There are different models for predicting erosion on long-term or event based time scale, from hillslope or watershed, from croplands or rangelands, in humid regions or semiarid environments, by sheet erosion or mass movement. Data input also differs for different models. Erosion prediction from its factors quantitatively or qualitatively provides an insight into the risk of erosion for the area of land for which the prediction is made. Erosion risk is therefore defined as the chance that soil erosion will take place on any unit of land in the future during an eroding rainfall depending on its causative factors, the biophysical properties of the land or due to human utilization of the land. According to Lal (1998), methods of assessing soil erosion have time dependency on them, i.e. past soil erosion, present soil erosion and future soil erosion. The predicted future soil erosion from its factors deals more with the risk of erosion than soil loss, which is the current erosion measured in run-off pots.

Erosion Proxies (indicators)

The use of erosion proxies was first suggested by Stocking (1987). An erosion proxy as applied in this thesis refers to properties of the terrain that stimulate the development or progression of soil erosion such as slope gradient, canopy cover, erodibility, management, slope length, etc), or other manmade or natural features that are in themselves not features of erosion. Features that act as barriers of soil erosion are included in the definition. In the landscape hierarchy, different proxies are found at different levels of the landscape hierarchy. Examples of erosion proxies in a field plot include, cover type, barrier structures, slope gradient, bunds and alley cropping. Examples of the erosion proxies in a watershed include drainage ditches, field boundaries, footpaths, animal tracks and other man made elongate features that cause water concentration and flow in the watershed. Barrier proxies or disrupters of erosion include: hedges, closed fences, grassed field boundaries, trashed field boundaries, bunded field boundaries, barrier ditches, constructed dykes, riparian strips or built earth-dams. Erosion proxies at the landscape level include rivers, streams, roads, built up areas and mining areas.

Features of erosion

In the context of this thesis, features of erosion are the visible products of the water erosion process, and they include sheet wash, rills, gullies, landslides, soil movement, flow patterns, stem wash, root wash, riverbank slumps and deposition features.

Field plot

The field-plot is defined as an elementary member of the landscape continuum created by human activity. The size is 4 x 4 metres ($16m^2$) in size or larger. The possession of a boundary is an important element for distinction because the boundary separates the internal erosion processes from erosion processes in the neighbouring field-plots. The field plot is both an observational as well as an agricultural domain.

Landscape

Landscapes are herein defined to be areas where ecological unity appears to be similar all through and where several attributes of the land (i.e. genesis, geomorphology, lithology, soils, land cover, land use, local faunas, human aggregations) tend to be similar and repeated across the whole area. This coincides with the definition given to the landscape by Schoorl (2002). Landscape units are normally several kilometres wide. Thus repeated clusters of elemental spatial landscape components characterise a landscape unit. In this thesis, geomorphology provides the boundary criteria for determining the spatial extent of a landscape unit.

Landscape features

The term refers to the naturally occurring biophysical elements in the landscape system that have distinctive properties that enable their recognition as individual ‘wholes’ within the system. Examples include roads, rivers, field-plots, towns, mountains, etc. Landscape elements is used interchangeably with landscape features in this thesis.

Landscape hierarchy

The structuring of a landscape unit into superordinate and subordinate parts based on some criteria produces a landscape hierarchy. Landscape processes in the higher level parts are slower than the ones in the lower level parts. The levels are asymmetric in their vertical properties but symmetrical in their horizontal properties. There are both classification and aggregation hierarchies. Classification hierarchies are based on selected thematic attributes while aggregation hierarchies are based on bigger object construction from single-theme elemental object aggregation. This thesis uses functional systems hierarchy (FSH) to define the different hierarchical levels.

Landscape holon

Any elemental component of the landscape system that is stable and is linked to higher or lower hierarchical features within a defined hierarchy. Holons retain properties of an individual *'sub-whole'* within the hierarchical system while at the same time are part of the larger system.

Landscape objects

Landscape objects refer to landscape features or elements captured and stored in a GIS system or any other storage medium where the biophysical properties are represented by descriptive thematic attributes and/or geometric attributes. Landscape objects enable mathematical computations during spatial modelling or for other kinds of digital manipulations.

Soil erosion, soil depletion and soil degradation

Due to confusion in terminology, it is important to define and distinguish among the three interrelated but distinctly different phenomena commonly used.

Soil erosion

Reduces soil productivity through physical loss of topsoil, reduction in rooting depth, removal of plant nutrients and loss of water. Soil erosion is normally quantified as an amount of soil lost from a given area over a specified period of time and expressed in standardised units mostly in tonnes per hectare per year (Van Noordwijk *et al.,* 1998). Erosion is based on the movement of soil particles, from a place of origin to a place of deposition. Soil erosion has on-site and off-site effects. Off-site effects include siltation of dams and reservoirs, eutriphication of inland waters, lowering of downstream water quality, and destruction of aquatic and marine life in downstream inland waters. Some beneficial effects include soil organic carbon sequestration, increase of productivity in depositional areas, improvement of some soil structures, textures and nutrient contents.

Soil depletion

Means soil quality loss or decline in soil fertility due to removal of nutrients by eluviation or cheluviation by water passing through the soil profile. The soil depletion process is less drastic and can easily be remedied through cultural practises and by adding appropriate soil amendments such as manure and fertilisers.

Soil degradation

Is an all-encompassing broad term. It implies decline in soil quality through deterioration of the physical, chemical and biological properties of the soil. Accelerated soil erosion is one of the processes that lead to soil degradation. Soil degradation may be caused by accelerated soil erosion, depletion through intensive land use, deterioration in soil structure, changes in soil pH, leaching, salt accumulation, build up of toxic elements such as aluminium or manganese to toxic levels, or inundation leading to reduced soil conditions and poor aeration.

Spatial modelling

Conceptualising the real-world space-time continuum into logical models of processes, patterns and features and their interactions in space constitute the process of conceptual spatial modelling. Using GIS for representing the conceptual model and performing simple mathematical computations on the stored GIS object attributes and displaying the results spatially constitute *spatial modelling*. In a spatial modelling operation, the real-world geographic objects are delineated and extracted using source data such as aerial photographs, satellite imagery, base maps, video or other sources. The objects are stored in GIS databases where they are allocated attribute values that represent the conceived value of the object. The attribute values could be qualitative or quantitative. Qualitative attribute values are used to group the features into specific themes or feature classes. Quantitative values are used in computational operations. A computational model is understood to refer to a simplified mathematical representation of reality carried out on the quantitative attribute values of the spatial database. In practice, many GIS operations are used in sequence to compute outputs of computational or manipulative models for digital storage and visualisation.

Watershed

Watersheds are defined to include both the catchment and the drainage channels within a single morphometric divide (Strahler, 1969). Neighbouring watersheds are therefore disjunct. Several watersheds can be nested within the same landscape unit depending on the incision of the particular landscape by streams, rivulets or river-tributaries. The boundaries of the watershed demarcate the morphometric divide between two watersheds. According to this thesis, the erosion processes in a single watershed are dominated by channel erosion (i.e. rills and gullies). Other flows include overland flow and sub surface flows (Lal, 1990). The selection of the watershed is still governed by the hierarchy theory as a ‘whole’ within a hierarchical system that has dual tendency to preserve and assert its individuality as a quasi-autonomous whole while also functioning as an integral part of an existing or evolving larger whole. The watershed is nested within a landscape unit and therefore is contained within it and is constrained by it. Watersheds as construed in this thesis are restricted to the hilly and youthful part of the river profile where more stream dissection of the landscape occurs. Sections of the river flowing in a plain where the relief is low lack the necessary terrain morphometry that coincides with the definition of a watershed. A single elemental watershed is also restricted within the longitudinal length and catchment of a single stream.

1

Introduction

Introduction

1.1 Why the research?

Soil erosion can be defined as the detachment and translocation of soil particles by moving water or wind from their original locations to new depositional areas. Soil erosion is commonly recognised by incisions or depositional features it forms on the surface of the land (Laflen and Roose, 1997). The word erosion is derived from the Latin word *erosio*, meaning *'to gnaw away'*. Distinguishable erosion features have been described by Nill *et al.* (1996) as 'finger prints' for evidence of erosion. Some examples of water erosion features include surface sheet-wash, rills, gullies and landslides (Nill *et al.,* 1996, Laflen and Roose 1997). Apart from rainfall and wind, soil erosion may also be caused by intensification of land use, tillage, construction structures, overgrazing, unregulated land use and deforestation. The destruction of land by water erosion has been recognised by many people over time. Many recognise it as a real problem and a threat to sustained agricultural production and soil productivity sustenance (examples are Bennett, 1939; Kilewe and Ulsaker, 1984; Lal, 1988; Dregne, 1982; Nill *et al.,* 1996; Gachene, 1995b; and Laflen and Roose, 1997). The currently known agents of erosion are water, gravity, ice and wind (Lal, 1990).

The recognition of soil erosion as a threat to agriculture was realised in earlier civilisations in the past. According to Bennett (1939) there were terraces constructed even before the time of Christ to protect olive trees from erosion in the Mediterranean Basin. Lowdermilk (1953) revealed that the agriculture that was thriving about 10,000 B.C. in Mesopotamia, present-day Iraq, was converted to a desert and shifting sand dunes by deforestation and soil erosion. Negev desert according to Olson (1981) had been inhabited since 10,000 B.C. Its loess plains were fertile and productive, but once again its soils, having succumbed to intensive land use and erosion, are now unproductive desert. Many civilisations according to Lowdermilk (1953), Eckholm (1976) and Olson (1981) succumbed to soil erosion. They included the Phoenicians, the Roman Empire, the Sardis in Western Turkey, the Golconda Fort in South Central India, the Harappan-Kalibangan in the fertile valleys of Ghaggar, Saraswati, and Old Yamuna in present day India and Sind province of Pakistan. It was however, not until the late 19th Century and early in the 20th Century that the problem became an issue in Canada and the United States. This occurred after recommendations of John Palliser were ignored. John Palliser a pioneer British Explorer was commissioned in 1857 to explore parts of North America for settlement by British immigrants. He described the triangular grassland region of Northwest Canada as hazardous for agriculture and that settlement was only recommended within a narrow belt surrounding the grasslands. This did not stop the urge for settlement and farming. By 1867 settlement of the triangle had started with farming and ranching as the major activities. Thereafter all the 259,000 square kilometres of the Palliser Triangle, which proved to be very good for wheat cultivation were settled.

In the period 1931 to 1939, the *'Palliser Triangle'* of Canada and *'the Great Southern Plains'* of the United States suffered a near decade of drought. In the beginning, crops withered and dried. The land became parched and the hitherto harmless winds picked up the loose soils and dust storms began. This persisted year after year for nearly ten years. The events were marked with devastating winds and *'Dust Bowls'* never experienced in the otherwise fertile area before. Huge powerful dust storms carrying millions of tons of stinging, blinding black dirt swept across the Plains. Wind erosion of unimagined proportions destroyed the livelihoods of many that had earlier settled in the region.

It was during this period of the *'Dust Bowls'* that Hugh Hammond Bennett (1881-1960) a career soil scientist in the United States Department of Agriculture (USDA) became convinced that soil erosion was a national menace in the United States. Its solution lay in tailoring conservation practices to fit the capability of the land and the desires of the landowners. His hard work and lobbying culminated in the formation of the Soil Erosion Service of the USDA in 1933. The fight against erosion had just begun in earnest.

Soil erosion in real terms puts to risk food security, soil productivity sustenance, surface water storage, surface water quality, aesthetic landscape beauty and natural ecological balance. The global recognition of soil erosion as a problem has in the past decades attracted attention at many fora including international, regional and local conferences and workshops. According to Nill *et al.* (1996), present investments in soil conservation efforts are small compared to the immense investment in civil engineering works aiming to repair the results of erosion.

Though most attention is normally put on the negative effects of soil erosion, soil erosion has also some beneficial effects. For example, the deposition of eroded soil material to lower areas has sometimes improved the quality of the soil receiving the sediment and thereby improved agricultural productivity of the depositional areas (FAO, 1995). Agricultural fields planted with grass or tree hedges have been observed to form benches on sloping ground due to upslope erosion and downslope deposition (Dabney *et al.,* 1999; Angima *et al.,* 2001). These barriers have reduced surface runoff and soil erosion (Dabney *et al.* 1999). Other examples of the beneficial effects of soil erosion emanate from observations of Follett (2001) and VandenBygaart (2002). According to them, the redeposition of eroded sediments in landscape depressions has been identified as a possible mechanism for carbon sequestration. The experiments they carried out showed that soils in depositional areas contained significant amounts of *'soil organic carbon' (SOC)* at depths beyond which the normal plough could attain. Progressive depositions in the depressions resulted in the burial of *SOC*, which decreased C mineralization, and produced a net gain in *SOC*.

However, from many observations in literature, the detrimental effects of soil erosion still outweigh the beneficial effects of soil erosion. For a period of 35 years, the St. Louis District U.S. Army Corps had to dredge over 14 million cubic metres of sediment from the Illinois River caused by deposition of eroded sediments into the river system (Illinois State Water Survey, 1994). The annual off-site damages caused by sediment in the United States is estimated to exceed US$ 6 billion, of which one third is attributed to erosion from cropland (Clark II *et al.*, 1985). In Ethiopia, it is reported that the annual soil loss due to erosion is 1.3 to 3 billion tons, ten percent of which is carried away by streams (Tesemma, 1997). In Costa Rica, in the Rio Terraba Basin, sediment yields of $112 \pm 11.4_{sd}$ t km^{-2} yr^{-1} were obtained for a headwater tributary whose basin measured 317.9 km^{-2} and 404 ± 141.7^{sd} t km^{-2} yr^{-1} at the river mouth with a basin of 4766 km^2 (Krishnaswamy *et al.*, 2001). Kaihura *et al.* (1999) measured soil quality depletion in Tanzania and found that available-Phosphorus declined by 41-62% on severely eroded soils and SOC similarly declined by 0.16-0.39% in the same soils.

Varying amounts of soil erosion have also been measured in Kenya. Measurements in the Tana Catchment in Central Kenya obtained sediment yields ranging from 500 to 600 t km^{-2}

yr^{-1} (Edwards, 1979). Other measurements produced sediment yields ranging from 20 t km^{-2} yr^{-1} in forested land to 3,000 t km^{-2} yr^{-1} in cultivated land (Ongwenyi, 1978). In Kiambu, Edwards (1979) measured sediment yield values ranging from 110 to 620 t km^{-2} yr^{-1} for Ruiruaka; 4,800 t km^{-2} yr^{-1} for Nairobi River; 12,200 t km^{-2} yr^{-1} for Ruiru River; 2,200 t km^{-2} yr^{-1} for Riara River and 1,780 t km^{-2} yr^{-1} for Riu River. Stoorvogel and Smaling (1990) in their review of nutrient depletion in Kenya reported values of 15-20 t ha^{-1} yr^{-1} for tea and coffee, 20-40 t ha^{-1} yr^{-1} for maize, and 20 t ha^{-1} yr^{-1} for cotton. From a *'nutrient monitoring'* research in three districts in Kenya, Van Den Bosch *et al.* (1998) estimated that the total consolidated nutrients lost by leaching, gaseous losses, erosion and human excreta from farm nutrients budgets constituted 86% of the total nutrients lost. Of these, nutrient losses attributed to erosion alone were 25%.

From what has been discussed so far, it is clear that there are several degrading effects of water erosion. The indication is that the debate on soil erosion and its effects should be viewed holistically beyond agricultural soil productivity depletion alone. The evaluation and underplay of soil erosion by the *'Skeptical Environmentalist'* (Lomborg, 2001) should be treated with caution. It concentrates more on plant nutrient depletion and its recuperation by fertilization ignoring other consequences of soil erosion. Agricultural soil depletion or its enrichment is only one form of the on-site or off-site effects of soil erosion. The detrimental effects of water erosion on surface water both in terms of storage and reduction of quality, the shading of sunlight from aquatic life by sediments, plant nutrient losses and land surface destruction are all deleterious effects of water erosion. They justify increased investments in research and for prevention of the scourge.

In Kenya, soil erosion was recognised as an environmental problem way back in the 1870s by the Colonial Administration (Pretty *et al.,* 1995). The first efforts in soil and water conservation were put in place in the 1930s as a response to the widely publicized *'Dust Bowls'* of the United States. After independence in 1963, due to the recognition and significance of soil erosion, the Government of Kenya with support from the Swedish government established in 1974 a programme in the Ministry of Agriculture to deal with the problem of soil erosion- *the National Soil Conservation Programme (NSCP).* Again in 1981, due to the global concern for the conservation of the world's environment, the Government of Kenya further established the Permanent Presidential Commission on Soil Conservation and Afforestation (PPCSCA). The Commission was primarily created with the broad tasks of reviewing legislation and to advise on the measures to be taken to protect watercourses and rural catchment areas. Its recommendations would form the basis for creating action among several actors to prevent river siltation and to preserve the soil resources of the country. In 1997, the Government of Kenya (GOK) established the Soil and Water Conservation Branch (SWCB) in the Ministry of Agriculture to strengthen its efforts in soil and water conservation. Another round of reorganization occurred in 1983 with the adoption of the World Bank sponsored Training and Visit system of extension for soil conservation.

In 1987, in response to a range of issues arising from its previous approach to conservation work, the Soil and water Conservation Branch of the Ministry of Agriculture in Kenya initiated a new approach to working on soil and water conservation, the *'Catchment Approach'* (Pretty *et al.,* 1995). The aim of the new approach was to concentrate resources and conservation efforts on a specified defined *'catchment area'* – a geographically and socially defined area sharing a common water resource base (typically 200-500 ha) – for a period of time (normally one-year). The Branch would work with all farms in the catchment and achieve a broad conservation design. The Catchment Approach (CA) meant interactive farmer-extensionist participation coupled with intensified publicity, training, farm demonstrations and tours. This was a shift from the more selective approach that had been operating for much of the 1980s under the Training and Visit (T&V) system (Harding *et al.,* 1996).

Though a lot has been done and achieved in erosion research and control in Kenya, most of the erosion research methods have put more emphasis on quantifying soil loss or measuring sediment yields rather than pinpointing to areas that are likely to suffer erosion. Examples include the works of Dunne (1974), Dunne and Ongwenyi (1976) Ongwenyi (1978), Ulsaka and Kilewe (1984), Gachene (1997a and 1997b), Okwach and Simiyu (1999). As a consequence, soil conservation efforts have also been geared more to curing areas already suffering from soil erosion than to conserve still useful but fragile environments. An effort to minimise the occurrence of soil erosion in fragile environments is therefore of critical importance to the country.

1.2 Current conceptual flaws in water erosion research in Kenya

1.2.1 Lack of a hierarchical perspective in tackling the problem of soil erosion

Most erosion assessment approaches in Kenya have in the past used plot level observations to extrapolate watershed or landscape unit erosion rates (e.g., Grunblatt *et al.,* (1991), Mantel and Van Engelen (1997)). In most cases the erosion processes have been assumed to occur in a uniform manner at all levels of the landscape construct and hence the results of one level observation were factored to cover other levels for which data were not collected. For that reason, assumptions were made that plot-level experimental results could be used for calibrating or extrapolating watershed level data (e.g. Mati *et al.*, 2000; Angima *et al.*, 2001). This resulted to many people extrapolating point data to cover wider geographic areas assuming uniformity of the erosion process over the region. Some have used the USLE (Wischmeier and Smith, 1978) to model watershed or catchment erosion despite caution of doing so from the authors of the equation (Wischmeier, 1976). Vanelslande *et al.* (1984) have reported miscalculations on tropical soils by using the equation. With the advent of hierarchical theory (Allen and Starr, 1982; Klijn, 1995), it has been noticed that landscape processes occur in different rates depending on the landscape entity and its position within the landscape hierarchy. This means that landscape processes can be partitioned according to their temporal and spatial extent.

Over the past four decades soil erosion assessment in Kenya was carried out by measuring suspended sediment loads in rivers or by using run-off plots, e.g., Ongwenyi (1978) and Okwach and Simiyu (1999) respectively. In the suspended sediment measurements, the sediment yields from selected watersheds provided a quantitative indication of the amounts of soil lost from whole watersheds. The exact origins of the sediment loads could not be traced back easily from the measurements. The run-off experiments on the other hand were mostly located on small experimental plots. The experimental plots most of the time typified erosion processes on very small and homogeneous areas where soil cover, soil type, and crop management were all dictated by the *a priori* experimental design of the researcher. The experiments at most highlighted site specific erosion processes and relationships. What could be happening on larger farm fields was never quantifiable from these experiments and there was always an assumption that the relationship was of a linear nature and therefore formed a basis for blanket recommendations and extrapolation.

The plots of course provided good experimental insight into the relationships between soil loss in different crops with different cover or on different soils and on different slopes. Stocking (1987) evaluated these experiments and categorised them as being good for data generation. Their limitation was lack of perspective on what happens to wider areas or regions with a multiplicity of situational variations. This was due to the small areas the experimental plots normally covered. Artificial borders preventing run-on and run-off water from interfering with the plots also introduced unnatural protective conditions in the plots. This was at odds with open erosion and deposition as it happens in open fields or slopes. Another limitation of the experiments was that their success was only guaranteed when there was adequate rainfall that produced surface runoff. When the rains failed then the experiments also failed. Comparison between seasons was difficult since different intensities and amounts of rainfall produced different results. Van Noordwijk *et al.* (1998) and Lal (1998) expressed similar views about the run-off experiments.

Data from studies of suspended sediments in streams or rivers show that sediment enrichment into streams or rivers from watersheds or catchments are normally only a fraction of the total sediment load of the river draining a watershed and vary according to the size of the catchment. Values as low as 3% have been recorded for large catchments and values of up to 95% for small catchments (Illinnois State Water Survey, 1994). Sediment yield data in semi-arid areas tend to either underestimate or overestimate erosion of the catchments (Sutherland and Bryan, 1991). According to studies in semi-arid regions of Canada and Kenya (Sutherland and Bryan, 1989a and 1989b), rating curves could not be established between suspended sediment concentration in the river water and discharge from the catchments. Their conclusion was that denudation rates (meaning erosion rates) calculated from sediment loads of rivers could be misleading. The importance of this observation is that it highlighted lack of a direct link between erosion in a catchment and the sediment delivery in the river channel draining the catchment. It also brought to light the errors associated with extrapolating soil loss results from small experimental plots to whole catchments, watersheds or regions. Edwards (1979), analysing sediment yield data from 41 stations in Kenya remarked that sediment yield data calculated from the measuring stations varied by orders of magnitudes and that there was no simple pattern relating area or mean annual discharge to sediment production in the rivers. According to him, the river sediment yields would have been reduced by a factor of 10 during converting of what might be termed *'point erosion'* to the sediment yields of a *'river'*. These inconsistencies in relating catchment erosion to sediment yields in rivers can be attributed to errors in comparing incongruent erosion data. Some of the suspended sediment loads in rivers emanate from riverbank erosion and cannot therefore be linked to catchment erosion.

It is currently becoming common knowledge that processes in landscapes generally have a certain range in their spatial extent and behaviour, which fits into a certain time frame. They should therefore be regarded within their specific spatio-temporal positioning (Allen and Starr, 1982; Klijn, 1995). The physical boundary of any landscape element occurring within a landscape system provides the opportunity for the analysis of the internally contained processes. When viewed from the same hierarchical level, the erosion processes taking place in each elemental component are comparable. The assessments for each level can therefore be carried out using the same indicators. At higher levels in a well-defined hierarchy, erosion conditions observable at the lower levels may be inherited upwards and generalised based on certain criteria, but mostly the higher level will portray new properties and indicators of soil erosion. This means that the observable features for assessing soil erosion must be viewed according to their specific location within the landscape hierarchy in an approach that zooms in or out of the landscape. Erosion measurements must also be based on their correct positioning within the landscape hierarchy. Landscapes are herein defined to be “areas where ecological unity appears to be similar all through and where several attributes of the land (i.e. genesis, geomorphology, lithology, soils, land cover, land use, local faunas, human aggregations) tend to be similar and repeated across the whole area” according to Forman (1995). This coincides with the definition given to the landscape by Schoorl (2002). Landscape units are normally several kilometres wide. Thus repeated clusters of elemental spatial landscape components characterise a landscape unit. In this thesis, geomorphology provides the boundary criteria for determining the spatial extent of a landscape unit. A landscape is therefore recognised as a large portion of land characterised by a repetition of similar relief types or an association of dissimilar relief types (e.g. valley, plateau, mountain, etc). Hierarchy on the other hand is defined as an ordering of systems into superordinate and subordinate parts depending on some chosen criteria and objectives. The higher level entities normally constrain the lower level entities and form the enforcing environment for the lower level entities. There are both classification and aggregation hierarchies. Classification hierarchies are based on selected themes while aggregation hierarchies are based on bigger object construction from single-theme elemental objects. This thesis proposes another kind of hierarchy, the functional systems hierarchy (FSH).

To illustrate the issue of assessing soil erosion in a FSH, the following example is provided. A watershed or a catchment could be composed of an aggregation of many field parcels, woodlots, forests, or built up areas all different classification themes, but in which soil erosion takes place. Erosion in each of these elemental components of the landscape would proceed differently and produce different erosion features. In fact some could even act as barriers stopping translocated soil by flowing water from reaching the river streams. Assuming uniformity of erosion processes on any slope of such an environment would be futile. It is therefore necessary to consider each individual field or parcel as an individual *‘whole’* where soil erosion is taking place independently and in isolation. What is important is how the properties of these elemental *‘wholes’* function together to influence the occurrence of soil erosion. The properties can be viewed from the factors of erosion as presented by Wischmeier and Smith (1978), or new spatial attributes not normally included in the USLE can be identified for their individual roles in soil erosion. A hierarchical level would thus be recognised as a construction where the internal properties that influence soil erosion can be compared similarly across the span. This means that the members of any hierarchical level are identified more from their functional properties such as genesis, membership to higher hierarchies, spatial extent, temporal resolution, biophysical properties and soil erosion manifestation rather than mere geometric or thematic attributes.

If one chooses individual parcels of land as the spatial elements for erosion assessment, the erosion processes will depend on cover, parcel management, slope steepness and the soil erodibility inside the individual parcel. Apart from their inherent properties, variations of erosion on different parcels may also depend for example on the orientation of the parcels in the slope (length parallel to or across the slope), boundary relationships with adjacent parcels, the position of the parcel on the landform (upslope, midslope or downslope), etc. All these factors must be placed in proper context when assessing soil erosion for individual field parcels.

In a watershed, for instance, mostly the linear features occurring on the watershed such as field boundaries, footpaths, animal tracks or roads networks could influence the occurrence of erosion. These may occur in any manner including cutting across individual parcels in the watershed. The factors for erosion assessment shift from areal properties of the parcels to linear flow channels in the watershed. The linear features as analytical tools for erosion are new emergent properties for assessing soil erosion in the watershed as opposed to the parcels. A new hierarchical level is thus created.

The beauty of such an approach is the opportunity it offers in providing comparable variables at different levels of observations. Variables ordered at different levels of organisation makes it possible to carry out and compare measurements and make predictions of phenomena for the same levels. Knowledge, management, attention, etc are similarly ordered in the same hierarchical manner thus sharpening decisions that aid in interventions. One of the objectives of this thesis is concerned with ordering the landscape system into superordinate and subordinate parts for assessing soil erosion and for modelling its risk within the hierarchy.

1.2.2 Terminology use

In Kenya, the Soil and Water Conservation Branch of the Ministry of Agriculture uses the 'Catchment Approach' (CA) as the appropriate strategy for soil erosion and water conservation. The CA according to Pretty *et al.* (1995) and Harding *et al.* (1996), targets a geographically and socially defined area sharing a common water resource base for a period of time (normally a year). This description of a catchment becomes a subject of scrutiny in this thesis. Due to the definition, catchments in Kenya have sometimes been equated to administrative boundaries with no relationships with the morphological configurations of the landscape nor actual contribution to soil erosion.

To illustrate the confusion in the use of the terminology, Edwards (1979) described a small experimental area in the Mbeya Range, which measured 0.2 km^2 as a catchment. In the same text he again gave the minimum dimensions of a catchment according to the American Society of Civil Engineers (1975) to be 259 km^2 or (100 square miles). Again, Sutherland and Bryan (1989) when working in Kenya used the term *'Catchment'* to describe the Katiorin experimental site in Baringo, which measured only 0.3 km^2. Bricquet and Claude (1998) used the terms watershed, catchment, and basins interchangeably when describing hydrological studies in watersheds. For them the different terms are used to mean the same thing in a single paragraph. Mati *et al.* (2000) in one paper on erosion modelling shows the same mix up. In computing soil loss for the Upper Ewaso Ng'iro River Basin using the USLE, they use for the conservation factor *(P),* maps of conserved catchments developed by the *'CA'*. The contradiction is shown in the concluding remarks of their paper. They write,

> *'This study developed and used a simple methodology to collect representative data quickly and simply, showing that in a GIS environment the USLE can be applied to determine field-scale soil loss data quantitatively and spatially to predict erosion hazard over large watersheds'.*

So which is which? Are they catchments or watersheds? From the definition of the *'CA'* according to Pretty *et al.* (1995) and Harding *et al.* (1996), it appears that other dimensions such as the social and time dimensions override the physical or geomorphologic connotation of the catchment definition. For Mati *et al.* (2000), it is assumed that the geomorphic characteristics of the catchment override the social aspects or that there is no distinction. The confusion is further illustrated by the definition of the *'CA'* by Kimaru (2000) when writing an overview paper on soil conservation in Kenya. According to him, the catchment in the *'Catchment Approach'* is construed to mean a 'limited focal area within which extension staff and other resources are concentrated over a pre-determined period of time for a better impact of conservation'. According to him, the *'CA'* focuses more on the socio-economic parameters than on the strict hydrological characteristics of the chosen area. This contradicts Mati *et al.* (2000) who stated in their paper that the *'Catchment Approach Programme'* ideally conserves an entire catchment. Due to some of these conceptual differences in the usage and application of the term, confusion has developed in Kenya on the correct biophysical environment of the term '*Catchment*'. Hence the activities of the Soil and Water Conservation Branch of the Ministry of Agriculture are not appropriately targeting defined landscape elements for attention. The *'Catchment Approach'* for example sometimes targets women groups living within a particular administrative area irrespective of their individual or collective landscape configurations. The result is that no proper landscape element is targeted for soil conservation. Whether this is important or not comes into play when transferring the *CA* strategy to other countries where the word *'Catchment'* might be construed differently. The use of the term should therefore be either done away with or be redefined as a *'social'* term in land management and given a new meaning. The mixing of abiotic spatial landscape attributes with administrative units and social domains contributes to the creation of confusion in terminology use especially when a selected *'Catchment'* is not representative of an area considered to be at risk of water erosion.

Other sources of confusion emanate from the use of the term by scientists. Some scientists have sometimes equated watersheds to be connotative of catchments (e.g. Mati *et al.*, 2000). Where is the distinction? Such questions will not be asked if a proper definition of the landscape elements relevant for water erosion are identified and defined. Geomorphic definitions should be based on their morphometric characteristics, positions in the landscape and geographic relevance. A water-catchment in the normal definition in literature refers to an elementary hydrographic surface where rain water falls before it drains into the drainage network or river-flow stream (Martínez-Casasnovas and Stuiver, 1998). Most of the flow on the catchment is by overland flow and finds its way into a small section of the stream bordered by two adjacent streams. A catchment thus could imply a single surface or an aggregation of several such surfaces depending on the spatial extent of the area being examined. One objective of this thesis is to define appropriate biophysical landscape elements that can be used for observing and managing soil erosion.

1.2.3 Obscurity of soil erosion with increase in population

In Kiambu, inadequate attention to the problem of soil erosion sometimes emanates from the fact that from a casual view of the landscape, one is not able to visualise the soil erosion going on below the crop canopy cover or vegetation cover. Apart from the lower lying areas of the district, most of the Kiambu District receives an annual average rainfall ranging from 1,100 to 2000 mm. This contributes to a high degree of vegetation vigour and high cover in the higher, wetter and steeper parts of the district. These areas due to their steeply sloping nature also suffer the highest risk of erosion (Angima, 2001). The areas appear to be free from erosion from casual view, while in reality they are not.

Currently in Kiambu, there is scarcely any new land available for expansion implying that an increase in food production must come from increases in the output of existing land. Due to the increasing population (Kenya's annual mean rate is 1.27%) there is even more pressure being exerted on the land due to settlement and survival demands. Steep areas of land previously set aside under natural vegetation for conservation purposes are now being opened up for cultivation and settlement. The risk of erosion caused by the increased and intensified land use activities on such land if understood are either ignored or assumed not to be destructive. This contradicts the findings of Tiffen *et al.* (1994) in Machakos.

In assessing environmental changes in Machakos District, Tiffen *et al.* (1994) used aerial photographs taken in 1948 and 1978 and compared land use and soil conservation during the same period. The visual photo data of the two dates was supplemented with intermediate data of 1961. The analysis showed that for the same area, a progressive change of land use from rangeland to cultivated agriculture had occurred. Distinguishable in the changes was that erosion features previously present in the 1930s for the same area seemed to have disappeared and have now been replaced by terraced agricultural fields and trees. Their observations and conclusions were that there was a remarkable change in land use in the area. Soil conservation efforts increased conspicuously after 1961 and that there could have been a direct link between population increase in the area, agricultural change and increase in soil conservation activities. They therefore wrote a book with the title *'More People Less Erosion'*. For Machakos area where the observations were made this is the factual truth. It might not be true for other areas in Kenya.

The current debate on the African environment and the changes that have taken place has been a subject of discussion for many people who have read Tiffen's book and who are interested in agricultural and environmental changes in Africa (Ovuka, 2000). The experience of Machakos district as reported by Tiffen *et al.* (1994) opened-up new thinking on land degradation and soil conservation generally. The environmental recovery paradigm has created a subject for analysis and debate. Examples include De Haan (2000), Boyd *et al.* (2000), and Boyd and Slaymaker (2000). In fact from the two analyses better insights into the environmental recovery in Machakos as reported by Tiffen et al. (1994) come to the fore.

According to De Haan (2000), the experiences in Machakos are best explained by the concepts of *'locality'* and *'social seclusion and sustainable livelihoods'*. *'Locality'* refers to cultural fragmentation and is limited to social and cultural domains. Ethnicity plays a dominant role. '*Social seclusion*' refers to lack of access to social security, to employment, etc. or in brief lack of access to decent living. *'Sustainable livelihoods'* on the other hand refers to the way in which people make themselves a living using their capabilities and their tangible and intangible assets. Livelihood is sustained if it is adequate for the satisfaction of self-defined basic needs and proofs against social shocks and stresses. According to De Haan (2000), five basic resources are needed for sustainable livelihoods. They include human capital, natural capital, physical capital, financial capital and social capital. These if properly deployed, result in sustainable livelihoods. The environmental metamorphosis in Machakos came about therefore, because the local people reshaped their livelihoods on the basis of their own needs, insights and knowledge.

The debate therefore is whether the metamorphosis in Machakos can be considered to be representative of African environments. According to De Haan (2000), from a localised perspective, Machakos is representative or rather 'exemplary'. Its success in achieving a more sustainable livelihood emerged from a specific constellation of factors. Population pressure, local knowledge enriched with experience from outside even as far as from India; profitable world market created by coffee cultivation; multi-locality in livelihood strategies due to migration; social capital of self help groups (Mweithya Women Groups); and enabling government policies. In fact he uses the term *'glocalisation'*, which integrates localisation and globalisation. The conclusion he draws is that the example of Machakos cannot therefore simply be duplicated elsewhere.

Those views are supported by the work of Ovuka (2000) who carried out a similar study in Murang'a district which borders Kiambu. Ovuka compared aerial photographs taken in 1960 and those taken in 1996 to unravel land use changes that have occurred in the area over the thirty-six years. The results of the study according to Ovuka was that despite the use of the '*Catchment Approach*' in soil and water conservation in parts of Murang'a district, aerial photographs taken in 1996 show less conserved land than in 1960. Old farmers in Murang'a remember that they were forced to dig terraces before independence and therefore dislike it. In comparison to Machakos, areas previously fallow and occupied by bush or grass in 1960 was in 1996 badly eroded land. After the construction of cut-off drains in 1974 more erosion in the form of gullies was observed on the aerial photographs of 1996. For Murang'a according to Ovuka, the population had increased by up to 100% in the period 1960 to 1996. During the same period there was an increase in soil erosion and a decline in soil fertility in eroded soils. He is therefore titled his paper '*More People More Erosion*'. The Kikuyu people of Kiambu are the same inhabitants of Murang'a District. The social capital, human capital, natural capital, physical capital, and financial capital are basically the same. Land use and natural resource endowment is also similar. The two districts are close to Nairobi though Kiambu is closer and more influenced by the city.

People of Kiambu District, and Machakos, because of their local differences have different livelihood domains and socio-economic capital. This makes land use preferences and soil conservation differ between the people of Kiambu, Machakos and people in other parts of Kenya. The people of Machakos have a different unique ethno-cultural background meaning that their organisational and social structures are quite different from those in Kiambu or elsewhere in Kenya. The drought incidences in Machakos and the low fertility of the land, has awakened the Akamba people of Machakos to the reality of maximising production on the little agricultural land that is available to them in order to achieve sustainable livelihoods. This means more work in soil and water conservation. Before knowledge gained from the Machakos experiences by Tiffen et al. (1994) can be transferred to other parts of Kenya, a lot of observations still need to be made in other parts of the country. The social structures, experiences and commitments seen in Machakos must be transferred to Kiambu and other parts of the country for the same prognosis to be drawn. Cultural re-engineering, would be a must. Otherwise Tiffen's observation remains a localised output whose applications still remain in Machakos district and can not be concluded to apply in other regions of Kenya or elsewhere. More similar experiences must be observed to make the results be of common notion. Boyd *et al.* (2000) and Boyd and Slaymaker (2000) confirm that several attributes, which differ from place to place, influence the way households invest in soil and water conservation (SWC). This means therefore, that there is no direct link between investments in SWC and increase in population. A link between land use and soil erosion highlights the impact of population on the agricultural environment. One objective of this thesis is to show that there is a relationship between soil erosion and landscape features associated with land use-the erosion proxies. An increase in population can be directly linked to an increase in land use activities and by extension soil erosion and its risk.

1.2.4 Perception of soil erosion

Another problem in Kenya is attributed to farmers' perception of soil erosion. From research carried out by interviewing farmers in parts of Embu and Meru districts, it was found that very few farmers if any recognised rill or sheet erosion as soil erosion problems (Kiome and Stocking, 1995). Most farmers were of course aware of the gullies whose occurrence and presence in the landscape is obvious. For that reason, gullies have been seen as the worst form of erosion and most conservation work by the Ministry of Agriculture is targeted at the gullies. Loss in soil quality caused by sheet erosion or inter-rill erosion goes unnoticed and has sometimes been guised in other contexts as over-use of the soil, drought or desertification (Kiome and Stocking, 1995).

From what has been discussed above, it appears that simple assessment and risk prediction procedures need to be devised and tested for validity. Measuring soil erosion is certainly the surest way of proving that soil erosion exists in an area. In a situation where areas likely to suffer soil erosion are identified and shown in a map appears attractive for directing control and management efforts. An individual farmer will most likely be interested in knowing which of his/her field plots are likely to suffer soil erosion so that he/she puts remedial measures in place. Residents of a higher hierarchical entity such as a watershed might be more interested in conserving their watershed or stopping soil erosion from devastating it. A regional authority might be more interested in the overall environmental conservation of a region or a district. This thesis tackles the assessment of soil erosion spatially as one of its objectives.

1.3 Existing opportunities for tackling the hazard of soil erosion

The discussions of section 1.2 create the basis for re-evaluating past approaches in soil erosion studies in Kenya and highlights some earlier assumed but unrepresentative paradigms. It is clear that a method, which represents soil erosion or its risk hierarchically in the landscape, and which categorises beneficiaries of the developed knowledge according to their responsibility hierarchies, has not been used in Kenya before. This is contrary to what is happening in the international research scene where there is new evolutionary thinking in research approaches. Current agricultural research strategies are proceeding towards procedures that produce decision support systems that target decision makers at different levels including field, farm, watershed, region or at the national level (Bouma and Jones, 1999). This is primarily to gain insight and to evaluate options for precise management or development of the natural resources.

Recent developments in geographic information systems (GIS) technology have made it possible to model and represent geographical real world phenomena in computerised spatial databases through which they can be stored, analysed, and displayed (Burrough, 1986; Heuvelink, 1993; Deursen, 1995). The use of GIS includes among others spatial landscape modelling, land use analysis, erosion modelling, and environmental planning (Janssen, 1994; Bergkamp, 1995; Suryana, 1997; Droesen, 1999). One of the GIS scientists' tasks is to extract meaningful information from an infinitely complex interaction of nature's geographic phenomena and processes. GIS can enable stepwise and ordered analysis of the landscape components as deemed by the landscape researcher. Modelling involves abstracting and simplifying geographic variables and relating them either as discrete objects in a feature space or by using derived functional algorithms or process relationships to link and obtain a particular desired output. Spatial models can be processed outside a GIS or linked to a GIS in a loose or tight coupling (Bregt and Bulens, 1998).

This thesis presents a method by which soil erosion can be assessed in the field hierarchically and its risk modelled using field data, remote sensing, aerial photographs and geographic information systems. Erosion risk is defined as the chance or probability that soil erosion will take place in any environment. An environment is considered to be at risk when any of the mitigating factors of erosion on the terrain (i.e., surface cover, slope, land management, soil erodibility) favour the creation of soil erosion. The risk factors change according to prevailing manmade or natural conditions of the terrain such as: soil surface cover, land use slope steepness, soil erodibility, type of management, conservation structures, etc. This research work is not about studying soil loss, the thrust is on observing features of erosion and how they can be used in the assessment and modelling of erosion risk. The treatise is limited to soil erosion by water and gravity.

Kiambu district is selected for the case study due to its intensive utilisation for agriculture and due to its rugged terrain especially in the upper footridges and footslopes of the Aberdare Mountains. Soil loss studies through river sediment yields in the district, indicate that there are alarming amounts of soil lost annually by water erosion. These range from 20 t km^{-2} yr^{-1} in undisturbed forests, to 3000 t km^{-2} yr^{-1} in cultivated to grazing lands (Dunne, 1974; Dunne and Ongwenyi, 1976; Edwards, 1979; Thomas *et al.*, 1981, Aubery and Wahome, 1983; Barber, 1983). Soil loss studies from runoff plots in Kiambu (Lewis, 1985; Okoth and Omwega, 1989; Omwega, 1989) indicate that cultivated land loses between 20 and 30 t ha^{-1} $season^{-1}$ and bare soil loses more that 70 t ha^{-1} $season^{-1}$.

1.4 Thesis objective

The general objective of this thesis is to develop and present a method, which can be used to assess the risk of water erosion in different levels of the landscape system using spatial methods. The broad aim is to define relevant levels that form the basis for assessing soil erosion and managing its risk.

1.4.1 Specific objectives

(1) To conceptualize and define from the landscape continuum hierarchically ordered landscape elements whose internal characteristics and parts influence the occurrence of soil erosion and whose spatial extent and geometry enable their capture and modelling by remote sensing and GIS.
(2) To prove that there are spatial features *(erosion proxies)* which are part-of, and internally contained in the hierarchically defined landscape elements that can aid in soil erosion risk assessment and modelling.
(3) To demonstrate that the selected *erosion proxies* can be related to actual occurrences of soil erosion by statistical methods and similarly be differentiated as either drivers or disrupters of erosion.
(4) To demonstrate that prediction models can be derived from field data collected on the erosion proxies and the developed models used for modelling of soil erosion risk spatially in a GIS for each of the defined levels.
(5) To test and validate the method in Kiambu.

The overall methodology is based on landscape ecological theories (e.g. Forman and Godron, 1986 and Forman, 1995), concepts of spatial modelling (Heuvelink, 1993; De Bruin, 2000), soil erosion theories (e.g. Morgan, 1986; Meyer, 1988; Imeson *et al.*, 1988, Lal, 1990), GIS theories (Burrough, 1986; Molenaar, 1989; Goodchild, 1992a and 1992b; Bregt and Bulens, 1998; Molenaar, 1998), the set theory (Ross, 1995) and statistical methods (Jongman *et al.*, 1987). The concepts for constructing the landscape hierarchy is shown in Figure 1.1 The steps through the method and the conceptual thinking are shown in Figure 1.2.

The strategy recognises a landscape unit as being composed of different landscape elements, with differing prominence, positions and processes depending on the level of analysis and hierarchical construction. Important is the fact that the methodology identifies spatial features that can be described as spatial movers *(drivers)* or barriers (*disrupters)* of erosion at different hierarchical levels. The analytical hierarchies selected for use are chosen to be in tandem with societal management responsibilities starting with the farmer at the lowest level to the regional authority or government at the highest level.

Hierarchical levels are defined based on a synergistic evaluation of the landscape in terms of its constituent parts, their genesis, actors who manage them, soil erosion processes, their biophysical properties and distinguishable levels where these inter-linked attributes show true evidence of hierarchical change and propagation of erosion. For each level, the elemental landscape component must have discernible boundaries and spatial resolution that can be captured by aerial photography or remote sensing at their individual level of analysis. In the whole process, soil erosion forms the guiding principle for conceptualising the hierarchical order of the landscape and the propagation of the erosion process. The definition and construction of the hierarchies are based on hierarchy theory (Allen and Starr, 1982; Klijn, 1994; Zonneveld, 1994; Klijn, 1994; Bergkamp, 1995; Klijn, 1995). The landscape elements forming the boundary conditions are distinguished and separated from their internal properties. They form individual levels of the hierarchy. The internal properties are used for the assessment of soil erosion and modelling its risk. New emergent properties of the landscape elements are used. Figure 1.2 shows the operational research steps.

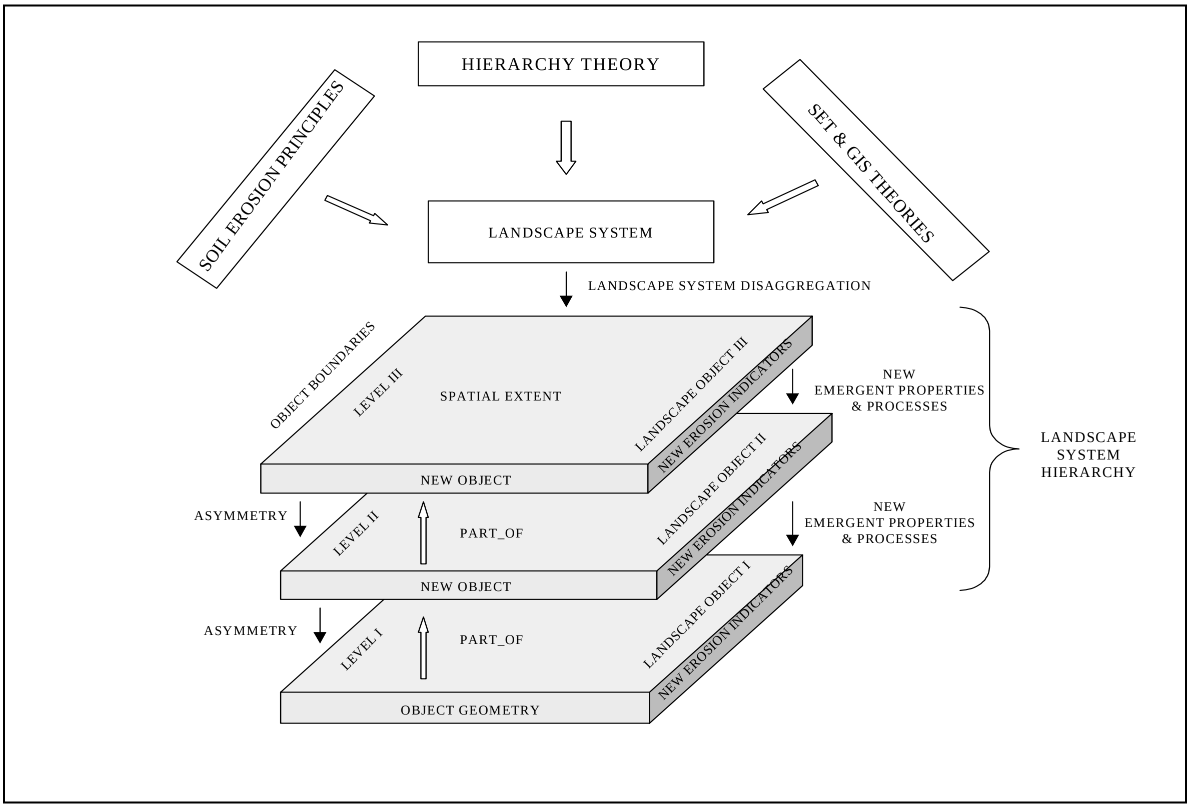

Figure 1.1 A model showing functional landscape system hierarchy and its construction

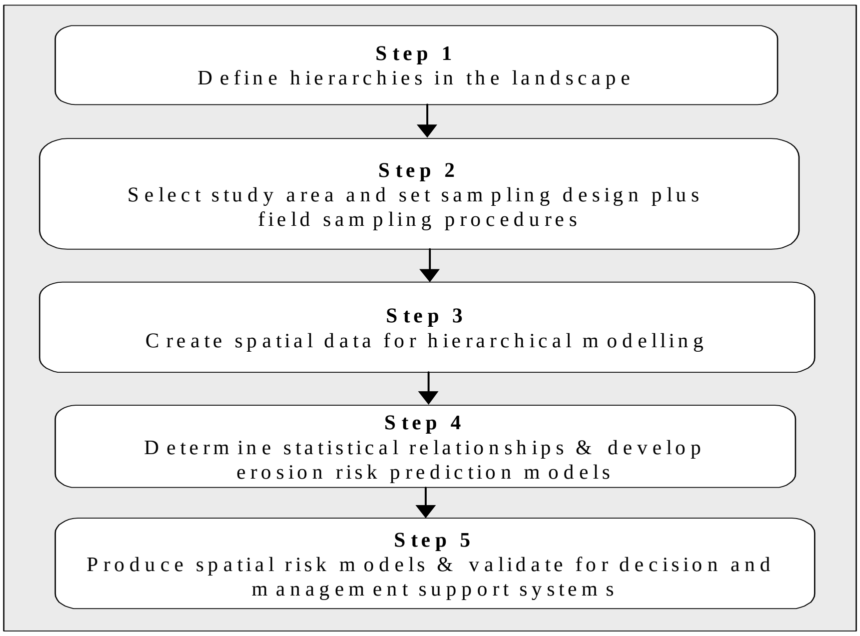

Figure 1.2 Implementation steps in the methodology

1.5 Scope, limitations, and outline of the thesis

1.5.1 Scope

This thesis presents a method, which assesses soil erosion and predicts its risk in a hierarchical landscape system construction. The field based assessment methods and the risk modelling in a GIS provides opportunity for people working in soil and water conservation (SWC) to employ similar techniques in assessing soil erosion, and possibly utilise the GIS products to channel conservation efforts. The hierarchical levels distinguish societal hierarchies that should be addressing soil and water conservation in a region. The emphasis is to identify the key factors contributing to erosion in a landscape system rather than an in depth study of soil erosion processes or soil loss. The method computes the probability for the occurrence of soil erosion within the selected landscape elements after developing relationships between the factors and the associated presence of soil erosion. Ground cover, soil type, slope gradient, visible erosion features, combine to provide an estimate of the risk of erosion occurring in different locations of a landscape system hierarchy on predefined erosion proxies. With these one is able to arrive at an estimate of erosion risk, i.e. severe, medium, or low risk. The different risk categories can be used to visualise the spread and distribution of different risk categories. The spatial distribution makes it possible to make location specific decisions for management intervention.

1.5.2 Limitations

The results presented in this thesis are case dependent and must therefore be tested and validated for new areas before being adopted for utilization elsewhere. The mathematical models can be used in similarly defined landscape elements. Erosion as described in the thesis is limited to water and gravity as the agents of soil erosion. Other agents of erosion such as wind and ice are not covered. The modelling is based on field observations of observable *(past erosion)* from which predictive models are developed using logistic and logit regression models. Soil loss or soil loss tolerance is therefore not dealt with. Process models are neither covered.

1.5.3 Thesis outline

Chapter 1 discusses the general introduction, the current flaws in erosion research in Kenya, some methods used in Kenya before, shortfalls of the methods, the thesis objectives, a general statement about the research and a general structure of the thesis.

Chapter 2 discusses the theories and concepts of spatial landscape modelling, including hierarchical modelling, the holon concept, classification hierarchies, aggregation hierarchies, functional system hierarchies and their link to erosion risk assessment and modelling. Spatial modelling data models and data structures and landscape ordering are also discussed. The link between the models and GIS are also presented. Statistical and soil erosion assessment methods are presented. Chapter 3 presents an overall view including detailed procedures of the developed methodology. Advantages and the disadvantages are discussed. Use of aerial photographs, remote sensing and field methods in data capture are presented. Statistical methods for field data collection, sampling strategy, erosion assessment, validation procedures and methods are discussed. Laboratory methods are also presented. Chapter 4 presents the location, climate, population, geology, general land use and landforms of study area.

Chapter 5 presents the results of the hierarchical organisation of the study area into landscape units relevant for assessing and modelling soil erosion. The products of the visual interpretation are captured into GIS databases from visual interpretation through digitisation and presented as intermediate products of the research. Areas used for erosion risk modelling are also selected and presented. In Chapter 6, statistical tests are used to confirm the links and relationships between the proxies and measured soil erosion. Results of the ANOVA statistics are provided. The intensity of erosion on the different erosion proxies at the field plot level, watershed level and the landscape level are provided. The chapter also identifies the features of erosion, which are most suited for assessing soil erosion at each level.

In Chapter 7, logistic regression is used to create the linear prediction models of soil erosion risk. The probability of erosion taking place is computed using an equation developed from predictor parameters derived from the linear logistic predictor. Validation of the results is obtained by correlating the developed probability models with independently measured erosion on the predicted landscape hierarchies. Chapter 8 presents discussions of the key findings and the conclusions. Other areas of research are also suggested. Recommendations are also provided in this chapter.

2

Theory, Concepts and Literature Review

Theory, concepts and literature review

In this chapter, concepts used in the hierarchical landscape construction, hierarchy theory, GIS theories, and theories of data capture in aerial photography and remote sensing are presented. Statistical methods are also presented. Also presented are soil erosion formation theories and assessment methods. Methods of water erosion assessment in Kenya are also presented. The chapter is an important entry to the subsequent chapters of the thesis.

2.1 Introduction and background

2.1.1 Landscape construction and soil erosion

In section 1.2.1 the flaws associated with up-scaling plot level erosion data to higher-level terrain units were discussed. The linear transformations in most cases were described as simple models, which assume uniformity and monolithic organisation of a landscape system. The diversity of a landscape system in terms of vegetation, soils, field parcels, land use, slopes and geomorphology makes linear soil loss extrapolations unrealistic (Van Noordwijk *et al.,* 1998). It therefore requires a thorough examination of the landscape and its parts before determining comparable levels of observation and extrapolation. It is currently becoming common knowledge that processes in landscapes generally have a certain range in their spatial extent and behaviour, which fits into a certain time frame and spatial distribution. They should therefore be regarded within their specific spatio-temporal positioning (Allen and Starr, 1982; Klijn, 1995). The need and importance of ordering a landscape into various levels of observation and processes has been recognised by many researchers. Examples include (Koestler, 1967 and 1978; Allen and Starr, 1982; O'Neill *et al.*, 1986; Haigh 1987; Zinck and Valenzuela, 1990; Smaling *et al.,* 1993; Andriesse *et al.*, 1994; Bergkamp, 1995; Fresco, 1995; Stoorvogel and Smaling, 1998; Wielemaker *et al.,* 2001; Veldkamp and Lambin, 2001; Veldkamp et al., 2001a and 2001b; Kok and Veldkamp, 2001; Kok *et al.,* 2001, Schoorl and Veldkamp, 2001). Concepts for constructing hierarchically ordered landscape system structures for water erosion assessment and modelling is therefore presented in this chapter. The operationalization of the concepts is presented in the subsequent chapters.

2.1.2 The confusion with scale

Most of the time people refer to spatial scales, multiple scale levels, or spatial resolution when referring to multiple level organisation in space (e.g. Stoorvogel and Smaling 1998; Turkelboom and Trébuil, 1998; Kok and Veldkamp, 2001; Veldkamp *et al.,* 2001). In many references to scale, there appears to be a confusion between multiple level organisation in space and time and the linear horizontal extent of spatial objects (see Goodchild, 1997). Spatial resolution for example links the visualisation of an object to a sensor (Droesen, 1999; Sanders, 1999). It is therefore a relative term depending on the observation sensor and spatial extent of the object. Scale means a different thing in different subject disciplines, for example, in economics, economy of scales refers to numeric multiple effects of economic products. In cartographic terms scale refers to a ratio of ground to paper distance (Richardson, 1993; Goodchild, 1997), it also has different meaning in process sizes and in temporal terms (see Schoorl, 2002). In landscape studies, it simply means a metric measurement in the Euclidian space, having implications in sizes but little on multiple levels of organisation of a landscape system. For different levels of organisation the correct concept would be *'hierarchical levels'*. Hierarchy in the landscape is more appealing because it involves identifying appropriate landscape elements occurring at different levels of organisation in the landscape system. Hierarchical levels are also constructed from a systems perspective making them powerful tools for landscape ordering, assessment, modelling, organisation, and management.

Ordering a landscape system in a hierarchical manner as opposed to generalisation has explicit beneficial effects, which include:

- Recognisable elements in the space-time continuum can be identified and used for observing landscape processes at different levels;
- Processes at the same level are comparable making it possible to extrapolate results of observations made in one area to another within the same level;
- The human dimension also exhibits a hierarchical organisation such that for different levels, different elements of the societal hierarchy can be identified for management action;
- Policies can also be drawn in such a way that they address the different hierarchical constructs of the landscape system;
- Resources and energy requirements can also be identified and linked to each level of hierarchy such that every responsible actor in an integrated management knows exactly what input is required of him/her; and
- Comparison between areas is made possible and enhanced.

2.1.3 The development of dynamic and hierarchical systems thinking

The development of the theory of open, dynamic systems began with works of Betarlanffy (1950, 1968) and Prigogine (1945). They postulated that open dynamic systems generate internal structure through the fluxes of energy, matter, water and the dissipation of entropy. Inspired by these early works, Weiss (1971) and Strahler (1952) developed dynamic systems thinking in biology and geomorphology respectively.

In hierarchy theory a dynamic system is perceived as an open, dissipative system that through the process of self-organisation can generate a hierarchically organised complexity (Koestler 1967; Betarlanffy, 1968; Weiss, 1971; Allen and Starr, 1982; O'Neill *et al.,* 1986). Generally two types of hierarchies are distinguished: functional hierarchies, which are process oriented (Levandowsky and White, 1977; Allen and Starr, 1982; O'Neill *et al.,* 1986) and structural hierarchies, which are entity oriented (Salthe, 1985). Entities provide boundaries for the internal processes. Structural hierarchies are not necessarily time or space dependent. Rather they are used for separating objects from their context (Allen and Hoekstra, 1990). Patterns and processes cannot be understood by looking only at the functional organisation. An integration of structure and function is necessary (Bergkamp, 1995).

In this thesis, the use of functional systems hierarchies (FSH) is proposed. What is important is how the properties of these elemental 'wholes' are organised to influence the occurrence of soil erosion. The subsequent sections of this chapter present the theories that enable landscape ordering at different hierarchical levels such that assessment and risk prediction at similar levels can be carried out. The subjects of hierarchy theory, landscape modelling, spatial modelling, spatial data capture, erosion modelling, and statistical modelling are elaborated. A generic procedure for ordering a landscape system into a hierarchical structure is presented in Figure 2.1.

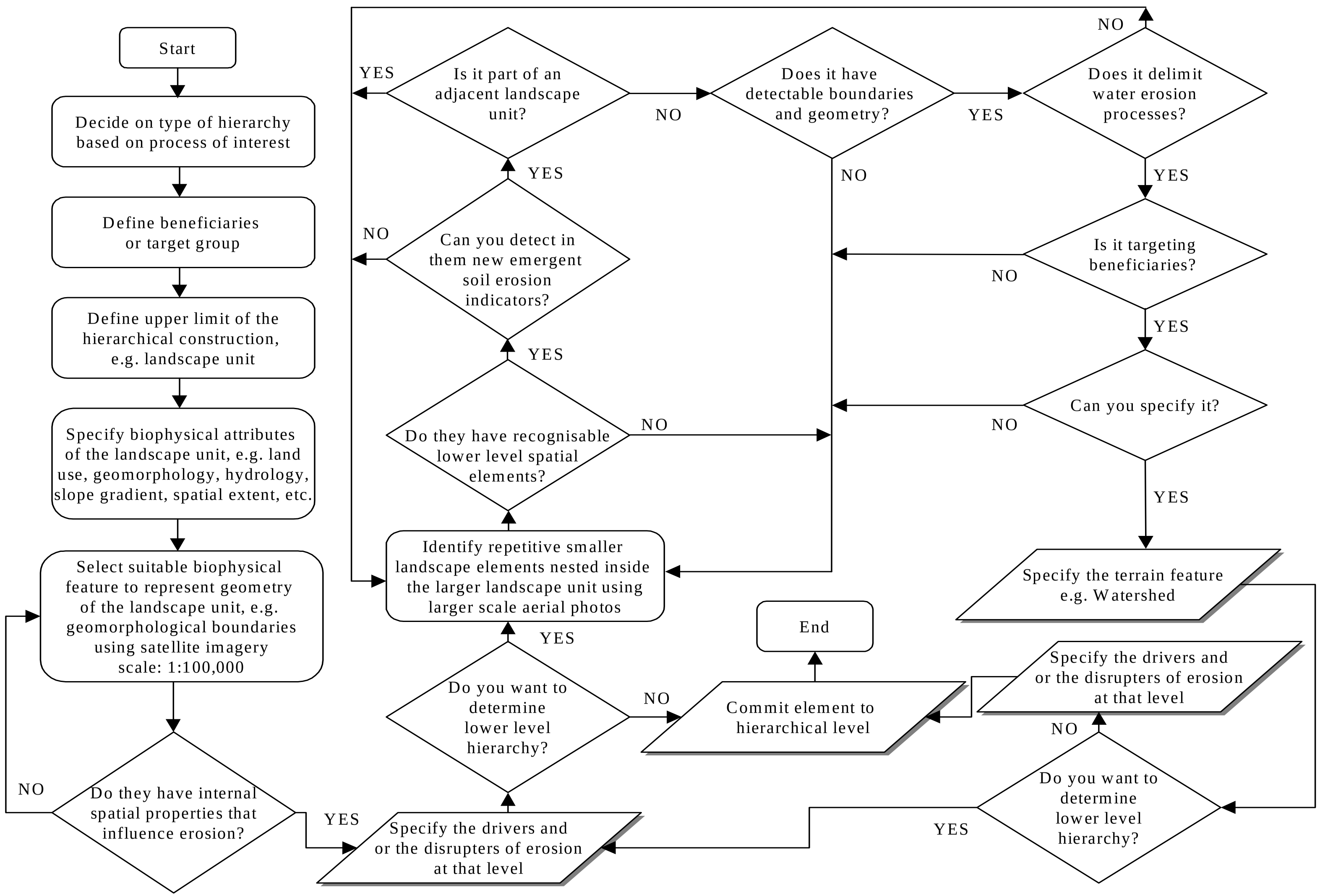

Figure 2.1 A flow chart showing a generic method for the construction of hierarchical levels for erosion risk assessment and modelling

2.2 Hierarchies, concepts and principles

Klijn (1995) describes hierarchy as a notion of how people, living and non-living things or abstract phenomena are organised, based on their position relative to each other. The notion includes the idea of inequality or asymmetry in relationships in the sense that one unit is more or less surbodinate to another. The Collins Cobuild English Dictionary puts forth the notion that a hierarchy of ideas and beliefs involves organising them into a system or structure. The hierarchy of an organisation such as that of the Catholic Church according to Klijn is connotative of a command structure as that of the Pope > Cardinal > Bishop > Priest > Chaplain. A further description is provided by Allen and Starr (1982), who define hierarchy as a system of behavioural interconnections wherein the higher levels constrain and control the lower levels to various degrees depending on the time constraints of their individual behaviours. Sometimes, the lower levels of the hierarchy are nested inside and in aggregate make up the higher levels and sometimes this is not the case. In the nested and non-nested cases, complexity comes from the nonlinearity and asymmetry of an entity affecting while also being affected by its environment (see Figure 1.2). The environment is the higher level, and it responds more slowly than the entities it constrains.

The use of hierarchical organisation has been recognised by many authors in landscape ecology. Examples are: (Allen and Starr, 1982; Haber, 1994; Zonneveld, 1994; Berkamp, 1995; Klijn, 1994 and Klijn, 1995). Just like all landscape phenomena, soil erosion and its manifestation exhibits hierarchical relationships for which it can be depicted, structured and described (this thesis). Since one of the objectives is to hierarchically and spatially model the landscape system for erosion risk prediction, it is incumbent therefore to present first, the hierarchical theories and principles and then relate these to spatial landscape attributes which make it possible to assess and analyse soil water erosion hierarchically.

2.2.1 Principles of hierarchy theory

Klijn (1995) has presented six principles, which are considered important in perceiving, describing and constructing hierarchical systems. First is the description of a system. A system according to Klijn is described as 'any structured set of objects and/or attributes together with the relationships between them'. Systems with their relationships and the characteristics of flows in them and other functions can be analysed and visualised by the use of mathematics to describe their functions. Systems can also be regarded as units with more or less clear boundaries. Boundaries are distinguished with respect to other systems or the environment that envelops and influences them. All systems and their behaviour and relationships can be analysed and understood by their roles in the flows, storage and transformation of matter, energy or information. Systems can be considered to be composed of subsystems that envelop smaller subsystems and so on. These concepts describe a situation of structural existence among parts, which points to hierarchical organisation.

Important in the systems theory is the manner by which hierarchies are derived from the systems components and the basic principle, which underlie this extraction. Hierarchies are based on common rules, which influence their behaviour and structure. As the system view is only a representation of the world, the observer is allowed to define holons and the hierarchical levels of organisation according to the aim of the investigation (Allen and Starr, 1982). Following is a presentation of the principles of hierarchy theory according to several authors and as applied in this thesis.

The principle of asymmetry

The first principle of hierarchies is that they are based on inequality or asymmetry in relationships. Levels in a hierarchy are often visualised as discrete layers. The levels in a hierarchy communicate with each other. Units or members of a level show asymmetric relationships with the next higher and lower levels. Asymmetric relationships do not occur within one level. Units of one level are related, but their relationships are equal. This poses the question of which criteria should be used for ordering and ranking phenomena. What exactly are the asymmetries upon which hierarchic levels should be based? Size could form one criterion of asymmetric relationships as will be shown later. Before any hierarchical ranking or ordering, clear goals must be set according to the intended objectives.

The principle of emergent properties

The principle of emergent properties is based upon the notion that, once levels have been tentatively distinguished, higher levels show distinct properties not found in lower levels. This is referred to as emergent properties (Miller, 1975), quoted by Klijn (1995). Emergent properties can also be understood and explained partly on the basis of the knowledge of the constituent parts of the lower level, but not completely (Allen and Starr, 1982). Some of the emergent properties can indeed be derived from lower level properties while some can be explained by looking more critically at the constituent parts and their configurations. On critical examination a new level will produce properties, which were hitherto not present in the lower level (Klijn 1995; Allen and Starr, 1982). Another part of the explanation of emergent properties is on the issue of scale (Klijn, 1995). On a higher spatial resolution, changes are observed in the relative importance of the laws of nature. Consider for instance the behaviour of water droplets at the molecular level where viscosity is an important physical property of bonding the water droplet together. The property of water masses at the ocean current levels is mostly based on coriolis (i.e., tidal flows as effected by the sun’s and moon’s gravitational pull). The cohesion forces of a water droplet by viscosity at the molecular level are different from Coriolis effect at the ocean level. Coriolis is not visible or imagined at the molecular level and can thus be described as an emergent property at the higher oceanic level.

The principle of constraint

The principle states that higher level hierarchies constrain the behaviours of lower level hierarchies. Higher levels give context and boundaries to the lower level hierarchies. e.g., the social control mechanism of a community regulates the behaviour of an individual within the community. Thus higher levels limit the degrees of freedom of the lower levels. This feature is often regarded as the essence of hierarchies (Allen and Starr, 1982; O’ Neill *et al.*, 1986). A logical consequence is that any change in higher level characteristics causes a change for the lower level, which influences the behaviour of its units, and so on descending the hierarchical ladder.

The principle of reaction time

According to Klijn (1995), the fourth principle connected to the described three is that higher levels tend to react more slowly than lower levels. An example of the principle is depicted in the process rates of the different levels. The higher level object being bigger in size takes a longer time for the same process within it to be completed compared to a smaller lower level object. Generally, there is an increase in reaction time going upwards through the levels. An example can be made of flowing water through agricultural fields down a slope. While the flow through one field will take a short time, the flow through all aggregated fields will involve making turns, finding new routes, etc. which will definitely take a longer time.

The principle of containment

The principle states that a higher level hierarchical object is contained of smaller nested units, which are also numerous in numbers. In nested systems, the smaller units of lower levels belong 'physically' to the higher level units. According to Koestler (1967), the number of units within a level are known as a *'span'* and the number of levels within a hierarchical system is known as the *'depth'* of the system.

The principle of indicators

The sixth principle of hierarchies is that of indicators. Higher levels and their performance within a hierarchy can often be characterised by fewer and simpler indicators. There is evidently no need to combine all knowledge on underlying levels in order to reach an adequate picture of the behaviour of a certain level.

2.2.2 Linking the principles with soil erosion

In conclusion, soil erosion development in the landscape system follows the same principles of hierarchy theory like many other landscape processes. First, it is necessary to observe the links between soil erosion processes and their manifestation in the landscape hierarchy to demonstrate this. Raindrop erosion for example manifests itself in small radial areas covered by jet streams of the falling raindrops. The jets cause the splashing around of soil particles (Eppink and Stroosnijder, 1994). This type of erosion process is very localised and can only be linked to the smallest landscape elements in a hierarchical construction. Overland flow which transport the detached soil particles, and flow associated with interill erosion cover slightly bigger areas and are easily disrupted by barriers on channel pathways, such as field-plot boundaries, hedges or micro-depressions. Raindrop erosion and interill erosion are erosion processes limited in size and are more linked to homogeneous lower-level landscape elements such as field plots. Extensive manifestation of erosion is normally enhanced by the presence of elongate water channels in the landscape (Lal, 1990). Such linear elements sometime extend beyond small segments of the land such as field-plots. Footpaths, field boundaries, irrigation furrows, animal tracks, drainage ditches all extending beyond small landscape areas are dominant motors in the erosion process in larger landscape features. In all of these, erosion processes are influenced by the presence of flow conduits, accelerated by slope and the absence of adequate flow barriers. Such flows are linked more to larger landscape features such as the watershed. Another example is the erosion processes conditioned by torrential flowing water currents. Water currents like those occurring in rivers, roadside streams, roof or quarry streams are linked to more rapid flow than overland flow as an example. The more energetic flows produce larger and elongate erosion features such as gullies, riverbank slumps, and landslides. They carry higher amounts of soil and are very destructive forms of erosion. Such processes extend beyond small landscape features. They are processes associated with bigger landscape regions. The processes have landscape elements with which they can be associated. The smaller less expansive process sizes belonging to smaller landscape features while larger processes belong to more expansive spatial features. This view of the landscape system enables one to discern and allocate specific processes to some specific features of the landscape based on spatial extent.

The postulate in this thesis is that the field plot, the watershed and the landscape unit all condition the manifestation of different resolutions of soil erosion processes. For each level, different erosion processes dominate and new drivers of erosion can be identified. Interill erosion and rill erosion for example can be the more dominant forms of erosion processes within field plots. Rills and gullies can be more dominant in watersheds while gullies, landslides and mass movements can be linked more to the landscape unit. This aspect apart from creating asymmetry within the levels of the hierarchy relates to the principle of new and emergent properties for each level of a functional hierarchical system. Since the processes can be associated with drivers of erosion and are located inside and are part of the specific landscape feature, (i.e. field-plot, watershed or landscape unit), and due to the nesting of the three landscape features within each other, the principle of containment is met. The principle of indicators for each level is met by the fact that different erosion drivers can be identified and linked to different holons occurring in different levels of the hierarchy. This means that for each level, different indicators of erosion are identified and used for assessing soil erosion. The biophysical properties and catalytic effects of these erosion drivers in the hierarchy determine the kind of erosion process that occurs. Apart from individual driving properties, background properties of the higher levels also play a part in the type of erosion that occurs in the lower level entity. This means that watersheds or field plots falling in a particular landscape unit will generally suffer soil erosion associated with the biophysical properties of the landscape unit such as the relief, inclination and geology. Similarly, field-plots occurring in one watershed will experience soil erosion according to the biophysical properties of the particular watershed. The biophysical properties of the individual *holons*, i.e. landscape unit, watershed, or field plot create the constraining background environments of soil erosion that occurs in the lower level features.

Additional properties that distinguish members of a hierarchy are attributes associated with the possession of a boundary. Each landscape unit, watershed or field plot has distinguishable boundaries and the soil erosion processes are construed to occur within the confines of the boundaries. This containment of erosion features inside any of these landscape elements ensures that the occurring soil erosion features can be linked to the specific landscape feature in which they occur. This property makes it possible to associate and assess soil erosion for any of the landscape elements of the hierarchy. Due to differences in the spatial sizes of the each of the features in the vertical hierarchical construction, erosion processes inside smaller features takes shorter time span to develop than erosion processes in larger landscape features. Hence temporal resolution of processes for different levels in the hierarchy conforms to the principle of reaction time in hierarchy theory.

This link between processes, landscape features, levels in a hierarchy make it possible to order the landscape system into a structured construction of processes and features.

2.2.3 Role of object boundaries and the emergence of the 'holon' within hierarchies

Koestler (1967) introduced a 'holon' as being equivalent to an entity in a hierarchical system. Allen and Starr (1982) further expounded on the concept of the holon. The holon according to them has a duality of nature in that it looks inward at its parts and outward at an integration of its environment. It plays two roles, first it plays the role of a complete and separate individual while also being part of a broader system composed of several members. At every level in a hierarchy there are these entities and they have this dual structure. Their description of the holon is important as it introduces boundary conditions to the systems concepts of a hierarchy, a fact that is used in the construction of functional hierarchical systems in this thesis. According to Haigh (1987), a holon is any stable sub-whole in a hierarchy. It is a self-creating, open system governed by a set of laws that regulate its coherence, stability, structure and functioning. It also possesses the potential of adaptation to the challenge of environmental change. There are two aspects to the operations of a holon. First, there are its relationships with the higher order wholes(s) into which it is integrated and by which its activities are constrained. Second, there is the fact that it is a whole in its own right, which integrates the operations of the lower level subwholes. According to Allen and Starr (1982), every holon has a dual tendency to preserve and assert its individuality as a quasi-autonomous whole; and to function as an integrated part of (an existing or evolving) larger whole. This polarity between the self-assertive and integrative tendencies is inherent in the concept of hierarchic order; and universal characteristic in life. The self-assertive tendencies are the dynamic expression of holon wholeness, and the integrative tendencies of its wholeness. Holons are considered to be subsystems, which consume and retain external energy for self-organisation and internal structure. Any internal disorder in stability is overcome by the release of entropy (disorder) and retention of introduced external energy. In contrast evolution changes releases energy to acquire states of equilibrium.

The essence of boundaries is that they act as the delimiters of soil erosion processes. They are like combustion engine chambers where heat energy is converted to steam energy and subsequently to mechanical energy. While the energy states change, the combustion chamber remains unchanged providing wholeness in itself as an environment for modelling the energy changes. In soil water erosion modelling and in this thesis, the *'landscape holon'* is considered to be the unit of assessment of erosion processes. The soil erosion processes occur within the holon and produce what is seen as the resultant soil erosion feature in the landscape. Visible and invisible processes take place inside the chamber, raindrop splashing of soil particles, soil scouring by flowing water, chemical dissolution and physical displacements are some of the processes, which continue to go on as rainfall comes into contact with the soil surface. The result is rills, gullies or interill erosion. It is further postulated that the manifestation of soil erosion is exacerbated by the internal structure and spatial parts of the holon.

One broad aim of this thesis is to create a basis for structured soil erosion management. The hierarchical system must therefore integrate human activities to meet this objective. Notions from Schoorl (2002), concerning the dimensions of a landscape become handy. According to him, a landscape has three dimensions in space and one in time, meaning that it is four-dimensional. He also introduces the fifth dimension, which is the human dimension in the landscape system construction. The human dimension he argues introduces the element of management to the landscape. The human dimension apart from triggering landscape level processes also helps in managing landscape processes. This aspect of the human activity makes it mandatory to include the human dimension in landscape studies and its management. With regard to this, a number of different efforts have been made to address issues of complexity in general systems thinking vís a vís sustainability in socio-ecological systems (Murray, *et al.* 1999). They include Complex Systems Theory (Schneider and Kay, 1994); Ecosystem Based Management (Allen and Hoekstra, 1992); Social and Collaborative Learning (Roling and Wagenmakers, 1998); Soft Systems Methodology (Checkland, 1981) and Sustainable Livelihoods Approach (Chambers and Conway, 1992; Singh and Wanmali, 1998). They all acknowledge that it requires the development of a mode of enquiry that uses a diversity of different strategies together in a common understanding and action in ecosystems management. In this work and emanating from the systems' concept in landscape holons, and the need for sustainable management of the holon, it is seen as important to integrate biophysical features of the landscape holon with the social, economic, policy, interventions and institutions of the society. Since holons possess spatial extents and boundaries, all technical and social action inside them constitute a synergistic symbiosis where properties combine with social action to attain management objectives and sustainability. The synergistic functional systems concept of the holon as is conceptualised is shown in Figure 2.2. Space, processes, and biophysical properties are inherent properties of the holon which are sometimes altered by human actions but mostly created by natural phenomena. Time as presented takes a bivalent role where in one instance it determines the process magnitude and in another it determines the period required for completing a specific intervention task within the holon. Energy also behaves like time where in one instance it is consumed by the holon for internal self organisation and in another instance determines the amount of effort required for social intervention action inside the holon. Resources as postulated include human capital, financial capital, technology and material capital that are required to effectively manage any activity within the holon. Similarly, interventions are related to social or biophysical knowledge that is relevant for managing the holon sustainably. Policies are linked to both social and political decisions that are necessary to achieve objectives of sustainable and satisfactory management of the holon. When all these attributes are simultaneously integrated and addressed, then sustainable management of the holon is made possible. This thesis only addresses issues concerned with the biophysical attributes namely, the hierarchical structuring of the landscape holons, the erosion processes inside them and the spatial parts of the holons associated with soil erosion. The resources, interventions, energy requirements and relevant policies can be dealt with as localised and separate issues, which differ and change from place to place. The biophysical features can be used in soil erosion assessment and for risk modelling in many landscapes.

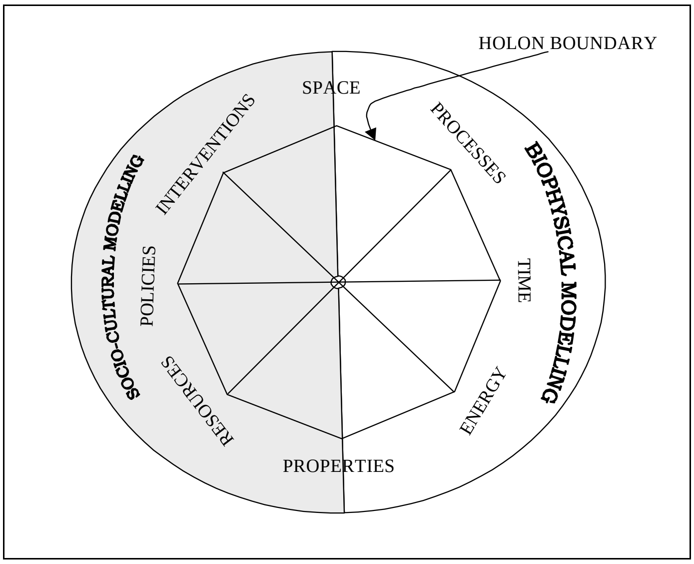

Figure 2.2 The *'functional system concept'* of the holon and its application in biophysical, spatial and socio-cultural modelling as perceived in this thesis.

In conclusion, the landscape can be ordered structurally in a hierarchy with lower level landscape objects, being contained (nested) within higher level objects. The higher level objects being bigger in size and slower in process reaction time. The higher level features provide the enforcing environment for the lower level features as will be shown in chapter 3.

2.3 Concepts of spatial modelling in a GIS

Spatial modelling starts from analysing and modelling the view of the landscape in any desired dimension for eventual representation and analysis in a GIS. Spatial data are always an approximation or generalisation of reality (e.g., abstractions from photo interpretation, digitisation, transformations, etc.). They are thus full of uncertainty and inaccuracy due to abstraction and transfer errors (Goodchild, 1992a). Spatial modelling also depends on whether the final output will be presented as cartographic analogue representations or whether analytical manipulations of the landscape attributes will be undertaken for various outputs as is the case with GIS manipulations. For a landscape researcher, the latter offers better possibilities for modelling landscape phenomena and presenting the results of the models. Cartographic representation of geographical data basically is concerned with describing the earth's surface in a two-dimensional model rather than analysing it (Openshaw, 1989). The storage, analysis, and display of geographic data in a GIS therefore offer more opportunities than just the 2-D presentation in a cartographic map. A GIS is herein connotative of the description presented by Goodchild (1992b) and quoted by Bregt and Bulens (1998) as:

> *"a database containing a discrete representation of geographical reality in the form of static, two-dimensional geometric objects and associated attributes, with a functionality largely limited to primitive geometrical operations to create new objects or to compute relationships between objects, and to simple query and summary descriptions"*

Using GIS for simple mathematical computations on the stored feature attributes and displaying the results spatially constitute part of spatial *modelling*. As part of the spatial modelling operation, after the real-world geographic objects have been delineated and extracted, they are digitised into a GIS database and allocated attribute values which represents the observed value of the captured object. This forms the basic manipulative process. Finally for analysis or prediction, mathematical computations using equations derived from statistical analyses or other sources are applied to the GIS data to obtain both spatial and thematic outputs. The attribute values of the object could be qualitative or quantitative.

Another way of using GISs in spatial modelling is performing part of the modelling operation outside the GIS environment and then integrating the results of the model into the GIS. For example, according to Bregt and Bulens (1998), many scientists have developed process models to demonstrate pesticide leaching, erosion, hydrological features, acid deposition, crop production, nutrient balances and all kinds of simulation processes. Many of the current models lack proper tools for proper data input and management, and have poor presentation facilities. GIS is strong in these areas.

GIS operations described above include obtaining data from a GIS database by simple data retrieval techniques such as finding the locations of all soil mapping units with pH values higher than 7, or delineating an area where elevation is above 1700 metres above the mean sea level. The use of structured query language (SQL) extends simple data retrieval to more complex queries such as determining the areas which are most likely to suffer erosion risk given particular geographic attributes stored in the database. Computation of regression equations on the GIS data are performed outside the GIS using '*Export and Import*' routines of the individual software before finally being integrated in the GIS database for analysis and display.

2.3.1 Modelling approaches

The following sections describe modelling approaches that ensure successful spatial modelling of the landscape in a GIS (Jansen, 1994; De Hoop, 1993; Droesen, 1999). These modelling approaches were applied at different stages in this thesis.

Conceptual modelling

Conceptual modelling takes place outside the GIS system. It is the human perception and simplification of the real world. According to De Hoop (1993), the conceptual model describes entities and the relationships among them, which are considered relevant for the intended application. The conceptual model is system-independent, meaning that it can be formulated without reference to implementation in a database management system or GIS. It constitutes the overarching spatial modelling activity. Photo interpretation or digital image analysis constitutes this phase of modelling (Forman, 1995). Peuquet (1984) refers to the conceptual model as an abstraction of the real world, which incorporates only those properties, thought to be relevant to the application or applications at hand, usually a human conceptualisation of reality. Conceptual modelling is followed by the logical and physical modelling phases (De Hoop, 1993). The logical data model describes the implementation of the conceptual data model in a database. The logical data model, therefore, depends on the type of data model, which is chosen for representing the geographical phenomenon or reality. Data models are discussed in a later section of this chapter. Finally, the physical data model designates the actual implementation of the logical data model in the computer and the physical storage of the data, which is system dependent. It mostly depends on the data structure system of the software. Hierarchical ordering of the landscape components into a hierarchical system is part of the conceptual modelling as applied in this thesis.

Descriptive modelling

Descriptive modelling according to Droesen (1999), aims at deriving a proper representation of landscape features in the space-time continuum. Data acquisition and inventory are the two most important aspects. Sometimes, this phase could also involve simple analyses and the characterisation of pattern and shape including trend estimation. This type of modelling involves the categorisation and labelling of the landscape components into discritized objects, which can be abstracted, and characterised for eventual integration into a GIS. It is a GIS system independent phase and mostly carried out in the field and/or the desk during photo interpretation.

Explanatory modelling

Explanatory modelling goes beyond the level of description and intends to discover the relationships between variables in order to explain their behaviour (Droesen, 1999). Statistical techniques are used in this modelling phase. Apart from statistical analytical procedures, many possibilities exist for the analysis of relationships in the space-time continuum, e.g. inductive modelling, (Burrough, 1986; Suryana, 1997) geostatistical interpolation, (Groenigen, 1997) and fuzzy clustering (De Bruin and Stein, 1998). Explanatory modelling can involve the inference of environmental conditions from the presence of certain indicator species or the explanation of one environmental variable from a series of known dependent or explanatory variables.

Predictive modelling

Predictive modelling involves the forecasting of the future aspects of the landscape. This phase of modelling can only take place after a good explanatory model has been developed for the landscape features and their integral components. Mechanisms determining landscape development are discerned and modelled. Variables associated with the occurrence of certain environmental conditions (indicator variables) are identified and used to infer the presence or future presence of a certain environmental condition which might not necessarily be measured at the time of making the conclusion or prediction. It means basically that the presence of proxies can be used to predict the occurrence of a particular condition without necessarily observing it. This means that data acquisition for predictive purposes is made independent of the landscape unit for which the prediction is to be made. The occurrence of soil erosion could be inferred from the presence of certain properties of the landscape after it has been concluded that soil erosion is closely associated with the occurrence of those landscape properties. As an example, footpaths in a tea plantation form water conduits, which stimulate erosion. A footpath is therefore a good indicator of potential erosion in the tea plantation. After establishing the association of soil erosion with footpaths, the prediction of erosion can be based on the presence or absence of footpaths in a specific locality.

2.3.2 The land mosaic

GIS Object construction involves the discretization of landscape entities from the spatio-temporal continuum. As discussed in section (2.3.2), spatial landscape features can be modelled either as objects or as fields in a GIS. In order to be able to decide on which model is best suited for a particular function it is necessary to configure the kind of spatial element(s) one is dealing with and how they are arranged in the space-time continuum. In Landscape-ecological studies, the recognised spatial elements included in the land mosaic are the patch-corridor-matrix model (Forman and Godron, 1986; Forman, 1995). This simple model provides a handle for analysis and comparison, plus the potential for detecting general patterns and principles in a landscape. When integrated with hierarchy and set theories, functional landscape hierarchies can be constructed and used for monitoring and controlling hazards associated with the use of the land or other natural hazards. The land mosaic components are thus described.

Forman and Godron (1986) define a ‘*patch’* as a non-linear surface area differing in appearance from its surroundings. Patches vary widely in size, shape, type, heterogeneity and boundary characteristics. In addition, patches are always embedded in a matrix, a surrounding area that has different structure or composition. A forested area surrounded by an agricultural area in a Landsat image corresponds to the definition of a patch. Since the forested area has a uniform texture and appearance which differs from its surroundings it is considered to be a patch inside an agricultural area. ‘*Corridors’* on the other hand are defined as narrow strips of land, which differ from the matrix on either side. Corridors may be isolated strips, but could also be attached to a patch. Forest galleries along riverbanks are examples of wooded riverside corridors in a Landsat satellite image. Nearly all landscapes are both divided and at the same time tied together by corridors. These dual properties characterise the major roles of corridors in a landscape. Corridors in real life include among others: railroads, highways, canals, hiking trails, power-lines, gas pipelines, windbreaks, stonewalls, vegetation strips, hedgerows, barriers, streams, fences, footpaths, etc. The same authors (Forman and Godron, 1986) define a ‘*matrix’* as the most extensive and most connected landscape element type and plays the dominant role in the functioning of the landscape. To distinguish the matrix from the patches or the corridors, the matrix is viewed as the relatively extensive, connected, and homogeneous landscape area that encloses scattered distinct patches and segmented by a network or isolated strips of corridors. The three when viewed from a point of vintage above the landscape shows the ‘*land mosaic’*.

Since a mosaic at any scale may be composed of patches, corridors, and matrix, they are the basic spatial elements of any pattern on land. The three described elements don’t of course inhibit the recognition of other landscape elements. According to Forman (1995), nodes are patches attached to a corridor, boundaries separate spatial elements and vary widely in structure.

In spatial modelling and in selecting data models for representing the spatial landscape elements, *patches* and *corridors* are best represented as *objects*. In this thesis, for each level of landscape hierarchy, appropriate patches and corridors are identified to represent the landscape feature objects.

Apart from the data models required for GIS object construction, another subject related with object construction, is the aspect of '*object discretization'*. In this thesis, object discretization is used to define the manner by which an object is conceived and built either from its elementary constituents through aggregation or through individual object recognition, segregation and isolation by applying '*cognitive knowledge*' about its properties. Cognitive knowledge is understood to refer to knowledge about a feature stored in the human memory and encoded as images. Lloyd (1989) has extensively discussed spatial knowledge and cognitive memory maps. In order to study or analyse the *'land mosaic'*, a method has to be applied that extracts the landscape elements from the complexity of processes, phenomena, scale, and hierarchy.

2.3.3 Hierarchies on land

In literature, (e.g., Huising, 1993; Jansen, 1994; Suryana, 1997; Droesen, 1999), hierarchical construction of spatial objects is achieved by, *classification, aggregation or association*. Classification links hierarchical objects by the 'is_a' link while aggregation links hierarchical objects by the 'part_of' link. *Association* links objects in a hierarchy through generally observed or developed rules which indicate the relationship between or among the objects. *Classification* is a thematic grouping while *aggregation* involves grouping both the thematic and geometric attributes of an object. Giving some reference with other objects or themes could attain association. So it could involve either thematic or geometric attributes or both. An example is the association of *airports* with aeroplane *runways*. This implies that any place with an aeroplane runway is an airport. Observing a runway will automatically link the area to an airport. This might not always be true but the likelihood is higher that the area will be an airport than it will not. A tree being part of a forest is an *aggregation hierarchy* while a maize crop classified as a cereal crop is an example of a *classification hierarchy*.

Classification hierarchies

Classification hierarchies are mostly thematic in their nature. They are naming systems branched in a hierarchic pattern. Classification hierarchy according to De Bruin (2000) can be represented as an inverted tree showing relations between nested thematic partitions. Sectioning a classification hierarchy at any level will produce a partition of the elements into disjoint groups. Each class of a lower level partition is wholly contained within a single class of a higher level partition. In a downward direction, class categories become more specific, so that the elemental descriptions are specialised. In the opposite case the descriptions of the elements become more generalised.

Aggregation hierarchies

Aggregation hierarchies deal more with higher-level hierarchy object construction from elementary objects. Sometimes aggregation hierarchies correspond to classification hierarchies, but the two are quite different. Aggregating a '*cereal crop area'* from 'rice fields' and '*wheat fields'* is an example of a rhyming match of classification and aggregation hierarchies. Rice is a cereal crop and wheat is also a cereal crop. This is classification nomenclature. Rice fields or wheat fields on the other hand are objects, which can collectively be aggregated to *'form cereal* *crops'* in classification hierarchy and a *'cereal crops area'* in an aggregation hierarchy. In aggregation hierarchies the objects are linked upwards by *part of* links. For example, a road can be part of a residential, industrial or commercial area. According to De Bruin (2000) in order to determine the type of area of which an object forms a part, it is necessary to evaluate adjacency relationships to establish the neighbourhood relations with other objects before merging them.

Spatial objects that are considered elementary at one scale may be regarded as composite objects at larger scales, whereas they may hold too much detail for representation and analysis at smaller scales. When elementary objects are aggregated, so will part of their attribute values. At the same time some data may be discarded, as they hold no significance for the composite objects. Usually, the geometric description of lower level objects is lost as a result of merging. Consequently, a terrain description at a higher aggregation level contains less detail than a description of elementary objects. In the opposite direction, disaggregation of composite objects requires that additional information be included in the terrain description (De Bruin *et al.*, 1999). For example when a composite object such as a town is decomposed into elementary objects such as roads, commercial areas, residential areas, recreational areas, etc, each of these elementary object parts must be specified both geometrically and their thematic classes added. In this way, more information will be included in their description and new topology created which links and relates the new composite parts.

Functional System Hierarchies

In this thesis, the construction of spatial objects is based on hierarchy theory as presented in section 2.2 and landscape ecological theories as presented by Forman and Godron (1986). The landscape hierarchy is constructed using the set theory of containment, internal properties, emergent properties, asymmetry, higher level objects constraining lower lever objects and the purpose for the construction of the hierarchies. Objects are defined according to their influence on soil erosion. What is important is how the properties of these elemental *'wholes'* are organised and influence the occurrence of soil erosion. Both the requirement of having discernible boundaries and the influence their internal properties have on water erosion are important. According to hierarchy theory, lower level objects must be part of and contained inside the higher level objects. This principle of hierarchy theory must be obeyed. Neighbourhood and adjacency properties are important to ensure that objects in a lower hierarchical level only belong to one object of the higher level hierarchy. The internal properties could be the factors of soil erosion as those of the USLE (Wischmeier and Smith, 1978), or new spatial attributes not normally not included in the USLE are identified for their individual roles in soil erosion. A hierarchical level would thus be recognised as a construction where the internal properties are encapsulated inside discernible landscape elements organised at the same level to create structure.

2.3.4 Extraction of landscape objects for use in a GIS

Data models

The landscape systems operate in a four-dimensional spatio-temporal continuum according to Bregt and Bulens (1998). Three dimensions in space and one in time. In order to analyse the landscape system, it is important to distinguish between processes and patterns. Whereas it is possible to recognise physical patterns the human eye or mind might not easily discern individual processes that create the patterns. Processes can thus be observed indirectly by observing the patterns they create. Process models can be developed separately and then coupled into a GIS for analysis and producing outputs using several management functions, process functions and interfaces (Bregt and Bulens 1998). Spatial modelling per say is therefore concerned with capturing spatial landscape phenomena and related properties, for representation and manipulation in a GIS. Process models on the other hand can be performed outside a GIS system and the results integrated into the GIS through a loose coupling interface or integrated inside the GIS for processing if the GIS system is tightly coupled (Bregt and Bulens 1998). This thesis is mainly concerned with static data modelling and will therefore not treat process models as such.

Spatial modelling can therefore proceed in two major ways. The *'field approach'* (Droesen, 1999) and the *'discrete object'* approach (Goodchild, 1992b; Bregt and Bulens, 1998; Droesen, 1999). Both the field and the object approach enable the combined modelling of landscape patterns or phenomenon. According to De Bruin (2000), The discrete object model views the world as being composed of well-defined spatial entities. A key feature of this view is that each entity is assigned to only one set of clearly distinct categories or classes. Each object has an identity, occupies space and has properties. Objects are homogenous within their boundaries, at least with respect to some properties. Examples include buildings, runways, field-plots, footpaths, roads, railways, etc. According to Droesen, a field is a feature, which is contiguously distributed over space and time in a non-discrete manner. In a field, the strength of the interacting forces is a function of the position within the field and the resulting pattern, which can also be expressed in terms of the position dependent field values. According to De Bruin (2000), a field assumes that every point in space can be characterised in terms of a set of attribute values measured at geometric co-ordinates in a Euclidian space. Examples are elevation and slope in undulating landscapes, concentration of algal chlorophyll in surface water, green leaf area index in an agricultural field, etc.

According to De Bruin (2000), the two data models are too restrictive when it comes to modelling phenomena that are conceived as nameable objects but without the object classes having clear-cut boundaries. He concludes that the boundaries of such objects are best described by the fuzzy set theory. According to him fuzzy set theory allows geographic phenomena to be modelled as objects whose boundaries are not exactly definable. In fuzzy categorisation the degree of membership of the object boundary to the object class, is allocated according to a sliding membership value ranging from 0 to 1, where 1 denotes full membership to the object class and 0 denotes non-membership. The spatial extent of fuzzy objects can therefore be determined by evaluating class membership functions in combination with adjacency relationships. Spatial modelling of objects also depends on the source of the data to be modelled. Good resolution of source data allows easy detection of objects and their boundaries in satellite data or from aerial photographs. In a hierarchical modelling exercise, source data for different hierarchical level objects must have appropriate spatial ground resolution to enable discrete object detection. This means that relevant sensor data must be obtained for different levels of the hierarchical system. In this thesis a combination of aerial photography and remote sensing visual images were used to extract the objects at different hierarchical levels.

Resolution

Resolution as applied in spatial applications and in landscape ecology is a terminology, which is concerned with relating objects on the ground with sensors used in capturing and visualising them. These include the sensors in remote sensing satellites, aerial photography cameras or the human eye. The visualisation of an object captured by a sensor depends on the distance between the sensor and the object and the aperture of the sensor. Geometrical or *spatial resolution* is defined as the smallest area in the terrain that has been measured by a sensor (Sanders, 1999). Spatial resolution in digital remote sensing images divides the features in the terrain into two groups (Strahler, 1969; Droesen, 1999). Features greater than a ground resolution cell of a sensor will appear in one or more cells or pixels and might thus be individually detectable. These features are named *high spatial resolution* features (Droesen, 1999). Features that are smaller than the ground resolution cell, are not individually detectable, and are termed *low spatial resolution* features. In remote sensing, satellite sensors are constructed with pre-defined spatial ground resolutions. Other resolutions include the radiometric, spectral and temporal resolutions. *Radiometric resolution* is defined as the smallest observable difference in reflectance that can be measured by a sensor (Sanders, 1999; Buiten and Clevers, 1993). *Spectral resolution* on the other hand is a measure of the width of the "*wavelength band"* in relation to its location along the "*electromagnetic spectrum*". Temporal resolution refers to snap-shots of situations extracted from the real time-scale continuum. Examples include the extraction of situational occurrences for defined periodic duration such as a second, minute, hour, day, week, month, year or century depending on the desired application or analysis. Capturing or cognition of landscape images by remote sensing techniques or by other means is also dependent on the temporal resolutions of the sensors. These properties of the sensor and the object on the ground enable object detection and cognition for spatial modelling and pattern analysis.

2.3.5 Data structures

Kemp (1997) observes that there is quite a complex relationship between data models and data structures. The two main data structures in use are raster and vector. The object data models, point, line; area and volume can be represented in both the vector data structure and the raster data structure. The field models polygons, TINS and contours are implemented in the vector data structure and for grid points and irregular points both the raster and vector data structures are used. Cell grids are implemented in the raster data structure. The raster or vector data structure depends on the system developer and there are several categories of each. Peuquet (1984), Burrough (1992) and Raper *et al.* (1992) have given a synthesis of the differently available and used data structures for the handling of the geometric attributes of the data models.

Vector data structure

According to De Bruin (2000), the vector structure uses points, lines and polygons to describe geographic phenomena. The geometry of these elementary units is explicitly and precisely defined in the database. Points are geometrically represented by an (x, y) co-ordinate pair, lines consist of a series of points connected by edges, and polygons consist of one or more lines that together form a closed loop. The thematic attribute data of a vector unit reside in one or more related records. The vector structure according to De Bruin (2000) is very suited to representing discrete geographic objects. It also lends itself to represent continuous fields and fuzzy objects.

The raster data structure

The other method for spatial representation in a GIS database is the raster data structure. A raster is a collection of points or cells, which cover the terrain in a regular grid. There are point raster formats and cell raster formats currently in use. According to Droesen (1999), in a point raster, each raster element contains thematic data that refer to a point position. The points can be regular or irregular. When a third dimension is added, the cells become volumes and are named voxells. According to De Bruin (2000), the raster data structure comprises a grid of *n* rows and *m* columns. Each element of the grid holds an attribute value or a pointer to a record storing multiple attribute data of a geographic position. The raster structure has two possible interpretations. One is the point or lattice interpretation and the other is the cell interpretation. The former represents a surface using an array of mesh points at the intersections of regularly spaced grid lines. Each point contains an attribute value (e.g. elevation). Attribute values for locations between mesh points can be approximated by interpolation based on neighbouring point. The cell interpretation corresponds to a regular tessellation of the surface. Each cell represents a rectangular area using a constant attribute value.

2.3.6 Data quality and sources of errors in a GIS

The problem of spatial data quality cannot be overstated since no map stored in a GIS is completely error-free (Heuvelink, 1993). The word *'error'* includes *'mistakes'*, *faults,* and *'statistical variations'* as presented by Burrough (1986). Errors emanate from a series of operations and processes right from the time of the data acquisition by satellite sensors or flying aircrafts to the time the data is transformed to digital data in a GIS. Tilting of the aircraft during aerial photography or small tilts in the satellite all entail errors, which manifest themselves in the final product unless corrected. It must also be recognised that the data in a GIS have been collected in the field, have been classified, interpreted, estimated intuitively, and so contain a certain amount of error. Errors also derive from measurement errors in the field and from mistakes in data entry. When geocoding digitised GIS data with geographic co-ordinates obtained using a global positioning system (GPS) errors due to the accuracy of the GPS equipment and errors due to rotational movement of the earth with reference to the positioning of the orbiting navigation satellites are also introduced.

When spatial data are entered into a GIS, this is often done by means of digitising a paper map. Clearly errors are introduced during transfer of the source map to the digital database. More important is that the uncertainties contained in the map are duplicated in the GIS (Goodchild *et al.,* 1992). The conceptual method of developing the map also introduces errors. As an example, soil boundaries in soil maps are sometimes gradual though in map representation, they are represented as crisp boundaries. In reality, boundaries are often gradual and map units in reality are rarely homogeneous (Burrough 1986; Goodchild, 1993). Therefore, the restriction to a chloropleth map inevitably causes the map to differ from reality. Heuvelink (1993) has discussed extensively on error propagation in quantitative spatial modelling. This section of the thesis is included to draw the attention of the reader to some of these errors which might not be completely removed during GIS data acquisition, digitisation, analysis and modelling. During the creation of the GIS databases in this work, the errors have been minimised by trying to deal with them at each of the stages. Errors could also be introduced by conversion from one data structure to the other.

2.4 Capture of the spatial features from the space domain

2.4.1 Spatial extraction of objects from aerial photographs or satellite images

In order to capture real-world geographic features or phenomenon for integration and analysis in a GIS, the geographic features must first be captured in a form by which they can be manipulated or handled in a GIS. Aerial photographs or satellite images offer an opportunity for the capture, manipulation, handling, analysis and processing of GIS data (Janssen, 1994; Bregt and Bulens, 1998; Droesen, 1999; Sanders 1999). The spatial extraction of geographic objects from satellite images or aerial photographs is achieved by several methods. First, geographic objects maybe extracted from aerial photographs by visual analogue interpretation. Remotely captured properties of the objects are separated on the aerial photographs by differences in colour, darkness, brightness, pattern, texture, height, shape, context, size, tone, resolution, site, shadow, association, scale, etc. These form the basis for the delineation of the different geographic objects and hence their extractions from the complexity of the land mosaic.

Another method of object extraction is by the use of digital methods. Aerial photographs can be scanned and digital methods used for discretization and extraction of the geographic objects. Techniques such as segmentation (density slicing, edge detection, region growing), a-priori classification, clustering, fuzzy clustering, seed detection or interpolation methods can be used (Janssen, 1994; Droesen, 1999; Sanders, 1999). Similar techniques are employed in the extraction of objects from satellite data. Important properties of the digital data for object extraction include spatial resolution, spectral resolution, temporal resolution and geographic positioning of the sensors (i.e. cameras or satellite sensors) during object capture. The detection of geometric objects by remote sensors depends on the ground resolution of the sensor. It has already been stated that objects larger than the ground resolution of the sensor will easily be detected and objects smaller than the ground resolution will not be easily detected. The choice of the sensor therefore will depend on the type of information to be extracted. In general, the extraction of geometrical object characteristics from digital data requires a higher resolution than deriving the thematic characteristics for objects with a known geometry (Janssen, 1994; Droesen, 1999).

2.4.2 Visual versus digital data extraction

Before the extraction of geographical objects by any of the methods, one is faced with the task of deciding which method to apply whether visual interpretation or digital segmentation techniques. Both methods have their own advantages and disadvantages. One argued disadvantage of visual interpretation is that the procedure cannot be formalised and hence similarly repeated on different sets of visual data (Janssen 1994; Sanders, 1999). Visual interpretation in most cases is dependent on the experience of the photo interpreter, reference knowledge about the area by the interpreter and the quality of the photograph being interpreted in terms of texture, tone/colour, parallax, size, shape, etc. For that reason an experienced photo interpreter is able to use combinations of these characteristics to perform the job in mono or stereo view. This makes manual interpretation a very robust method that can deal with highly complex spectral patterns and performs well even if the image quality varies (Lillesand and Kiefer, 1994). Despite these advantages, according to Droesen (1999), visual construction of objects using manual interpretation suffers some disadvantages, some of which may be stated as:

- Delineated objects only represent discrete terrain features properly and not fields;
- Due to the subjectivity of the method, the consistency of the object geometry and classification is limited, especially when objects are amalgamated from lower order features in the image;
- The spatial and thematic accuracy of the objects is generally not specified; and
- The interpretation process is not formally defined; i.e. many decisions in the process are performed implicitly and cannot be recovered to perform the interpretation on new images.

Despite the disadvantages of visual photo-interpretation techniques as a method of object extraction from aerial photographs as discussed in section 2.4.2, in this study, visual photo interpretation presented better opportunities than disadvantages for the following reasons:

- It was not possible during the study in Kenya to obtain digitally scanned aerial photographs for which digital interpretation techniques could be used;
- The available data for use at the lowest and intermediate spatial levels were unscanned visual aerial photographs (scale 1:10,000);
- The extraction of the spatial objects from satellite images or aerial photographs was based on 'visual cognitive characteristics' of the landscape feature elements as seen on printed aerial photographs and satellite images;
- What could be considered to be a landscape matrix at low spatial resolution, becomes a delineable patch at higher resolution. For example, field plots are recognisable at lower hierarchical levels as patches, which can be delineated on large-scale photographs while in a satellite image they appear as the landscape matrix due to their spatial resolution. This aspect, forces the use of multi-scale image sources for extracting different landscape features;
- The software that was available for GIS work during the study was more appropriate for object-based capture and analysis, with a vector data structure-the PC Arc-Info Software. It was therefore more plausible to use vector-based object oriented geometric primitives than the rasterised field-based digital data structures;
- There was need to limit raster to vector conversions for the final GIS modelling as a way of minimising errors due to data structure conversions (i.e. vector to raster and vice-versa). Meaning that even the satellite images were visually interpreted; and
- Though digital methods of interpretation can be formalised and replicated easily, and might have produced more precise results, the raster data structure sometimes deforms the geometry of the object due to the rigid cell sizes and the square shapes used in the geometric representation, introducing errors of shape deformation.

Advantages of digital interpretation techniques according to Droesen (1999) include:

- Both objects and fields can be constructed in a digital manipulation;
- The interpretation rules are consistently applied over the whole area;
- There are many methods to quantify the geometric and thematic accuracy of the interpretation results;
- The procedure is largely formalised, although some steps might still be subject to subjectivity, like the selection of training areas; and
- In case of stereo images automatic elevation measurements can be performed.

2.5 Statistical theory

In landscape ecological studies field data must be linked to the landscape elements in some manner as a means of detecting the relationships between processes like soil erosion, which are linked to the landscape.

From a methodological point of view, landscape ecological investigations into natural phenomena and processes represent a complex area of research especially during statistical analysis. The landscape ecologist often encounters all possible difficulties of empirical science at the same moment according to Jongman *et al.* (1987). Some of the problems include:

- A wide variability in the variables studied;
- A complex interaction between explanatory variables (independent variables) and response variables (dependent variables); and

- Uncertainty about the causes of observed relationships.

These difficulties are closely bound up with the fact that landscape ecological research is mostly field research, which is different from experimental research where the variables are controlled. The great variability in the variables observed in the field is caused by the existence of many influencing, but also changing abiotic and biotic factors.

Several methods exist for linking measurable independent landscape response variables such as measurable soil erosion with dependent explanatory variables such as its factors. The methods include statistical methods (Jongman *et al.*, 1987), evidence theory (Ross, 1995), expert systems (Suryana, 1997), probabilistic and possibility distribution theories (Droesen, 1999) and fuzzy membership theories (De Bruin, 2000). The method selected depends on the objective and the specific situation of the variables under study. It also depends on the observation platform. That is, whether the data is captured from digital remotely sensed data or whether it is through field observations and measurements. When dealing with fuzzy objects in remotely sensed images, they sometimes may appear as complex mosaics in low-resolution images. In high-resolution images, they appear as crisp objects. Fuzzy methods are ideal for allocating membership classes to the fuzzy objects or objects with fuzzy boundaries. Another issue for consideration is whether the variables under study are captured as nominal, ordinal, interval or ratio scale data. When dealing with nominal or ordinal data and their relationships, fuzzy logic is the best tool for creating the existing links. Expert systems and evidence theory draws more from cumulative individual knowledge and experience. Unless the certainty factor as discussed by Suryana (1997) is inbuilt into the process, the expert systems remain subjective and unreproduceable qualitative knowledge. This implies that expert systems are good when quantitative data is lacking, if there is a chance of obtaining interval or ratio data then statistical methods offer better quantitative relationships. In this particular case, it was possible to obtain quantitative measurements of erosion features and delineate the observable objects in both satellite images and on aerial photographs, probabilistic statistical methods were therefore preferred.

The type of analysis is therefore dependent on the objectives to be achieved. In order not to loose sight of the overall objectives of the research, null hypotheses must be postulated which link the overall objectives of the study to the statistical tests.

Data used in landscape ecology are mostly multivariate i.e. each statistical sampling unit is characterised by many attributes. This means that:

- data are complex, showing noise, redundancy, internal relations and outliers;
- data are bulky;
- some information in the data is only indirectly interpretable; and
- some data are only possibly expressed as presence or absence data.

According to Jager and Looman (1987), statistical analysis can result to misleading conclusions if the analysis is not based on the correct premise. There are two types of errors associated with statistical analysis. Type *I errors*, which are made by the rejection of a true null hypothesis (H_0) and type *II errors*, which are made by accepting as true the null hypothesis when in reality it is untrue. The two types of errors are coded as α and β respectively according to (Jager and Looman, 1987). The probability of rejecting the null hypothesis when it is false is obtained by $1-\beta$ in a statistical test. *'The Power of a statistical test'* determines the reliability of the statistical conclusions made and is recommended for any statistical analysis (Cohen, 1973; Jager and Looman, 1987).

Figure 5.4 illustrates the power of statistical testing in accepting or rejecting the null hypothesis *(H_0)* at any of the confidence levels *(0.1%, 1%, 5% or 10%)*. The indices can be either the *'Student's t test'* or *'Snedecor's F test'*. The null hypothesis assumes that there is no real difference in the data being compared. The inverse hypothesis (H_1) rejects the null hypothesis and creates the condition for accepting the conclusion that there is a real difference in the data. The confidence levels 0.1%, 1%, 5% and 10%, determine the error levels with which the null hypothesis is either accepted or rejected. The number of degrees of freedom also determines the critical level for acceptance or rejection of the null hypothesis as illustrated in Figure 5.4. If the lowest of the critical limits is taken as an example, then the area below it is classified as the acceptance zone and the area above it as the rejection zone. As to the percentage value of the critical limits, this shows the percentage probability of being wrong when one rejects the null hypothesis.

Measurement scales also determine the quality of the results that is obtained from a statistical analysis. There are four known types of scales of measurement namely the nominal scale, the ordinal scale, the interval scale and the ratio scale. In a nominal scale the values have no relationship with each other and are often referred to as classes. As an example, the factor soil type classified into 'clay', 'peat' and 'sand' may be assigned to class labels 10, 11 and 17 respectively. These labels do not imply any differences between the soil classes. In comparison, an ordinal scale places values in an order of ranks. An example is the ranking of the soil drainage classes into: '*well drained*' coming before *'moderately well drained'* and *'moderately well drained'* before *'poorly drained'* soils. Even if the well-drained soils are assigned a value 1 and the poorly drained soils a value 3, the numerical values 1, 2, 3, have no significance from any point of reference.

The interval scale, which is the next measurement scale, places an object on a number line with an arbitrary zero point and an arbitrary interval (choice of distance to be called *one*) (Chrisman, 1997). This interval can be shifted around on the number line without changing the meaning of the measurement. In interval measurements, the difference between values can be compared with each other. This leads to the fact that a certain difference is twice as large as the other is. Means and standard deviations can be calculated from interval scales. An example is when one compared measured distances between two points.

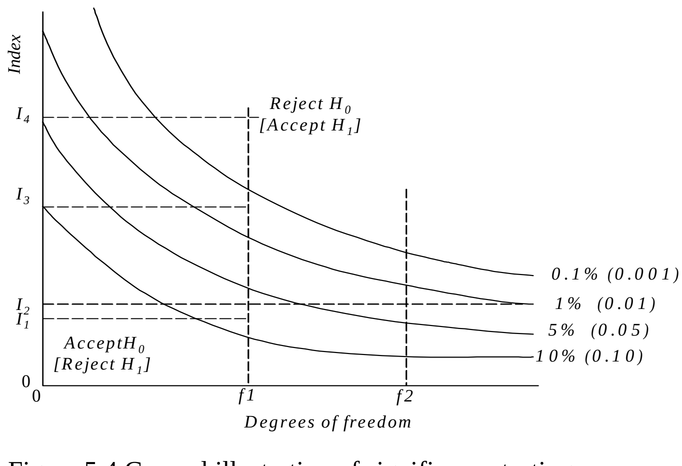

Figure 5.4 General illustration of significance testing

The difference between two interval scale measures becomes a measure on the ratio scale. The ratio scale, which is the strongest measurement scale, is like an interval scale, but with a fixed zero point. An example is the expression of measurements in percentages or indices. Ratio measures have a true origin (zero value) and an arbitrary interval. These properties support the arithmetic operations of addition, subtraction, multiplication, and division. The elapsed time in running a race is calculated by subtracting two interval measures for the start and finish. The result is a ratio scale measurement. The expression of the standard deviation as a percentage drift from the mean is also an expression in the ratio scale. Numbers of individuals or proportions in a population measured in percentages are also ratio scales.

2.6 Soil erosion theories and assessment

The previous sections of this chapter dealt with the theories of hierarchy, spatial modelling, object construction and object extraction for manipulation and handling in a GIS. A link is still missing which ties the above theories with the occurrence of soil erosion. The first subsection highlights theories associated with soil erosion processes and the second subsection presents existing erosion assessment methods from literature and those that have been used in Kenya.

2.6.1 Water erosion processes

According to Rose (1988), soil erosion by water can be regarded as a result of four processes:
- detachment by raindrop impact;
- transport by raindrop impact (splash erosion);
- detachment by the shearing forces of flowing water; and
- transport in surface runoff (sheet or interill erosion, rill and gully erosion).

Sheet and splash erosion occur in areas of shallow sheet or interill flow (few millimetres deep) whereas rill erosion is caused by concentrated rill flow. In the rills, fine sediments are transported as suspended load whereas coarser particles are dragged along as bedload.

Aggregate breakdown

Ellison (1947) states that soil erosion starts with the breakdown of soil aggregates into individual components. A soil aggregate can be regarded as a naturally occurring cluster of inorganic and organic particles combined in such a way that the strength of the forces combining the particles within the aggregates exceeds external forces applied from the environment in which the aggregate exists (Eppink and Stroosnijder, 1994). The breakdown of the soil aggregate is caused partly by the internal properties of the soil aggregate and partly by the external rainfall impact (Lal, 1988). Important internal characteristics include the colloidal cementing clay network, which enmeshes and binds the silt and sand fraction together. This electro-kinetic theory of flocculation applies not only to clay particles, but also to other groups of colloidal material found in soil aggregates, i.e. hydrous oxides of iron and aluminium, which carry a net positive charge and other binding organic particles.

Two introduced forces acting on the aggregate according to Farres (1980) cause the breakdown of a soil aggregate by raindrop impact. First, once the raindrop hits a soil aggregate, some of the water is splashed away while another portion is absorbed into the soil aggregate. The absorbed water upsets the electro-chemical and electro-kinetic status of the aggregate by reducing the strength of the originally dipolar water bridges binding the clay to the other components of the aggregate. This in turn reduces the internal strength of the aggregate. In the process some of the cations bonding to the colloids are replaced by means of cation exchange due to substitution by the hydrogen proton from the water. This weakens the aggregate through weaker hydrogen bonds replacing the cationic bonds.

Another distortion of the aggregate is caused by the entry of water molecules in the crystal lattice of the originally unwetted clay minerals. This causes an expansion and stress in the clay mineral. A similar process occurs in the organic substances hence expanding and increasing the magnitude of the stress in the soil aggregate. In addition, water will replace air previously occupying the micro-voids, starting by entering the smallest voids first. The air inside the aggregate may not readily find an escape hence increasing the internal stresses and explosion of the aggregate. The described stresses causes slaking and collapse of the soil aggregate and is considered to be the mechanism which is involved in aggregate breakdown and subsequently soil erosion.

Splash and crust formation

When a raindrop falls on a soil surface with a thin vinear of water, it produces a crater in the water due to the impact of the pressure. The water drop produces water jets which exit radially from the central axis of the falling raindrop (Reeve, 1982). The jet streams theoretically move at speeds close to 70 m/s according to Eppink and Stroosnijder (1994). From experimental measurements, the speeds go up to 30 m/s. These jets cause the splashing around of the soil particles, which sometimes go into suspension and are carried in flowing water in the erosion process. Some of the soil particles may form a seal on the soil surface or they may flow into the soil pores resulting in clogging up of the soil. Both processes result in a drastic decrease of the infiltration rate and consequently an increase in the surface runoff. According to Ghadiri and Payne (1977), the increased lateral jetting velocity is the result of initially high pressures and is responsible for soil detachment. The jet flows exert large shearing stresses on the soil surface and may cause compression and cracking on micro-irregularities on the soil surface. The jet stream greatly increases the soil susceptibility to tensile failure and is believed to be the most damaging process in raindrop impact-soil detachment.

Transport of soil particles

Turbulence, burst and sweep phenomenon during flow according to Eppink (1994) is the best explanation of particle lift in a flowing fluid. Flow velocity is not equally distributed over the depth of the flow. In a laminar flow, velocity (v) increases to the square of depth (d) from the bottom of the flow (Horton *et al.*, 1934) which means that the water layer at the water surface is much faster than the layer close to the soil. Differences in the flow velocity of the different flowing shear layers causes the development of a horse-shoe type swirling and forward rotation of water between the upper faster flowing water and the lower layer slow velocity water. The formation of the horseshoe tunnel of flowing water between the flowing layers creates a high instability in the system thereby causing a collapse of the systematic flow. The collapse results to high turbulence, which is responsible for the particle lifts into the stream of flowing water. This cyclic and continuos process helps to uplift the soil particles which are then transported in the flowing water mass in the form of erosion.

Depending on the particle size, the soil particles are either rolled or dragged along the soil surface as bed load or lifted up into flow and transported as suspended load. In the shallow sheet flow, velocity is small. However, soil loss is enhanced by the energy supplied by the pounding raindrops. The drop impact causes turbulence in the flow. Particles are heaved up, settle down and heaved up again, thus being transported towards the rills. In experiments of Mutchler and McGregor (1983), maximum soil loss occurred in flow depths of 2mm.

These described erosion processes result to soil erosion features that occur on the land surface. The erosion features manifest themselves differently on the landscape depending on the internal properties of the holons and the constraining environment of the higher level holon. The features provide opportunities for observing and measuring soil erosion in the field. The erosion features include, sheet wash, pedestals, soil movement, scoured flow channels, soil movement, rills, gullies, landslides, mass movements and deposition features. In this thesis, the erosion features made it possible to quantify the degree of erosion occurring on different levels of the landscape hierarchy on different erosion proxies.

2.6.2 Soil erosion and risk assessment methods

Aerial photography

Several people in order to show the distribution of soil erosion in agricultural or other environments have used aerial photographs. Examples include Bergsma (1980) and Morgan (1997). Though the use of aerial photographs in the assessment of soil erosion has assisted in distinguishing the land areas with occurrences of visible erosion, they have not been able to show the extent of erosion that goes on below the plant canopy cover. This is mainly due to obscurity of below-canopy phenomena to above ground observation in remote sensing or aerial photography.

River sediment yields

Another method for assessing the rates of erosion has been by collecting river sediment data. Examples include Ongwenyi (1978) and Edwards (1979). The use of river sediment yield data also, though important in aggregating data on total sediment output from a watershed or river basin, have so far not been able to trace the erosion back to the original source. The result is that the data so derived is only useful for dam construction design and estimating river sediment loads. The data cannot easily be used for soil and water conservation activities since they don't *pinpoint* to the actual *hot spots* where soil erosion is taking place.

Predictive mathematical models

The development of mathematical models for estimating soil loss started with Zingg (1940) who related soil loss to slope length and gradient. Smith (1941) included factors for the influence of crops and conservation practices on soil loss. The addition of the rainfall factor resulted in the Musgrave equation (Musgrave, 1947). Finally data collection and analysis of 10,000 plot years from 49 locations led to the 'Universal Soil Loss Equation (USLE) of Wischmeier and Smith (1978) which, today is still the basic tool for soil conservation in the US and other countries. The famous equation is written as:

$$A = R * K * L * S * C * P$$

Where soil loss (A) is the mean annual soil loss in tons/ha on a long-term basis. Rainfall erosivity *(R)* is calculated from rainfall charts for single erosive rains during a period of 22 years and represents the mean annual erosivity for the period. Soil erodibility *(K)* indicates a soil's susceptibility to the erosive forces and gives the amount of soil loss per unit erosivity. L, S, C and P are expressed as ratios of soil loss on a given unit plot.

The USLE was designed to predict annual soil loss from sheet and rill erosion on a field scale. The model is a lumped equation (Foster *et al.,* 1980) and does not account for deposition nor does it predict sediment yield. The USLE estimates erosion from moderate slopes and medium soil textures. It may be inaccurate at extreme slopes and textures, and in regions where the erosive forces are primarily from overland flow (Robinson, 1979). Since the development of the USLE it has been modified several times and other models such as the modified universal soil loss equation (MUSLE) and the revised soil loss equation (RUSLE) have also been developed from it.

Williams (1975) and Foster and Meyer (1975) developed the modified USLEs, the MUSLEs. What they all have in common is that they adjust the *R* factor of the USLE, by introducing besides the rainfall factor *R*, a hydrological runoff factor. All other characteristics of USLE remain basically the same.

RUSLE, the Revised USLE as presented by Renard *et al.* (1991) includes improvements in the USLE model. The improvements include an expanded erosivity or the iso-erodent map for the Western United States-based on data analysis from more than 1000 locations. Also modified are changes in the *R* factors obtained from the Eastern United States, where flat slopes occur in regions of long, intensive rainstorms. Erodibility data from around the world are also included, and an equation developed that gives useful estimate of *K* as a function of average diameter of the soil particles.

WEPP (Water Prediction Program) of the USDA by Lane and Nearing (1989) is a continuous simulation model that has been developed to replace USLE as a legal instrument of soil conservation in the United States of America. Other deterministic, process, and spatial erosion prediction models are integrated. The model is subdivided into several components, climate, hydrology, soils, erosion and deposition. The lumped profile model is applicable to field sized areas of up to 250 ha without permanent channels. The watershed version has a distributed character and deals with rangeland areas with large concentrated flow.

EPIC, the Erosion Productivity Impact Calculator was developed by Williams *et al.* (1990). The model was created to evaluate management measures over tens or even hundreds of years, if necessary. The model uses daily time steps and monitors continuously the short duration output, like soil water content. The drainage area considered by EPIC is about one ha because soils and management are assumed to be homogeneous. In the vertical direction, the soil can be subdivided into a maximum of ten layers.

EUROSEM, the European Soil Erosion Model developed by Morgan *et al.* (1991, 1992) is a single event process-based model for predicting soil erosion by water from fields and small catchments. It can also be used to assess the risk of erosion and to evaluate the effects of soil protection measures.

CREAMS, the Chemicals, Runoff and Erosion from Agricultural Management Systems was developed by Knisel *et al.* (1980) to be used for planning of management practises. The mathematical model aims at the evaluation of non-point source pollution for fields. A field is defined as a management unit having a single land use, relatively homogeneous soils, spatially uniform rainfall and a single management practise. CREAMS consists of four components, namely: a hydrologic submodel, an erosion submodel, a nutrient submodel and a pesticide submodel. CREAMS include evapotranspiration and percolation in its computation in order to complete the water balance.

SLEMSA, the Soil Loss Estimation Model for Southern Africa developed by Elwell and Stocking (1982) was to be used when there was little finance and data available. Basically, the model works like the USLE, only the management factor P is left out of the model.

ANSWERS, the Areal Nonpoint Source Watershed Environment Response Simulation was developed at Purdue University by Beasley, *et al.* (1980). It was developed to predict the effect of land use, management, and conservation practices or structures on water quality and quantity for both agricultural and non-agricultural watersheds of up to 10,000 ha.

Many mathematical models exist as empirical, process-based or deterministic models. Each model has its strengths and/or weaknesses. The choice of any model for use depends on the application, and available data.

The Wischmeier plots

Another method for estimating soil loss and erosion is by the use of the Wischmeier plots. The Wischmeier plots are normally 22.1 m long and 1.87 m wide and placed on a 9% slope. The weakness with the method is that estimating soil erosion from run-off plots is usually site and time specific such that the results cannot be conveniently extrapolated to cover other geographic areas unless many data points are included for validating the experiments (Stocking, 1987 in: Blaikie and Brookfield, 1987).

Fractal processes

Van Noordwijk et al. (1998) has explored the use of fractal dimensions in modelling and scaling the rate of sediment yield in a GIS. A fractal dimension is defined as the ratio between the length and width of an eroding area during sediment yield computations. Scaling as used implies soil and water translocations from one point of origin to another point of exit through a terrain having length, width or depth dimensions. The terrain especially as it extends from a plot to a landscape is considered to comprise slopes, flow barriers, sinks, etc, which create opportunities for flow delay, infiltration and deposition of soil. The total sediment yield in a landscape area with different land use types, sediment yields and filters, is computed by taking a sum of all and individual land use strata, unit sediment yield of each strata, cumulative effects of all filters (erosion barriers), the fractal scaling factor.

The fractal approach deviates from the linear approach such the USLE in computing the sediment yield. It also takes into account of filters on flow pathways and computes area sediment yields for all patches of land use kinds present in an area. It requires data on fractal scaling rules, total lengths of filters, unit areas of the existing land use strata, the net reduction in sediment flow due to the filter effects of each class of filters.

In estimating sediment yield from the fractal model, a spatially distributed model is used in a GIS. In the model runoff occurs when rainfall and incoming runoff from neighbouring upper cells exceed the infiltration capacity of the soil. The velocity of the runoff is calculated with the manning formula, with the mean water depth in a cell as the hydraulic radius. The routing of runoff is determined by the steepest slope gradient as calculated from elevation data within the area. Soil can be detached by raindrops and by overland flow (Meyer and Wischmeier, 1969) and is thereafter transported using the Yalin transport capacity equation (Yalin, 1963). When the soil load exceeds the capacity, the excess of soil is deposited.

Other methods

Several other indicators exist that can be used to deduce the extent of erosion in any environment (Nill *et al.* 1996). Root exposures and pedestals have been used by several workers (e.g. Lamarche (1968); Rapp *et al.*, 1972; Dunne *et al.*, (1978) to assess soil erosion. According to Stocking (1987), using the fact that many trees and bushes can be dated, it is possible, by measuring the difference in height between the present surface and the old ground surface, to calculate a mean rate of erosion per year. Thus for the Shinyanga region of Tanzania, it was found that over twenty years preceding 1986, the mean erosion rate was 22.4 t ha^{-1} yr^{-1}. Erosion pins are also commonly used to determine rates of erosion in a given locality. They are wooded or metal stakes driven into the ground to act as fixed reference against which the lowering of the ground level may be monitored. Other indicators of soil erosion according to (Nill *et al.*, 1996) include soil type, soil layering, soil colour, soil texture, soil moisture, soil organic matter contents, etc. The relief of the landscape (new and rugged or old and smooth), slope gradient and length, climate, geology, road constructions, land cover and vegetation can also be used to infer the degree of erosion. The indicators are like fingerprints that can be used to give information on the '*potential occurrence'* of soil erosion (Nill *et al.*, 1996).

2.6.3 Erosion assessment methods used in Kenya so far

Soil erosion has been assessed in Kenya in the past by using several methods. Some of the methods were site specific while others focused on wider geographic regions. The following section presents the methods used so far as gleaned from existing literature.

Suspended river sediments

Most of the pioneer research in soil erosion in Kenya started with the trapping and measuring of suspended sediment loads in the Kenyan rivers. The earliest were the works of Dunne and Ongwenyi (1976), Dunne (1979), Edwards (1979) and Ongweny (1978). Dunne carried out a study on sediment yields under different land use kinds by measuring suspended river sediments. Edwards used suspended sediment data from 41 rivers in Kenya to assess soil erosion under different geologic formations to evaluate the soil erosion rates and their significance to agricultural development. The Tana catchment in Central Kenya was found to have the highest sediment yield of between 500-600 tonnes/km^2/year. Ongweny (1978) studied the hydrology of sediment production within the Upper Tana Basin in Eastern Kenya also using suspended sediment data. Sediment yields ranging from 20 tons/km^2/year in forested land to 3,000 tons/km^2/year in cultivated land were recorded. In Kiambu District, Edwards (1979) recorded values ranging from 110 to 620 tons/km^2/year for Ruiruaka; 4,800 tons/km^2/year for Nairobi River; 12,200 tons/km^2/year for Ruiru River; 2,200 tons/km^2/year for Riara River and 1,780 tons/km^2/year for Riu River. Sutherland and Bryan (1989) estimated the colluvial reservoir life of the Katiorin experiment basin using a sediment budgeting method. The total sediment output from the Katiorin Catchment was 7,190 tons/km^2/year plus or minus 1,420 tons/km^2/year. In addition, Sutherland and Bryan (1989) studied sediment output from a small semi-arid catchment in Baringo District, the Katiorin Catchment measuring 0.3 km^2. Their output was basically the amount and particle sizes of the derived sediments.

Run-off plots using natural rainfall

Several people have used run-off plots in Kenya to study the effects of soil erosion under different crop, slope and cover conditions.

Othieno (1975) studied surface run-off and soil loss on fields of young tea in Kericho in Kenya using run-off plots under natural rainfall conditions. He found that young tea with no mulch suffered the highest rates of soil erosion. Young tea with grass mulch suffered less erosion. Ulsaker and Kilewe (1984) studied run-off and soil loss caused by natural erosive rainfall to understand the influence of rainfall, soil erodibility, land management, crop cover and mulches from the analysis of the run-off water and collected soil. They also evaluated the key parameters of the universal soil loss equation for a Nitosol in Muguga, Nairobi, Kenya. They concluded that soil erosion decreases soil productivity through loss of storage capacity for plant-available water, loss of plant nutrients, degradation of soil structure and decreased uniformity of soil conditions within a field. Ulsaker and Onstad (1984) studied the influence of climate, soil and management practices on soil and water losses using run-off plots. They concluded that, runoff, in addition to soil erosion, is affected by contouring and tillage. If the soil surface is rough, more water is temporarily stored in the depressions for infiltration. The same is true when tillage tool marks are on the contour. Kilewe (1987) studied the effect of de-surfacing the topsoil artificially to evaluate soil erosion rates and soil productivity loss using run-off plots in Katumani, Machakos under natural rainfall conditions. The de-surfacing of 0, 3, 6, 9, 12 and 15 cm of the top-soil by artificial means produced maize yields per hectare per year of 1920, 1670, 1060, 230 and 150 kgs indicating a direct link between topsoil removal and yield reduction. Omwega (1989) reported in her work the influence of crop cover and rainfall energy on soil erosion using run-off plots in the Githunguri area of Kiambu district. She found that land cultivated with annual crops loses between 20 and 30 tons/ha/season while bare land loses about 70 tons/ha/season. Lately, Gachene (1997a and 1997b) has reported the effects of soil erosion on soil properties, crop performance and enrichment of eroded soil material using run-off plots in Kabete Campus in Nairobi. He found that bare plots with no conservation suffered soil loss ranging between 16.7 tons/ha/year to 247 tons/ha/year. On fertilised maize plots he found soil loss ranging between 0.77 tons/ha/year for plots protected with fine wire mesh to 171.3 tons/ha/year for plots protected with course mesh wire. The average runoff and soil loss from bare plots was 5.2 and 14.8 times higher than from fertilised and mulched plots respectively. The eroded soil material was richer in nutrients than the source material. The highest value of enrichment ratio recorded was for available phosphorous (P) at a value of 10.3 indicating that P is the most vulnerable nutrient to losses through water erosion.

In summary, the field plots represent well-designed, regular and isolated experimental surfaces, which bear little similarity to actual real-life conditions. The results thus obtained can be compared to field plots of similar sizes and conditions in real life if replicated. To extrapolate the results to cover wider areas introduces uncertainty and errors in the finally extrapolated data. The information from the run-off plots are therefore good for building an understanding of how the different factors of erosion contribute to the final soil loss under regulated conditions but not for replication to cover wider spatial regions. The indices derived from them can be used in empirical process models.

Field run-off plots using simulated rainfall

A few experiments have been carried out in the field using simulated rainfall to assess erosion risk. An example is the work by Okoth and Aore (1993a and 1993b) who used the portable

Kamphorst (1987) rainfall simulator to calculate the erodibility of the soils of Baringo and West Pokot districts as a soil erodibility input into a soil loss predictive model. Other scientific work using simulated rainfall has been carried out though not reported. An example is the work by Sutherland in Baringo, which is not reported.

The simulated rainfall experiments suffer the same disadvantages as the field run-off plots in terms of their area coverage. Many spot checks need to be carried out in order to obtain an indication of what happens in a wider geographic region. The results from the simulated rainfall experiments also classify as spot checks of erosion potential on the specific locations. The data collection so far has not been designed in a hierarchical manner and thus ignores the different landscape components that are relevant for representing erosion risk at different scales.

Laboratory and greenhouse experiments

Gachene (1982) and (1986) calculated the nutrient enrichment ratios of some Kenyan soils by packing topsoil samples in specially designed run-off trays and used simulated rainfall to induce erosion under laboratory conditions. The eroded soils were analysed for their nutrient contents, which were compared with the original soils to compute the enrichment ratios. He found that the enrichment ratios were greater than 1 for all the soils. The eroded material from the nine soils showed that 1.05 to 2.23 times potassium, 1.3 to 2.00 times calcium, 1.06 to 2.09 times magnesium and 1.10 to 2.08 times phosphorus were lost in the eroded soil materials as were present in the uneroded soil materials of the soils. Kilewe (1984) studied the physical properties of soils in the laboratory from which he derived dispersion ratios, erosion ratios and erosion indices of the soils. He found higher dispersion ratios (59.4-78.8) for the Katumani soils, which were classified as Ferro-chromic Luvisols compared to the Muguga soils (16.3-38.5%). The Muguga soils classified as a Nitosol by then. The erosion ratios were also higher for the Katumani soils (42.4 – 71.6%) compared to the Muguga soils with ratios ranging from 10.2 to 48.1%. The erosion index values followed the same trends as those of the dispersion and erosion ratios with Katumani having values ranging from 42.4 to 71.6 and Muguga 6.5 to 35.0.

In all these laboratory experiments, important erosion indexes were obtained which create more understanding of the occurrence of erosion under a set of conditions. As earlier stated, such indexes can be integrated into soil loss predictive and process models.

Effects of conservation measures on field experiments

Kiome and Stocking (1995) studied the influence of conservation measures (hand tillage, contour tillage, tied ridges, trashlines and fanya juu terraces) in evaluating soil and water conservation measures and crop-yield performance in a semi-arid environment with poor soils. The study was necessitated by what they termed farmers' perception of soil erosion. Trashlines were found to be most effective in the less compacted soils and tied ridges most effective in the poorly structured highly compacted soils. Gicheru (1994) reported on the effects of conventional tillage, residue mulching and tied ridges on soil moisture conservation and crop production in Laikipia district of Kenya. According to him, residue mulch was most effective in conserving soil moisture and hence causing better crop performance and yield than both conventional tillage and tied ridging. Conventional tillage performed better than tied ridges due to lack of surface runoff during the experiment period. Conservation measures are important deterrents of soil erosion. Appropriately selected conservation structures should be utilised for different scale levels and landscape hierarchies.

Soil traps in agricultural fields

Lewis (1985) used 53 soil traps in Kiambu and Muranga districts to measure soil loss under varying crop conditions for purposes of calibrating the universal soil loss equation. Measured soil loss values during the long rainy season in Kiambu ranged between 57.4 to less than 1.0 metric ton per hectare. According to him, in Kiambu, the highest soil losses were from fields planted with maize. He also observed that the lowest soil loss from any field planted with maize was 11.5 metric tons per hectare though in one field in Murang'a field planted with maize had a value of 1.4 metric tons per hectare. No reason was given for this major difference. The general observation was that in both Kiambu and Murang'a consistent pattern of high soil losses from fields under annual subsistence crops emerged. Maize resulted to the highest soil losses. Perennial cash crops generally had the lower soil losses but when they are grown on very steep fields they too resulted in high soil loss. Mati (1994) also evaluated raindrop erosion under different annual crop conditions using splash traps to collect soil particles transported by raindrop splash. Soil splashed down-slope was found to be higher than that splashed up-slope on a 25% slope.

This method of data collection can be used to cover wider geographic regions for studying soil erosion in the landscape than the run-off plots due to their simplicity and ease of installation and wide coverage. If the data collection is designed to target different cascading landscape entities in a hierarchy then the can be used for a hierarchical multi-level data collection depending on the selected landscape entity. Assessing soil loss and assessing the risk of erosion are two different tasks. Soil loss is basically concerned with the actual soil loss while the risk portrays the potential loss when a set of conditions prevails in a particular area. It is the probability that soil loss would take place in the area.

Erosion risk mapping at single scales

Gachene (1995) carried out a grid survey of the Erosion Research Farm at Kabete Campus. He combined a map of soils, slope gradients, slope-segments, rainfall erosivity and soil erodibility to produce an erosion susceptibility map of the farm. Gatahi and Okoth (1992) combined rainfall erosivity from annual rainfall data, soil erodibility using transfer functions and terrain steepness based on landform characteristics to develop an erosion hazard map of Kenya. In order to be used in a hierarchical risk assessment objective, the mapping exercise should be designed to address each landscape entity in the hierarchy stepwise such that each of the landscape components are assessed for the potential risk.

Predictive modelling

Lewis (1985) compared actual soil loss from erosion traps to estimated soil loss using the universal soil loss equation for Kiambu and Murang'a districts. He was able to calibrate the USLE using the Kiambu data to predict the Murang'a soil loss with a reasonable level of accuracy. The estimated soil loss had a direct linear relationship with the measured field soil loss. Okoth and Aore (1993a and 1993b) used the Morgan, Morgan and Finney method of (1984) to estimate soil loss under different terrain conditions in Baringo and West Pokot districts as a basis for the design of dams for construction by the Ministry of Water Development. Mantel and van Engelen (1997) applied the modified universal soil loss MUSLE model on the soil terrain database of Kenya KENSOTER to produce an-erosion risk map of Kenya, scale, 1:3,000,000.

Application of expert knowledge in a GIS environment

Crompvoets (1997) made an evaluation of the suitability of the KENSOTER terrain units (Van Engelen, 1995) for modelling soil erosion vulnerability in Kiambu using a qualitative expert knowledge system based on the Automated Land Evaluation System (ALES). Photo-interpretation assisted in the delineation of smaller landform-units, which were thereafter related to the KENSOTER units. No hierarchical structuring either by aggregation or classification is shown in the results that relate the KENSOTER units to the smaller photo-interpretation units. A qualitative erosion modelling is however carried out on the smaller units using expert knowledge systems derived from an interview of several experts. The expert knowledge systems could form a basis for allocating a soil erosion class to a known landscape unit (Suryana, 1997; Crompvoets, 1997). This is only possible when the characteristics of the landscape units are well known in advance by the experts and the experts are very well versed with the environment for which they are to allocate the erosion risk.

Use of the USLE predictive model at a single scale in a GIS environment

Grunblatt *et al.* (1991) used GIS in a methodology they developed for desertification assessment and mapping in Baringo District. Soil erosion was modelled using the universal soil loss equation as one of the input parameters into a bigger model to assess and map desertification. Other model inputs included a vegetation degradation status model, range utilization status model, a human settlement status model, and a wind erosion status model. A desertification hazard map of the district was derived from a summation of the contribution of the individual indicator models. Predictive modelling in a GIS environment offers one opportunity for erosion risk assessment. Data on erosion in relation to some selected indicators is collected, calibrated and entered into a GIS database after which it is spatially modelled to represent soil erosion risk in any selected landscape element.

3

A New Framework for Hierarchical Modelling of Soil Erosion

A new framework for hierarchical modelling of soil erosion

This chapter presents a new methodology developed in this thesis for assessing and modelling the risk of soil erosion hierarchically in the landscape. First, a presentation is made of the overall concepts, techniques used, importance of the methodology, the execution steps and the advantages that are inbuilt with the methodology. Secondly, an in depth description is made of the steps used during the implementation of the methodology.

3.1 An overview of the methodology and model

3.1.1 Underlying concepts

The model integrates knowledge with activities. First there is *a priori* knowledge that is collated in order to facilitate the studying of soil erosion in the context of a landscape system. Knowledge and practice are invoked to organise the landscape system into hierarchical levels through which equally ordered erosion processes can be studied, assessed and measured. The conceptual model revolves around the construction of hierarchical levels in a landscape system and how the landscape elements and their parts relate to soil erosion assessment, prediction and management. The major motivation is that scale levels as is commonly used by landscape researchers, does not correspond to hierarchical levels in a landscape system, a factor which masks the intricacies and resolutions in a landscape system and the inbuilt processes. Scale levels as is commonly used is linked to linear object aggregations in a horizontal plane, which are not necessarily organised at different hierarchical levels. This assumption has contributed to linear extrapolation of research measurements from small research plots to larger landscape units without considering the heterogeneity that is sometimes involved. The result is normally an overestimation or an underestimation of the extrapolation results.

Hierarchical construction of the landscape system allows an ordered organisation of the landscape system into superordinate or subordinate parts that correspond to process time-scales and their corresponding spatial extents. Such an arrangement of the landscape system allows for relevant observations and measurements to be made of the ordered processes. The concept deviates from viewing the landscape as an agglomeration of parts in which processes occur presumably in a uniform manner and where only size changes allowing for smoothing of measured results in a linear generalisation transformation. The method identifies *'individual wholes'* at each level of the landscape hierarchy in which processes occur within comparable time scales and for which data interchange and modelling can take place. They are termed *'holons'*. At some levels, flow channels and terrain conditions in the holon are considered to be the *drivers* of erosion while barriers, placed on the flow paths are considered to be the *disrupters* of erosion. Table 3.1 shows the derived hierarchical levels for soil erosion risk modelling in a landscape system as conceptualised in this thesis and Table 3.2 shows the derived erosion proxies, the landscape system holons and erosion features also as articulated in the thesis.

The method uses the geographic properties of landscape elements to extract them from the broader landscape mosaic. Aerial photographs and satellite images are interpreted in order to extract the landscape features before they are digitised into a geographic information system (GIS) and processed. The occurrence of soil erosion on each feature is measured and recorded for presence or absence. Logistic regression is used to produce algorithms for predicting soil erosion risk on any selected landscape element. Hierarchy theory, landscape ecological theories, spatial theories, soil erosion theories, and GIS theories are integrated to produce an integrated methodology for spatial assessment and modelling of erosion risk.

The method identifies *'the field-plot'*, *'the watershed'* and the *'landscape'*, as three components of a hierarchical landscape system that can be used for erosion risk modelling. Their individual architecture is such that they posses manmade or natural '*boundaries'* in which internal erosion processes take place and can be considered to be both closed and open systems at the same time. These selected landscape elements act as *'erosion chambers'* in which soil erosion processes take place almost uniformly depending on the conditions inside them. The internal properties and features of the landscape holons act as either *'drivers'* or *'disrupters'* of erosion.

Important in the method, is its hierarchical analytical nature of approach. The strategy recognises the landscape as being composed of different landscape elements, with differing prominence, positions and processes depending on the level of analysis and hierarchical construction and ordering. The three landscape levels have a strong link with societal management responsibilities and are good erosion assessment niches. The field plot is the concern of a single farmer while the watershed is the concern of several farmers or a group of farming communities and in some cases, few farmers with big land. The landscape is normally the concern of a regional authority such as the divisional or district managers. The hierarchical ordering enables one to discern the processes taking place at different levels of the landscape hierarchy. Figure 3.1 shows the overall model of the thesis and the relationships between the conceptual model and the interlinked implementation components required for planning and managing the risk of soil erosion.

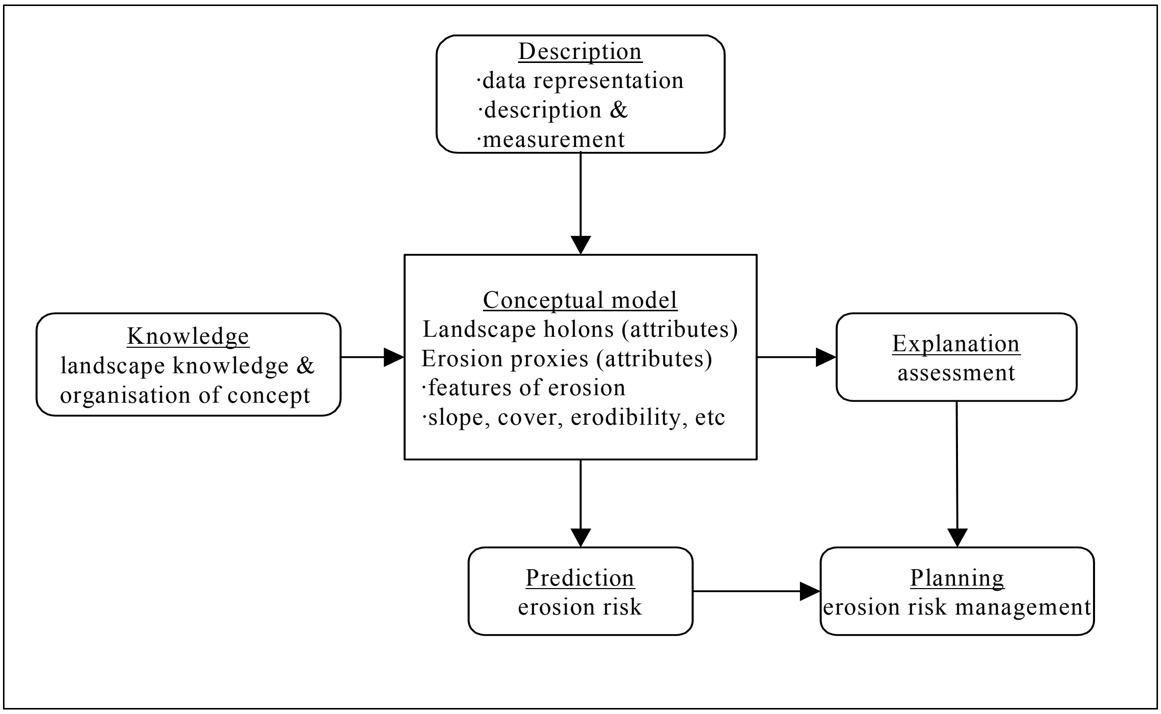

Figure 3.1 The overall thesis model and the interlinked implementation components

Through field observations, the erosion drivers and disrupters are linked statistically to the risk of soil erosion. The *drivers* or *disrupters* of erosion are identified and assessed separately at each level. For each level, new drivers or disrupters are identified. The drivers or disrupters can have polygonal or linear formation shapes. Linear features, which are channels of water-flow in the landscape, appear to be more relevant for the *'watershed level'* holons. Other land use attributes, such as *field plot sizes, crop types, cover* and other forms of land management appear more applicable as drivers or disrupters of erosion at the *'field plot'* level. A high intensity of erosion *'drivers'* in any landscape holon means a high risk of erosion while the presence of many disrupters of erosion reduces the risk. The net risk can therefore be represented by the difference between the *'drivers'* and the *'disrupters'* or their relationships can be computed as percentage ratios of each other.

The method uses aerial photo interpretation techniques to capture the landscape elements from aerial photographs or satellite images, and GIS to digitally store, analyse and model the objects in a geographical feature space. Figure 3.2 shows the actualisation of the conceptual model through different modelling procedures and Figure 3.3 shows the sequential steps for implementing different parts of the methodology.

3.1.2 The conceptual model

The conceptual model is centred on the landscape system hierarchy, comprising the landscape unit, the watershed, the field plot, the erosion proxies and the spatial and thematic attributes of all these landscape features and their relationships with soil erosion. The conceptual model is effected using *a priori* knowledge, its description, representation and its contribution to the perceived outputs. The outputs include explanation of the interrelationships between the holons, the erosion proxies, and soil erosion. The prediction of soil erosion risk that enables the planning and management of the risk are also parts of the conceptual model. Figure 3.1 shows the graphical representation of the position of the conceptual model and the overall thesis model.

3.1.3 What the model seeks to achieve?

The model seeks to establish a method by which erosion can be assessed and modelled at multiple levels in a landscape. It deviates from other single-level erosion assessment and risk evaluation methods. It rather views the landscape as a medium in which water erosion processes are taking place in an intricate manner at different spatial hierarchies and which are also the entities for land use and erosion management. These spatial attributes of the landscape offer the opportunity to predict and view the distribution of the erosion risk on the broader landscape and at different attention levels. These created opportunities are powerful tools for preventing or managing soil erosion. In summary, the method seeks to offer an erosion risk prediction technique, which relies on easily observable and measurable historical erosion and landscape attributes, majority of which can be manipulated for erosion control. The beneficiaries of the method outputs are seen as farmers, government departments, and other non-governmental organisations that are involved in soil and water management.

3.1.4 Strengths of the model

The model has the following strengths:

- The spatial multiple-level entities selected are regions where soil erosion and deposition occurs in a real world situation and differs from experimental plots;
- The method reduces errors associated with summing up the risk of erosion in a watershed or catchment by simple linear mathematical conversions from observations made at lower levels of observation;
- It incorporates a GIS component, which enables spatial data modelling, analysis and representation;

- It distinguishes and combines biophysical landscape features with societal management cadres;
- The method assesses soil erosion risk with relevance to societal target groups who manage soil erosion in the field;
- The method creates a body of knowledge for relating the spatial landscape features, soil erosion, and the management of soil erosion; and
- The method is flexible and applicable in any environment with hierarchical landscape structures as defined in this thesis.

Table 3.1 Properties of the functional hierarchical levels for soil erosion risk modelling in a landscape system

Spatial extent	*Holon genesis*	*Societal attention domains*	*Dominant erosion processes*	*Classification criteria*	*Erosion Proxies**
Landscape unit (part of higher land region)	- geology - geomorphology - climate - land cover	- local authorities - community - state	- stream flow - mass movements - gullies - slumps - landslides	- geomorphology and morphometry	- ground cover - terrain gradient - stream & river density - built up area - road networks - presence of disrupters - part-of landscape
Watershed (part of landscape unit)	- geology - geomorphology - hydrology	- community - community institutions - NGOs	- rills - gullies	- morphometry and genesis	- slope gradient - linear water channels - presence of disrupters - part-of watershed
Field-plot (part of watershed)	- land use - land tenure - slope - soils	- individual farmer	- raindrop - interrill - micro flow channels	- use	- use/crop - slope gradient - soil cover - presence of disrupters - part-of field plot

* Details of the erosion proxies are shown in Table 3.2

3.1.5 Modelling the landscape system

The functional systems concept shown in Figure 2.2 enables one to visualise all the aspects of individual levels in a hierarchy that can be modelled and included into a holistic study of the space continuum of the landscape system. The *'spatial extent'* attribute in Table 3.1 ensures that every holon has discernible area and boundaries in which its properties can be studied and measured. The *'genesis'* component ensures that the construction of the hierarchy attains vertical asymmetry as dictated by hierarchy theory. *'Societal attention domains'* ensure that someone in the societal hierarchy is able to address whichever processes or erosion hazards occurring in any holon within the hierarchy. The societal domains also have a hierarchical order of organisation. They provide an entry point for the management and control of soil erosion. The *'processes'* component provides an idea on the kind of dominant erosion processes occurring at the different levels of the hierarchical organisation. In fact this element makes it possible to study relevant water erosion processes for each level of organisation. Understanding the manifestation of different processes at different levels enables the disentangling of erosion-process complexes and from this, it is possible to develop more targeted erosion process-models at different levels of the landscape system. The *'classification criteria'* allows thematic classification nomenclature to be allocated to the holon entities. Membership to a class enables the allocation of geometric and thematic attributes to the landscape holon a factor which enables spatial modelling. Individual separation or characterisation of the members is therefore made possible. The *'erosion proxies'* component enables the recognition of biophysical drivers or barriers of erosion. The barriers of erosion can be used for the control of soil erosion, the drivers to assess the degree of erosion occurrence. Table 3.2 shows the kinds of features of erosion and erosion proxies that can occur inside each of the landscape holons.

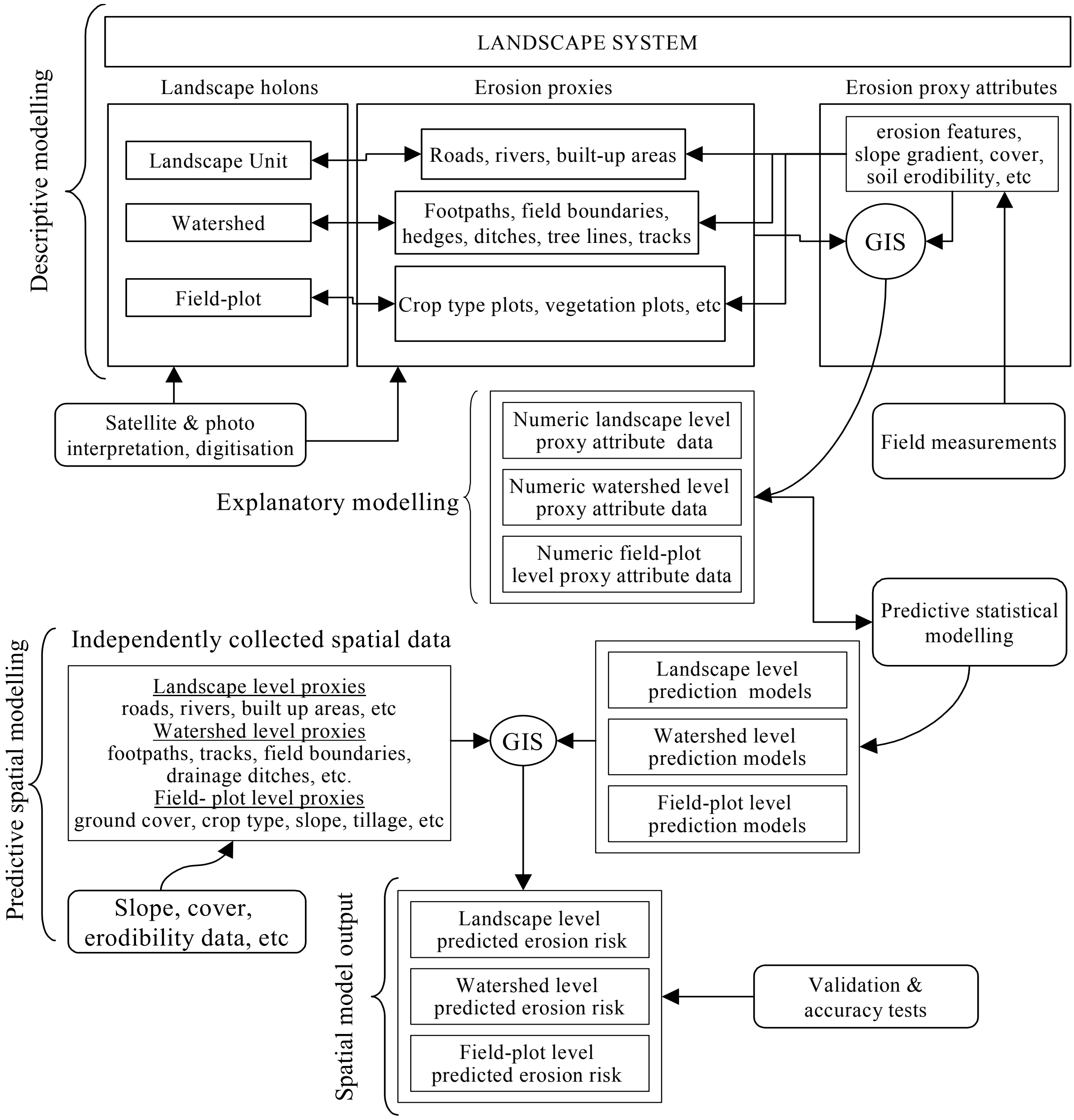

Figure 3.2 The actualisation of the conceptual model through different modelling procedures

The spatial prediction of erosion risk is preceded by a series of modelling approaches. Details of these modelling approaches have been provided in Chapter 2. The individual approaches include conceptual modelling, descriptive modelling, explanatory modelling, and predictive modelling. All these are modelling approaches that constitute spatial modelling. Conceptual modelling relates more to mental ordering and simplification of the real world, which precedes the construction of the hierarchical levels of the landscape hierarchy. Descriptive modelling aims at deriving a proper representation of landscape features in the space-time continuum, where data acquisition and inventory are the two most important steps. Explanatory modelling goes beyond the level of description to discover the relationships between variables in order to explain their behaviour. In this thesis, statistical modelling methods were preferred due to preferred use of object oriented modelling. Landscape features were captured as object data models and their computation attribute data stored as numeric data. The descriptive data were stored in alphanumeric data formats. The modelling approaches are shown in Figure 3.2. Soil erosion risk was predicted for each level separately using slope and cover properties of the erosion proxies after establishing that there exists a strong relationship between the occurrence of soil erosion features and the erosion proxies. Aspects of spatial modelling are presented in later parts of this chapter.

Table 3.2 Possible water erosion proxies and observable soil erosion features that can be used for the assessment and modelling of soil erosion risk in the hierarchical landscape system-construct in each holon type

Landscape-holon	*Erosion proxies*		*Erosion features*
	Drivers of erosion	*Disrupters of erosion*	
Landscape	- built-up areas - roads - roadside ditches - stream valleys - river valleys	- well drained & dyked construction sites - trapped and channelled roof catchment water - paved roadside ditches, - grassed road sides, - bushed or forested river banks	- soil movement - translocated surface litter - root exposures - stem washing - flow channels - rills - gullies - river bank erosion - mass movement
Watershed	- drainage ditches - field boundaries - footpaths - animal tracks - sloping terrain	- closed barrier hedges - closed fences - grassed boundaries - trashed boundaries, - constructed dykes - hillside ditches - benched terraces - vegetative networks	- soil movement - translocated surface litter - root exposures - stem washing - flow channels - rills - gullies
Field-plot	- bare plots - sparse cover - sloping terrain - sparse crop spacing - tillage direction	- level terrain - dense cover - alley cropping - mulch - planted row hedges - constructed ridges - constructed bunds - grass strips - bush/tree strips	- soil movement - translocated surface litter - root exposures - stem washing - flow channels - rills

3.1.6 Weakness of the methodology and model

The method and model suffers some implementation weaknesses like all others methodologies. The following are the foreseen as the *a priori* weaknesses during implementation:

- In intensive annual farming systems, the features of erosion are usually obscured by frequent tillage practices making their assessment only possible immediately after tillage and after the event of an eroding rainfall or during minimum tillage periods;

- The above reason means that temporal considerations must be imbedded in the methodology where the observations in the field are timed to coincide with rainfall and field preparations; and
- Any organisations opting to use the method must be fully equipped with GIS facilities and technical capacity to manipulate the spatial databases and modelling their attributes. Technical capacity is also required in the fields of soil erosion assessment and statistical analysis methods. Remote sensing knowledge and data have the best opportunities for capturing landscape objects for integration into a GIS. Acquisition of the data and capacity to analyse and model the images both digitally and manually are unavoidable requirements of the methodology.

3.2 Implementing the model and methodology

This section provides a detailed description of the different steps and procedures used during the study to formalise the conceptual model. The conceptual model of the landscape hierarchy appears repetitively in all other subsequent sections and chapters of the thesis. Figure 3.3 shows the steps used during the implementation of the overall thesis methodology. Each step is made up of several procedures. The objectives of the study were formulated in Chapter 1 and will not be repeated here. The objectives guide the implementation of the overall thesis model. The following sections and subsections describe the steps and the individual procedures associated with the step.

3.2.1 Step 1 – Defining the hierarchies

Figure 3.4 shows the sequence of procedures used for defining the hierarchies and ordering the holons hierarchically for erosion risk assessment. The following subsections show how this is achieved.

Procedure 1: Conceptualising and determining the landscape hierarchies

This procedure involved gleaning from literature the definition of a landscape. Thereafter observations were made in the study area to isolate and understand the types of landscapes that existed in the area. Thereafter, a graphical representation of the landscape elements and their hierarchical ordering was made. This was important as it enabled the construction of asymmetric hierarchical landscape system levels as required by the hierarchy principle of asymmetry. The key attributes of the landscape elements considered were spatial extent, thematic description, slope gradient and geometry. The landscape attributes included for hierarchical construction included:

- Geology;
- Geomorphology;
- Land use; and
- Hydrology.

Geomorphology was particularly important as it provided the basis for allocating geometry to the landscape unit. Other parameters such as attributes of the erosion proxies, thematic attributes of the landscape unit provided other individual landscape components comprising the landscape system.

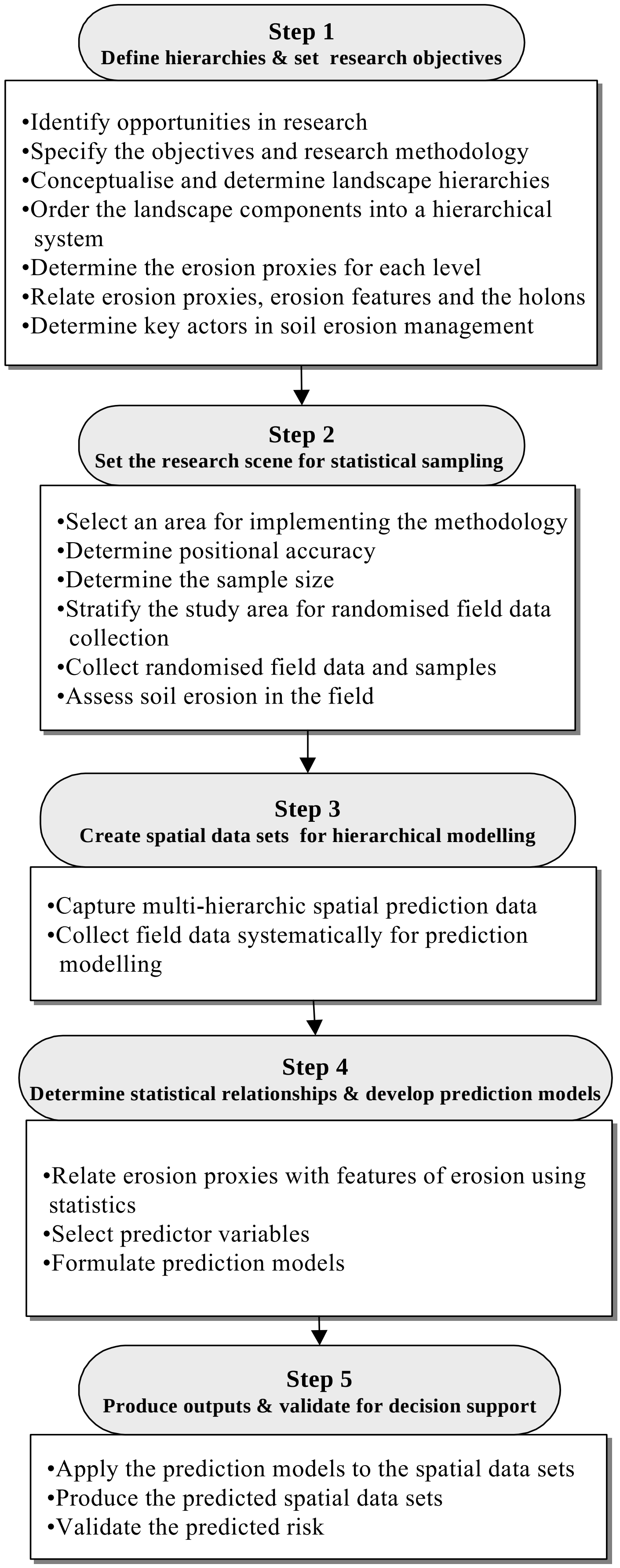

Figure 3.3 Sequential steps during the implementation of the methodology

Procedure 2: Ordering the landscape components into a hierarchical system

This procedure involved arranging individual thematic landscape holons (elements) into super ordinate and subordinate parts. Only landscape holons seen to have influence on soil erosion were considered. Geomorphology, land use and hydrology were considered to be the most important due their roles in the genesis of the landscape features, the influence they have on soil erosion, their possession of boundaries, their possession of geometry, and their link to hierarchic human hierarchies. The ordering was then organised as follows:

- *Geomorphology:* landscape unit>Landform>landform facet>slope facet;
- *Land use:* Land use zone> land use clusters>individual field plots; and
- *Hydrology:* Basin>watershed>catchment.

The final hierarchical order fitting the requirements of hierarchy theory such as asymmetry, soil erosion manifestation and GIS theories were field plots, watersheds and landscape units. Field plots are smaller than and nested in watersheds and watersheds are smaller than and nested in landscape units.

Procedure 3: Determining the erosion proxies

In order to study soil erosion, it was necessary to be able to observe features associated with it. In soil loss models, factors such as cover, slope, slope length, soil erodibility, rainfall, management factors are studied and model parameters are established which relate the factors with soil erosion.

In this study, some factors of erosion and spatial terrain attributes are considered to influence the occurrence of soil erosion. Factors such as percent cover of the soil surface, type of crop, slope steepness, soil erodibility were taken into consideration. Other important determinants of soil erosion and not included in the list are spatial features of the landscape which determine the occurrence of soil erosion. They have been termed erosion proxies in this thesis as defined in Chapter 1. Erosion proxies are features that have spatial forms by which they can be recognised, abstracted and related to soil erosion. These spatial properties make it possible to isolate and model these features in a GIS. These spatial features occur at different levels of the landscape hierarchy. Important attributes of the erosion proxies include:

- Currently defined landscape factors of erosion namely: ground cover, soil erodibility, slope steepness, etc; and
- Spatial features with properties that drive soil erosion such as: incisions, drainage channels, pathways, dissecting corridors, rain water concentration areas, built-up areas, sparse cover, road networks, river channels, etc.

Procedure 4: Linking erosion proxies, erosion features and the holons

Attributes of the landscape holons considered to influence soil erosion included:

- Occurring erosion proxies (e.g. crop types, vegetation types, hedges, footpaths, roads, etc);
- Occurring erosion features (e.g. soil movement, stem washing, root exposures, rills, gullies, etc; and
- Occurring barriers of soil erosion.

Details of possible links have been described and presented in Chapter 2.

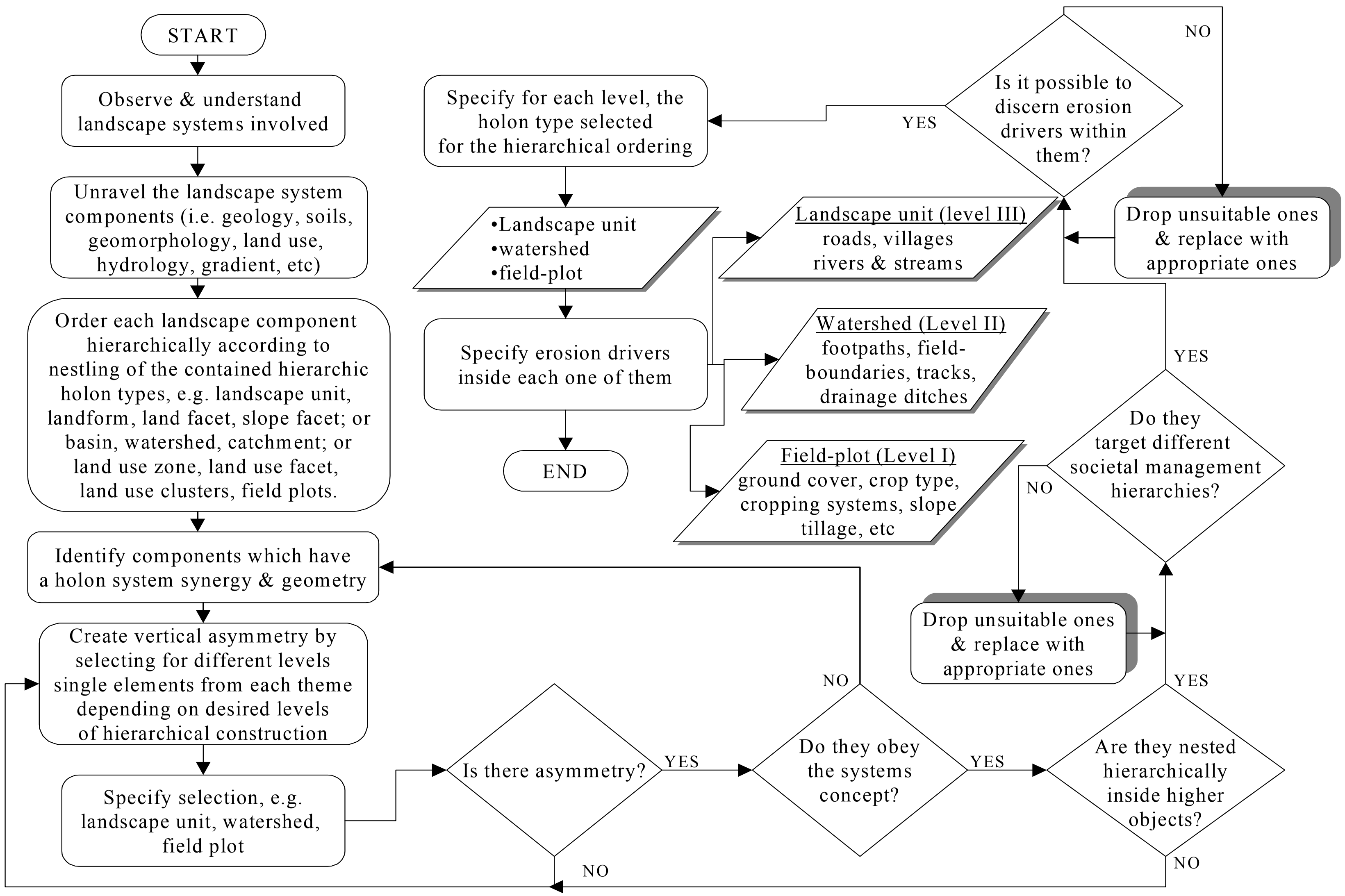

Figure 3.4 Flowchart showing the sequential procedure of defining the functional hierarchical landscape holons for soil erosion assessment

Procedure 5: Determining key actors in erosion management and control

The construction of the landscape hierarchies for human management should be such that the human elements within it occur in a hierarchical order of societal structure. A single field plot is for example normally managed mostly by an individual farmer or by members of his/her household. If you examine a higher hierarchical element of the landscape such as a watershed, then an agglomeration of farmers who stay together as members of a community become the managers of the landscape at that level. Such agglomerations are constituted of clan structures, or they could be constituted of neighbours living within the same neighbourhood and sharing the same resources. Some have formalised groupings while some are members of strategic groupings (De Haan, 2000). Political realms in a given locality could also create higher social hierarchies. It is important therefore to identify and link each hierarchical level to specific community groups associated with it to create responsibility and management lines for each hierarchical level. These human attributes are essential for more focused management of the landscape resources.

3.2.2 Step 2 – Setting the research scene for statistical sampling

Procedure 1: Selecting the study area

All issues described in this subsection form part of descriptive modelling. Before discussing the subject matter, a few issues were dealt with such as the selection of the study area, positional accuracy and accuracy attributed to the sampling strategy. First, areas in Kiambu district and parts of Nairobi province were selected for implementing the methodology due to the obscured but existing soil erosion risk. Secondly, issues relating to positional accuracy and sampling procedures were dealt with. Positional accuracy ensures that the collected data is referenced to specific locations on the earth's surface while statistical accuracy minimises errors due to bias in data collection.

Procedure 2: Determining positional accuracy

Position can be thought of as a combination of two measurements, *x* and *y*, representing the easting and northing of a pair of UTM co-ordinates, or longitude and latitude (Goodchild *et al.,* 1994). Each of these measurements is subject to error. Positional accuracy is defined as a standard error in each co-ordinate direction. It is a measure of variability that includes the effects of both bias and random error. According to Merchant (1985), it is computed as:

$$RMSEx = \left[\frac{1}{N} \sum_{i-1}^{n} \left(\delta X_i - \delta X_c \right) \right]^{\frac{1}{2}} \qquad (3.1)$$

Where: $RMSE_x$ is the standard error in the *x* co-ordinate direction, *N* is the sample size, X_i the actual (measured co-ordinate location, and X_c is the true co-ordinate location as determined by a source of higher accuracy.

In this work a GARMIN 45 GPS was used in the field to obtain the observation sites and to ensure positional accuracy. The positional accuracy of the data was ensured in the following ways:

- The observation points were first plotted on Survey of Kenya (1978) base maps;

- Geo-referenced digital satellite data was used to read the geographic co-ordinates of the observation points before the data were entered into hand-held GARMIN 45 Global Positioning Systems (GPSs);
- The *a priori*-collected co-ordinates were used to locate the points on the ground; and
- The ground positions were checked against the points in the base maps and aerial photographs for accuracy.

The handheld GARMIN 45 GPS has a positional location accuracy of approximately 6 to 12 meters (GARMIN, 2000). This can be improved to between 3 and 5 metres by installing a reference Differential GPS receiver station with a known precise location to reduce errors, this was not done during this study due to the high costs involved.

Procedure 3: Determining the sample sizes

The purpose of collecting data is to analyse it in order to make references about the population the sample represents. In other words, the sampling design should permit the investigator to capture the variations in the subject under study as it exists in the real world. The sampling design implemented for accuracy assessment during the field assessment of erosion should adhere to the scientific principles that govern sampling and statistical analysis and also be practical. Specifically, the assessment methodology should satisfy the following objectives (Stoms *et al.,* 1994):

- It should be scientifically sound. As such the method should be repeatable, and the sampling design should permit adequate representation of the population about which statistical inferences are to be drawn;
- The methods used should be applicable to all areas that are part of the project; and
- The method should be economically feasible in view of both time and cost constraints.

In order to ensure statistical accuracy and confidence in the results, the following procedures were implemented to address the issues raised above.

The appropriate number of sample sites to use for accuracy assessment depends on the level of error that is permissible and on the level of confidence desired. The sample size problem is usually resolved using the binomial distribution (van Genderen and Lock, 1977; Aronoff, 1985; Ginevan, 1979, Goodchild *et al.,* 1994). According to Goodchild *et al.* (1994), the sample size and a given acceptable error in the sample can be calculated directly from the binomial distribution using the formula:

$$n = \frac{pq}{\left(\frac{E}{z_\alpha}\right)^2} \tag{3.2}$$

Where: p is the required accuracy of the data in percentage, q is *(1-p), E* the allowable error and z drawn from the normal curve for the given level of significance.

The variation of sample size with level of confidence and level of acceptable error is shown in Table 3.3 (derived from Goodchild et al., 1994). In order to remove bias and ensure accuracy of the collected data, a total of 164 data sampling points were randomly selected and plotted onto maps for sites covering the entire study area for the field plot level data. This would ensure statistical results with 95% confidence interval and an error level of 0.07. For the watershed level, a total of 89 random sampling points were selected and plotted on field maps. This conforms to a 95% confidence interval and an error level of 0.07. For the landscape level, a total of 104 random sample sites were selected and plotted. The sample conforms to 95% confidence interval and an error level of 0.07. The sampled sites for all the three levels are shown in Figure 3.13. Table 3.3 assisted during decision on how many samples provided the desired confided as described above.

Table 3.3 Relationship between sample size, confidence intervals, and acceptable error

Level of acceptable error	A = 0.10 (90% confidence)	A = 0.05 (95% confidence)	A = 0.01 (99% confidence)
		Number of samples	
0.01	2,704	4,330	8,656
0.02	676	1,082	2,164
0.03	300	481	962
0.04	169	271	541
0.05	108	173	346
0.07	55	88	176
0.10	27	43	87
0.15	12	19	38
0.20	7	11	22
0.25	4	7	14

Procedure 4: Stratifying the study area for randomised field data collection

In order to assist in the collection of representative field data, the study area was first, stratified according to slope and land use categories. Figure 3.5 shows the main sequential procedures followed during random field data collection. First was the initial preparation of spatial datasets for field data collection and secondly the field data collection itself. Before the random field data collection, the study area was stratified to ensure that most of the variability in the area due to slope and land use differences were taken into account. During stratification, contour lines of the area after being digitised into a GIS were used to create a slope map as the first product. The contour lines had vertical intervals of 20-meters. The digitised contours with their embedded elevation data were then exported to IDRISI software where they were rasterised into 20, 40, and 80 metre grid cells. The grid cells were then converted into individual slope values by using the maximum likelihood method for classifying neighbouring spatial grid-cells. The 40 metre grid cells produced the best slope clusters with good comparisons with the actual ground conditions. The individual slope cells were further clustered into five slope classes (i.e., 0-5, 6-10, 10-15, and slopes > 15). The slope class map is shown in Figures 3.10. Secondly, a multi-spectral Landsat satellite image scale 1:50,000 of 19th January 1995 was visually interpreted for land use zones occurring in the study area. Eight broad zones were delineated.

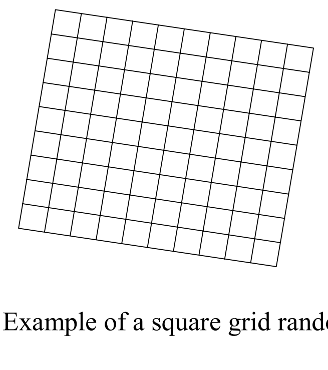

Figure 3.6 Example of a square grid random sampler

The slope map was again re-imported into ArcInfo software as polygons of equal slope area and overlaid with the land use/land cover map. From this product a map was printed at scale 1:100,000. A combination of the two enabled the stratification of the study area into 40 slope-land use clusters. The random sites for field data collection were then plotted using a standard random square grid sampler whose example is shown in Figure 3.6. A hand held calculator was used to generate random points on the grid mesh. The square grid mesh (Figure 3.6) was placed on top of the map at random before selecting the random points.

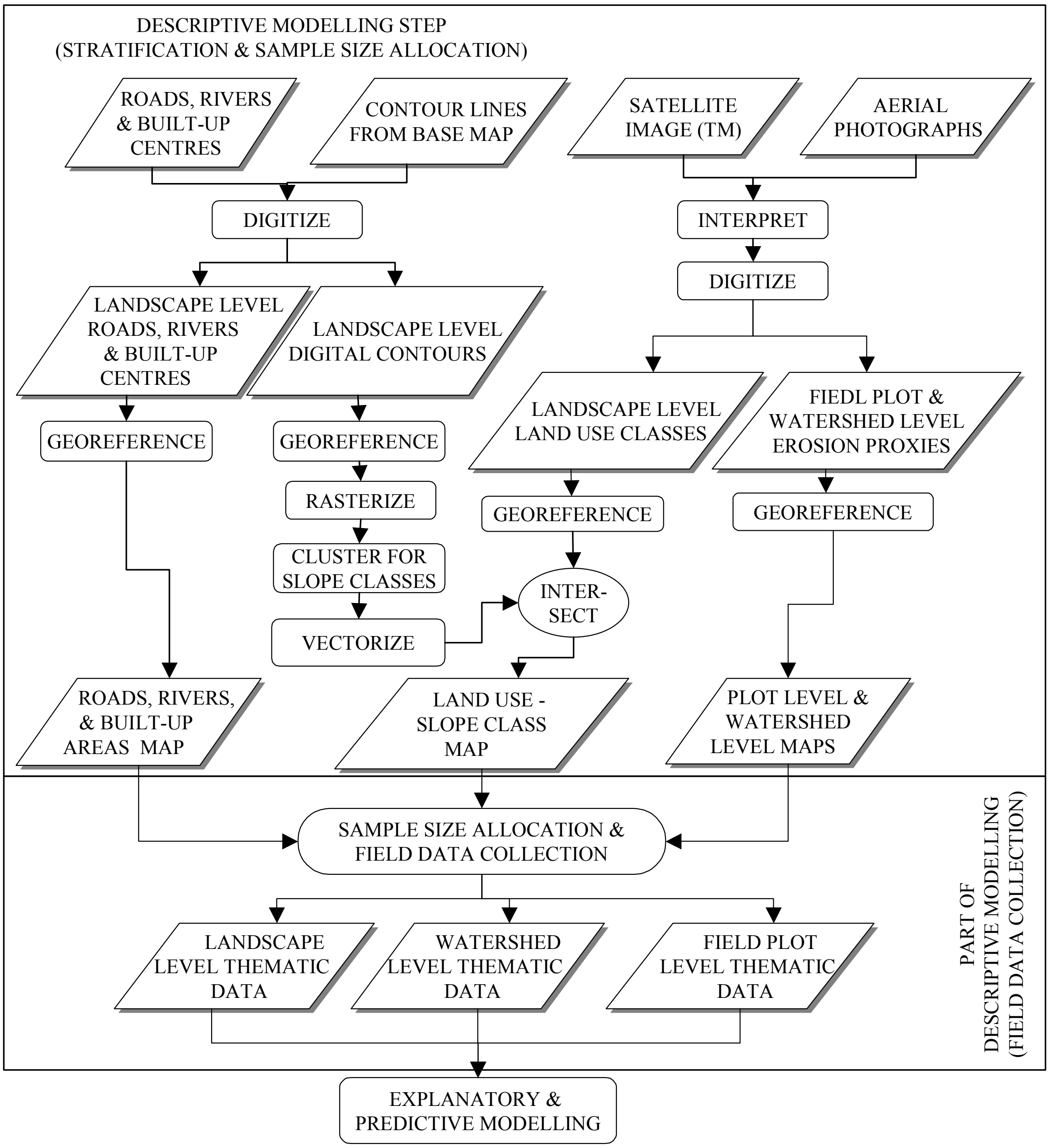

Figure 3.5 Stratification of the study area for sample allocation and field data collection

Procedure 3: Collecting field data and samples for laboratory analysis

After plotting the random points on the field map, field data collection involved driving to a specific sampling location with a GPS in which the co-ordinates of the location had been pre-entered. Before proceeding to the field, paper map-prints of the three sampling levels were produced. The first map was to be used for collecting field plot data (i.e. erosion data in different crops, vegetation, homesteads, etc). The second map was to be used for collecting watershed level data (i.e. erosion data on footpaths, field-boundaries, hedges, forest and tree lines, etc) and the third map was used for collecting landscape level data (i.e. erosion data on roads, river banks, built-up centres, schools, etc).

The data collected for the lowest level in the individual field plots included:
- Land use on plot;
- Measurable erosion (in cm);
- Slope gradient (in %);
- % surface cover;
- Run-off (using Kamphorst rainfall simulator);
- Soil loss (using Kamphorst rainfall simulator);
- Infiltration (using Kamphorst rainfall simulator);
- Percent cover (measurements of crop canopy cover, vegetation, or mulch cover);
- Soil texture;
- Soil organic matter;
- Soil nutrients; and
- Geographic co-ordinates.

Some of the data collected in this way were ready for statistical analysis while others required laboratory analysis before statistical analysis. Soil texture, soil organic matter and soil nutrients were obtained by analytical methods in the laboratory.

Data collected for the watershed level holons along elongate erosion proxies included:
- Erosion features;
- Slope gradient of the proxies (in %);
- Percent surface cover of the erosion proxies where present; and
- Type of watershed level erosion proxies

Data collected for the landscape level holons on landscape level-erosion proxies included:
- Erosion features;
- Slope gradient of the proxies (in %);
- Percent surface cover of the erosion proxies; and
- Type of landscape level erosion proxies

Filed measurements and observations

Observations and measurements in the field were carried out using both visual observations and physical measurements. Visual observations included observing biophysical features such as, land use kinds, crop types, type of erosion proxies, erosion features, conservation measures, etc. All the collected data were entered into pre-designed forms for each observation site. Percent soil surface cover, was obtained by measuring three replicates of 10 metre transects where ground cover and open surfaces were measured and expressed as percentages of the 10 metre distance. The 10 metre tape was laid on a transect in the plot and the distance covered by vegetative matter, litter, mulch or other forms of cover measured and expressed as a percentage of the total distance. Soil erosion was measured on the observable erosion proxies as described in subsection 3.2.2 using 3-metre tapes. Slope gradients were obtained by a handheld slope metre. The geographic co-ordinates of the sample plots were collected by a GARMIN-45 hand-held global positioning system (GPS).

Erodibility data collection

Infiltration data, soil loss data and run-off data were collected using a portable Kamphorst (1987) rainfall simulator. The collected data were used to compute the erodibility of the soils. The runoff data and the sediment data were converted to sediment concentration (assumed erodibility of the soil) using a conversion formula provided by Kamphorst as:

$$Erodibility = \frac{S_{wt} * 1000}{R_{vol}} \qquad (3.3)$$

Where

S_{wt} = Weight of collected sediment in gms
R_{vol} = Volume of collected runoff water in mls

The results of the conversion represented the erodibility of the soils since the data was collected on constant slopes of 20% on bare pre-prepared soil surfaces according to Kamphorst (1987) which can be used as the *K-factor* in erodibility studies (Kamphorst, 1987).

Laboratory analysis

Soil texture, soil organic matter and soil nutrients were collected alongside the erosion and erodibility data. Their laboratory analyses were carried out according to the methods described by Hinga, et al. (1980). Organic Carbon was analysed using the Walkley and Black method (Black, 1965); available Nitrogen by the Kjeldahl digestion method (Black, 1965); soil pH in (1:2.5 soil-water suspension); available P by the molybdenum blue/ascorbic acid method (Mehlich *et al.,* 1962); and K by the flame photometer method. Results of the chemical analysis are shown in chapter 4, Table 4.1.

Procedure 4: Assessing soil erosion features in the field

The assessment of soil erosion features in the field was modified from Clark's (1980) method. Clark identified different erosion features that could be used for assessing soil erosion in the field. The features of erosion included: soil movement, surface litter translocated, extent of root exposure, pedestals, extent of rock exposures, extent of stem washing, occurrence of flow patterns, occurrence of rill erosion, occurrence of gully erosion, occurrence of mass movement or landslides. The features were only recorded if found to represent current soil erosion status on the erosion proxy being observed. Only data associated with recently occurring soil erosion was recorded to avoid comparison of erosion processes occurring during different time frames and formation duration. Data collection was restricted during the two to three weeks after the onset of the long rains. Both the depth and width of the occurring erosion features were measured in centimetres and recorded. Caution was taken to ensure that differences in the erosion features caused by the most recent rainfall storms are the only ones recorded. It is easily recognisable in the field and enabled the distinction between recent erosion and past erosion. Fresh soil disturbances in plants were recognised as freshly washed surfaces on the stems or roots, which contrast with disturbances by soil erosion processes that took place in the previous season or past years. Following below are the descriptions of the erosion features that were used to assess the occurrence of soil erosion.

Soil movement

This refers to the evidence of recent soil movement from their original positions to new locations by flowing water. Visible scouring and translocation features observable on the soil surface detect evidence of the soil movement by water. Other features include evidence of recent deposits around obstacles, or in micro-terraces and/or the depth of truncated areas. Pedestals are also other forms of evidence of soil movement. The visible features were attributed to raindrop erosion and overland sheet wash or interill erosion. To quantify soil movement, measurements are made in different parts of a field plot and each measurement recorded in centimetres. Depth of removal of soil around rock and stone fragments was also considered to be evidence of soil movement. The overall erosion in a plot is obtained by taking an average of three measurements from different locations in the plot. .

Surface litter translocated

Surface litter refers to dead plant material, leaf debris, grass or mulching material, which is found on the soil surface. The recent movement of the litter by surface runoff and overland flow were recorded for each site. In this case, the measurement was based on visual observations of the amount of litter disturbed by flowing water on the surface or of general movement of surface litter from a stable state to a state of disarray. The measurements were expressed as percentages of the movement on a site. The percentage was obtained by the amount of disturbance over a unit area. Like for soil movement, an average was computed from a minimum of three measurements.

Occurrence of flow channels

Flow channels appeared on the soil surface as previous water pathways during rainfall. They were easily detectable where surface litter occurred or where there were no herbaceous growth or grass growing on the soil surface. Where there was no surface litter, they appeared in the form of flowing water pathways. These were considered to be recent channels carrying the soil displaced by splash erosion into the rill or gully channels. The occurrence of flow patterns was considered to be evidence of soil erosion. Like surface litter translocation, flow patterns were recorded according to their intensity of occurrence within the field plot in percentages of the site being observed. An average of occurrence for the whole field plot was obtained from a minimum of three measurements.

Stem washing

Stem washing of old plant stems is also a good indicator of soil erosion. The depth of recent stem washing was obtained by observing evidence of recent water erosion around the base of the stem. It was possible to observe in the field basal rings on the stem showing the old soil surface compared to the new soil surface after an eroding rainstorm. Stem washing was examined and only if representative of the situation was recorded. Like all the rest, an average of the stem-wash values in centimetres was obtained from a minimum of three measurements. Figure 3.7 illustrates the evidence of stem washing.

Root exposure

Root exposure is like stem washing only that it indicates a more severe form of water erosion. It refers to the depth of recent soil removal around the plant roots due to, interill or channel erosion. Recent root exposure is clear in the field, as the washed portion of the root appears fresh when compared with the older surface. Evidence of the old soil surface can also be seen and compared with the new surface. Measurements were made of the new exposures that represent the distribution of the phenomenon in the field and an average obtained from a minimum of three measurements. Figure 3.8 illustrates root exposure as seen around plants or crops in the field.

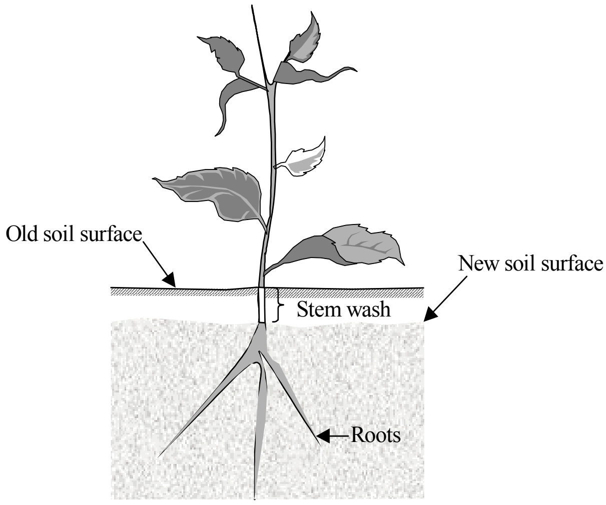

Figure 3.7 An illustration of stem washing around the stem of a plant

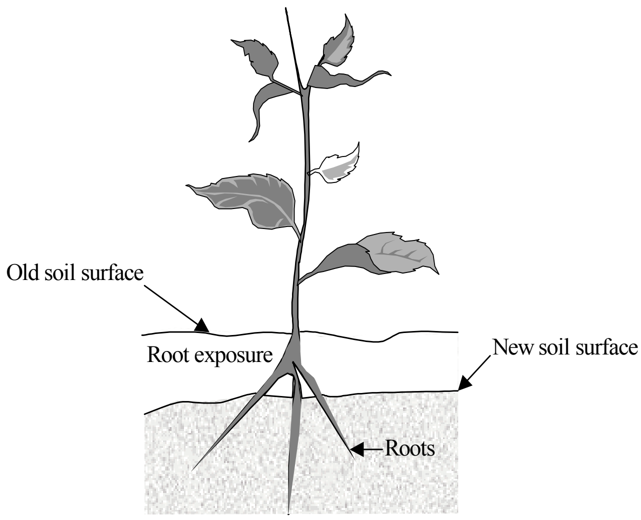

Figure 3.8 An illustration of root washing below the stem of a plant

Occurrence of rills

The occurrence of rills in the field or on footpaths, roads or commercial centres was also recorded. Width, depth and frequency of occurrence defined the severity of rill erosion. By definition, rills are less than 20 cm in depth with a maximum width of about 150cm. The frequency of occurrence is determined by the distance separating two neighbouring rills or by their coverage of a unit area in percentage. Interpretations of the occurrence of the rills depend on whether the feature entity is elongate or trapezoidal. The frequency of occurrence might be a more important attribute in a rectangular field, while the depth and the width might be more relevant for elongate linear features like roads and footpaths. Apart from the occurrence of rills on field plots, rills are also very good indicators of soil erosion at the watershed and landscape level where the extent of rill erosion occurring on the erosion proxies are measured. As for the other erosion features, rills were only recorded if found to predominantly occur in the erosion proxy being observed.

Occurrence of gullies

Gullies may occur in field plots, on roadsides and in commercial centres or in rangelands. Gullies are erosion features that are bigger than rills. Gullies are in most cases more than 20 cm deep with a minimum width of 30 cm. Gullies can be as wide as 15 metres or less. Their depths could also go up to 5 metres from their rims. The gullies commonly found in Kiambu vary in sizes depending on their causes and rates of development. Gullies were only used for characterising watershed and landscape level erosion proxies into erosion risk classes.

Occurrence of mass movements and riverbank slumps

Mass movements were recognised by the transportation of mass soil debris from a higher location within a hilly terrain to a lower position within the slope under the influence of gravity and water. These displaced soil debris are commonly referred to as landslides or mass movements. Landslides are commonly caused by differential water contents in the soil mantle in comparison to the saprolite or between the surface-horizon and the underlying sub-surface soil horizon where a shear boundary is created. Rapp (1963) distinguished three movement types: fall, slide, and flow. According to Lal (1990) two important factors of mass movement on steep lands are the soil strength and ground water conditions. Both factors are influenced by vegetation cover and in turn influence soil strength. Erosion along the banks of streams and rivers is caused by the force of running water and by undercutting. Their quantification was based on the degree of vertical displacement of translocated soil-mass.

3.2.3 Step 3 – Creating spatial datasets for hierarchical modelling

After collecting erosion data covering the entire area, it was necessary to create spatial data sets for predicting soil erosion risk in a GIS environment for the three levels defined in subsection 3.2.1. Both geometric and thematic data were necessary for this. This was a part of the descriptive modelling described in subsection 3.1.5. Table 3.3 shows how the different properties of the landscape holons were captured and incorporated as modelling attributes in the created spatial databases.

Procedure 1: Capturing multiple-hierarchic spatial data

The spatial datasets were captured in a GIS in an object data model having two components. The first components were the geometric data categories while the second components consisted of tables having attribute data of the spatial objects. The holon types and the erosion proxy types were captured as geometric data while the descriptive, and numeric attributes of the holons and the erosion proxies were entered as attribute data in tabular databases. The holon data types represented the levels in the landscape hierarchy while the proxy data represented the disrupters and drivers of soil erosion inside the holons. A listing of the possible erosion proxies and erosion features is shown in Table 3.2. Spatial attributes of the holon types, erosion proxy attributes and features of erosion are shown in Table 3.4.

Table 3.4 Spatial properties of the landscape holons and the erosion proxies

Landscape holons		*Erosion proxies	
Holon types	*Spatial & thematic attributes*	*Spatial attributes*	*Thematic attributes*
Landscape unit (Level III)	- geometry & shape - boundary - spatial extent - determines neighbourhood topological relations - is part of a higher land region - forms object class	- area objects - determines internal erosion proxy topology - spatial erosion risk modelling objects - are parts of the landscape unit	- slope gradient - ground cover - use - erosion condition - spatial proxy attribute data
Watershed unit (Level II)	- geometry & shape - boundary - spatial extent - determines neighbourhood topological relations - is part of the landscape unit - forms object class	- linear objects - determines internal erosion proxy topology - spatial erosion risk modelling objects - are parts of the watershed	- slope gradient - ground cover - use - erosion condition - spatial proxy attribute data
Field plot unit (Level I)	- geometry & shape - determines boundary - determines spatial extent - determines neighbourhood topological relations - is part of the watershed - forms object class	- area objects - determines internal erosion proxy topology - spatial erosion risk modelling objects - are parts of the field plot	- slope gradient - ground cover - use - erosion condition - soil erodibility - spatial proxy attribute data

* See details on specifics about the erosion proxies in Table 3.2.

Field-plot level data collection using aerial photographs

Nine sample areas were identified and selected to represent the field-plot holon types. The selected areas included: Githiga, Lynton, Gatono, Gatwikira, Kenyatta University, Ruiru, Kitamaiyu and Bradgate. The sample areas were selected to represent areas with differences in land use and geomorphology (landscapes). For field-plot level data, positive colour slides of aerial photographs taken by the Department of Resource Surveys and Remote Sensing (DRSRS) in June 1997 were developed as paper prints with scales varying between 1:5,000 and 1:10,000. The photographs showed the individual field-plots occurring in each sample area. A transparent film was overlaid on the aerial photographs before interpretation. The photographs were interpreted visually without the use of a stereoscope. Disjoint snapshot photographs of the study area represented each sample area. The individual field plots were visualised, isolated and separated based on their individual properties, which included crop type, shape, vegetation, field boundaries, colour, and tones. Each individual field plot was placed in a unique object class and allocated a unique number for its identification and characterisation in the field.

After the visual extraction of the individual field plots, the photo interpretation results were manually digitised into a vector GIS the PC ArcInfo. The same numbers allocated for each of the field plots was entered as the unique identifier of the specific field plot. Topology of the individual fields was created using ArcInfo's '*build*' command, which generated polygon topologies for all the digitised polygons. The generated coverage was then read in PC ArcView and a field map of the sample area generated each with unique field-plot numbers. This formed the field base map for the field data collection. The collected data included data on slope gradients, ground surface cover and type of land use. Other collected data included: type of erosion, i.e., root exposures, stem-wash, soil movement, rills, gullies, surface litter, observed flow patterns and channels and other relevant explanatory variables considered necessary for understanding the occurrence of the erosion features. A minimum of six ground points spread throughout each sample area were used as tic points during digitisation and their geographic co-ordinates captured in the field using a portable GPS equipment. The WGS 84 UTM co-ordinate system was used.

Watershed level data collection using aerial photographs

The same photographs used for delineating the field-plot level holon types were used to extract watershed level holon types. The erosion proxy objects selected and delineated included: field boundaries, hedges, footpaths, tracks, roads, streams, forest lines, etc. They were extracted based on their shape, appearance, texture and association with other neighbouring features. Similar procedures used to enter the geometric data in PC ArcInfo for the field-plot level data were used. Since most of the features had elongate morphological properties, their topology was created using the *'line topology builder'* in ArcInfo's 'build' command. They were built as lines and stored in an arc attribute table (AAT). The watershed level erosion proxies were also assessed for the occurrence of soil erosion in the field in the same way the field-plot level objects were assessed. Other data collected included slope gradients and percent cover of ground surface where it occurred. The same geographic reference points used for the field plot level observations were used for the watershed level observations.

Landscape level data collection using Thematic Mapper satellite imagery

The landscape level digital data was extracted from two sources: paper product satellite images, scales 1:100,000 and topographical thematic maps from the Survey of Kenya, scales 1:50,000. Data on rivers was digitised from the Survey of Kenya maps scale 1:50,000.

Roads, rivers, towns, and contour lines were digitised separately in ArcInfo. Like the two lower levels, polygon and line topologies were built for each of the data sets depending on whether the data were entered as geometric primitives or as line segments. Roads, contours and rivers were built as lines while towns and land use categories were built as polygons.

Procedure 2: Collecting field data systematically for prediction modelling

After preparing the spatial data sets for each of the holon types, paper maps were printed for each of the holon types representing the three levels of observation. The paper maps bore unique identifiers for the captured objects with their geographic locations. The maps for the field-plots and the watershed erosion proxies were carried to the field where slope gradient data, ground cover data, land use data, and other types of erosion proxy data were collected in pre-designed field forms. After the field data was collected, the data were entered into the earlier prepared GIS database tables. The datasets were now ready for predictive modelling in a GIS. For the landscape level, data on slope and surface cover were integrated by overlaying the towns, roads and rivers data with slope data (Figure 3.11) and cover data (Figure 3.12 and Table 4.2). These were subsequently considered to be ready for prediction modelling.

3.2.4 Step 4 – Determining statistical relationships and developing prediction models

Procedure 1: Relating erosion proxies with measured erosion features

In evaluating the existence of relationships between the erosion proxies and the presence of erosion, the occurrence of significant differences between the measured erosion on each proxy is used for confirming the differences in occurrence within the erosion proxies. This is the explanatory part of spatial modelling. From this process, it is possible to distinguish between the occurring erosion proxies (i.e. some drivers, some disrupters of erosion). The existence of features of erosion among the erosion proxies is assessed in the field. If erosion features are found, measurements are made to quantify the dimensions of the features and by extension the degree of erosion. The measurements include the width, and depth of the features as already described in Chapter 3. It is important to take note that soil erosion is a process, which in normal circumstances is difficult to measure. We can only measure and assess its effects. Effects include soil particles that are detached, entrained and deposited in barriers or collected in reservoirs and measured. The degree of soil scouring by water such as depicted by rills or gullies also offers an opportunity for quantifying soil erosion. According to Lal (1990) and Nill *et al.* (1996) features of erosion act as evidence of soil erosion. What does this imply? It implies that features of erosion can be used to quantify the degree of soil erosion (Ritcher, 1977; Stocking, 1987; Lal, 1990; *Nill et al.,* 1996). The measurements of features of erosion within the proxies create data that can be analysed statistically to prove that the erosion proxies are linked to soil erosion through its features and can therefore be used to model its risk. Before analysing the data, several null hypotheses are postulated for statistical testing. The null hypotheses postulated were that:

- The selected erosion proxies did not relate to the occurrence of soil erosion; and
- Differences between the individual erosion proxies if any had no statistical significance and erosion differences observed could have occurred by chance.

The null hypotheses as stated were either accepted or rejected through descriptive statistics and through the analysis of variance (Jongman *et al.,* 1987 and Snedecor and Cochran, 1989). Two statistical packages STATISTIX for Windows developed in the U.S.A by Analytical Software (1996) and SPSS were used for all the data analysis presented in this work. Results of the analyses are presented in Chapter 6.

Procedure 2: Selecting predictor variables using correlation statistics

Correlation analysis was used to determine the factors of erosion that had significant correlation with the measured erosion on the erosion features (i.e. slope, cover, and erodibility, etc) which are all properties of the erosion proxies. Factors with significant correlation coefficients in a multiple correlation analysis were selected as the main variables for predicting erosion risk using logistic regression. Results of the correlation analyses are presented in Chapter 7.

Procedure 3: Formulating the prediction models for spatial risk modelling

In most prediction modelling, collected data is analysed by regression analysis to determine the relationship between two or more variables for which association or relationship is sought (Jongman *et al.,* 1987; Analytical Software, 1996). When dealing with landscape features, the prediction of one variable from another using the normal linear regression prediction is sometimes complicated in that the response variable being investigated is sometimes present at the observation site and at times absent in areas where it is expected. Treating such data using the parametric linear regression becomes unrealistic due to the presence of too many zeros in the data. Instead of analysing such data using parametric methods, the measured response variable data are first converted to presence or absence categorical data and logistic regression used for prediction modelling. When making observations in the field, if the sought response is encountered, the particular case is allocated a value 1 for presence. If nothing is encountered the case is allocated a value 0. Field sampling methods usually involve visits to predetermined random points where presence or absence is recorded. Logistic regression is then used to obtain the estimation parameters of the explanatory variables. The parameters are afterwards entered into the prediction equations to model or predict the response variable.

Prediction response data (i.e. erosion feature attributes) and the determinant attribute data (i.e. cover, slope gradient, soil erodibility, etc) are collected simultaneously as described in Section 3.2.2. A functional relationship between the response variable and the determinant independent variables is determined through multiple logistic regression techniques. After the prediction equations are developed, they are used to manipulate independently collected spatial data having both geometric and thematic determinant values. The thematic values are used for the computations while the spatial attributes are used for visual display of the objects. Results of the computations are displayed in a GIS as spatial areas having different values of predicted erosion risk. The predicted risk values are stored as thematic values in the GIS database while the spatial attributes inherit the geometric shapes of the erosion proxies. Some proxies are modelled as area objects while others as line objects. Object oriented modelling is applied.

Logistic regression has been used in many landscape studies to predict the occurrence of particular events or conditions from known independent variables (examples include; Sanders, 1999; Hosmer & Lemeshow, 1989; Jongman *et al.,* 1987; Analytical Software 1996). Logistic regression attempts to express the probability that an event or feature is present as a function of the independent or explanatory variables. Field sampling methods usually involve visits to predetermined random points where presence or absence is recorded.

Many of the data collected in this study had many cases of absence or presence of erosion. On analysing the data with the normal parametric linear regression, the R_{adj}^2 obtained ranged from 0.045 to 0.3005 meaning that the fraction of variance accounted for, lay between 0 and 30%, the rest 70% of the variance being unexplained due to the presence of too many zeroes. Another handicap with the zero values was that during analysis, they were considered to be readings of the variable for which covariance and R_{adj}^2 are computed in a linear model. Logistic regression therefore offered better opportunity for developing the prediction probabilities, since it entirely deals with 1 and 0s as the values of the response variable.

Logistic regression is explained as follows. The equation of the straight line $E_y = b_0 + b_1x$ is not satisfactory for presence and absence data because $b_0 + b_1$ can also be negative yet presence and absence data lies between 0 and 1. This difficulty is solved by taking the exponential curve, thus *(Ey),* which is the predicted response is obtained by the expression: $Ey = exp\ (b_0 + b_1)$. According to Jongman *et al.* (1987), this can also be a problem as the right side of the exponential equation can be greater than 1. So the curve can once more be adapted to:

$$Ey = p = \frac{[\exp(b_0 + b_1x_1 + b_2x_2)]}{[1 + \exp(b_0 + b_1x_1 + b_2x_2)]} \tag{3.4}$$

Where:

b_0 is the intercept of y-axis
b_1 is the constant for variable x_1 (i.e., either slope or cover)
b_2 is the constant for variable x_2 (i.e., either slope or cover)

This curve satisfies the requirement that its values are all between 0 and 1. The part $(b_0 + b_1x)$ is termed the linear predictor. For probabilities, *p* instead of *Ey* is used (Jongman *et al.,* 1987). As a continuation, equation 3.4 can also be written as:

$$Log_e\, [p/(1-p)] = linear\ predictor \qquad (3.5)$$

The response in this case can have only two values, i.e. 1 or 0 hence the error distribution is the binomial distribution with a total of 1. The variance of y is therefore *p(1-p)*. The left side of equation 3.5 is termed the link function of the generalised linear model (GLM, McCullagh and Nelder, 1983).

In GLM, the parameters are estimated by the maximum likelihood principle. The likelihood of a set of parameter values is defined as the probability of the responses actually observed when that set of values were the true set of parameter values (Jongman *et al.,* 1987). The maximum likelihood principle says that we must choose that set of parameter values for which the likelihood is maximum. A measure of the deviation of the observed responses from the fitted responses is the residual deviance, which is $-2\ \log_e L$, where L is the maximum likelihood. In general, the parameters of a GLM must be calculated in an iterative fashion as in the least squares regression (Jongman *et al.,* 1987). Provisional estimates of parameters are updated several times by applying repeatedly a weighted least square regression, in which responses with a small variance receive a larger weight in the residual sum of squares than responses with a large variance. In logistic regression, the variance of the response is obtained by *p(1-p)*. So the weight depends on the fitted value of *p* and hence on the parameter estimates. Calculations must therefore be iterative and mostly done using a computer package designed for it.

The good thing about the logistic response function is that it can be linearised easily (Neter *et al.,* 1996). Since the response probability *p* from equation 3.4 is a probability, when the response variable is a 0 or a 1 which are indicator variables, then *p* can be transformed as follows:

$$p' = \log_e\left(\frac{p}{1-p}\right) \qquad (3.6)$$

The transformed p' according to (Neter *et al.,* 1996) can be written as:

$$y = p' = b_0 + b_1 x \qquad (3.7)$$

The transformation of *p'* is called logit transformation of the probability *p*. The ratio *p/(1-p)* in the logit transformation is called the odds. The transformed response function $b_o + b_1x$ in equation 3.7 is referred to as the logit response function, and *p'* is called the logit mean response. The logit mean response has a range of values from -∞ to ∞ since the predictor variables range between -∞ to ∞. b_0 and b_1 are obtained from logistic estimation of the parameters. The logit linear predictions were used for validating the predicted erosion with independently collected data on erosion features.

3.2.5 Step 5 – Producing outputs and validating predicted erosion risk for decision support

Procedure 1: Integrating the prediction models with spatial data sets

After the development of the spatial datasets for the three levels as described in section 3.2.3, the polygon attribute tables (PATs), or the arc attribute tables (AATs) are exported as Dbase files from Arc-View GIS. Before this is done, it is ensured that the GIS tabular database contains both geometric and thematic attributes of the object classes for which erosion risk is to be modelled. Thematic data include slope gradients, ground cover and the object class. Geometry and topology data include nodes, edges, x, y locations of the nodes and edges and object topology. Prediction variables must be added as thematic attribute data within the spatial database. Pre-named prediction fields are added within the thematic attribute structure of the tabular database. The following section describes the steps for applying the prediction models at each level of the landscape hierarchy. The sequential procedures from data collection to the prediction modelling are shown in Figure 3.9.

Field-plot level data

Field plot level erosion proxy data are stored as area geometric primitives in the spatial data set. Slope and cover data are added as thematic attributes to the tabular database of the spatial objects. If more variables are desired for the prediction modelling, they must be included in the structure of the tabular database and their attribute values added. These are linked to other existing attributes of the database such as area, polygon-id, and all automatically generated data of the topology, i.e. nodes, vertices, edges, areas, etc. The data can be entered in Arc-Info Arc-Edit module using the interactive data entry *'Forms'* command or entered in Arc-View's table editing module. When the plot data set is completed the PAT file is exported into the statistical package or an excel package. The logit predicted erosion or probabilities of erosion are then computed. After the computations, the data are re-exported to ArcView GIS. After re-exportation the classification module of Arc-View is used to display the image according to the desired number of probability or prediction classes using automatically graduated values in the software as may be desired. When the results are satisfactory, a cartographic layout is prepared of the image and all cartographic requirements added. The map is then ready for validation using existing data, or it is taken to the field for validation.

Watershed level data

The watershed level data is treated in the same way as the plot level data. The only difference is that instead of polygons, line topology is used instead of polygon topology to capture and display the erosion proxies of the watershed. Prediction equations specifically created for the watershed level erosion proxies are used to compute the probability values and the predicted erosion. The same procedures used for the plot level data are used again for the watershed data. The results are similarly displayed in Arc-View. The erosion proxy data and the holon spatial and thematic are linked by spatial overlay methods in Arc-info (i.e. *identity, union,* etc. commands) before displaying the results in Arcview.

Landscape level data

The landscape level procedures are a little bit more complex. The road network data are first buffered on each side with a buffer distance of 8 metres to represent its actual occurrence in real geographic space in Arcinfo. Rivers are similarly buffered with an 80 metre buffer distance on each side to cover the valley sides, to coincide with riverbank erosion and massive soil slumps and erosion. Before proceeding, the slope map earlier developed as described in section 3.2.2 is combined with the land use map to create an overlay of the two maps, the '*identity*' or '*union*' commands in Arc-Info is used. The roads, rivers and towns inherit slope and cover data from the slope data and cover data when *'intersected'* with the slope-cover overlay map. After this, the attribute data of the river buffers, the road-buffers and the town areas are used to extract slope and cover data from the overlaid data sets so that only the road buffers, river buffers and the town areas geometry are displayed. The *'intersect'* command of ArcInfo is used. Prepared prediction algorithms are then used to compute erosion risk for the GIS data sets produced.

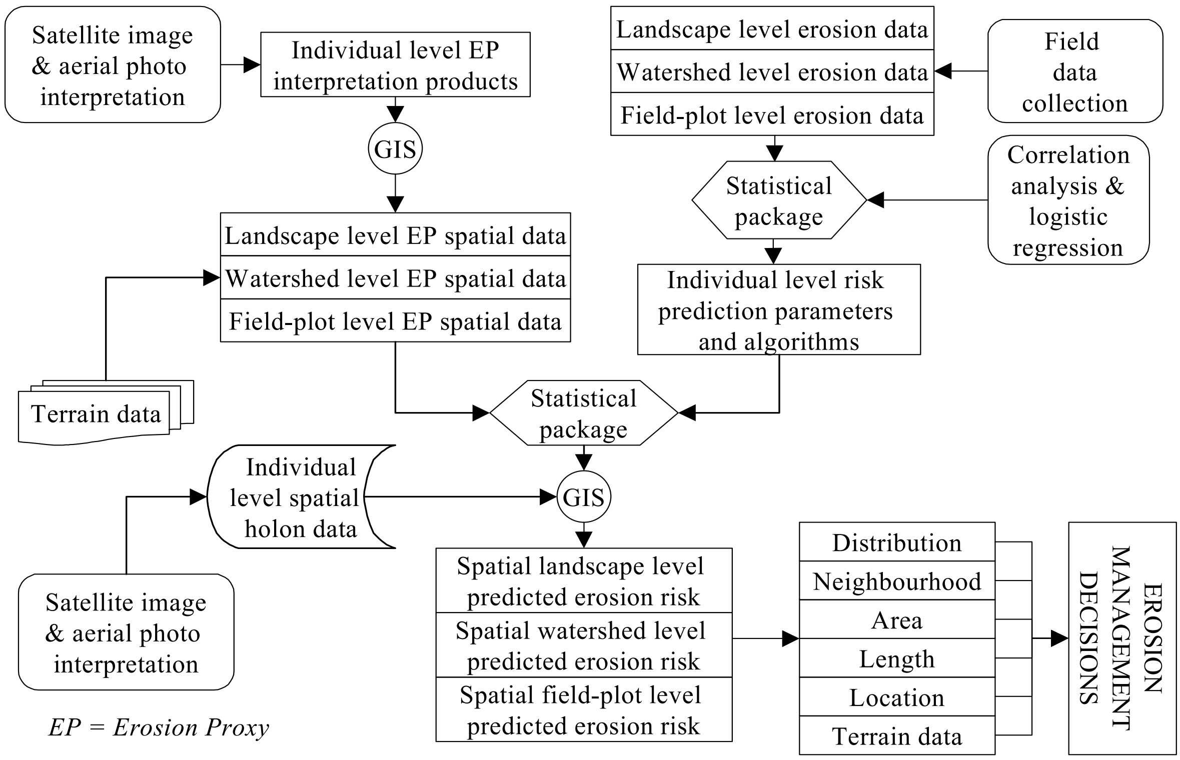

Figure 3.9 Spatial erosion risk prediction from data collection to management decisions

Procedure 2: Validating the predicted risk

Field validation methods

Section 3.2.3 showed how spatial GIS data were captured from aerial photographs and satellite images for prediction modelling. All in all there were two categories of field data collected. The first set was described in section 3.2.2. This set of data was used for creating the prediction models. The second set of data collected was used for validating the predicted risk of erosion on independently captured and predicted spatial data.

In order to validate the results, independent soil erosion features data were collected from the same field plots where the predictions had been made. Timing of the field data collection for the erosion is important as the season when the data is collected determines the possibility for observing the erosion features. Data collection after heavy rainfall storms two to three weeks after planting yield the best results for both annual and perennial crops. Timing of data collection in the perennial crops should coincide with periods immediately after the onset of the long or shorts rains (i.e. the first two or three weeks on before weeds obscure visible features of erosion). Validation data is also supposed to be collected at random and to cover about 10% of the total sample population in order to be economical on costs. The validation data collected for individual field plots should include: soil movement, surface litter translocated, extent of root exposure, extent of stem washing, occurrence of flow patterns, and occurrence of rill erosion. The same erosion features are required to validate the watershed and landscape level holon types in addition to data on gullies, mass movement or landslides depending on the erosion proxies encountered in the different holon types.

Statistical validation methods

Correlation statistics offers a good opportunity of comparing two independently collected data sets. In many statistical problems, there is need to compare sets of data in terms of the extent to which a change in one set is reflected by a change in the other set. The focus is not upon differences but upon degrees of association. This implies that the individual items of the two sets of data co-exist either in time or space, such that the possibility of interrelated changes can be considered. In correlation statistics, an index is required that reflects the degree to which changes in any direction (+ or –) and magnitude in one set of data are associated with comparable changes in the other set. Indices of this sort are termed correlation coefficients and are designed to range from +1 (perfect positive correlation) through zero to –1 (perfect negative correlation). Pearson's product-moment correlation was used because the validation data was in parametric interval scale form. In the Pearson's product moment correlation, an evaluation is made on the degree of direction (+ or –) by which the deviations of the data from the mean of compared data sets vary when all the data is parametric. Equation 3.4 shows how the Pearson's product-moment correlation coefficient is obtained.

$$(r) = \frac{\frac{1}{n}\sum(x-\bar{x})(y-\bar{y})}{\sigma_x.\sigma_y} \qquad (3.8)$$

Where:

x, y = two sets of data x, and y

x-bar and *y-bar* are the individual means of the two data sets

σ_x and σ_y are the respective standard deviations

The student's *t-test* is used to test the significance of the correlation and is based upon the sample population. During validation, predicted erosion values are compared in a correlation analysis with the independently collected data on soil erosion features. To be safe in making any of the interpretations of significance, the correlation coefficient should always be tested by Student's *t* test. The *Student's t* distribution uses the following formula:

$$t = \frac{r.\sqrt{n-2}}{\sqrt{1-r^2}} \qquad (3.9)$$

Where:

n = the number of pairs of data studied
n-2 = the degrees of freedom
r = the correlation coefficient

The significance of the students' test is obtained from the graph of significance (Figure 3.10) which relates the degrees of freedom, the r-value and the Student's t distribution.

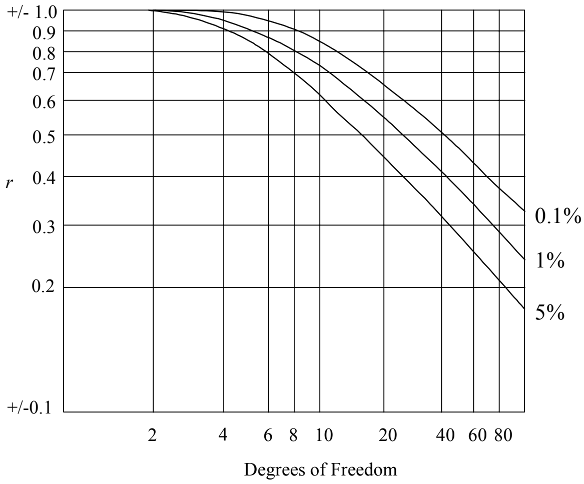

Figure 3.10 Graph of significance levels for correlation coefficients using Student's *t* distribution

The results of the findings, validation and recommendations are documented in chapters 5, 6, 7, and 8 which are presented in the subsequent chapters of this thesis.

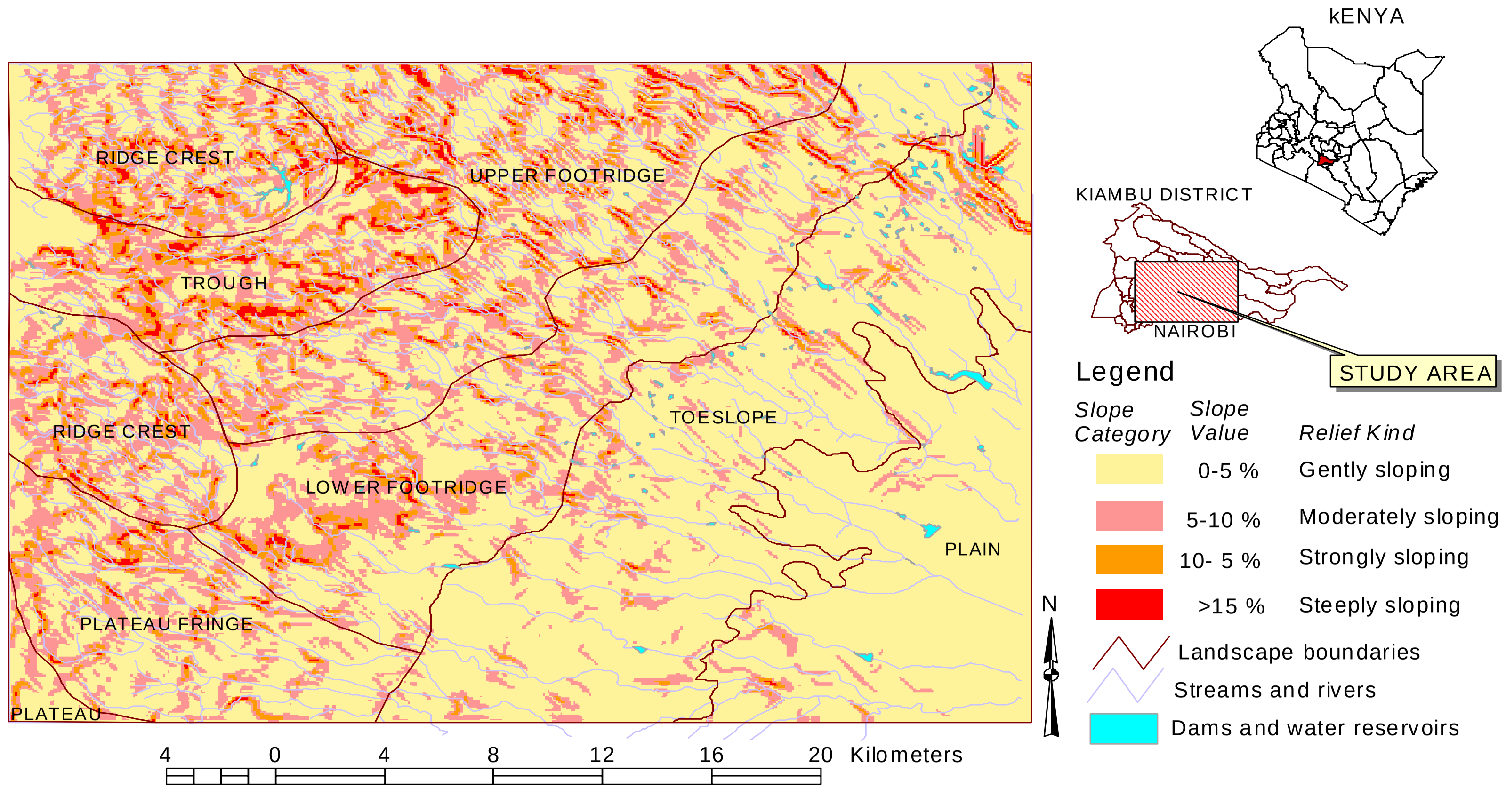

Figure 3.11 Slope and landscape units in the study area

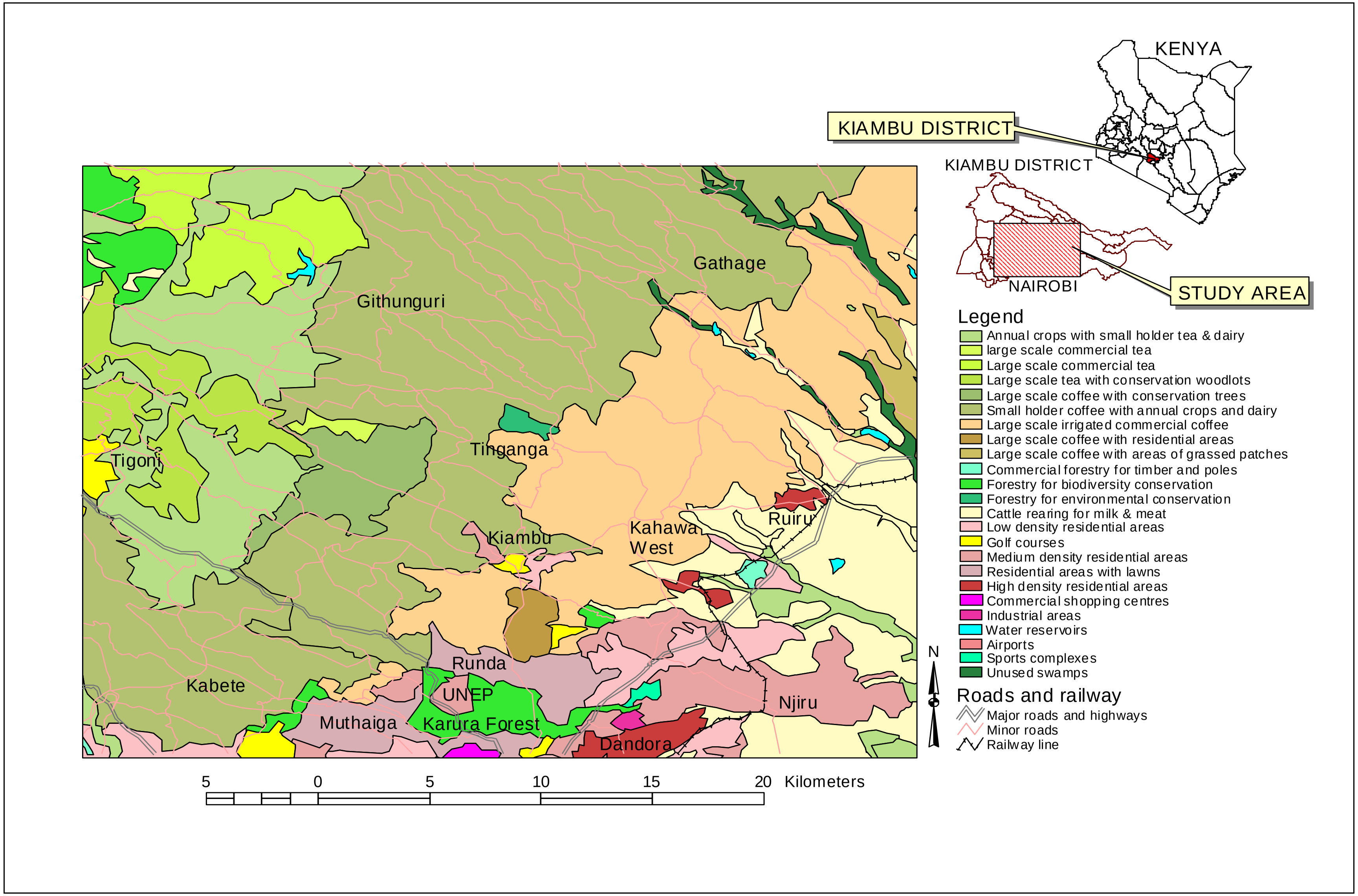

Figure 3.12 Distribution of the major land use kinds in the study area

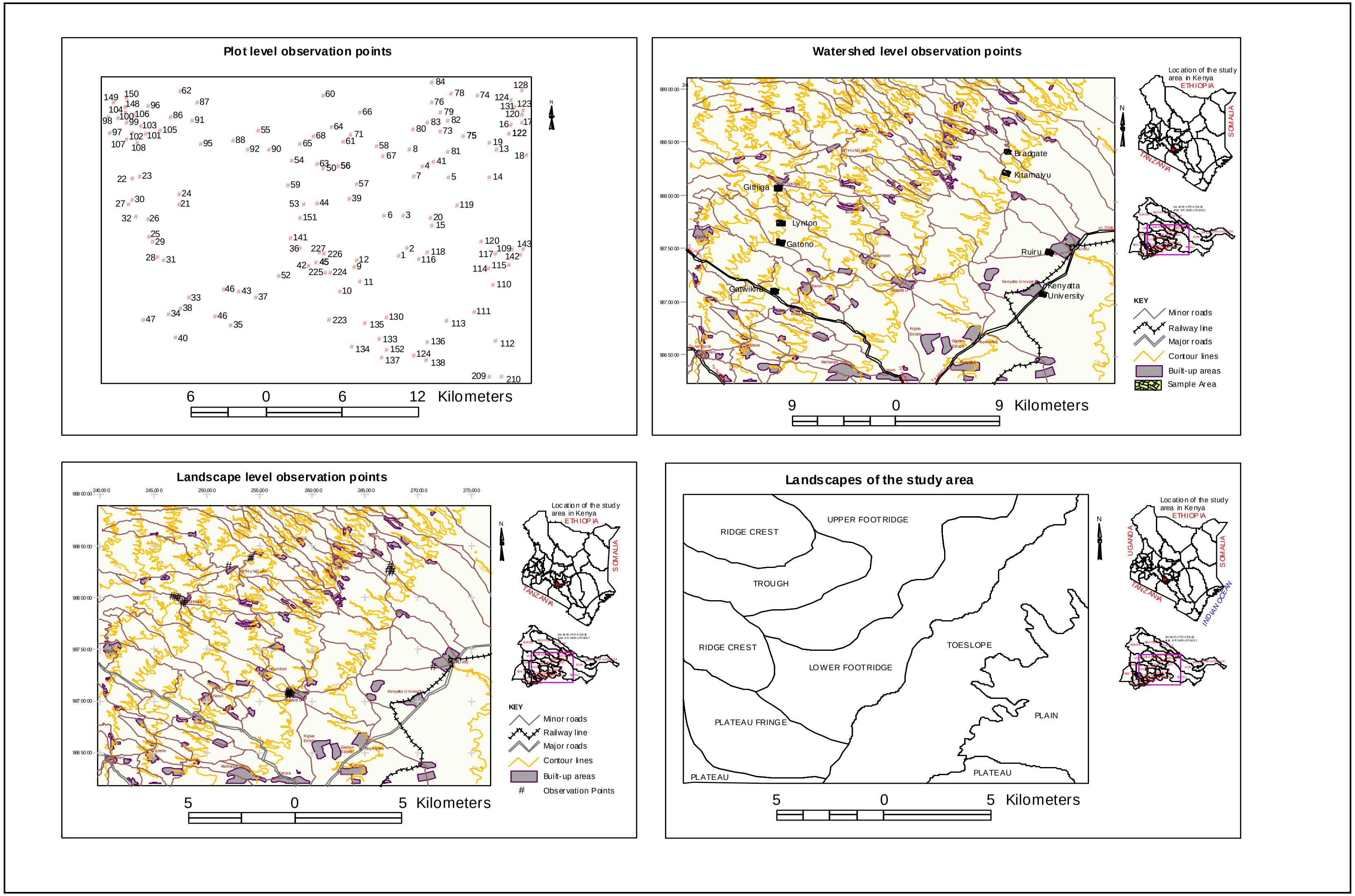

Figure 3.13 Location maps of the observation points in the study area

4

The Study Area

The study area

This chapter presents a description of the study area in terms of location, climate, geology, geomorphology, soils, land use and population. The study area was selected due to its proximity to the city of Nairobi. The area is experiencing rapid land use changes and beneath canopy soil erosion which is hidden to vintage view due to high vegetation vigour.

4.1 Location of the study area

The methodology was tested predominantly in Kiambu district and parts of Nairobi province. Kiambu district lies between latitudes 0° 46' and 1° 31' south of the Equator and longitudes 36° 30' and 37° 20' east of Greenwich. It boarders Nairobi province to the South, Muranga district to the North, Machakos district to the East and Nakuru and Nyandarua district to the West. It is well linked to the bordering districts by tarmac and all weather roads, airstrips in private large-scale farms and modern postal and telecommunication services. Figure 4.1 shows the location of the study area.

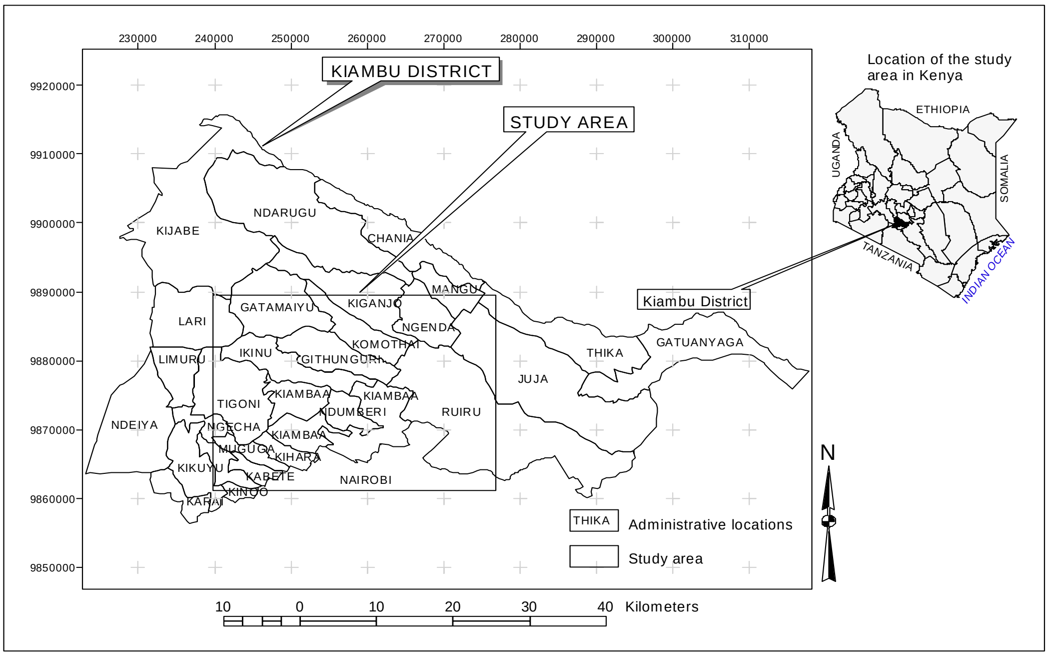

Figure 4.1 Location of the study area in Kenya and parts of Kiambu and Nairobi districts

4.2 Climate and agro-climatic zones

Rainfall in the study area is mostly influenced by altitude. The mean annual rainfall ranges from 500 mm in the lower parts around Thika to the east of the study area increasing gradually to 2000 mm in the upper region of the district in the Northwest of the study area. The rainfall regime is bimodal with the long rains falling in April and May. The rainy season is followed by a cool dry season during the months of July and August. The short rains fall from October to December. Figure 4.2 derived from Sombroek *et al.* (1980) shows the climatic zones of the study area. The highest rainfall is recorded in the Kikuyu Escarpment in the Northwest (climatic zone I-7 in Figure 4.2) and decreases progressively towards the low areas of Munyu Ngoliba in the Southeast (climatic zone V-4 in Figure 4.2) and Ndeiya-Karai in the Southwest (climatic zone III-5). The mean annual rainfall for the district is 1100 mm. To the east of Kiambu town (climatic zones III-4, IV-4 and V-4), the rainfall decreases from 900 mm in the centre of Figure 4.2 to 600 mm at the borders in the eastern parts. On the side west of Limuru (i.e. climatic zones II-4), the mean annual rainfall progressively decreases from an average of 1000 mm in the zone to 700 mm towards the Southwest. The middle and northwestern parts of the study area receive an average annual rainfall ranging between 1000 to 2000 mm with the middle parts having the lower rainfall and northwestern parts the highest rainfall. The areas north of Nairobi (South of the study area) receive between 800 and 1000 annual average rainfall.

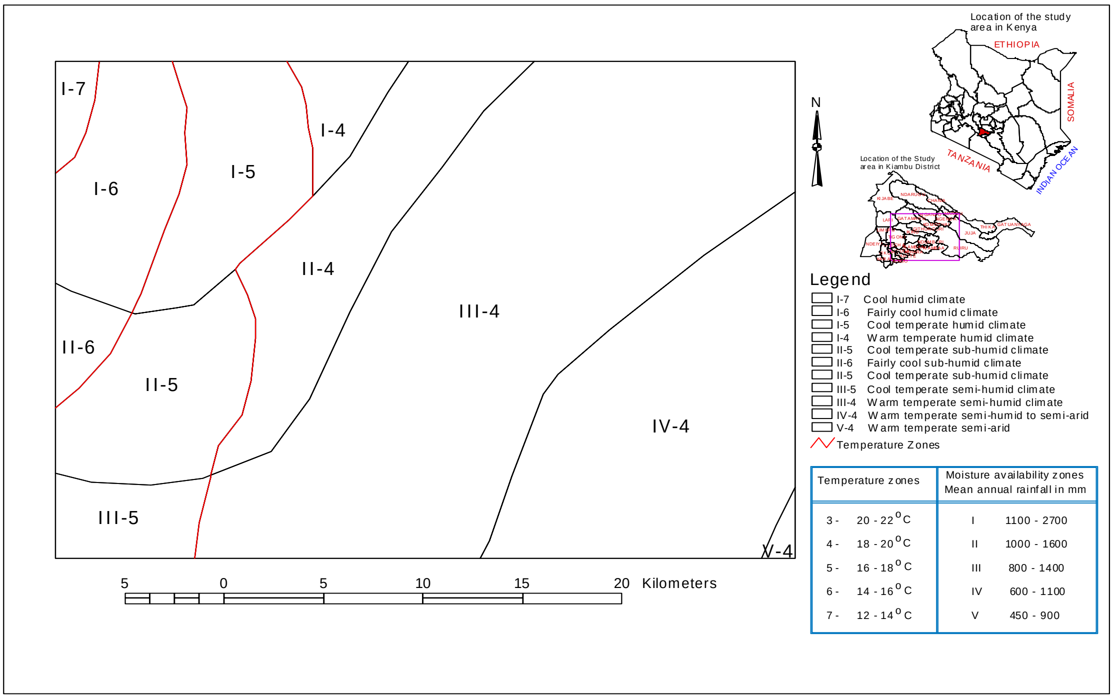

Figure 4.2 Climatic zones of the study area (Source: Sombroek *et al.*, 1982)

The mean maximum temperatures range from 26^{o} to 28^{o} C in the East and the Southern parts. Temperatures ranging from 18^{o} to 20^{o} are experienced in the Northwest. The mean minimum temperatures vary between 14^{o} and 16^{o} in the eastern parts and 6^{o} to 8^{o} in the northwestern parts. According to Sombroek et al. (1980), the climatic zones range from Zone V-4, which is fairly warm, semi-humid to semi-arid in the southern parts to Zone I-7, which is cool and humid in the northwestern parts.

Climate soils and rainfall patterns dictate the agro-climatic zoning in the study area (see Figure 4.3 developed by Jaetzold and Schmidt (1983). The climatic zones are coded as UM1, LH1, UH1, and UH2 respectively. UH refers to the upper humid zone and LH to lower humid zone, UM refers to the upper moist zone and LM to the lower moist zone. The humid zones are wetter than the moist zones. The drier southeastern parts fall in the Livestock-sorghum *(Sorghum vulgare)* zone and the Sunflower *(Helianthus annuus)*-Maize *(Zea mays)* zone according to. The central parts of the study area fall in the marginal and main coffee zones respectively. The drier parts in the Southeast fall in the Wheat *(Triticum aestivum)*-Barley *(Hordeum vulgare)* and

Wheat-Maize-Pyrethrum *(Chrysanthemum cinerariaefolium)* zones. The north and northwestern parts fall in the Coffee *(Coffea arabica, Coffea canephora)* -Tea *(Camellia siniensis)* Zone, Tea-Dairy Zone, Sheep Dairy Zone and the Pyrethrum-Wheat *(Triticum aestivum)* Zone.

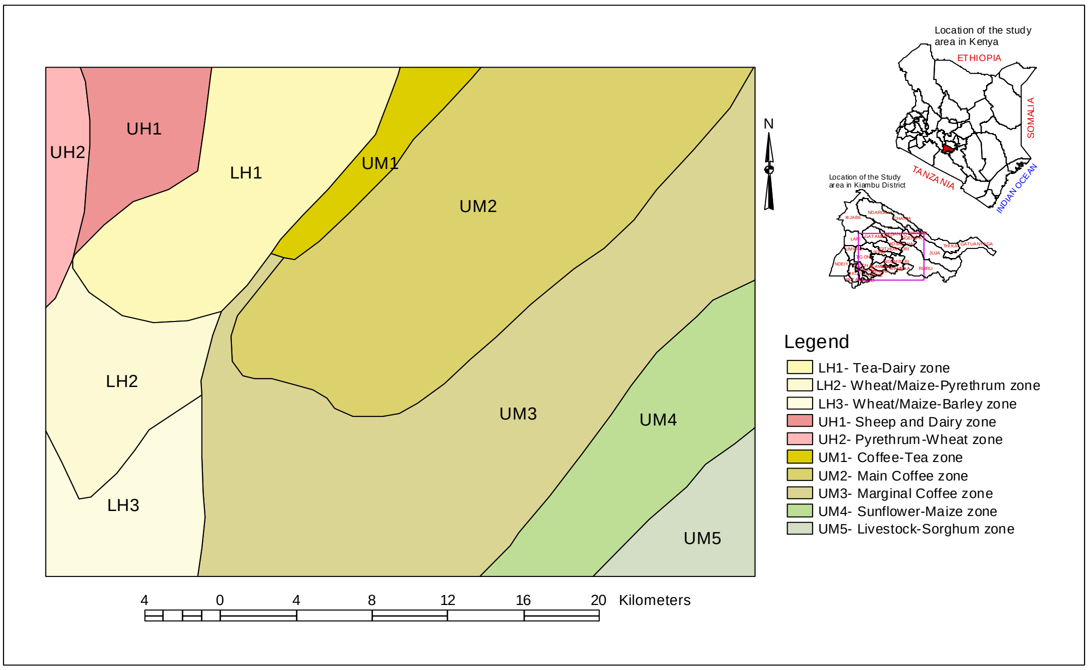

Figure 4.3 Agro-ecological zones of the study area (Source: Schimdt, et al., 1985)

4.3 Geology and geomorphology of the study area

According to Saggerson (1967), the study area is mainly composed of volcanic rocks of varying ages. The geological history and rock composition has led to the development of various geological rock formations and landforms. To the northwest of Kiambu town, the geology varies from Miocene to Pleistocene volcanics. This is mainly in the Aberdare Mountain Ranges. Towards the south of these ranges where Kiambu district borders Nyandarua district, the Sattima series occur. These are dominantly intermediate and basic lavas. The Pleistocence volcanics are grouped into four broad classes; The Upper trachytes, the Middle trachytes, the Middle and Upper Kerichwa Valley tuffs, and the Lower Kerichwa Valley tuffs. The Upper trachyte division includes the Kinari tuffs and the Limuru trachytes. The Middle trachytes are composed of the Tigoni, Karura, Kabete and Ruiru Dam trachytes. To the East of Kiambu town, the geology ranges from Pliocene to the Pleistocene Basalts and intermediate lavas of the Laikipian and Sattima series to the Miocene Basalts of the Simbara series and Pyroclastic rocks deposited on eroded surface of the Simbara basalts. The Simbara basalts occur in the central and southern parts of the study area. In the direction of Kamiti Kahawa, the geology is composed mainly of Tertiary volcanics. These are predominantly trachytic tuffs and agglomerates on the plateau surface. The Kapiti phonolites and the Simbara basalts and agglomerates are exposed in the major valleys.

The topography of the study area is shown in Figure 4.4. To the northwest of Kiambu town the landscape is represented by a high level mountain range (the Aberdare Mountains). Long slopes

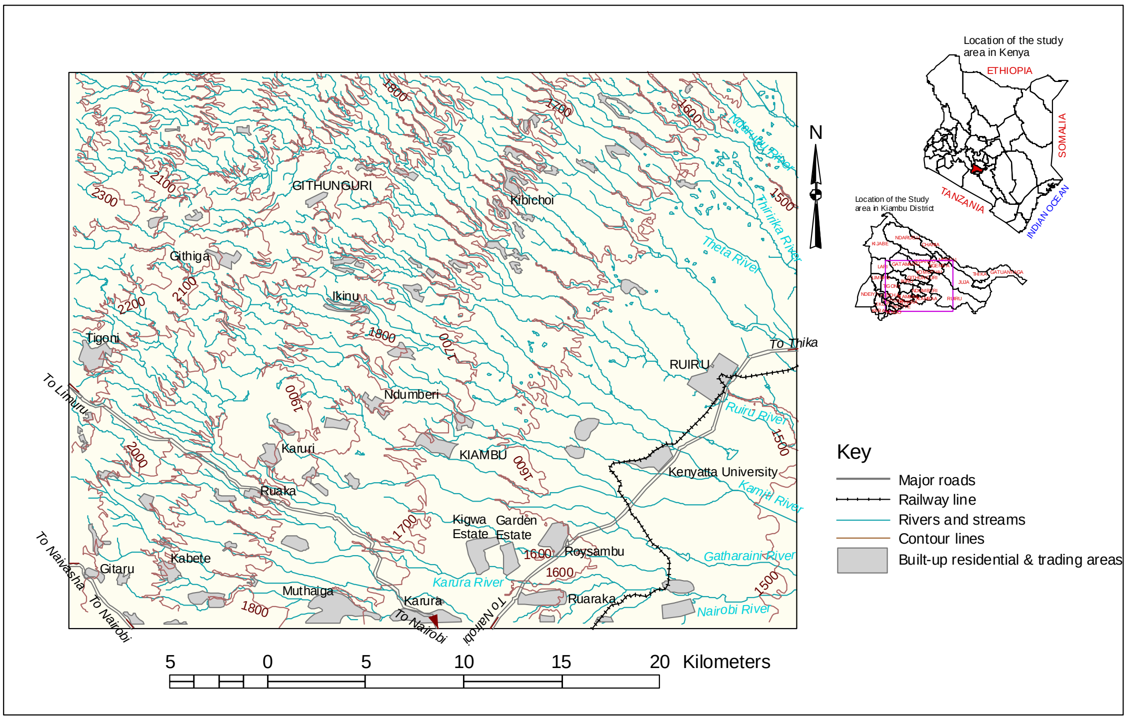

Figure 4.4 Topography of the study area

leading to narrow valleys with occasional crags and rocky hills characterise the geomorphology of the mountainous landscape. The mountainous landscape changes to low interfluves and flat bottomed valleys extending back from the top of the Rift Valley Escarpment to the footslopes of the Aberdare Ranges in the direction of Kinale. Further to the Southwest of Kiambu town, in the direction of Kikuyu, the landscape changes to long narrow approximately parallel ridges separated by narrow winding valleys of varying widths and local streams. To the East of Kiambu town, the landscape changes to an extensive toe slope with broad long undulations and gentle depressions and occasionally dissected by winding, steep sided, flat-bottomed valleys in places very wide. The areas to the east of Nairobi are characterised by a plain landscape where occasional low hills occur.

4.4 Soils of the study area

4.4.1 General

Figure 4.5, extracted from Sombroek et al. (1980) shows the distribution of the soils in the study area. The distribution of the soils in the study area is directly linked to the geomorphology of the area. The lower parts in the plains are mainly occupied by Ironstone soils, Lithosols and Vertisols according to Sombroek *et al.* (1980). Eutric-Nitisols and Nito-chromic Cambisols mainly occupy the toe slopes of the volcanic foot ridges. Humic Nitisols, Mollic Andosols and Ando-humic Nitisols occupy the volcanic foot ridges and Humic Andosols occupy the upper ridge crests of the study area.

Several authors in different parts of the study area have carried out more detailed work on soil characterisation and classification. Shitakha (1983) mapped the soils on the toe slopes currently under large-scale coffee cultivation *(i.e. Coffea arabica & Coffea canephora)*. He described the soils as well drained, strongly weathered, extremely deep and dark red to dark reddish brown friable clay soils. According to him the topsoils had medium, moderately strong, sub-angular blocky structure while the B-horizons were slightly hard when dry, friable when moist, sticky and plastic when wet. The soils were acidic with pH in the topsoils varying between 6.0 and 6.6 and between 5.1 and 6.6 in the B-horizons. Cationic exchange capacities (CEC) varied between 19.0 and 34 cmol/kg in the topsoils and 10 to 28 cmol/kg in the B-horizons. He classified the soils as Mollic and Humic Nitisols according to the FAO-UNESCO (1974) Soil Map of the World.

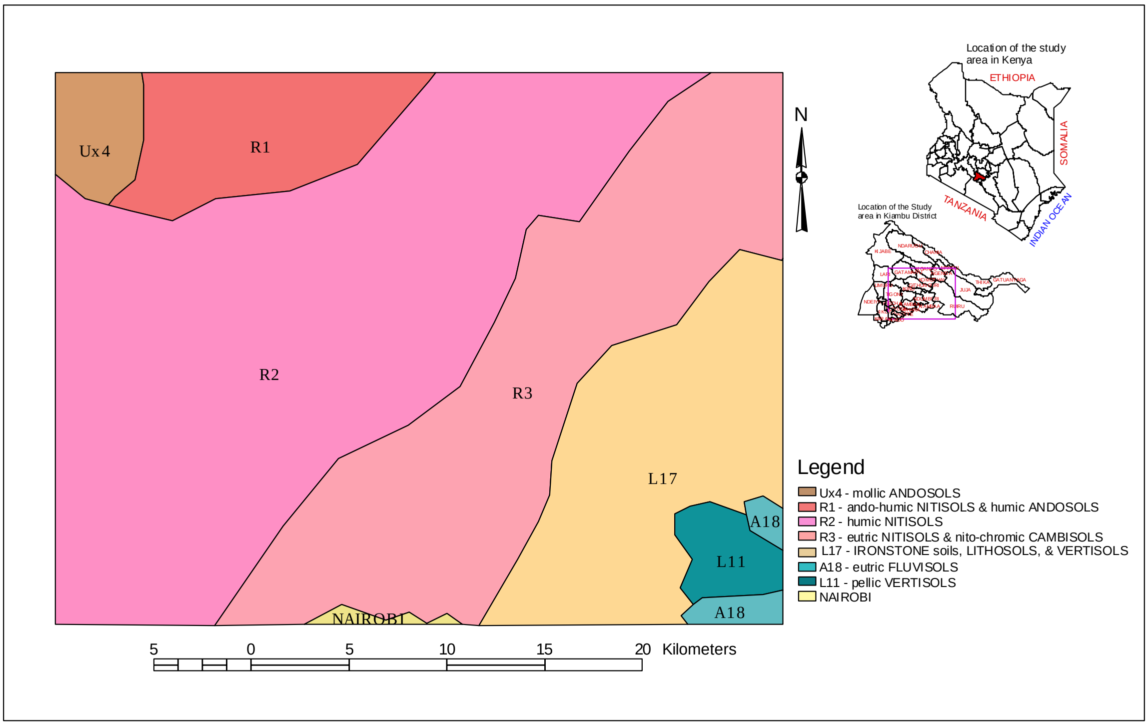

Figure 4.5 Distribution of soils in the study area (Source: Sombroek et al., 1982)

Siderius also working at the National Agricultural Research Laboratories, and an in the same geomorphologic environment classified the soils as clayey, kaolinitic, non-calcareous, acid, isothermic, very deep Paleustults in the USDA (1975) system of classification. They classify as Humic Nitisols in the FAO-UNESCO (1988) Revised Soil Map of the World.

It can be said that most of the study area is dominated by Nitisols. Nitisols according to the FAO (1977), are generally soils with an argic B-horizon, with clay distribution, which does not show a relative decrease from its maximum by more than 20% within 150 cm of the soil surface. They show gradual to diffuse horizon boundaries between the A and B-horizons and have nitic properties in some sub-horizons within 125 cm of the soil surface. The Nitisols, which cover about 50% of the study area are well-drained, dark red to dark reddish brown clay soils with good structures and high infiltration rates. The depths vary between extremely deep soils (in the flatter areas) to moderately deep in the steeply sloping parts. Most of the soils have a high concentration of organic matter in the topsoil. The Vertisols, which occupy the plains, are poorly drained, dark coloured soils with wedge-shaped or parallel prismatic structures. They are shallow to moderate in depth with few pockets that are deep. Areas to the Northwest of Kiambu town have Andosols as the predominant soils. The Andosols are low bulk density soils (bulk density less than 0.85 gm/cm^3) developed on volcanic ash and tuffaceous deposits. They are extremely deep, well drained with pockets that are poorly drained in bottomland areas. Planosols, Lithosols and rock outcrops are found in the Southwestern parts of the district along and adjacent to the rims of the Rift Valley Escarpment. Planosols are moderately deep to shallow, moderate to poorly drained soils that support semi-arid and grass vegetation. Lithosols are limited in depth by the presence of a continuously hard rock within 10 cm of its surface.

4.4.2 Sampled soil properties

Table 4.1 shows the physical and chemical properties of the topsoil of the soils collected during the study.

Table 4.1 Average values of measured soil properties in the study area grouped according to land use (150 samples covering the entire area)

Soil Properties	Land Use						
	Coffee	Coffee & Macadamia	Fallow	Forest	Grass	Intercrop (annual & perennials)	Tea
Sand (%)	22	25	18	31	24	23	20
Silt (%)	20	26	22	32	21	25	20
Clay (%)	58	49	60	37	55	52	60
Silt/Clay ratio	0.3	0.5	0.4	0.9	0.4	0.5	0.3
KE (gm/l)	19	10	24	11	11	27	19
SOC (g kg^{-1})	2.2	2.5	2.9	3.8	2.9	2.9	3.5
pH-H_2O (1:2.5)	5.3	4.9	4.9	5.2	5.2	5.2	5.5
S-P (mg kg^{-1})	51	122	138	128	108	87	47
S-K (mg kg^{-1})	1.1	1.0	0.4	0.9	1.1	1.0	1.1
S-Ca (mg kg^{-1})	5.7	5.9	5.3	9.3	5.4	6.4	6.3
SEC (mmhos/cm)	0.2	0.3	0.2	0.3	0.3	0.2	0.3

KE = Kamphorst Erodibility; SOC = Soil Organic Carbon-Walkley and Black method (Black, 1965); S-P = Soil Phosphorous (Mehlich et al., 1962); S-K = Soil Potassium (Flame photometer method); S-Ca = Soil Calcium (Ammonium acetate method, pH 7); SEC = Soil Electrical Conductivity (1:1.5 soil:H_2O ratio)

From the data in the table it can be seen that nearly all the soils have high clay-contents (i.e. equal to or greater than 50%). It is only the forest soils that have lower clay contents (i.e. 37%). It shows that most forests are occurring on young moderately weathered soils, mostly on steep land. The erodibility determined by the Kamphorst (1987) seems to vary according to the clay contents and the kind of land use. The coffee-macadamia soils, forest soils and the grasslands have the lowest erodibilities (i.e. 9.5, 10.7 and 11.1 respectively). The soils with the mixed annuals and perennial crops have the highest erodibility with a mean sediment concentration value of 27.1 gm/l. This is followed by soils in the fallow land and thereafter by soils of the tea plantations. All the soils in the area have low pHs with the values varying between 4.9 and 5.5. Phosphorus contents vary according to land use with the fallow land having the highest accumulations (138 mg kg^{-1}) and tea the lowest (46.9 mg kg^{-1}). Soil organic carbon values range from 2.2 g kg^{-1} in the coffee plantations to 3.8 g kg^{-1} in the forested land. The tea plantations also have high organic carbon contents with a mean value of 3.5%. Soil calcium ranged from 5.25 mg kg^{-1} in the fallow soils to 9.3 mg kg^{-1} in the forest soils.

4.5 Land use, land tenure and its history

4.5.1 Current land use

Land use categories in the study area follows closely the pattern of the agro-ecological zones and soils distribution pattern. The current land use pattern is a relict of the pre-independence Swynerton (1954) land use plan. The Swynerton Plan had an objective of maximizing land output through deliberate planning of rural land.

Land use in the study area can be grouped into five broad classes; i.e., the intensive smallholder mixed farming, large holder tea *(Camellia siniensis)* and coffee *(Coffea arabica)* farming, grazing grasslands and ranches, nature conservation forests, and built up areas.

The smallholder mixed farming includes: subsistence mixed farming of annual crops and zero grazing, cash crop farming of tea, coffee and horticultural crops, which are sometimes intercropped with maize *(Zea mays)* and beans *(Phaseolus vulgaris)* for food. Most of the smallholder farms are between three and five acres. In extreme cases the farms are less than half an acre, which hardly supports a single farm household. In these farming systems, family members working in Nairobi bring in extra income.

Table 4.2 Mean values of soil surface cover and slope by the different land use or cover kinds

Land use/cover	% Mean cover	% Mean slope
Bare	10	28
Coffee	68	8.3
Fallow	70	3.5
Forest	92	8.7
Grass	73	4.2
Intercrops of annual & perennial crops	65	11.2
Coffee with macadamia	69	9.2
Tea	82	20

In larger holdings, the farm sizes are mostly more than ten acres having a single crop. Examples are the coffee and tea farms in the area. Individual farmers own some of the tea and coffee estates. Private companies run many of the coffee estates. Examples of private coffee estates are Machure Estate and Socfinaf Company. Privately owned large estates include Farly Dam, Kipenda Estate, and Menengai Estate, which also own large tea plantations. Coffee and macadamia *(Macadamia integrifolia)* are grown as intercrops by Nando and Bob Haris estates. Anak Estate and Sukari Ranch keep grade cattle and local breeds for the production of milk and beef. They also grow forage on their large estates. The large estates with tea are located in Limuru, Tigoni, Githiga and Kambaa. Kiambu, Ruiru and Juja are areas of large-scale irrigated coffee cultivation. Small-scale tea and small-scale annual crops are found in Githunguri, Githiga and the adjoining areas. Small-scale coffee and annual crops are grown in Kiambu, Ikinu, Waruhiu, Kikuyu, Gachie, and the adjoining areas. Grasslands and ranches are mostly found in Ruai. Sisal used to be grown in areas around Juja and Thika in large-scale European farms. Conservation forests are found in Uplands and Kereita in Lari Division and in Karura Forest. Some plantation forests are also located in the large-scale European farms such as the Socfinaf group of estates. Measured cover and slopes associated with land use and vegetation kinds in the entire study area are shown in Table 4.2.

4.5.2 History of the land use in the area

Originally when the European settler first came into contact with the Kikuyu, the native inhabitants of Kiambu, the traditional system of land tenure and land use was the '*'githaka' system*' (Beech, 1917). 'Githaka' means land and the term included all of the land owned by '*mbari*', an extended family or sub-clan. The traditional type of agriculture was entirely of a subsistence nature. Although each 'mbari' may have had a fairly large acreage, only part of it would be under cultivation at any time. Each man within the 'mbari' owned a small portion of land known as 'ngundu' as his individual holding (Taylor, 1966). After clearance, cultivation on a 'ngundu' seems to have been continuous. The common land of the 'githaka' seems to have been used for communal grazing, part of it being given to each male when he came of age. Once the elders had granted a man land it was himself and his dependants who cultivated the land. There seems to have been no new land issued to a landholder of the 'mbari'. The average individual holding size was 3.7 acres with a range of 1.1-5.1 acres (Meinertzhagen, 1957; Taylor, 1966). Shifting cultivation appears to have been practised but there is little reliable information on the form that this took.

In the traditional Kikuyu agricultural pattern both seasonal and perennial crops played a part. The chief seasonal crops were millet *(Eleusine coracana),* maize (*Zea mays*), beans (*Phaseoulus vulgaris*) and other pulses. Millet was by far the most important cereal crop and was planted in the short rains. A local sorghum *(Sorghum bicolor)* of a sweet white variety was also planted. These were considered minor crops. The chief long-rains crop was the bean 'njahi' scientifically known as *Dolichos lablab.* Cow peas *(Vigna citiana)* and pigeon peas *(Cajanus indicus)* were also planted during the long rains. The chief perennial crops were bananas (Musa spp), sugarcane (Saccharum spp.), sweet potatoes *(Ipomea batatus),* cocoyams *(Colocasia antiquorum)* and yams *(Dioscerea Minutiflora).* Sheep and goats were also kept and herded communally on the common land of the 'mbari'.

The traditional pattern of land holding and agriculture began to change when the Kikuyu came into contact with Europeans (Barlow, 1934). By 1920, they were confined to their own area and surrounded on all sides by land alienated to the Europeans. The first result of this was that the common land in 'githaka' was rapidly brought under cultivation as individual 'ngundu'. With the common land of the 'mbari' exhausted and all of the land in the Kikuyu reserve occupied, the systems of a sub-clan control of land began to decline rapidly and the individual began to play an increasingly important part. It is from this time that fragmentation of land became an increasingly important problem. By 1930 almost all of the common land had been used up and as there was no new land available, the only source of land for a young man was from the subdivision of the father's holding.

The fragmentation of land had negative impacts such as declining soil fertility, and lower economic returns. This period also saw the introduction of new crops and the conception of selling agricultural surplus for cash. Soil erosion became an increasing problem as the population density increased. As land became scarce, even slopes of 30^o and more were utilized without any precaution being taken (Taylor, 1966). The topography of the area and the growing of maize on the same land year after year made the situation even worse. The problem culminated into political agitation and violence by the 1950s (Taylor, 1966). In (1952-1960), a state of emergency was declared and this precipitated the introduction of the Swynerton Plan in 1954. It was during this period that the people were forced by the colonial administration to take action against soil erosion. The Swynerton Plan paid attention to eight main points: the consolidation of fragments, security of land tenure, technical assistance to develop land on sound lines, the introduction of marketing facilities preferably of co-operative nature, access to sources of agricultural credit and agricultural bias towards education.

Originally, the Swynerton Plan aimed at a very careful planning of land use, to be carried out after consolidation in three stages: the minimum standard layout, the simple farm layout and the farm plan. In the minimum standard layout, all farm buildings are sited so as not to obstruct subsequent development. The farmer was advised to plant food crops on slope less than 20^o, cash crops on slope between 20^o and 35^o and trees and permanent grass on slopes greater than 35^o. This established a basic land use pattern, which once established, was difficult for the farmer to change. The aim of the plan was the fullest possible use of the land. The farmer was given detailed advise on phased development of his holding and assisted in obtaining superior quality livestock and seed to create a self-sufficient and sustaining unit independent of loan capital.

Such careful land use planning proved to be beyond the resources of the Kenya Government then. Only the minimum standard layout was adopted on all the farms by 1960. Though the other stages of land use planning were not implemented and only 20% of the holdings reached the simple farm layout stage, the Swynerton Plan introduced coffee and wattle trees *(Acacia mearnsii)* as cash crops in Kikuyuland. It also introduced pyrethrum *(Chrysanthemum cinerariaefolium)*, tea, pineapples *(Ananas comosus)* and tobacco *(Nicotiana tabacum)* on a lower scale. Originally coffee was restricted to European farms prior to 1950. Reasons for the restrictions being quality and quantity control. Later coffee was extended to Kikuyu holdings with very good success in quality. It was difficult then to control quantity.

There is no doubt that the Swynerton Plan initiated an agricultural revolution in Kikuyuland and brought about a great increase in the wealth and standard of living of the people. Increases of upto 2,000% in monetary incomes were realized by the 1960s (Taylor, 1966). Though successful, the plan had its shortfalls. Land consolidation actually intensified landlessness and refragmentation. By 1962, the ratio was half an acre to the individual (ROK, 1964). After independence in 1963, further changes in land use took place as some former European lands were subdivided and taken over by African farmers and natural forests converted to commercial farming. To date the effects of the changes in land use and reduced individual land holdings on soil erosion are not well documented. Areas under severe threat of soil erosion are not precisely known and mapped. This creates the need to study the effects of land use on the occurrence of soil erosion. Such a study will provide information on areas suffering higher soil erosion risks. The identified areas with their inherent characteristics will form the basis for soil erosion control and management.

The current land use distribution in Kiambu still has a major semblance with the original designs of the Swynerton Plan. Most of the settlements are on the crests of the interfluves, with annual crops following on the upper shoulder slopes. The cash crops are mostly planted on the midslopes and napier grass on the lower slopes. Wattle trees occupy the stream banks as a gallery forest and source of firewood. The land use kinds in the study area are shown in Figure 4.6. The land use kinds were abstracted from the satellite image shown in Figure 4.7.

4.6 Population

Kiambu district is densely populated and has a population of 1,438,458 people according to the 1989 Republic of Kenya, Population Census (ROK, 1989). The mean density is 588 people per square kilometre, whereas the 1979 census (ROK, 1979), the population showed a mean density of 280 people per km^2. The data shows that the population increases at a rate of 6.05% per year. The ever increasing population in Kiambu district besides intensification of agriculture requires more land than the currently available land which is suited to agriculture with low erosion risk. This is the reason that farming in the area is encroaching the otherwise fragile steep slopes and forests formally left under natural vegetation to protect against soil erosion.

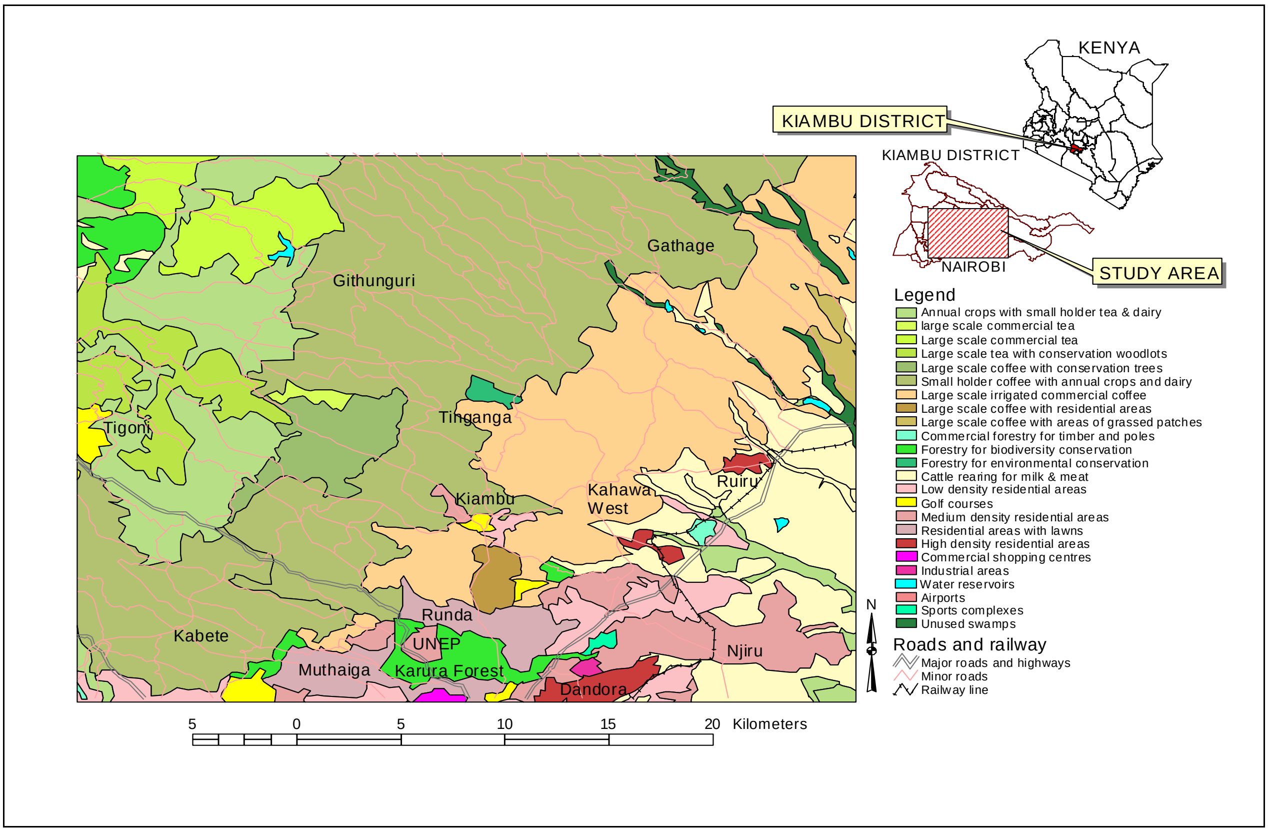

Figure 4.6 Land use kinds in the study area

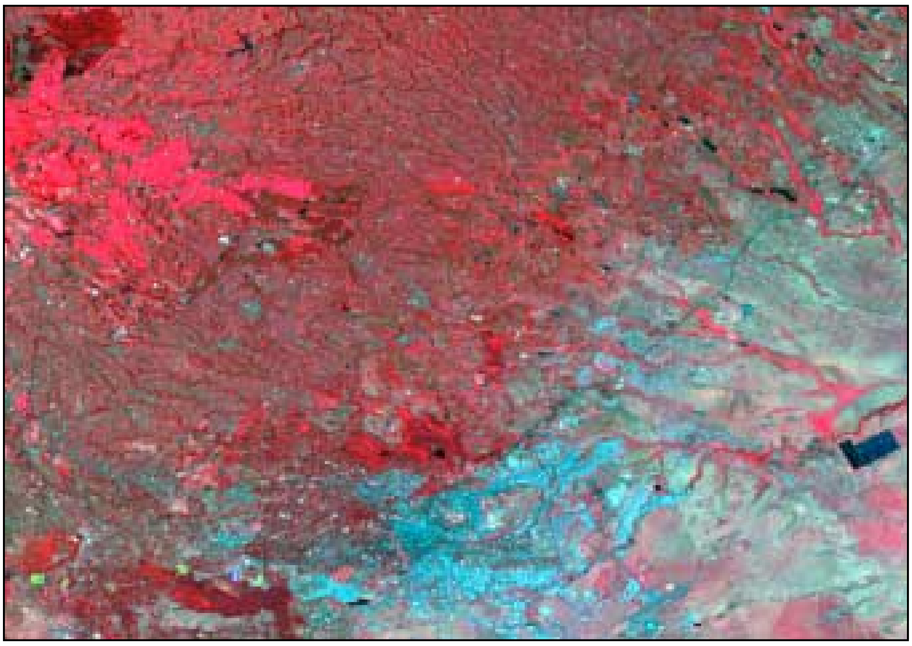

Figure 4.7 A Landsat satellite TM image combination of bands 4, 3 and 2 on red, green and blue false colour composite of the study area taken on 19th January, 1995.

5

Capture of the Spatial Data using Satellite Images, Aerial Photographs and GIS

Chapter 5

Capture of the spatial data using satellite images, aerial photographs and GIS

This chapter presents the results of the spatial capture of landscape features for predicting soil erosion risk as defined in Chapter 3 and occurring in Kiambu and parts of the adjoining Nairobi area where the method was tested. The presentation includes the ordered hierarchical levels and landscape features representing each level, the identified erosion proxies for each level, the objects extracted through interpretation of aerial photographs and satellite images and key findings from this process. The objects described and created in this chapter represent the spatial objects for modelling soil erosion risk in the landscape.

5.1 Holons of the three hierarchical levels

From the procedures presented in section 3.2.1, it was possible to identify three levels of the landscape-space continuum for modelling soil erosion risk. The landscape elements representing the three-level landscape system hierarchy are shown in Figure 5.1. The three defined levels offered the best solution for an asymmetric ordering of the landscape system for soil erosion assessment and risk modelling. It is necessary to mention that it was not easy to find landscape features above the landscape unit to create additional levels that meet the requirements of hierarchy theory for soil erosion assessment and risk modelling. This might be possible for other purposes other than for soil erosion assessment but still possible if appropriate soil erosion drivers can be identified that correspond to a land region.

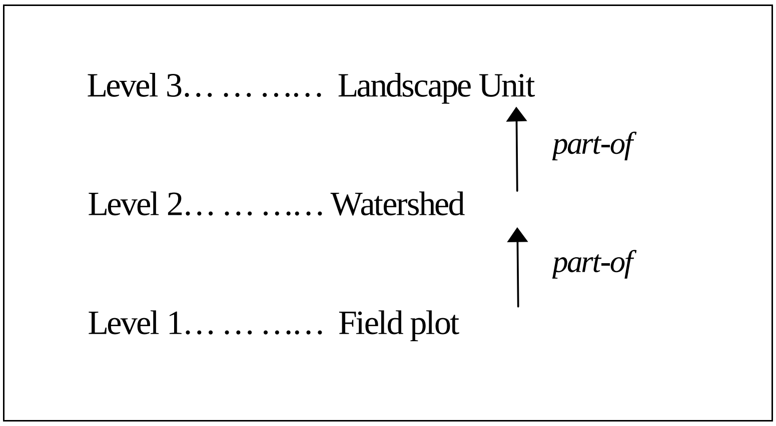

Figure 5.1 Spatial hierarchical ordering of landscape entities as used in this thesis

Other considerations of landscape features lower than a field plot would be the choice of slope facets as defined in a catenary hierarchy by Wielemaker *et al*. (2001). This is possible because slope facets have boundaries and can demarcate slope differences in the field plots. Due to working logistics, it was decided that the three levels were adequate for testing this methodology. Intermediate levels like having a farm between the watershed and the field-plot was not possible due to lack of major hierarchical difference such as asymmetry between the farm and the field plot. A farm as a landscape element can sometimes lack discernible boundaries and in most cases lack internal homogeneity. Higher levels than the landscape unit such as a land region of Forman (1995) is possible so long as one is able to find erosion proxies that are linked to that level of hierarchical construction (see Figure 5.2b). Allen and Hoekstra (1990) and Forman (1995) (Figures 5.2a and b) have provided other examples of hierarchical levels and ordering in ecology. The conventional levels of Allen and Hoekstra (1990) of organisation in ecology (Figure 5.2a) do not correspond to multi level spatial landscape system organisation. The hierarchic levels are a mixture of organisms and landscape elements, which do not correspond to hierarchical organisation of a landscape system using spatial attributes. It is therefore not appropriate to borrow the

levels from it. They have discussed this deficiency of the mixing thematic ecological classification and landscape features and the contradictions that the different levels present in spatial modelling (Allen and Hoekstra, 1990).

Level 8 ………..Biosphere
↑
Level 7………..Biome
↑
Level 6 ………..Landscape
↑
Level 5 ………..Ecosystem
↑
Level 4 ………..Community
↑
Level 3 ………..Population
↑
Level 2 ………..Organism
↑
Level 1 ………….Cell

Figure 5.2a

Level 5 ………….Planet
↑
Level 4 ………..Continent/Oceans
↑
Level 3 ………….Region
↑
Level 2 ………...Landscape
↑
Level 1 ………Local ecosystem

Figure 5.2b

Figure 5.2 Organisational ordering in ecology and land according to Allen and Hoekstra (1990) and Forman (1995)

Forman's (1995) notion that *drainage basins, catchments, and watersheds* are sometimes too wide in size and therefore not good for spatial hierarchical organisation is not a view held in this thesis. In this work, first, basins, watersheds and catchments were distinguished as three different landforms each with its own definition and configuration. The disadvantages such as having poor boundaries for delimiting animal, human, and wind-driven flows or protecting home ranges, are outweighed by the opportunities watersheds offer for the task of assessing water flows in soil erosion processes. Moreover, in this particular case, the matter of interest is the containment of soil erosion processes within a particular landscape element in a particular hierarchical level of assessment and modelling. Watersheds, due to their concave, basin-like architectural cross-sectional profiles create perfect boundaries for internal water and matter-flows making them ideal landscape-holons for erosion processes. Lal (1990) also settled for watersheds as good landscape elements for studying soil erosion. Basins also, by definition are different from catchments and watersheds. Basins are extensive land units, which include all tributaries, catchments, sub-catchments and major channels of a single river from points of origin to their estuaries and can traverse several landscapes. They are therefore heterogeneous and open systems in behaviour, origin, and formation processes making them unsuitable for use as landscape-holons for erosion risk modelling in a small area. Watersheds and catchments have also been defined and it is established that catchments are sub-sets of watersheds.

5.1.1 Description of the landscape holons

Field plots

The field-plot is defined as an elementary individual of the landscape system created by human activity. The size as defined is 4 x 4 m (16m^2) in size or larger. The possession of a boundary is an important element for recognition because the boundary separates the internal erosion processes from erosion processes in other neighbouring field-plots. Falling at the lowest level, the field plot is both an observational and an agricultural domain. It is well recognised as a land use unit and as an experimental unit in research studies. A field-plot is also recognised by the farmer as an area of uniform agricultural practise.

In this thesis, the interior of a field plot is considered as an encapsulated region where soil erosion processes are catalysed by the internal properties of the field plot and are different from processes outside it. Soil surface cover, slope gradient, soil erodibility and conservation measures, for example, dictate the occurrence of soil erosion in the field plot. The cover could be both in the form of vegetation or other kinds of cover such as surface mulch. Different crops and different land use kinds provide different cover conditions. Slope steepness and soil erodibility of the plot are controlled by the landform facet where the field plot is situated, and the geology of the rocks upon which the soils are developed. The erosion processes in a field-plot plot are dominated by interill erosion (raindrop and shallow flow erosion or overland erosion).

An individual farmer or members of his family normally control the farming practice inside a field plot. External influence on the utilization of a field-plot may emanate from government policy such as broad land use planning or the need of certain farming practices such as soil and water conservation. Others could be geared towards specific land use planning.

Soil conservation policies affecting the field plot would therefore be different from those affecting the watershed or the broader landscape unit and would be mostly directed towards the individual farmer.

Field plots have internal properties with spatial attributes that cause the occurrence of soil erosion, the erosion drivers. Parallels to these are features that disrupt the occurrence of erosion, the disrupters of erosion. For the field plot, the drivers of erosion are perceived as the space occupied by the plot and the crop, vegetation or other land use that is part of the field plot. The combination of area and its vegetation or cover constitutes the spatial modelling object. The measured slope gradient, the ground cover, the crop or use type and soil erodibility form the properties of the plot that are allocated attribute values and can be used for their description and classification. The erosion proxies and the kind of soil erosion features that could occur in a field plot are shown in Table 3.2.

The watershed

Watersheds are defined to include both the catchment area and the drainage channels within a single morphometric divide of a drainage system. Several watersheds can be nested within the same landscape unit. The boundaries of the watershed demarcate the morphometric divide between two watersheds. The divide also separates the erosion processes in one watershed from those of the other. According to this thesis, the erosion processes in a single watershed are dominated by channel erosion (i.e. rills and gullies). Watersheds also exhibit *'holon wholeness'* in a hierarchical system with a dual tendency that preserves and assert its individuality as a quasi-autonomous whole and functions as an integral part of an existing or evolving larger whole. Field-plots being parts-of a watershed in an agricultural environment are inherited upwards by the watershed but on the understanding that they remain as individuals with their own domineering individual erosion processes. Watersheds being smaller landscape elements are normally part-of the broader landscape unit. The erosion processes inside the watershed are constrained by the properties of the higher-level landscape unit.

Instead of soil erosion processes driven by area attributes, the erosion processes in a watershed are more influenced by channel erosion. Soil erosion is driven by the presence of flow conduits in the watershed. Therefore the presence of elongate or linear features in the watershed, provide the driving factors for the occurrence of soil erosion. Exploring the occurrence of soil erosion therefore entails the inventory of elongate features associated with waterflow. Examples include field-plot boundaries, footpaths, animal tracks, etc. Other features, which disrupt the flow process and soil erosion also exist. They are also mostly elongate features. Examples include compound hedges, tree lines, grassed field boundaries, hedged field boundaries, riparian forests, etc. The elongate driving and disrupting erosion features (proxies) are shown in Table 3.2. The risk of erosion due to these proxies are also normally linked to the terrain steepness of their geographic positions and whether they are bare or covered by vegetation or mulch. These erosion proxies are also linked with the occurrence of erosion features (i.e. scouring or depositional). Details of the possible erosion features are shown in Table 3.2.

Any single person or individual does not manage a watershed being a naturally formed geographic feature. Its protection and use is connected to the people living in it or that of an external authority such as a regional authority or a regional government concerned with the management of the area. The watershed can therefore be a good landscape feature for soil and water conservation for communities living in it. Management policies governing the conservation policies of the watershed would therefore be different from those governing the individual field-plots. The policies could emanate from the resident members or from an external authority. Those living inside it must come together to conserve it. A leader or committee can be selected to oversee the conservation with technical support coming from individuals, institutions, non-governmental organisations or the state.

The landscape unit

The broader landscape unit is selected as the highest-level in the hierarchical system construction. Landscapes are herein defined to be areas where ecological unity appears to be similar all through. In a landscape unit several attributes of the land (i.e. genesis, geomorphology, lithology, soils, land cover, land use, local faunas, human aggregations) tend to be similar and repeated across the whole area'. This coincides with the definition given to the landscape by (Schoorl, 2002). Landscape units are normally several kilometres wide. In this thesis, geomorphology provides the boundary criteria for determining the spatial extent of a landscape unit. Individual landscapes are separated by changing characteristics, such as changes in vegetation, land use and landform characteristics. The dominant soil erosion process in the landscape is stream-flow erosion. Stream-flow erosion is caused by rapidly flowing water torrents from roadsides, rooftops, rivers and streams especially during rainfall storms. They cause the formation of big gullies, mass soil translocations, landslides and collapsing riverbanks in the landscape.

A landscape unit being wide in nature and extending several kilometres and having shared amenities such as roads, trading centres rivers, etc, is more difficult to allocate to any community. Its management and conservation is more the problem of a regional authority. All the drivers of erosion in the broad landscape are features, which cannot be controlled by any particular individual or individuals in the community. The management is therefore directed at several actors. The regional government is the dominant actor who prepares policies such as riverbank protection, proper drainage for the trading centres, proper protection of the roadsides, etc. In this scenario, even participatory methods cannot be of much assistance, because some of the policies are directed to technocrats such as building contractors and architects. Residents in a landscape unit can of course air their opinion on what they want implemented by the state or regional authority.

In conclusion, the three selected spatial landscape entities have the spatio-temporal attributes that make them ideal generally for landscape-ecological studies, and specifically for soil erosion studies in that:

- They have manmade or natural boundaries;
- They have internal similarities but compare with each other across the span;
- Soil erosion processes inside them are driven by different manmade or natural factors;
- They obey the hierarchy theory of vertical asymmetry in genesis and internal processes (i.e. '*field-plots'* are created by human activities, '*watersheds'* by natural processes of hydrology and '*landscapes*' by natural processes of geology, geomorphology and climate);
- They are nested upwards into each other (i.e. field-plots being part-of watersheds, and watersheds being part of the landscapes); and
- Internal differences in soil erosion are due to different spatial drivers of erosion.

5.1.2 Decision rules for constructing the individual levels

The following rules are considered important during the construction of the hierarchical landscape system:

- The selected landscape elements must have conditions that link them with the occurrence of soil erosion;
- Each level holon type should have its own genetic properties, which are different from the other levels;
- Each selected holon type should have manmade or natural recognisable boundaries;
- Each selected holon type must have internally detectable soil erosion proxies;
- The erosion proxies should be linked in some way with the presence of soil erosion;
- Each lower level elementary holon must be part of the higher-level landscape element and be constrained by the higher level holon;
- Each holon type should have its own erosion proxies;
- The higher level holons should integrate functions and properties of the lower level holons; and
- Each level holon must be clearly specified and be extractable from the space-time continuum.

The following section presents details of the captured objects data. Satellite images and aerial photographs were used to capture the landscape features and the conversion of the features into digital objects was realised by GIS digitisation techniques.

5.2 Capture and spatial display of the landscape features

This part of the thesis presents results of the visual and digital capture of the landscape features presented in section 5.2 and described in Chapter 3 Subsection 3.23. The captured objects provide the means for spatial modelling of erosion risk in a GIS system. Once the features are captured and entered into a GIS database, their geometric and thematic attributes are used to model the risk of soil erosion. The subsequent subsections show the results of the photo interpretation and GIS data capture. Each landscape level is treated separately.

For each of the holon types, different internal erosion proxies are shown as spatial objects. The subsequent subsections illustrate the obtained objects.

5.2.1 Field plot level

In total eight sample areas were selected for the prediction modelling. The Lynton sample area was located in the large-scale tea zone area occurring to the Northwest of Kiambu town. The Githiga sample area was located in small holder tea and annual crops zone in the north of the Lynton area. The Gatono sample area was located south of the Lynton area in a region of small holder coffee, tea and annual crops. Gatwikira situated south of Gatono was located in an area dominated by intercrops of annual crops with occasional fields of coffee. The Bradgate and Kitamaiyu sample areas were located north of Ruiru town in the eastern portions of the study area in a land use zone dominated by the cultivation of large scale coffee. The Ruiru sample area was located to the west of Ruiru town in a transition zone between large-scale coffee and grasslands in the south east of the study area. The Kenyatta University sample area was located in a low density, residential area dominated by grasslands. All the field-plots occurring in the sample areas were delineated and allocated to a land use class, slope steepness in % and ground cover also in %. The land use categories were used to depict the heterogeneity or homogeneity occurring in the area. The slope steepness category and the ground cover were collected as variable inputs for the erosion risk modelling.

The land use classes present in the study area

The allocation of the land use classes was based on a hierarchical classification method developed by Okoth, (1998) for the FAO (Figure 5.3). Agriculture was first broken into two classes. Crop production and animal production. Both components were further subdivided according to socio-economic considerations, i.e. whether for commercial or for subsistence production. These were further subdivided into crop and livestock production. The crop production component was further subdivided according to arable or irrigated crop production. These were further subdivided into production domains, i.e. cereals, pulses, sugar crops, beverages, oil-crops, fruit crops, medicinal crops, etc. The individual crops were thereafter placed under each branch category. This meant that a crop type could fall in either commercial production or subsistence production. Animal production was similarly subdivided into lower subclasses first on socio-economic considerations and subsequently on rearing systems and production domains. First, animal production was subdivided into commercial or subsistence systems. These individual classes were further subdivided according to rearing domains; i.e., free ranging, confined grazing or paddocked rearing and migratory grazing. Each of the produced subclasses were further subdivided into production domains such as meat, wool, skins, hides, milk, etc by specific animals. Only the encountered classes were recorded and captured in the database. Table 5.1 and figures 5.8 to 5.11 show only the specific crops in four-selected sample areas.

Forestry was also subdivided first according to socio-economic considerations, i.e. for commercial, subsistence or for conservation use (Figure 5.4). The commercial subclass was further subdivided according to specific production domains such as forestry for timber production, forestry for posts production, forestry for leather tanning, etc. The nature/biodiversity conservation subclass was further sub divided according to specific type of conservation i.e. environmental conservation and habitat conservation. For more details see Figure 5.4.

The built up area was also divided into lower class subdivisions (Figure 5.5). First according to socio-economic and production domains; i.e., residential, commercial, industrial, transport and communication, recreation and waste disposal areas. Other land use kinds categorised into subclasses the water bodies occurring in the study area (see Figure 5.6). The water bodies were only subdivided according to socio-economic considerations, i.e. for fishing, drinking, irrigation, sports, power generation, etc. Figures 5.3 to 5.6 show the land use classification hierarchies according to Okoth (1998). The spatial attribute selected for display is the polygonal geometry of the individual field-plot and the land use kind. Figures 5.8 to 5.11 show the field plot objects and their class names. Only the names of the specific crops are provided.

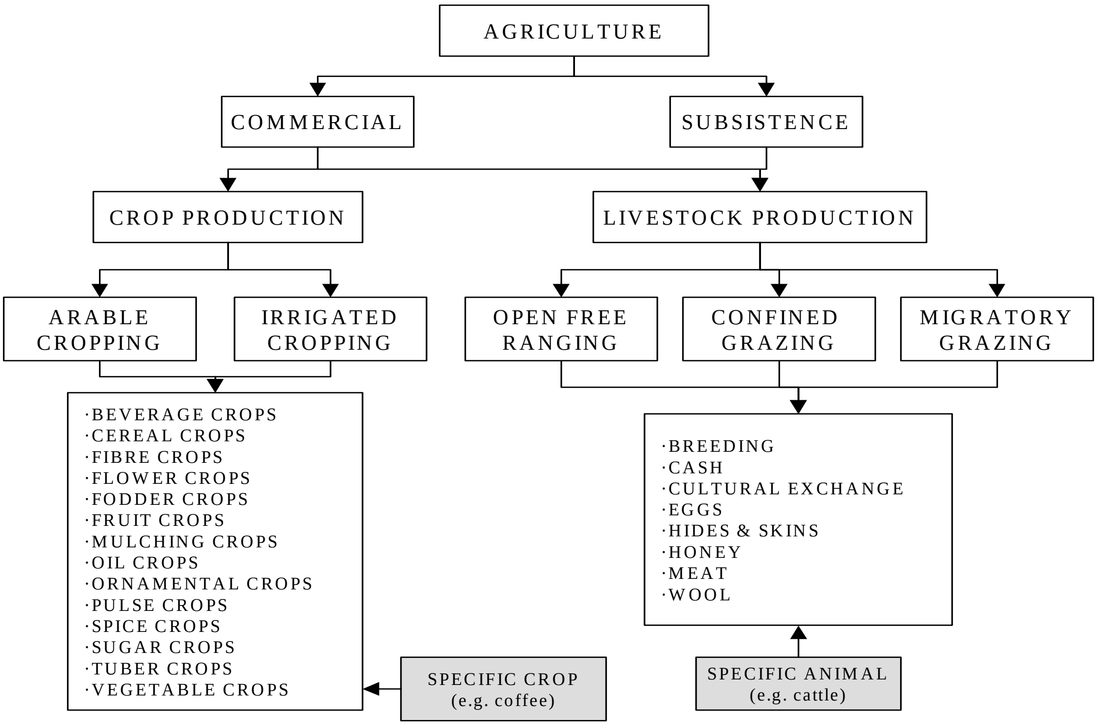

Figure 5.3 Agriculture land use classification hierarchies according to Okoth (1998)

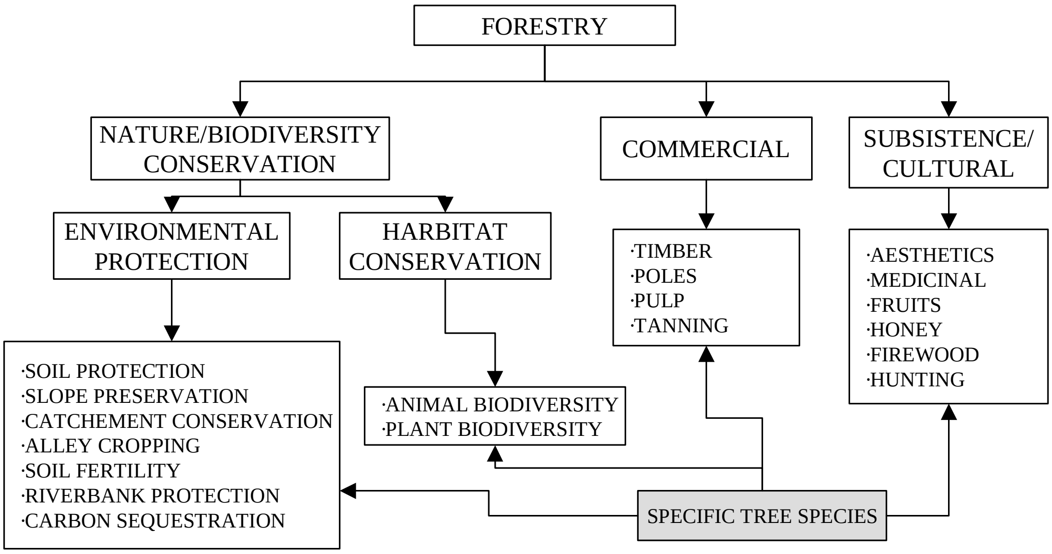

Figure 5.4 Forestry land use classification hierarchies according to Okoth (1998)

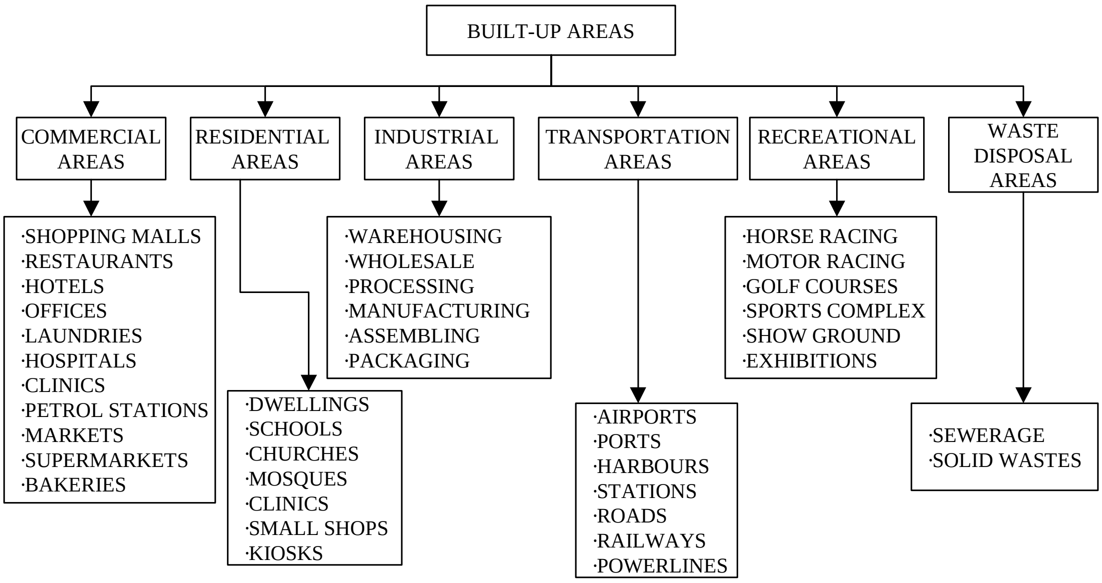

Figure 5.5 Built-up areas classification hierarchies according to use (Okoth, 1998)

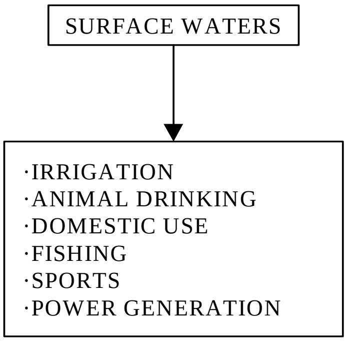

Figure 5.6 Surface water classification hierarchies according to use (Okoth, 1998)

5.2.2 Watershed level

The same sample areas used to model the field-plot level risk of erosion were interpreted and used for watershed level erosion risk modelling. Instead of the field plot polygons, linear or elongate features occurring in each watershed were delineated, allocated a unique value, and a slope gradient. Each of the objects was also allocated a class name according to its recognition in the field and during photo interpretation. Different land use zones and watersheds showed different features. The linear or elongate features encountered included:

- Bare field boundaries;
- Bunded field boundaries;
- Bunded and grassed field boundaries;
- Grassed field boundaries;
- Grassed footpaths;
- Bare footpaths;
- Tree lines;

- Hedges;
- Stone walls;
- Closed field boundaries;
- Forest edges; and
- Wash stops in tea plantations.

A sample of selected watershed features isolated, delineated and captured by GIS are shown in Figure 5.12 and Figure 5.13.

Table 5.1 Field-plot level erosion proxies captured in the study area

Field plot erosion proxies in the area		
Arable & irrigated commercial cropping	*Arable Subsistence cropping*	*Uncropped areas*
Coffee	Arrow root	Grass
Coffee with Macadamia trees	Maize	Grass with trees
Tea	Maize with beans	Fallows
Young tea	Maize & Potatoes	Shrubs
	Maize with tea	Wooded grassland
	Maize with coffee	Woodlots
	Maize & Fruit trees	Homesteads
	Maize with grass	Homesteads & maize
	Maize with Napier Coffee	School
	Maize with trees	Junk Yard
	Maize with shrubs	Quarry
	Beans	Bare
	French beans	
	Potatoes	
	Vegetables	
	Napier grass	

Table 5.2 Watershed level erosion proxies captured in the study area for prediction modelling

Field boundaries	*Other elongate features*
Bare field plot boundaries	Bare footpaths
Grassed field-plot boundaries	Grassed footpaths
Closed field-plot boundaries	Bare roadsides
	Grassed roadsides
	Hedges
	Forest edges
	Trees in a line
	Access pathways
	Wash stops in tea

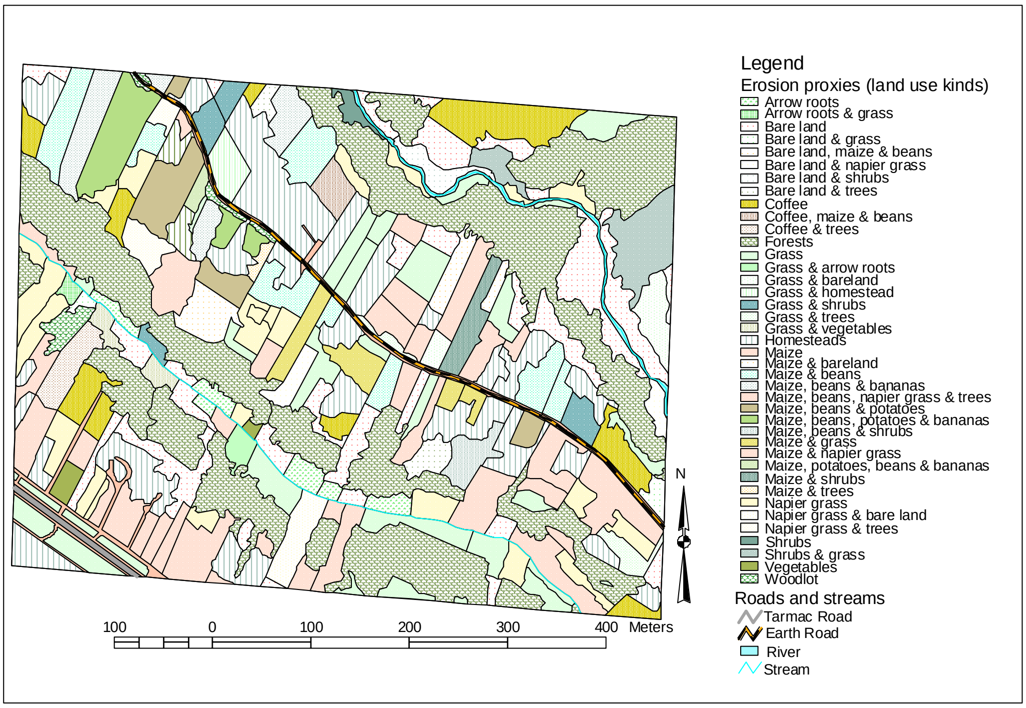

Figure 5.8 Field plot level erosion proxies in the Gatwikira area

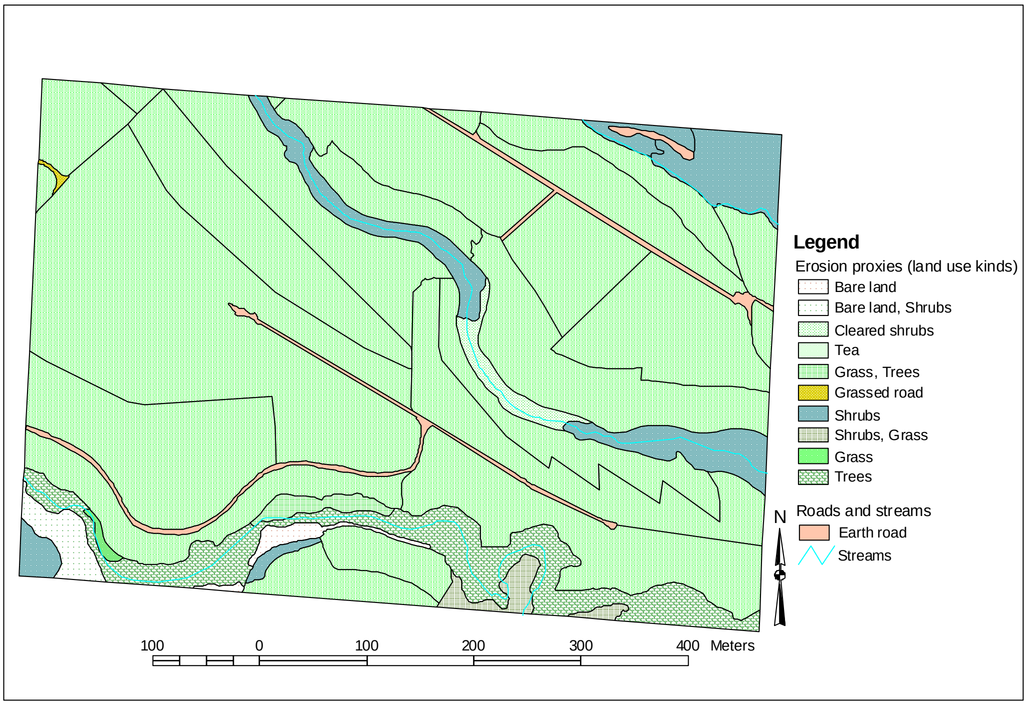

Figure 5.9 Field plot level erosion proxies in the Lynton area

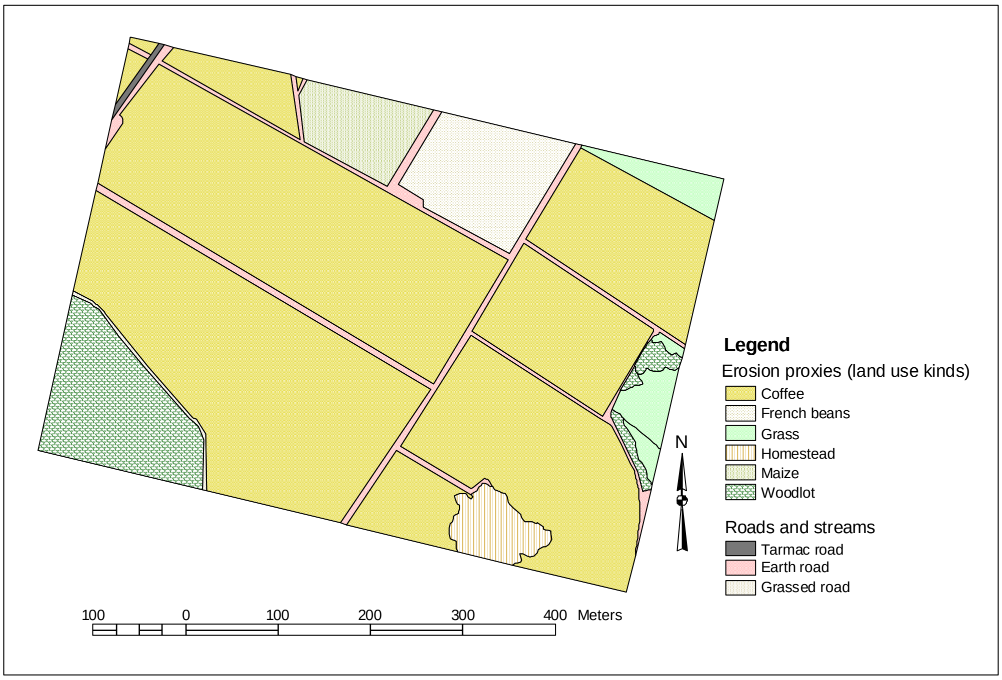

Figure 5.10 Field plot level erosion proxies in the Kitamaiyu Farm

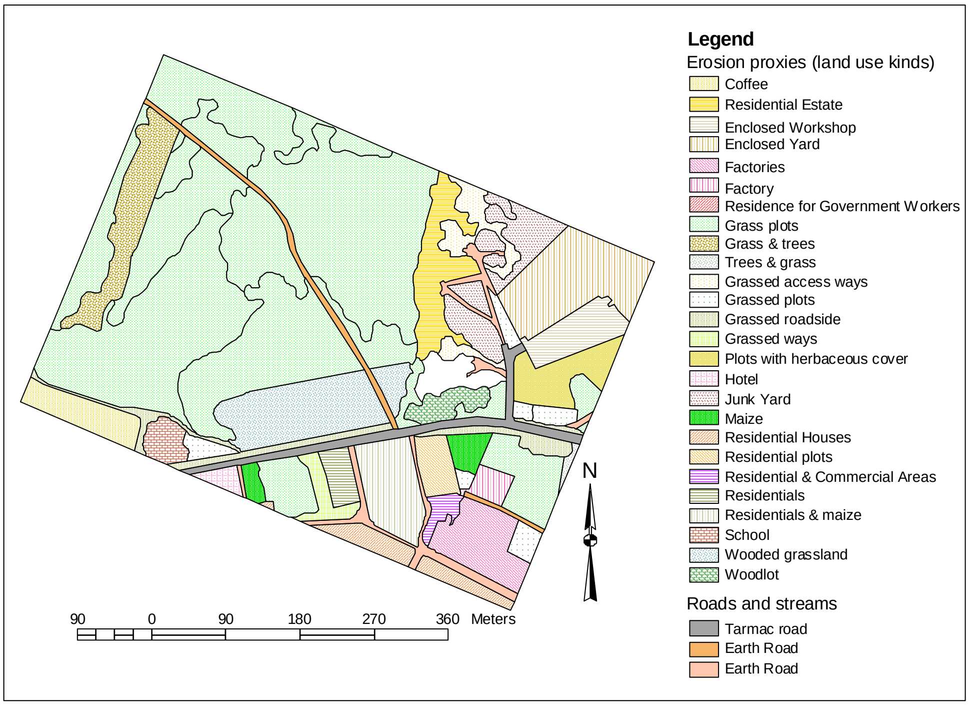

Figure 5.11 Field plot level erosion proxies in the Ruiru area

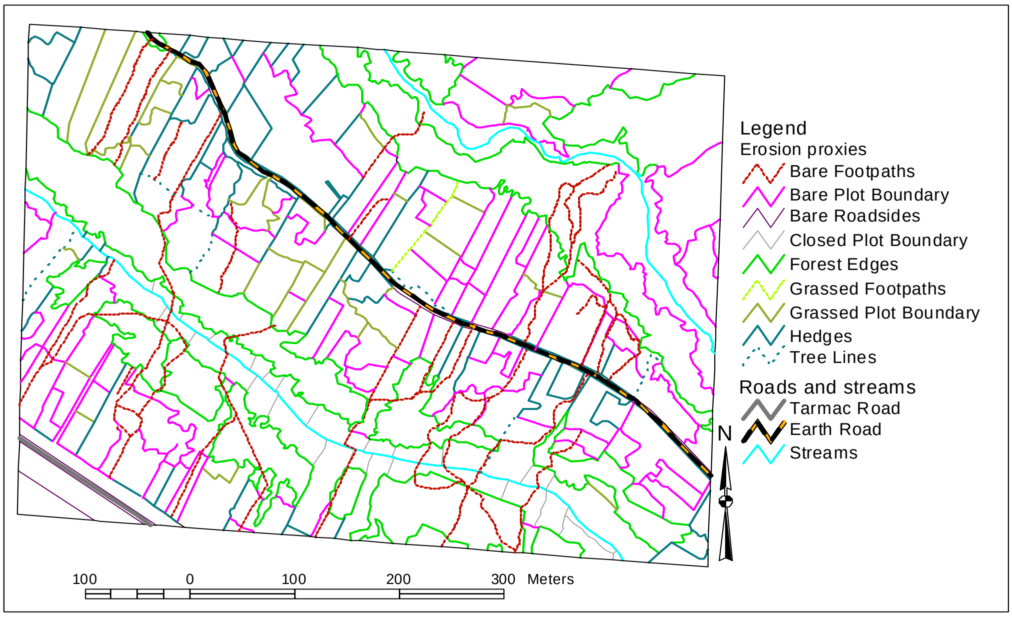

Figure 5.12 Linear or elongate erosion proxies of the Gatwikira watershed

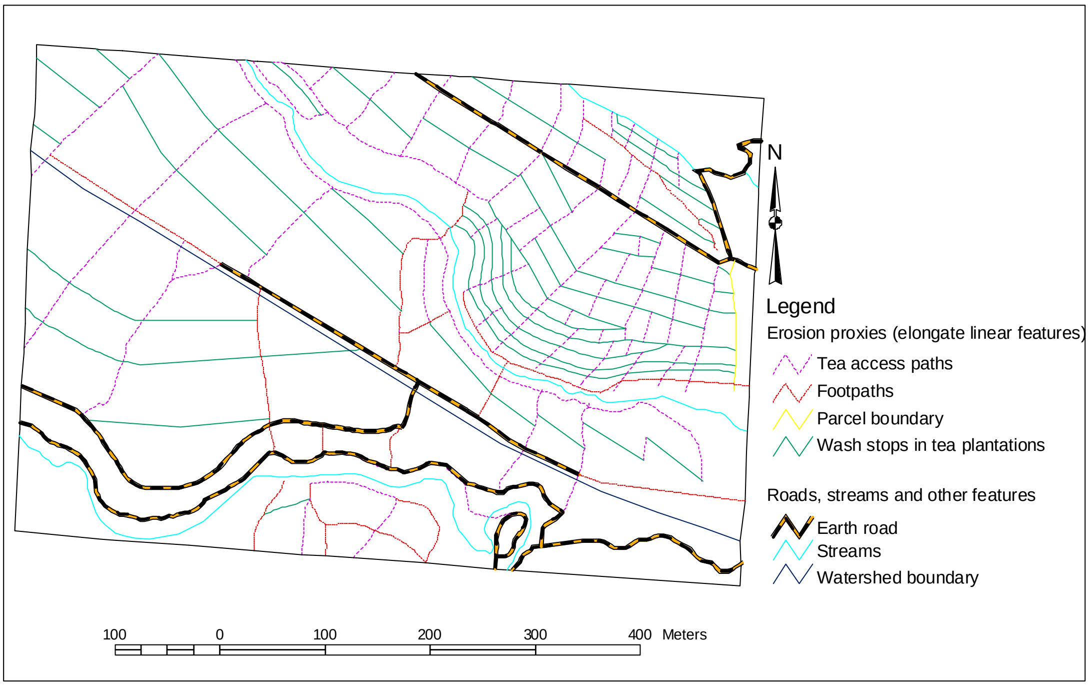

Figure 5.13 Linear or elongate erosion proxies of the Lynton watershed

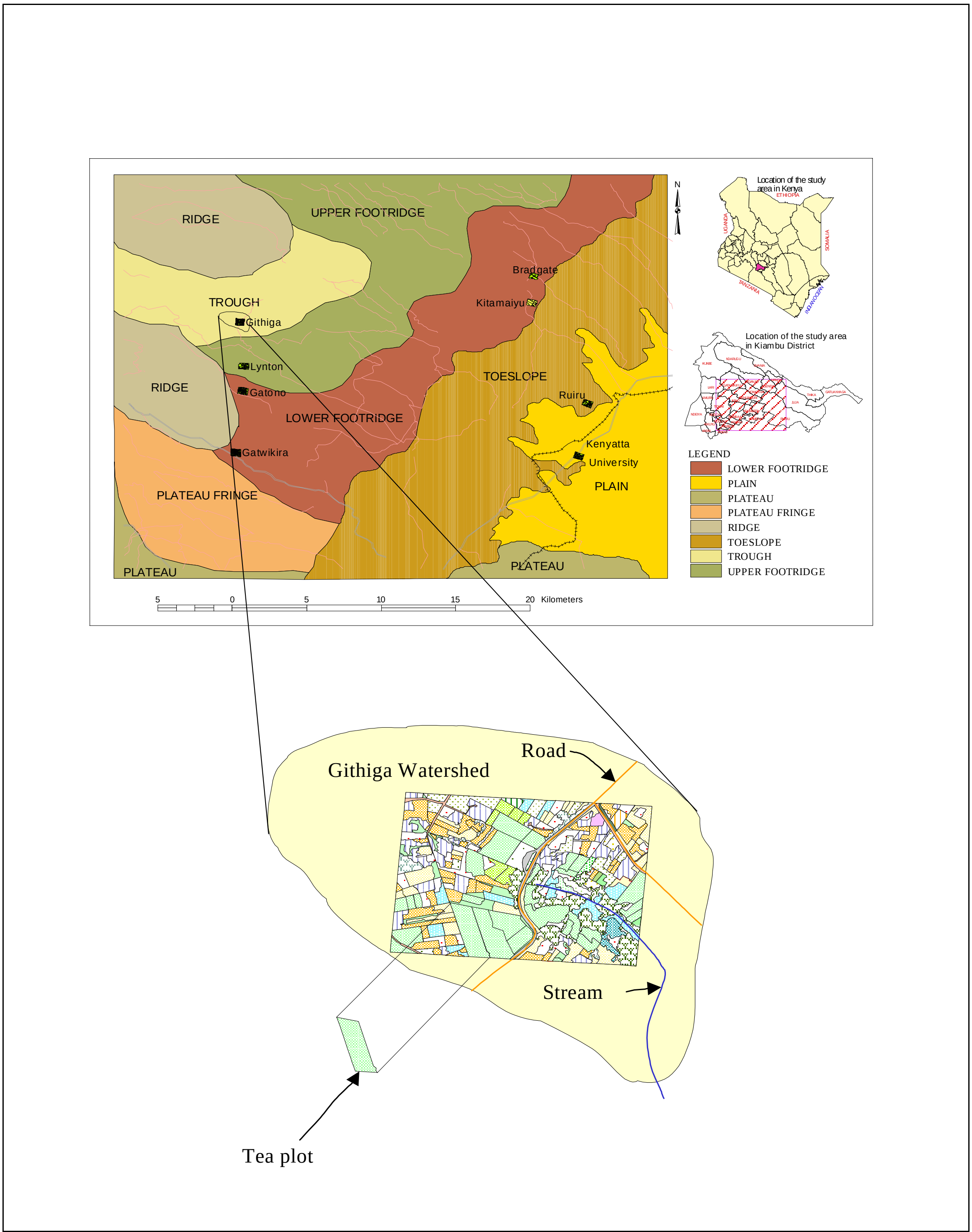

Figure 5.14 An illustration of the nesting of the field plots inside the watersheds and the watershed inside the broad landscapes of the study area with a zoom-in into the Githiga sub-watershed and field plots

5.2.3 Landscape level

The landscape level had completely different erosion proxies selected for assessing and modelling the risk of erosion (see table 5.2). They were all captured separately based on their spatial forms. Roads, rivers, contours, were captured as line primitives while trading centres and built up areas were captured as areal geometric primitives. The landscape units were captured as area geometric primitives. In summary, the features used for modelling erosion risk at the landscape level included:

- Incision of the landscape by rivers and streams;
- Presence and degree of built up areas;
- Road network present in the landscape unit;
- Slope categories present; and
- Ground cover as portrayed by land use differences.

The landscape categories were obtained from aerial photo interpretation and from the visual interpretation of satellite imageries. The landscape units occurring in the study area are linked to the geomorphology of erosional features of volcanic mountain landscapes since the study area occurs on the midslopes and footslopes of the Aberdare Mountains. The following landscape units were thus discerned in the study area:

- Ridge Crests - occurring on upper northwestern parts of the study area;
- Hanging Trough Landscape - occurring between the Ridge Crests;
- Upper Footridges of the Mountain - bordering the Crest and Trough landscapes;
- Lower Footridges - bordering and below the Upper Footridges;
- The Toeslope - occurring below the Lower Footridges;
- The Plateau Landscape - Bordering the Kenyan Rift valley to the left;
- The Plateau Fringe; and
- The Plain Landscape - occurring in the eastern sections of the study area.

The landscape level features are shown in Figure 5.14. The erosion proxies associated with the landscape holons included; roads (both earth roads and tarmac roads), river and stream valleys, and built-up trading centres. Figure 5.14 also shows the nesting of a tea plot in Githiga area into the Githiga watershed and the Githiga watershed into the Trough Landscape unit.

5.3 Spatial data storage

All the holons, i.e., the field-plot, the watershed and the landscape units were stored as area objects with their spatial attributes. Thematic attributes and topological relations were stored in tabular databases. The field-plot level proxies were stored as area objects, the watershed proxies as line objects and the landscape level proxies as area objects. The roads and rivers of the landscape level proxies were first captured as line objects and afterwards converted to spatial area objects by buffering. Their properties and topology description were stored as thematic data, which included slope gradients and soil surface cover. These spatial datasets were thereafter ready for predictive modelling as spatial objects with attribute values.

All the holons representing each level of hierarchical structure were stored as area objects. Due unavailability of aerial photographs covering entire watersheds, it was not possible to delineate watershed holons occurring in an entire landscape unit to demonstrate this. Only segments covered by the available aerial photographs have been used for illustration. Figures 5.7 and 5.13 shows how the different landscape holons are nested into each other and how the relationships are perceived. All the proxies occurring in each landscape holon are linked to the specific holon by part-of relationships. Attribute lists and attribute values of the proxies are stored in the attribute table of the holon. Queries regarding the holon and its proxies can therefore be directed and inferred from its attribute data.

The field-plots are linked to a specific higher level watershed and the watershed linked to the higher-level landscape unit using both positional attributes and part-of links. This creates a multi-level hierarchic database where individual databases can be queried based on integrated relational attributes. Figure 5.7 shows the part-of links between the holons representing the three levels of the hierarchic landscape system construct and the relational attribute links between the unique identifiers of each object class and the specific individual. The higher-level object carriers the attribute values of the lower-level objects and its composition by the lower-level objects can be queried from its attribute table. The relationship of a higher-level object to the lower-level objects is that of *'one to many'* relationship as described by Molenaar (1998) for composite objects. Unique identifiers of the lower level objects must be contained in the attribute list of the higher level object and their values specified. New knowledge about any holon is added to its attribute list or attribute values. Spatial and thematic attributes of individual level erosion proxies are linked to the specific holon object within the hierarchy structure as shown in Figure 5.7 using position and spatial attributes of both the holon and the proxies.

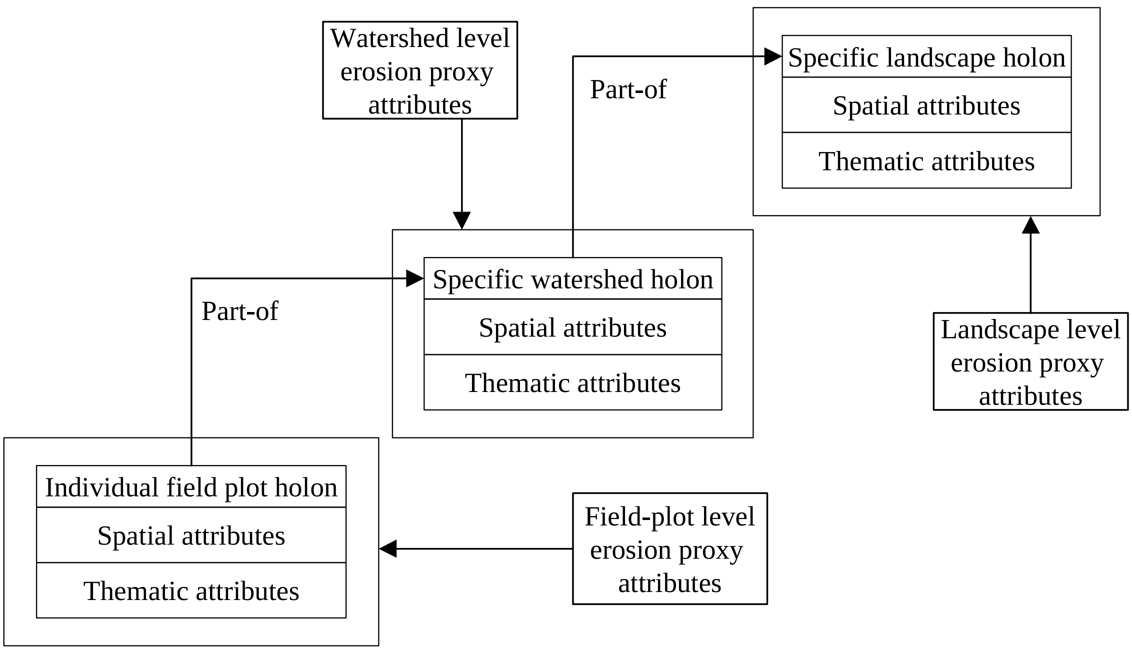

Figure 5.7 Part-of and relational attributes that links a multi-hierarchic GIS database

6

Linking Soil Erosion with the Erosion Proxies and the Landscape Holons

Linking soil erosion with the erosion proxies and the landscape holons

The preceding chapters have elucidated on the concepts of hierarchical modelling, the erosion proxies and the erosion features. A link must be established to exist between the proxies and soil erosion so that when the proxies are used for modelling its risk, the existence of the link is not in doubt. This chapter shows the link between soil erosion features and their occurrence on the erosion proxies by analysing data collected in Kiambu and Nairobi areas.

Three types of statistical analysis were used: (1) the descriptive mean values of measured erosion on the individual proxies, (2) analysis of variance to detect significant statistical differences between the proxies as a basis differentiating them, and (3) Bonferroni pairwise and multi-comparison of the means. The following subsections report the statistical analyses, the key findings, discussions and interpretation of the results. The erosion driver proxies are identified and separated from the disrupting proxies. Recommendations are also made. Figure 6.1 shows a representation of the procedure from field data collection through analysis, explanations and management decisions. The analysis is organised according to the spatial level of analysis each with its own independent data sets though the statistical analysis method is the same for all the levels concerned.

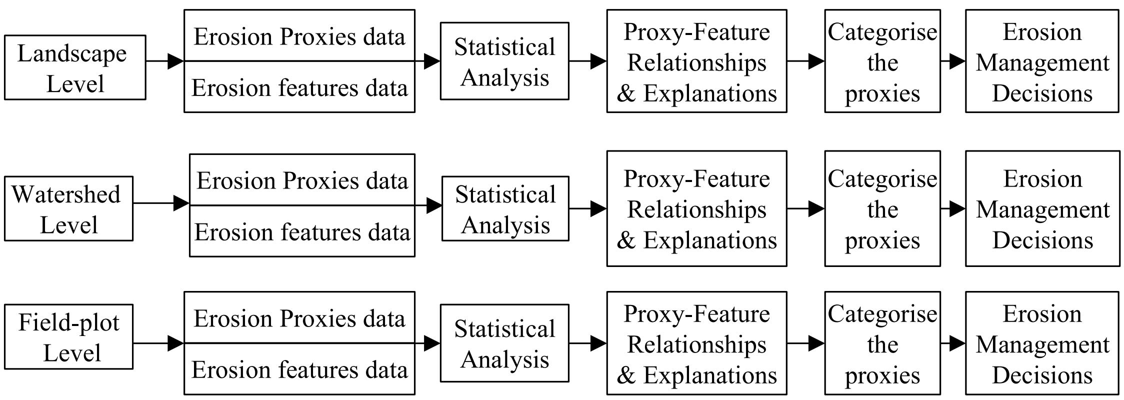

Figure 6.1 A scheme showing the assessment procedure, analysis and expected outputs

6.1 Erosion assessment

6.1.1 Key findings of erosion assessment at the field plot level

Occurrence of erosion features in the erosion proxies

In total, six soil erosion features were used to assess the occurrence of soil erosion in the erosion proxies. The features of erosion included: flow channels, surface litter translocated, depth of rills, depth of root exposures, depth of stem-wash, and depth of soil movement. Flow channels and translocated surface litter were recorded according to their cover of the total plot area in percentages.

The computed statistics in this chapter were based on unequal sample sizes due to difficulty in obtaining equal sample sizes for all the existing categories of erosion proxies using random sampling procedures. It was for example not possible using random sampling methods to obtain more than two fallow plots. This has to do with the relative abundance of the proxies in any survey area. This situation resulted in an overrepresentation of the most occurring types of erosion proxies. The analysis of variance and the Bonferroni analysis of the means are therefore before hand based on a pre-determined 95% confidence interval and computed on the basis of unequal sample sizes of the erosion proxies. Confidence intervals for rare erosion proxies will therefore be wider than the intervals for more abundant classes of erosion proxies. Unequal sample sizes influence the certainty of the results, which are computed and reported as significance levels or as probability of error levels, expressed as *P-values* of the obtained statistics. Values closer to zero are less uncertain. It is noteworthy to mention that the data analysed are discrete and follow a binomial distribution and not a normal distribution due to the absence of erosion features in some sampled locations. Such locations are allocated a value of zero. The zero values are included in the analysis and not transformed to logarithmic or any other transformation due to the difficulty of obtaining the logarithm transformation of zero or finding an alternative suitable transformation that obtains a normal distribution bell-shaped curve for the random binomial data.

Rills, washed stems, exposed roots and translocated soil were quantified on the basis of their depth of scouring of the soil mantle from an initial, uneroded horizontal soil surface. The flow channels and the translocated surface litter were mainly caused by shallow overland flow and affected mostly the upper soil surface. The flow channels had depths not more than 2cm below the horizontal soil surface. They were therefore recorded according to their percentage coverage of a particular field-plot. The rills were deeper than the surficial flow channels and sometimes attained lengthwise dimensions close to the entire length of the field-plot. Root exposures were encountered where substantial amount of the topsoil had been truncated by overland flow and the plant roots were consequently exposed. Only the most current vertical soil truncation was quantified by measuring the vertical depth of the most recent wash. Most recent truncations appeared as white cleaner surfaces compared to brown older surfaces. Washed stems occurred in the same manner like the exposed roots only that the washing was restricted to the plant stems while the roots remained buried below the soil surface. Soil movement was observed as lateral translocations of soil from a consolidated soil body to lower slope positions. Only the vertical displacement was recorded as an indication of the depth of scouring by the flowing water. Depth is an important parameter of the erosion features that enables the distinction of one feature from the other. According to the Soil and Water Conservation Society of America (1982), the distinction between a gully and a rill is one of depth. A gully is sufficiently deep that it would not be obliterated by normal tillage operations, whereas a rill is of lesser depth and would be smoothed by ordinary farm tillage. The occurrence of interill or rill erosion is also related to the water-flow depth and velocity. Shallow overland flow, which causes interill erosion according to Lal (1990), has less energy compared to channel flow that causes rill erosion. The depth of channel flow according to Lal (1990) may be 50 times that of overland flow and the velocity 10 times greater and increases with slope gradient. With gentle slopes, sediments originating in interill areas are not delivered to rills because of limited transport capacity. The reverse is true on steeper slopes (Foster and Meyer, 1975). The truncation depth can therefore be used as an indication of the severity of erosion as used in this thesis. Table 6.1 shows the mean rates of measured erosion under different proxies at the field plot level.

Table 6.1 Mean rates of measured erosion under different proxies at the field plot level

Plot level erosion proxies	*Mean value of measured erosion features (cm)*					
	a	b	c	d	e	f
Coffee Plots$_{(n=18)}$	8.4	6.6	0.3	1.3	2.8	2.1
Coffee & Macadamia$_{(n=4)}$	3.5	4.7	3.3	0.7	1.3	2.3
Forest Plots$_{(n=20)}$	0.9	0.6	0.2	0.4	0.5	0.5
Intercrop Plots$_{(n=63)}$	8.3	7.6	1.9	1.0	1.6	2.6
Tea Plots$_{(n=16)}$	3.2	2.3	1.8	3.7	4.8	12.2
Grass Plots$_{(n=34)}$	0.6	0.6	0.2	0.02	0.1	1.1
Fallow Plots$_{(n=2)}$	1.0	1.0	0.0	0.0	0.0	0.5

a-f = erosion features; where a = flow channels in (%); b = surface litter translocated in (%); c = depth of rills in (cm); d = depth of root exposures in (cm); e = depth of stem-wash in (cm); f = depth of soil movement in (cm);); $_{n=4}$ refers to group sample size.

From table 6.1, in terms of vertical truncation, soil movement provided the highest values of measured erosion on the erosion proxies. Rill depths, depths of stem wash and depths of root exposure were much smaller with almost equal mean values all through. Surface flow channels and translocated surface litter were almost of equal values in all the erosion proxies except in the coffee and coffee intercropped with macadamia where higher values were recorded. The tea plots appear to have suffered the highest degree of erosion compared to the other proxies based on soil movement, exposed roots and washed stems.

Comparison between the proxies

Table 6.1 shows the means values of measured erosion in different proxies. One finding from the data is that tea plots suffer soil erosion like the other crops or vegetation with the highest values obtained from soil movement. The erosion prevalent in the tea plantations was depth of soil movement and depth of exposed roots. Washed stems were also present in the tea plantations but to a lesser degree than root exposure and soil movement. What could be happening is that the soil erosion that goes on beneath the tea canopy is most of the time obscured to visual observation by the high aboveground tea-canopy. The tea-canopy being a good interceptor of falling raindrops acts as a funnel which during rainfall allows water to percolate the tea canopy steadily. This process creates a steady supply of waterflow beneath the canopy, which drops onto and erodes the bare soil surface. The falling waterdrops detach soil particles on bare patches of the soil surface and create flowing water currents that transport the soil particles. The vertical height between the tea canopy and the soil surface (0.5-0.7 m) often offers adequate height for the falling water drops to slake and detach the soil particles from the soil body both through drop impact and through weakened particle bonds. Epema and Riezebos (1983) found that artificially produced raindrops from a height of 50 cm attain accelerated and laminar flow velocity of about 3 m sec^{-1} that has sufficient kinetic energy. The kinetic energy of the raindrops is related to the mass of the drops and the fall velocity by the following equation.

$$Ke = \frac{1}{2}mv^2 \qquad (6.1)$$

Where *Ke* is the kinetic energy, *m* is the mass and *v* is the velocity. Since there is a steady supply of water from the aboveground thick canopy, it is believed that water concentrates in the canopy and flows onto the soil surface in bigger drop sizes than would occur during natural rainfall in the absence of such canopy cover. This makes tea have high beneath-canopy soil erosion compared to the other erosion proxies (see Table 6.1). Coffee suffers a similar type of erosion but to a lesser degree. Rills appear to scour deeper in the coffee-macadamia plantations than in tea or other proxy types. This is explained by the fact that coffee-macadamia bushes are planted in straight rows with open space occurring between the individual bush strips. These inter-bush spaces occur on lower slope positions and therefore concentrate more channel water, which encourages the occurrence of rills. Forests with low undergrowth also suffer beneath-canopy soil erosion with all features of erosion in Table 6.1 being encountered. Erosion in the intercrops saw more erosion in the form of flow channels and translocated surface litter dominating compared to the other erosion features.

According to Lal (1990) rills are initiated by a gullylike headcut developing along the slope. The rate at which the headcut advances depend on many factors that include slope, soil properties and flow velocity. Both depth and velocity of flow are important in determining rill erosion. According to Lal (1990), the velocity of flowing water in small channels is given by the Manning's formula:

$$V = \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{\eta} \qquad (6.2)$$

Where *V* is the average velocity of flow *(m/s), R* the hydraulic radius *(m), S* the land slope *(m/m),* and η the coefficient of surface roughness. The hydraulic radius is related to the cross-sectional area and wetted perimeter. The transported particles is related to the flow velocity by:

$$G = aV^b \qquad (6.3)$$

Where *G* is the quantity of transported material, *V* the flow velocity and *a* and *b* are constants. The value of *b* is about 4 according to (Laursen, 1953; Meyer and Monke, 1965).

The means of measured erosion features reported in Table 6.1 were obtained for the different erosion proxies despite differences in slope and cover conditions of the encountered proxies. To see whether slope or cover had strong influence on the different means, the obtained values were tested using the analysis of variance. The response variables were the measured values on the erosion features, namely percent flow channels, percent translocated surface litter, depth of rills, depth of root exposures, depth of stem-wash and depth of soil movement. Table 6.2 shows the results of the analysis of variance.

From Table 6.2, it is possible to see that flow channels, surface litter translocated, depth of soil movement, depth of stem-wash and depth of root exposures showed significant differences between the different proxy groups using the F-test. The F-test compares mean values of different factor categories using the analysis of variance to test the hypothesis *(Ho)* that there is no difference between all the factor categories (erosion proxy groups).

Table 6.2 Analysis of variance and the F-test for significance for difference among the seven erosion proxies based on measurements on individual erosion features

Erosion features	*Erosion proxies*	*Sum of squares*	*Degrees of freedom*	*Mean square*	*F*[1) 2)]	*Significance (P-value)*
Flow channels	Between groups	1933.1	6	322.2	5.425 *	0.000
	Within groups	8908.2	150	59.4		
	Total	10841.3	156			
Surface litter translocated	Between groups	1572.5	6	262.1	5.076 *	0.000
	Within groups	7744.7	150	51.6		
	Total	9317.1	156			
Depth of soil movement	Between groups	1056.5	6	176.1	4.355 *	0.000
	Within groups	6065.4	150	40.4		
	Total	7121.9	156			
Depth of stem-wash	Between groups	170.3	6	28.4	4.025 *	0.001
	Within groups	1058.0	150	7.1		
	Total	1228.3	156			
Depth of root exposure	Between groups	78.4	6	13.1	2.979 *	0.009
	Within groups	657.9	150	4.4		
	Total	736.3	156			
Depth of rills	Between groups	149.0	6	24.8	1.496	0.183
	Within groups	2489.7	150	16.6		
	Total	2638.7	156			

[1)] Seven categories of erosion proxies as shown in Table 6.1; [2)] F critical = 2.16; * Significant difference between the different groups of erosion proxies shown in Table 6.1.

If the F-test is found to be significant then the null hypothesis that there is no difference between all the factors is rejected and the inverse hypothesis that there is a difference accepted. The test is performed by comparing the within group variance and between groups variance ratios from an overall mean by analysing values of *'between groups mean sum of squares'* with the *'within group mean sum of squares'* also known as variance for the *'between'* and the *'within'* variances. If the *'between groups'* mean sum of squares is larger than the *'within group'* mean sum of squares a larger F-ratio is obtained and it is concluded that the difference can be attributed to differences between the means of the factor groups as opposed to internal variations within individual groups. If the *'within'* variances have higher values than the *'between'* variances, a smaller F-ratio is obtained and it is concluded that there is higher variance within the individual proxy groups and that there no differences between the mean values of the individual groups. If the two variances are equal or close to each other, and the F-ratio is 1.0 or close to it, then the factor level means are considered to be equal. The variance ratio or the F-test is read against a standard *F* statistical table such as found in Snedecor and Cochran (1989) which bases the analysis on desired significance level and the degree of freedom of the groups and those of the total population. Critical values are compared with the calculated values in order to decide on significance levels of the F-tests. If this test establishes that there is a difference between the factor group means, then it is confirmed that there is a relationship between the factor groups (erosion proxies) and the response variable, which in this case is soil erosion (Neter *et al.,* 1996). Flow channels, surface litter translocated, depth of soil movement, depth of stem-wash and depth of root exposure all had significant F-test results indicating that the inverse hypothesis that there is a difference between the erosion proxy groups is accepted and the null hypothesis rejected.

Results in Table 6.2, show no significant difference in the depth of rills among the different groups of the erosion proxies. Otherwise all there other erosion features indicate from the F-test a difference between the means of the sampled erosion proxies. By examining the results of the analysis obtained on the rills, the indication is that the occurrences of the rills do not indicate any difference between the different the erosion proxy groups. This may be attributed to the fact that the occurrence of rills is conditioned by concentrated more energetic channel flow compared to the other erosion features, which are developed mostly by shallow, less energetic overland flow or by splash erosion whose erosive impact is intercepted by canopy cover. The channel flow being of higher velocity, larger energy and based directly on the soil surface is able to propagate itself more vigorously compared to the overland flow or raindrop splash impact and thereby obliterating the effect of the proxies. Proxy differences such as percent canopy cover will therefore not affect rill erosion formation. Though the analysis of variance show differences between the erosion proxies for other erosion features, it was necessary to determine individual values of differences between some of the proxy groups to show the direction of effect of the highest obtained means. A comparison of the individual difference between two or more group means was carried out using the Bonferroni multiple comparison procedure. According to Neter *et al.* (1996), the Bonferroni multiple comparison procedure is used for comparing the means if the family of interest is a particular set of pairwise comparisons, contrasts, or linear combinations that is specified by the user in advance of the analysis of variance. The Bonferroni procedure is applicable whether the factor level sample sizes are equal or unequal and whether inferences centre on pairwise comparisons, contrasts, linear combinations, or a mixture of these. Table 6.3 shows a comparison of the different means of erosion features occurring in the erosion proxies using the Bonferroni pair-wise and multiple comparison procedure for a family confidence of 95% ($P<0.05$). The family is the group of all the erosion proxy categories whose means are compared.

Table 6.3 Comparison of the means using the Bonferroni multiple comparison procedure ($P<0.05$)

Erosion proxies	*a*	*b*	*c*	*d*	*e*	*f*
Coffee Plots$_{(n=18)}$	m,n,p	m	m	m,o	m	m,n,r
Coffee & Macadamia$_{(n=4)}$	m	m	m	m	m	m
Forest Plots$_{(n=20)}$	m,o,q	m,n,p	m	m,p,q	m	m,o,r
Intercrop Plots$_{(n=63)}$	m,o,p,q	m,n,o,p	m	m	m	m,q,r
Tea Plots$_{(n=16)}$	m	m	m	m,n,p,q	m	m,n,o,p,q,r
Grass Plots$_{(n=34)}$	m,n,p,q	m,o,p	m	m,n,o,q	m	m,p,r
Fallow Plots$_{(n=2)}$	m	m	m	m	m	m

a = flow channels in (%); b = surface litter translocated in (%); c = depth of rills in (cm); d = depth of root exposures in (cm); e = depth of stem-wash in (cm); f = depth of soil movement in (cm); m = no significant difference between the proxy groups; n,o,p,q,r = significant differences between the proxies with the same alphabets.

From Table 6.3, and by comparing the means of the flow channels, there were significant differences between the means of the grass plots, the forest plots, the intercrop plots and the coffee plots. A nearly similar comparison was obtained for translocated surface litter only that in this case there was no significant difference between the means of the grass and forest plots with that of the coffee plots. The plots with coffee and macadamia and the fallow plots were not sensitive to the test due to their small sample sizes. When soil movement was analysed, there was significant difference between the mean values of the grass plots, the forest plots, the tea plots, the intercrops, and the coffee plots. This confirms the analysis of variance in Table 6.2 that there is a difference among some of the erosion proxies based on the erosion features used in the analysis. Depth of soil movement provided the best basis for comparing between some of the measured means. From Table 6.1, it was observed that tea had the highest measured mean for soil movement. It was important to compare it quantitatively with the other proxies to see the magnitude of difference and the direction of the difference using the Bonferroni multiple comparison procedure. Table 6.5 shows the comparison of the means using the Bonferroni multiple comparison procedure for a family confidence of 95% (P<0.05).

Table 6.5 Comparison of the means using the Bonferroni[1)] multiple comparison procedure (P<0.05) for soil movement as the indicator erosion feature

Erosion feature	*Reference erosion proxy*	*Comparison Proxy kind*	*Computed mean difference*	*95% family confidence interval*[2) 3)]	*P*
Soil movement	Tea	Coffee	7.86*	(1.11; 14.61)	0.009
		Forest	9.50*	(2.91; 16.09)	0.000
		Intercrop	7.39*	(1.89; 12.89)	0.001
		Grass	8.93*	(2.97; 14.89)	0.000
		Fallow	9.50	(-5.24; 24.24)	1.000
		Coffee + Mac	7.75	(-3.24; 18.74)	0.647
	Forest	Coffee	-1.64	(-8.02; 4.75)	1.000
		Intercrop	-2.11	(-7.16; 2.93)	1.000
		grass	-0.57	(-6.11; 4.97)	1.000
		Tea	-9.50	(-16.09; -2.91)	0.000
		Fallow	0.00	(-14.56; 14.56)	1.000
		Coffee + Mac	-1.75	(-12.52; 9.01)	1.000
	Grass	Coffee	-1.07	(-6.80; 4.66)	1.000
		Forest	0.57	(-4.97; 6.11)	1.000
		Intercrop	-1.54	(-5.73; 2.64)	1.000
		Tea	-8.93*	(-14.89 ; -2.97)	0.000
		Fallow	0.57	(-13.73; 16.23)	1.000
		Coffee + Mac	-1.18	(-11.57; 9.21)	1.000
	Intercrop	Coffee	0.47	(-4.78; 5.73)	1.000
		Forest	2.11	(-2.93; 7.16)	1.000
		Tea	-7.34*	(-12.89; -1.89)	0.001
		Fallow	2.11	(-12.00; 16.23)	1.000
		Coffee + Mac	0.36	(-9.77; 10.50)	1.000
	Coffee	Forest	1.64	(-2.44; 5.72)	1.000
		Intercrop	-0.47	(-3.83; 2.89)	1.000
		Tea	-7.75*	(-14.61; -1.11)	0.009
		Fallow	1.64	(-7.73; 11.00)	1.000
		Coffee + Mac	-0.11	(-7.06; 6.83)	1.000

[1)] Takes care of unequal sample sizes. [2)] Based on the mean, (1-α) confidence level, family degrees of freedom, total degrees of freedom and standard deviation. Mac = *Macadamia integrifolia.* [3)] Any interval going through 0 is not significant; + or – indicates the direction of influence. Values without + or – have no direction of influence and are not significant.

From the Table 6.5, tea contributed to the obtained differences in the means in a positive direction meaning that compared to the other proxies, it exhibited a property of increasing the occurrence of soil erosion. The other proxies having significant differences with tea namely: forest plots, grass plots, coffee plots and intercrop plots showed erosion-reducing characteristics with a negative interval direction compared to the tea plots. From Table 6.3, and by comparing the proxies using mean values of the flow channels in the proxies, there were significant differences between the mean values of the grass plots, the forest plots, the intercrop plots and the coffee plots. The fallow plots and coffee with Macadamia plots were not sensitive to the analysis due to their small group sample sizes. These differences indicate that the proxies selected for the study show significant statistical differences and can be differentiated as either drivers or disrupters of erosion. A standard is needed for this. Table 6.6, a modification of Clark (1980) erosion features classification system shows the soil erosion severity classes based on the different erosion features prevalent in Kiambu area. The values of severity classes in the table are based on field observations of erosion status in Kiambu. Values initially given by Clark (1980) were found to be too low. The depth of the erosion features were given in mm which would have lumped nearly all the erosion features into one or two classes, i.e. stable or severe. The units in Clark's (1980) classification were therefore modified to cm and some intervals changed to conform to actual realities on the ground.

Table 6.6 Erosion feature classification according to severity classes. (Classification based on a modification of Clark's (1980), classification system based on field observations in Kiambu and Nairobi areas)

Depth of erosion feature	*Severity Class*				
	Stable	*Slight*	*Moderate*	*Critical*	*Severe*
Soil movement	0 -1.5 cm	1.5 - 3.0 cm	3.0 - 5.0 cm	5.0 - 8.0 cm	> 8.0 cm
Surface litter (%)	0 - 2%	2 – 10%	10 - 25%	25 - 50%	> 50%
Root exposure	0 - 0.5 cm	0.5 - 2.0 cm	2.0 – 3.0 cm	3.0 - 5.0 cm	> 5.0 cm
Stem washing	0 - 1.0 cm	1.0 - 3.0 cm	3.0 - 5.0 cm	5.0 - 7.0 cm	> 7.0 cm
Flow channels (%)	0 -2%	2 - 10%	10 - 25%	25 - 50%	> 50%
Rills:					
Depth	0-4cm	4-8cm	8-12cm	12-20cm	> 20cm
Width	< 10cm	10- 25cm	25- 45cm	45-80cm	>80cm
Frequency	10 -5m	5– 4m	4-3m	3 -2m	< 2m
Gullies:					
Depth	< 20 cm	35-55 cm	55-75 cm	75-95 cm	> 95 cm
Width	30-60 cm	60-100 cm	100-150 cm	150-200 cm	>200 cm
Frequency	> 500 m	500- 150 m	150 -50 m	50 -15 m	15 - 5m

Separating the disrupters from the drivers of erosion

In order to distinguish between the drivers and disrupters of erosion Table 6.6 was used. Table 6.6, shows the soil erosion severity, conditioned by the different erosion features. A value ranging from 0.0 to 1.5 cm for soil movement is considered stable. Forest plots with mean values of 0.50 cm and grass plots with mean values of 1.10 cm were considered stable and therefore disrupters of erosion. Fallow plots though not having significant differences were considered to be disrupters of erosion. Flow channels and the translocated surface litter also confirms the three as the best disrupters of soil erosion based on Table 6.6. Erosion proxies with mean values of soil movement higher than 1.5cm were all considered to be drivers of erosion with tea plots being the most severe drivers with a mean value of 12.00 cm (Table 6.1 and 6.6).

Discussions and recommendations for erosion management of the field plots

Figure 6.2 shows the relationship between slope and soil movement in tea plots. From the figure, it is evident that soil erosion in the tea plots occurred when the slope gradients exceeded 6%. It is therefore not all the tea plots that were high drivers of soil erosion, mostly the plots located on slope gradients having values greater than 6%. This aspect must be taken into consideration during the management of erosion in the tea plots since it will be full hardy to put efforts in tea plantations that are located on lower slope gradients. Walsh (1958) and Templer (1971) observed that ploughing land during forest clearing with slope gradients greater than 10% exposed the cleared land area to soil erosion. Their value of 10% is higher than 6% but shows that there is a threshold value of slope gradient which must be utilised with due care especially towards the hazard of soil erosion.

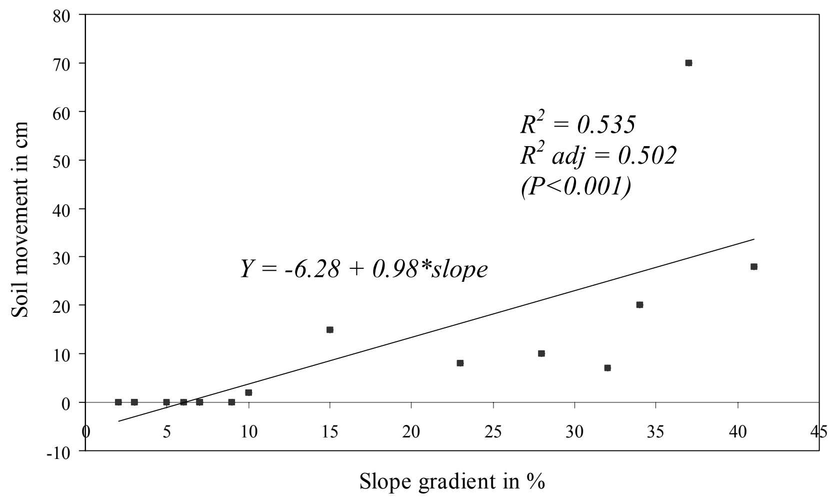

Figure 6.2 Relationship between slope and soil movement in tea plots.

The presence of different features of erosion in different proxies can be explained by a host of factors. They are the type of canopy cover present, percent open soil surface, soil type, slope-gradient, tillage practise, rainfall erosivity, energy of flowing water currents, and the presence or absence of barriers in the pathways of the flowing water. These factors influence raindrop, overland flow and channel erosion differently thereby creating the different features of erosion. Management practise such as the addition of manure, fertilisers, mulch, time of planting and weeding associated with a particular proxy also have an influence on the type of erosion feature that develops. Reasons for the formation of different features of erosion was not one of the objectives of this study and has been extensively covered in literature (e.g. Lal, 1990; Nill *et al.,* 1996; Lal, 1998).

Key issues emanate from the presentations of the assessment and analysis of the erosion proxies and the erosion features. The first management step is the distinction between the drivers and the disrupters of erosion. From the erosion proxies analysed, grass plots and forest plots showed the lowest values of soil movement and have been classified as good disrupters of interrill erosion if they are located on lower slope positions. As a management measure they can also be located on downslope positions neighbouring the driver proxies such as bare field-plots, tea plots, coffee plots, or intercrops. They can act as natural dykes against upslope soil erosion.

It is not enough to know that one field-plot proxy kind is a driver or a disrupter of soil erosion, the information can be more valuable if it is translated to erosion management gains. For erosion control and management the spatial arrangement of erosion proxies can be exploited to counter the driving characteristic of the driver-proxies. The disrupting proxies can be planted in midslope positions to create a pattern of alternating plantation strips of driver-proxies with strips of disrupting-proxies. Other opportunities which present themselves from the two identified disrupting proxies (i.e. grass plots and the forest plots), include the use of grass plots as a source of animal fodder or as a source of grass seeds. Many farmers in Kiambu keep cattle and maintain napier grass in their field-plots. This can be intensified and the plots located in erosion hazard areas. Changing their pattern of arrangement in the slope is still what needs to be done. Another opportunity with grass plots is one of economic gain. Grass seed business is slowly gaining momentum in Kenya as the Arab countries of the Middle East continue to place high values and demands on grass seed exports from Kenya. This opportunity can be enhanced by having several grass plots across the slope to serve both as conservation barriers while at the same time providing the opportunity of generating income to the farmer in the form of export seeds.

Woodlots or riparian trees have several uses other than just soil conservation (Roose and Ndayizigiye, 1997; Van Noordwijk, 1998; Angima, 2001; Van Rompaey *et al.,* 2002). They can be used for soil nutrient cycling *(e.g. Calliandra calothyrsus, Leucaena trichandra, Leucaena diversifolia, Sesbania sesban)* if they are nitrogen fixing or can be used as animal fodder (Angima, 2001). Woodlots can also be used as sources of fuelwood, fruits or for carbon sequestration (Angima 2001; Chivaura *et al.,* 2000; Pfaff *et al.,* 2002). Other opportunities for the use of erosion disrupters include their use inside the field plots as in-field erosion barriers. The disrupters of erosion can be planted inside the field plots with crops that are considered to be drivers of erosion.

The use of erosion barriers in field-plots has been reported by Mango (2002). From studies in Siaya district in Kenya, the planting of *Tithonia diversifolia* has been used as a barrier against soil erosion in farmers' field-plots. From observations in the field, grass, mulch in tea and coffee plantations proved to be good disrupters of soil erosion. According to Kiepe (1995) two cassia hedgerow systems planted as erosion barriers on a moderately-steep slope in semi-arid Kenya showed that both systems diminished runoff and soil loss and did not depress crop yields when used for soil and water conservation. Soil and water conservation was highest where prunings were applied as surface mulch, understandably, because of the cumulative effect of erosion barrier and surface cover. Similar findings were reported by Angima (2001) who found that

Calliandra hedges and Napier grass strips reduced soil loss in a soil conservation experiment in Kianjuki area of Central Kenya.

In conclusion to the above discussion, physical measures with the disrupters of erosion alone cannot ensure success of conservation ventures. Farmers' innovations alone might also not offer required solutions. The biophysical solutions must be blended with sustainable livelihood programmes where benefits of using certain technologies are clearly evident to the farmer or other beneficiaries. Participatory approaches as described by Pretty *et al.* (1995) and Harding *et al.* (1996) can be used. Even when employing these approaches social networks (Doreian, 2002; Kadushin, 2002; Leenders, 2002), and information dissemination (Lai, 2002), should be combined with the biophysical knowledge. Multi-disciplinary and participatory solutions must be sought between appropriate technology and beneficiaries of the technologies. Solutions must be availed which addresses energy requirements, time constraints, human resources, mechanical resources, financial resources and technological innovations. Much still needs to be done to unearth the link between soil erosion management, economic returns and social livelihood promotion for farm field plots in Kenya and in many other parts of the world.

6.1.2 Key findings of erosion assessment at the watershed level

Occurrence of erosion features in the erosion proxies

Erosion features similar to those used at the field plot level were also measured on proxies at the watershed level for different types of proxies. Gullies appeared as new features of erosion not encountered for the field plot erosion proxies. Table 6.7 shows the erosion features and the measured erosion on the watershed level erosion proxies.

Table 6.7 Mean rates of erosion measured under different proxies at the watershed level

Watershed level erosion proxies	*Means of measured erosion features (cm)*				
	a	b	c	d	e
Bare plot boundaries$_{(n=36)}$	0.00	10.00	0.00	0.00	0.00
Bunded bare plot boundaries$_{(n=8)}$	2.50	3.75	0.00	0.00	0.00
Bunded and grassed boundaries$_{(n=9)}$	0.00	0.00	0.00	0.00	0.00
Grassed plot boundaries$_{(n=3)}$	0.00	0.00	0.00	0.00	0.00
Grassed footpaths$_{(n=4)}$	0.00	0.00	0.50	3.25	2.00
Bare footpaths$_{(n=17)}$	14.71	11.18	1.12	5.94	1.00
Tea paths$_{(n=8)}$	0.00	0.00	5.87	11.85	12.50
Trashed boundaries$_{(n=3)}$	0.00	0.00	0.00	0.00	0.00

a = depth of gullies in (cm); b = depth of rills in (cm); c = depth of root exposures in (cm); d = depth of stem-wash in (cm); e= depth of soil movement in (cm); $_{(n=3)}$ refers to group sample size.

From the table, it is seen that if erosion features occur, on average the highest rates of erosion were obtained from the encountered gullies. However, gullies only occurred on bunded and bare plot boundaries and in bare footpaths. Gullies were differentiated from rills based on both depth and widths (see Table 6.6). Rill depths were highest in the bare footpaths and bare plot boundaries. Bunded bare plot boundaries also had rills. There were no gullies associated with field-plot boundaries. The deepest gullies were however encountered in the bare footpaths. The bunded and bare field boundaries also had some gullies. The value in the Table 6.7 is a mean of several bunded bare field-plot boundaries. Root exposures were encountered on grassed footpaths, along bare footpaths and along paths in tea plantations. This was mostly attributed to the fact that plants grow next to the paths and roots can occur as protrusions on the paths. The highest values of exposed roots were in tea plantation paths. Stem-wash occurred in a similar pattern to exposed roots and with comparable orders of magnitude. Soil movement also occurred in grassed footpaths, in bare footpaths and in tea paths. These observations are attributed to the fact that most paths normally truncate their trails below the normal terrain surface and most erosion features can be observed on the edges of the paths.

Comparison between the proxies

By looking at Table 6.7, the bare footpaths though having lower values of soil movement influenced the occurrence of all the erosion features including gullies. Their evaluation can therefore not be based on soil movement alone. Having gullies with mean depths of 14.7 cm makes them be the worst drivers of erosion among the proxies. Tea paths that also had soil movement, washed stems and rills follow the bare footpaths in the order erosion severity. Bare field boundaries with deeply incising rills (10.0 cm) follow the tea paths. These are then followed by the bunded and bare field boundaries, which have more shallow gullies and rills. Grassed footpaths also showed some erosion on it edges but less severe than those in the already mentioned proxies. This leaves the bunded and grassed field boundaries, the grassed field boundaries and the trashed field boundaries as the erosion free proxies that can be used as conservation remedies. To confirm these differences the analysis of variance was used. Though the obtained means in Table 6.7 were observed to be different for some erosion proxies, the observed difference could have occurred by chance and can only be confirmed by the analysis of variance and by the comparison between the means. Table 6.8 shows the results of the analysis of variance and the F-test for significance for difference among the eight erosion proxies based on measurements on individual erosion features.

Table 6.8 Analysis of variance and the F-test for significance for difference among the eight erosion proxies based on measurements on individual erosion features

Erosion features	*Erosion proxies*	*Sum of squares*	*Degrees of freedom*	*Mean square*	*F*[1) 2)]	*Significance (P-value)*
Depth of soil movement	Between groups	1061.6	7	151.7	16.144*	0.000
	Within groups	751.5	80	9.4		
	Total	1813.1	87			
Depth of root exposures	Between groups	245.8	7	35.1	5.906*	0.000
	Within groups	475.6	80	5.9		
	Total	721.5	87			
Depth of gullies	Between groups	2898.1	7	414.0	2.304*	0.034
	Within groups	14373.5	80	179.7		
	Total	17271.6	87			
Depth of rills	Between groups	2013.3	7	287.6	1.846	0.090
	Within groups	12463.9	80	155.8		
	Total	14477.3	87			
Depth of stem-wash	Between groups	1274.1	7	182.0	1.462	0.193
	Within groups	9960.6	80	124.5		
	Total	11234.6	87			

[1)] Eight categories of erosion proxies as shown in Table 6.7; [2)] F critical = 2.12; * Significant difference between the different groups of erosion proxies in Table 6.7.

The analysis of variance was for the purpose of establishing whether the variances observed in one group of proxies were due more to internal differences among the bare footpaths than to the difference between the other proxies such as the grassed plot boundaries or bare plot boundaries. From Table 6.8, soil movement, depth of root exposures and depth of gullies showed the most significant difference among the proxies. This means that the differences could be attributed to the occurrence of gullies, the occurrence of root exposures or the occurrence of soil movement. Since soil movement occurred on more proxies than the gullies and the root exposures, it was decided to use it to compare the effect of the other proxies by determining the range of the difference and the difference between the means using the Bonferroni multiple analysis procedure of mean differences. Table 6.9 shows the obtained differences using the Bonferroni multiple analysis procedure. The significant differences according to the table were obtained for the depth of gullies, depth of root exposures and depth of soil movement. The depth of rills and the depth of stem wash showed no significant difference among the proxy groups. All in all the major difference observed by the pairwise analysis is the difference between the tea paths and the other proxies both in terms of root exposures and in terms of soil movement. Gullies show significant differences between the bare plot boundaries and the bare footpaths. Lack of significant differences for the depth of rills is for reasons similar to what was described for the field plots. The occurrence of the features of erosion was also selective for the different proxies. Soil movement having a higher variance ratio was selected for the quantitative test of the Bonferroni procedure.

Table 6.9 Comparison of the means using the Bonferroni multiple comparison procedure ($P<0.05$)

Watershed level erosion proxies	*Means of measured erosion features (cm)*				
	a	b	c	d	e
Bare plot boundaries$_{(n=36)}$	m,n	m	m,n,s	m	m,n,s
Bunded bare plot boundaries$_{(n=8)}$	m	m	m,o,s	m	m,o,s
Bunded and grassed boundaries$_{(n=9)}$	m	m	m,p,s	m	m,p,s
Grassed field boundaries$_{(n=3)}$	m	m	m,q,s	m	m,q,s
Grassed footpaths$_{(n=4)}$	m	m	m,r,s	m	m,r,s
Bare footpaths$_{(n=17)}$	m,n	m	m,s,t	m	m,s,t
Tea paths$_{(n=8)}$	m	m	m,n,o,p,q,r,s,t	m	m,n,o,p,q,r,s,t
Trashed boundaries$_{(n=3)}$	m	m	m,s	m	m,s

a = depth of gullies in (cm); b = depth of rills in (cm); c = depth of root exposures in (cm); d = depth of stem-wash in (cm); e= depth of soil movement in (cm); $_{n=3}$ refers to group sample size; m = no significant difference; n,o,p,q,r,s.t = significant differences between the proxies with the same alphabets.

Table 6.10 shows the comparison of the mean values of measured depth of erosion using the Bonferroni multiple comparison procedure for 5% significance levels with soil movement as the indicator erosion feature. From Table 6.10, it is quite evident that the bare plot boundaries, the bunded and bare boundaries, the bunded and grassed boundaries, and the trashed boundaries had the nearly equal mean differences. From Table 6.8 it can be concluded that the best disrupters of erosion among the proxies were the bunded and grassed plot boundaries and the grassed plot boundaries. Bare plot boundaries and bare footpaths would be the worst choice of disrupting proxies.

Table 6.10 Comparison of the means using the Bonferroni multiple comparison procedure (P<0.05) with soil movement as the indicator erosion feature

Erosion feature	*Reference erosion proxy*	*Comparison Proxy kind*	*Computed mean difference*	*95% family confidence interval[1) 2)]*	*P*
Soil movement	Tea paths	Bare plot boundaries	12.25*	(8.38; 16.12)	0.000
		Bunded bare boundaries	12.25*	(7.29; 17.20)	0.000
		Bunded grass boundaries	12.25*	(7.44; 17.06)	0.000
		Grassed field boundaries	12.25*	(5.54; 18.96)	0.000
		Grassed footpaths	10.25*	(4.18; 16.32)	0.000
		Bare footpaths	11.25*	(7.00; 15.50)	0.000
		Trashed boundaries	12.25*	(5.54; 18.96)	0.000

[1)] Based on the mean, (1-α) confidence level, family degrees of freedom, total degrees of freedom and standard deviation; [2)] Any interval going through zero shows no significant difference; * = Significantly different.

Discussions and recommendations for erosion management of the watershed

The proxies that returned zero values for recorded erosion, namely grassed bunds on field boundaries, grassed field boundaries and trashed field boundaries can be used against the occurrence of soil of soil erosion on the elongate field plot boundaries. The bare footpaths, the tea paths in tea plantations and bare field boundaries which had erosion features, can be fortified against soil erosion by either planting grass on them or planting hedges along field boundaries that ensure protection of the field-plots against pests and theft. Other added advantages is if vegetative intervention is used other attractive opportunities for the farmer such as the provision of green manure, fodder, fruits, shade, etc can be of benefit to the farmer. The strategy can also benefit environmental concerns such as carbon sequestration and reforestation if trees instead of hedges are planted. Nill *et al.* (1996) have recommended *Grevillea robusta, Sesbania sesban,* and *Calliandra calothyrsus* as some suitable tree species and *Axonopus affinis, Brachiaria mutica, Pennisetum clandestinum, Eragrostis curvula, Cynodon dactylon, Pennisetum purpureum, Digitaria decumbens* as some grass species that can be planted on field hedges for erosion control, and for fodder. Leguminous cover along the field boundaries would include *Mucuna capitata, Stylosanthes guianensis*, *Lablab purpureus*, *and Indigofera spicata*. *Leucaena leucocephala*, *Euphorbia balsamifera, Leucaena trichandra, and Leucaena diversifolia* can be used as live hedges.

If the linear channels such as dug field boundaries are well conserved with grass or hedges, then watershed erosion will be reduced to a bare minimum and most channel water will infiltrate downwards for crop production or to recharge the ground water system. Planting of hedges along field boundaries has dual advantages in that they can both create fodder and sequestrate carbon dioxide in the soil. This has dual effect of conserving the watershed while at the same time acting as carbon sinks and sources of fodder and tree crops.

If diversion ditches have to be constructed in the watershed, they should be paved with concrete or grass or other forms of vegetation planted in their course way to the major stream or river draining the area. Footpaths can also be protected against soil erosion by planting grass on them or by paving them with stones to minimise incidences of soil erosion.

The management of the watershed differs from the management of a field plot both in terms of the their architectural configurations and their ownership. A field plot in most cases belongs to a single farmer. A watershed in an area like Kiambu is most of the time inhabited by many individual families. Like for the field plot, issues appertaining to the management of the watershed discussed for the field plot should be accompanied by a participatory approach in order to introduce sustainability in soil erosion management. The managers of the watershed should mainly be its inhabitants. Though it is more difficult to demonstrate improved livelihoods for individual members of the watershed, individually well managed field boundaries will certainly benefit individual farmers. Social research can qualify what can be achieved qualitatively or quantitatively for the residents of a watershed in a participatory and integrated approach as herein proposed.

Important issues for consideration include constituting watershed management committees with which any intended interventions must be channelled. Such committees can be constituted using participatory methods of Pretty *et al.* (1995) and other existing socially accepted methods. Constituting such committees is beyond the scope of this work and can be handled during dissemination and management teams set up deliberately for that. As earlier said, biophysical solutions must be blended with sustainable livelihood programmes, where benefits of utilising certain technologies are clearly evident for the farmer or the community to avoid farmers distancing themselves from the technologies as observed by Mango (2002). Even when employing these approaches social networks (Doreian, 2002; Kadushin 2002; Leenders, 2002), and information dissemination (Lai, 2002), should be combined with the biophysical knowledge. Institutions concerned with soil and water conservation such as NGOs, government departments and Donors should be involved in an integrated approach. Solutions must be availed which addresses energy requirements, time constraints, human resources, mechanical resources, financial resources and technological innovations in the soil erosion management of the watershed. Partnerships between social, biophysical scientists, farmers and intervention institutions must be strengthened in a quest to find solutions that ensure sustainable management of soil erosion in the watershed. No single actor will have a final say in this regard. This level of the landscape hierarchy forms a good entry point that the Ministry of Agriculture for addressing issues on soil and water conservation. It will bring people of common cause and benefits together in the context of the watershed.

6.1.3 Key findings of erosion assessment at the landscape level

Occurrence of erosion features in the erosion proxies

Table 6.11 shows the mean rates of erosion measured under different proxies at the landscape level. As in the watershed and field plot levels, the selected erosion proxies were analysed for their influence on soil erosion and tested for differences in the occurrence of erosion. Depth of gullies, depth of mass movement, depth of exposed rocks, depth of rills, depth of root exposure, depth of stem-wash and depth of soil movement were analysed as the erosion features linked to soil erosion on the erosion proxies. From Table 6.11, it is evident that new features, i.e., mass movement, and exposed rocks indeed show emergent erosion features occurring in the landscape level proxies. Gullies also occur in four out of the six erosion proxies. Average values obtained where the proxies occur indicate that mass movement and gullies had the deepest incisions observed in the proxies. The gullies occurred at the edges of tarmac roads, on the edges of earth roads and in built-up trading centres. Mass movement occurred in built-up centres and on valley sides. Rills occurred in all the erosion proxies and were most prominent on edges of earth roads. Rock exposures occurred mainly in the built-up areas and on edges of earth roads. Exposed roots occurred on valley sides and to a low extent in the built-up trading centres. Soil movement occurred almost equally in the built-up centres, on edges of earth roads and in the valley sides.

Table 6.11 Mean rates of erosion measured under different proxies at the landscape level

E*rosion proxies*	*Measured means of erosion*						
	a	b	c	d	e	f	g
Built-up areas$_{(n=32)}$	9.69	15.63	2.62	8.44	0.00	0.94	3.75
Earth Roads$_{(n=45)}$	9.78	0.00	12.13	3.33	0.00	0.00	3.78
Grassed Roads$_{(n=5)}$	0.00	0.00	4.20	0.00	0.00	0.00	0.00
School Compounds$_{(n=3)}$	0.00	0.00	12.00	0.00	0.00	0.00	5.00
Tarmac Edges$_{(n=8)}$	25.63	0.00	1.87	0.00	0.00	0.00	0.00
Valley Sides$_{(n=12)}$	1.67	8.75	5.08	0.00	2.33	3.00	3.50

a = depth of gullies in (cm); b = depth of mass movement in (cm); c = depth of rills in (cm); d= depth of rock exposure in (cm); e = depth of root exposure in (cm); f = depth of stem-wash in (cm); g = depth of soil movement in (cm); $_{(n=12)}$ = group sample size; [1)] Averages computed for the erosion proxies where the erosion features occurred.

Table 6.12 Analysis of variance and the F-test for significance for difference among the six erosion proxies based on measurements on individual erosion features

Erosion features	*Erosion proxies*	*Sum of squares*	*Degrees of freedom*	*Mean square*	*F*[1)2)]	*Significance (P-value)*
Depth of root exposure	Between groups	57.87	5	11.57	9.191 *	0.000
	Within groups	124.67	99	1.26		
	Total	182.54	104			
Depth of stem-wash	Between groups	94.64	5	18.93	2.677 *	0.026
	Within groups	699.87	99	7.07		
	Total	794.51	104			
Depth of mass movement	Between groups	5245.30	5	1049.06	1.541	0.184
	Within groups	67393.75	99	680.75		
	Total	72639.05	104			
Depth of gullies	Between groups	3538.23	5	77.65	1.035	0.401
	Within groups	67683.19	99	683.67		
	Total	71221.42	104			
Depth of rills	Between groups	2159.24	5	431.85	1.393	0.233
	Within groups	30687.29	99	309.97		
	Total	32846.53	104			
Depth of rock exposure	Between groups	1098.13	5	219.63	0.635	0.673
	Within groups	34221.88	99	345.68		
	Total	35320.01	104			
Depth of soil movement	Between groups	167.47	5	33.49	0.099	0.992
	Within groups	33382.78	99	337.20		
	Total	33550.25	104			

[1)] Six categories of erosion proxies as shown in Table 6.11 [2)] F critical = 2.30; * Significant difference between the different groups of erosion proxies in Table 6.11.

Comparison between the erosion proxies

The erosion proxies used for the assessment of soil erosion occurrence at the landscape level were different from the ones of the field-plots and those of the watershed holons. The proxies at the landscape level generally caused larger erosion features than those of the field plots and the watersheds. Table 6.11 shows the mean rates of erosion measured as depth of erosion feature on different proxies at the landscape level. The proxies that were selected included built-up areas mostly in trading centres, edges of earth roads, edges of grassed roads, edges of tarmac roads, school compounds, and valley sides. From the table, the most devastating erosion features, i.e. gullies and mass soil movement occurred in the built-up areas, on the edges of tarmac roads, on edges of earth roads and on valley sides. The most severely affected were the built-up areas and edges of tarmac roads. School compounds were mostly eroded by rills and by soil movement. Earth-road edges were likewise eroded by rills and by soil movement. The valley sides were mostly eroded by mass movement and by rills. The valley sides also had root exposures and washed stems. It is apparent therefore that the different erosion proxies had different erosion features occurring on them. From Table 6.11, it can be observed that the occurrence of the erosion features were different based on the obtained mean values. Gullies for examples affected the tarmac edges than the earth roads and the built up centres. Mass movement affected the built-up areas than the valley sides. Rills affected the school compounds and edges of the earth roads than edges of the valley sides, grassed roads, the built-up areas and edges of the tarmac roads. It was necessary to determine whether the observed differences bore any statistical significance because though the school compounds and edges of grassed roads lacked gullies, they were on the other hand eroded by rills. Mass movement was similarly occurring only in the built up areas and in the valley sides and not in the other proxies. The other proxies in Table 6.11 however had rills or soil movement occurring on them. As was the case with the field plots and the watershed holons, the analysis of variance was used to determine whether the measured features of erosion demonstrated significant difference among the erosion proxies so that some could be classified as disrupters of erosion and others as drivers of erosion.

Table 6.12 shows the analysis of variance and the F-test for significance of difference among the six erosion proxies based on measurements of erosion features on individual proxies. Seen from Table 6.12, significant difference among the erosion proxies was shown only by the depth of root exposures and by the depth of stem-wash. This is not a result that bears weight of analysis since root exposures were only encountered on the river valley sides and in no other proxy. Similarly, washed stems occurred on the valley sides and to a small extent in the built–up areas. Using them to compare the erosion proxies would therefore be unrealistic considering that the other erosion proxies had other features of erosion occurring on them other than root exposures and stem-wash. The hypothesis that the are no differences in the erosion proxies based on depth of gullies, mass movement, rills and soil movement, is accepted from the analysis of variance. This implies that the erosion features occurred nearly equally on all the erosion proxies and based on this conclusion they can not be placed into two categories. Since they all had erosion features occurring on them they can all be concluded to be drivers of erosion. On closer scrutiny, none of the selected proxies had erosion-disrupting characteristics. From Table 3.2 some of the features that are considered to be disrupters of erosion include:

- Drained and dyked construction sites;
- Trapped and channelled roof catchment in built-up centres and schools;
- Paved roadsides;
- Grassed roadsides; and
- Bushed, grassed or forested riverbanks and valleys.

These disrupters of erosion were rare in the area and were therefore not included in the samples during data collection.

Discussions and recommendations for management

From what has been presented concerning soil erosion on the landscape level holons, it is clear that the proxies at this level are larger based on their incision of the terrain as seen from data on the proxies. Since different features are prominent on different proxies, the management of soil erosion in the built up areas must address soil erosion processes that result to the formation of gullies, mass movement, rills and rock exposure. Earth roads and tarmac roads must be likewise protected from roadside erosion in the form of gullies and rills. Schools like the built-up centres must be protected from rill erosion emanating from water originating from roof catchment. The river valleys must be protected from valley slump and mass soil movement in riverbank erosion. Surface erosion due to sloping terrain along the river valleys must also be contained and managed. After establishing that most erosion on the selected landscape level erosion proxies emanate from construction of built up centres, roads and schools, the management of the hazard differs from those proposed for the field plot or the watershed. The management requires that appropriate policy be directed to the construction companies and the inspector of works. The monitoring and supervision of the works can be vested to a community committee, which integrates all interest groups, such as non-governmental organisations, community based organisations, women groups, development groups and political leaders. Features to counteract soil erosion at this level could be built dykes, trapped and channelled roof water, paved roadsides, grassed roadsides and bushed or forested river banks. They must all be made integral pats of rural development projects.

Issues of soil and water conservation vís a vís sustainable management of landscape units and riverbanks must be addressed. Technical experts and society must find technological innovations, policies, structures, resources, and equipment necessary for managing soil erosion at the landscape level in Kiambu sooner than later because the erosion features at the landscape level are mostly caused by higher energy flow processes resulting into rills and gullies. Mass movement along riverbanks is also normally caused by the removal of vegetative material, a decrease in shear stress and an increase in shear resistance due to gravity (Lal, 1990). Riverbank slides are according to Lal (1990) caused by the force of running water and by undercutting. The removal of vegetation along riverbanks or cutting of the soil profile on the lower part of the slope according to Zaslavsky (1977) can result to an increase in the seepage flow pressure as soon as saturation of the soil occurs. The exposed boundary under suction acts as an impermeable layer and a streamline. A slight and local dent on the soil surface can cause a local concentration of streamlines and highly increase seepage forces. According to Zaslavsky (1977) water flowing out of the soil causes the seepage forces. The seepage forces can decrease the stabilising downward force of a horizontal soil surface mantle. The seepage forces can be such that a slight drag due to seepage would roll out the particle of the overlying soil mantle. According to Eppink and Stroosnijder, (1994), if the seepage forces amount to 90% of the aggregates' weight, the necessary turning drag would be reduced to 10%. The seepage forces can combine with the drag forces to enhance soil erosion. To maintain the resultant force at the turning point, the drag force must be decreased in proportion to the reduction in the stabilising force. It is therefore important not to leave sharp edges along river channels and should it be the case, then vegetation or filter material must protect them.

6.2 General overarching discussions and conclusions

From the preceding sections of this chapter, some points that were discussed in Chapter 1 justifying the development of this research work become handy for review. First there was the issue of a hierarchical perspective in tackling soil erosion.

It has been shown that soil erosion at the field plot level, the watershed level and the landscape level can be distinguished based on the erosion proxies occurring at each level of the landscape hierarchy. It is further demonstrated that for each level, and in different erosion proxies, different erosion features dominate. Flow channels, translocated surface litter, soil movement, shallow rills, exposed roots and washed stems dominated nearly all the field-plot level holon types. For the watershed holons gullies emanated as new erosion features occurring on bare footpaths and on bunded field-plot boundaries. Rills occurred on bare field-plot boundaries, on bunded but bare field-plot boundaries and on bare footpaths. Root exposures occurred on edges of grassed footpaths, in tea paths and in bare footpaths. Washed stems were also observed in grassed footpaths, in tea paths and in bare footpaths. Soil movement was observed on edges of the grassed footpaths, along tea paths and along bare footpaths.

The landscape holons also saw the occurrence of new and emergent soil erosion features. These included mass movement, bigger gullies and exposed rocks. Gullies occurred in built-up areas, on edges of tarmac roads, on edges of earth roads and on valley sides. Mass movement and exposed rocks occurred in the built-up areas and on valley sides. Rills occurred in all the erosion proxies of the landscape making them the dominant form of erosion at the landscape level. Soil movement on the other hand occurred in four out of the six proxies but were less prominent compared to the rills or the gullies. The occurrence of root exposures and stem-wash was also less pronounced at the landscape level. From all these observations, a conclusion may be drawn that erosion processes forming the erosion features in the landscape unit were different from the processes of the lower hierarchical levels represented by watershed and field-plot holon types. Lower energy overland flow processes dominating the field-plot level holons and the higher energy channel-flow processes dominating the watershed and landscape holon types. In addition to channel flow processes the landscape level also had gravity and seepage flow processes producing the mass movement and river slumps that were observed in the proxies of that level. It is therefore of primary importance to study soil erosion processes in a landscape system from a hierarchical perspective where processes and features are linked to specific levels of the hierarchy.

Other works such as that of Van Loon (2002) supports these observations. According to Van Loon (2002), in spite the role overland flow plays in various instances like modelling soil erosion in a terrain, it has hardly ever been observed to occur over areas larger than a few hectares through direct measurements or field observations. According to him, there was a tendency to incorporate overland flow into mathematical models as a uniform sheet of water while it has never been observed and quantified over areas beyond a field plot. These observations by Van Loon augment the isolation of overland flow processes to a field plot as argued in this thesis. Rills and gullies on the other hand are linked more to elongate features in the watershed and field plots where overland flow concentrates to become channel flow. Rills sometimes develop in areas without incisions when overland flow concentrates adequate energy to start scouring the soil surface. According to Lal (1990) changes in the slope gradient can cause an exponential increase in surface flow until shallow flow changes from overland flow to rill flow. The presence of incisions and channels in the terrain such as the linear erosion proxies in the watershed encourage overland flow concentration into channel flow that develops into rill or gullies (Lal, 1990; Van Loon, 2002). According Lal (1990), backward head cutting and undercutting of lower soil layers cause the development of gullies from rills especially if a more porous soil mantle overlies a semi-pervious subsoil and if the flow channels discharge into steep slopes or cliffs. There is however a critical discharge required for gullies to form. Mass movements, riverbank slumps found in the landscape level holons are caused mostly by seepage water, gravitational forces and saturated through-flow or pipe-flow (Lal, 1990; Holden *et al.,* 2002). It can therefore be inferred that soil erosion manifestation in the landscape system is dependent on the proxy type in which it occurs and is influenced by the velocity of the flowing water, which causes the observed erosion. Lal (1990) showed that different flow types have different flow velocities where overland flow had the slowest velocity and stream channel flow the highest velocity. Table 6.13 shows the flow classifications according to Lal (1990). It is possible therefore to link soil erosion processes with the erosion proxies on which they occur. Based on this, it appears plausible therefore to make scientific observations and measurements according to the landscape hierarchy such that any extrapolations are directed to equal levels within the structure of the hierarchy.

Table 6.13 Flow velocity for different types of flow

Type of flow	*Velocity of water flow*
Overland flow	3 to 15 cm/s on slope of 0.40; less than 0.1 cm/s on low slopes with thick vegetation cover
Vertical percolation	Less than 7.5 cm/day in Whitehall Watershed, Georgia
Saturated flow	20 cm/h; 0.2 to 37.2 cm/h saturated hydraulic conductivity values collected from various field measurements
Through flow	80 cm/day in B-horizon in East Twin Brook Catchment, Sommerset; 50 cm/day in B/C horizon
Pipe flow	10 to 20 cm/s in Nant Gerig Catchment, Central Wales
Stream channel flow	Average 45cm/s

Source: (Lal, 1990)

From the observation that there are drivers and disrupters of erosion for each of the landscape hierarchy levels represented by different holons, sediment deliveries into streams should therefore be viewed less from a perspective of linearity as perceived in many linear models. They should be conceptualised from a perspective of the presence of drivers or disrupters of erosion along the pathways of flowing water based on the level of observation. The number of barriers as shown by Van Noordwijk (1998) must be taken into consideration during estimation of sediment deliveries. The view of erosion barriers and sediment delivery ratios has been recently discussed by Święchowicz (2002) who confirmed that it is only when the catchment is directly coupled with the stream or river that the sediment deliveries can directly be related to the size of the catchment. When barriers exist, then sediment delivery ratios are much lower.

From the previous discussion, it is clear that the management of soil erosion or its risk can be based on its position in the landscape hierarchy. Strategies must be tailored to conform with the holon types and their internal erosion proxies. Different intervention options must be availed which satisfactorily address the encountered erosion proxies at whichever level of the landscape hierarchy one could be dealing with. Field plot level erosion disrupters are for example: dense grass cover, tree or crop cover, mulch in cropland, hedges, ridges, bunds, grass strips, alley cropping and dykes on steep land. Watershed level erosion disrupters include: hedges, closed fences, closed field boundaries, dykes, terraces, cut-off ditches, vegetated corridor networks, grassed field boundaries, paved footpaths, grassed footpaths, bunded field boundaries, and vegetated field boundaries. Features to counteract soil erosion at landscape unit level are dykes, trapped and channelled roof water, paved roadsides, grassed roadsides and bushed or forested riverbanks.

From the assessment and definitions presented in the previous sections, the confusion in terminology especially in the definition of the landscape features as presented in Chapter 1 has been removed. The watershed has presented itself as the best management unit for many members of a community and can be adopted by any organisation interested in managing soil erosion for a particular community. The field plot remains the preserve of a single farmer while the landscape unit requires more of State interventions, policy, construction rules and community participation. The 'Catchment Approach' involving farmers and others in soil and water conservation can be addressed for the watershed unit or for several watersheds. Where larger areas are desired, then the landscape unit would be the best entry point if assessed and found to be at risk of soil erosion. A holistic approach that addresses, the contained field plots, watersheds and the landscape unit offers the most effective approach in landscape conservation.

Another conclusion that can be drawn is related to the erosion assessment procedures. Due to the assessment of soil erosion using erosion features, it was possible to show that soil erosion goes on even in tea plantations, coffee plantations and in forests. Most of the time, there is an assumption that there is no soil erosion in tea plantations, forests or in coffee plantations. This assumption must be discarded if a sustainable management of the plantation crops has to be achieved. Another issue of concern is the assessment of soil erosion at single levels of observation. If erosion assessment was only based on field-plots, then the erosion in the watershed or the landscape unit would be masked in the assumption that serious erosion only occurs in agricultural fields. Most assessment studies of soil erosion must be holistic taking consideration all the levels in the landscape hierarchy. Managing soil erosion at one level will also, not necessarily address the other two levels. For example, if a farmer manages soil erosion in his field-plot, this will not necessarily stop the soil erosion going on in the riverbanks, in footpaths, in the roads and in the trading centres. Managing field boundaries will not necessarily alleviate the erosion inside the field plot. For a complete management of erosion in an area such as Kiambu, all the three levels must be addressed holistically by the concerned actors. Individual farmers should target the field-plot and the watershed while the government agencies and constructors target the landscape unit more zealously. When the management of all the three levels are simultaneously addressed, a better net conservation will be obtained. Sustainability will only be ensured if the desires of the local communities, resources, equipment and human capital are available to tackle the problem synergistically.

In all these talks of soil erosion, a matter requiring monitoring is the one to do with increasing human populations. Human populations in rural and urban areas will continue to increase in the foreseeable future. This will be accompanied with an increase in the number of field-plots, field boundaries, footpaths, animal tracks, road-networks built-up areas and riverbank cultivation. From this, it is possible to infer that an increase in human populations will equally increase the erosion proxies and the risk of erosion. Management of soil erosion will therefore need to take cognisance of the changing populations and their patterns. Forward planing and early involvement in areas considered to be at high risk will need to be prioritised and provided with adequate financial resources, technology, human capital and collective participation. In doing this benefits of soil conservation will need to be explicitly demonstrated. Chapter 7 that follows shows how areas likely to suffer soil erosion can be predicted using field data and statistical methods.

7

Prediction and Spatial Modelling of Soil Erosion Risk

Prediction and spatial modelling of soil erosion risk

Prediction as used in this thesis refers to predetermining the risk of soil erosion on unvisited locations using data and knowledge gained from independently collected data to build prediction models. Regression analysis is used. In normal regression models, the response variable is estimated from data of known explanatory or predictor variables. Before the predictions, regression models are developed using measurements obtained from features of soil erosion as the response variable with slope, cover and erodibility as the predictor variables. Data on soil erosion were obtained by measuring vertical depths of encountered soil erosion features. These were afterwards regressed with slope, cover, erodibility, etc to obtain regression parameters. The regression parameters were thereafter introduced into logistic and logit models to predict the occurrence of soil erosion on the unvisited locations. How each of the individual models is derived has been presented in chapter 3. Due to the complexity of determining the prediction parameters in a logistic regression, a statistical software package was used. The logistic prediction parameters are normally determined by the log maximum likelihood estimation in a series of iterations according to Neter *et al.* (1996). In this case, before estimating the regression parameters, multiple-correlation analysis was used to determine predictor variables with significant correlation with soil erosion out of the known land-based factors of water erosion including: slope, cover, soil erodibility, etc., and which are also properties of the erosion proxies. Only variables with significant correlation were included in the prediction variable list.

The factors of erosion as enumerated above were selected due to their roles as properties of the erosion proxies that determine the development of erosion features within the proxies. The erosion proxies on the other hand exhibit spatial properties that allow their capture and extraction from the landscape system complex using aerial photography and remote sensing techniques.

7.1 Results of the analysis and erosion risk prediction for the field-plot holons

7.1.1 Correlation analysis

Correlation analysis was used to determine the relationship between the measured erosion (response variable) and the explanatory variables as already mentioned above. In this case study only three variables were analysed, i.e. slope gradient, ground cover and soil erodibility. It is possible to use other variables such as length of field plot, management of field plot, conservation of field plot, etc, if the data is available. It was not however possible to collect all the additional data and they were not therefore included in the prediction models. Table 7.1 shows the results of the correlation analysis of the field-plot level variables.

As stated in the preceding paragraphs, soil erosion was quantified on the basis of observable erosion features. The features were flow channels, translocated surface litter, depth of soil movement, depth of stem washing, depth of root exposure, and depth of rills. The total number of cases examined for the field-plot level observations were 165, and the degrees of freedom 163. Results of the correlation analysis are reported in the subsequent paragraphs.

Table 7.1 Correlation analysis for the plot level erosion data

Erosion features	*Multiple correlation analysis (150 cases included, 15 missing)*		
	Slope	Cover	Erodibility (Sediment concentration)
Flow channels*	0.46†	-0.32†	0.08
Surface litter translocated*	0.43†	-0.35†	0.09
Depth of soil movement	0.53†	-0.12	0.03
Depth of stem washing	0.49†	-0.12	0.09
Depth of root exposure	0.50†	0.02	0.01
Depth of rills	0.37†	-0.24♀	0.00

*Refers to areas where all features of erosion were present and their vertical depth values summed up. Flow channels and surface litter translocated were not summed-up since values were recorded in % and not in interval ratio. † Significant at 1% (P = 0.000) ; ♀ Significant less than 5% (P = 0.002).

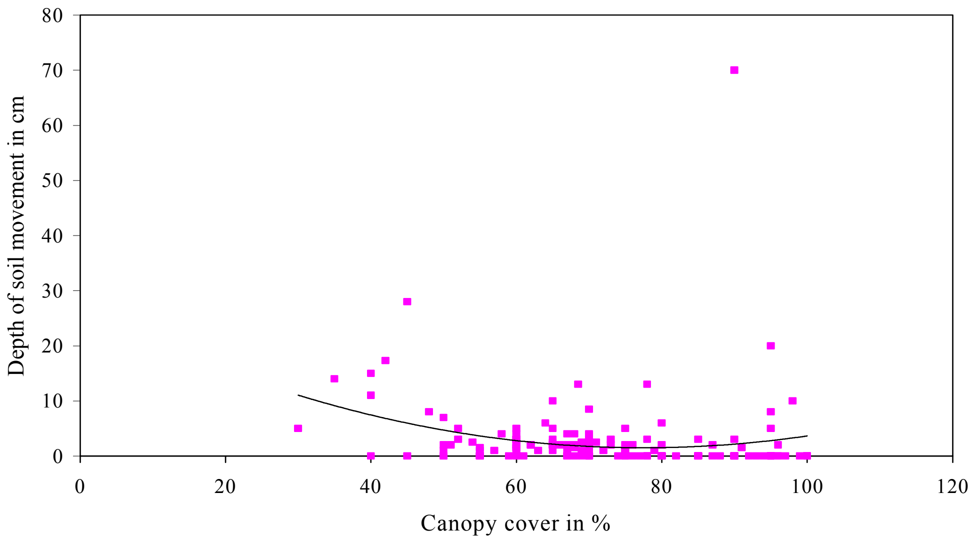

Figure 7.1 Values of soil movement plotted against percent cover for all the observations in the study area

Soil erodibility

Table 7.1 shows that there was no significant correlation between the soil erodibility with the measured erosion variables in a multiple correlation analysis in the study area. This does not imply however, that in other areas where the soil properties are more diverse than the study area, a similar result would be obtained.

Cover

Next, the relationships between cover and the measured erosion were analysed. From Table 7.1 it is observed that cover had significant correlation with flow channels, translocated surface litter and rill depths. The other response variables had no significant relationships. This is explained by the fact that unexpectedly high rates of erosion occurred in tea plots than would normally be expected when cover values are above 90%. Details have already been explained in chapter 6. Figure 7.1 shows the relationship between canopy cover in the x-axis and soil movement in the y-axis. In normal occurrences, cover conditions above 90% are usually associated with low occurrence of soil erosion unlike the trend depicted in Figure 7.1. According to findings by Elwell and Stocking (1976), Elwell (1980), Stocking (1988), and Gachene (1995b) cover conditions above 60% are normally associated with low erosion rates. Since soil erosion features occurred and were measured in the tea plots with above 90% canopy cover, an unexpected mismatch occurred during correlation analysis. Another unusual occurrence in the correlation analysis was the occurrence of low values of soil erosion features under cover conditions ranging from 50 to 60%. Whereas it is expected that high rates of erosion occur under cover conditions below 60% (Stocking, 1988), this appeared not to have been the case for some of the sites. This was partly due to the fact that there were conservation measures in some field-plots that deterred the development of soil erosion features under conditions where they are normally expected to occur. These included mulching, terracing or agro-forestry in the fields where the data was collected. Mulching in some plots like the coffee plots reduced the occurrence of soil erosion in cover and slope conditions where erosion is normally occurring especially in the range from 50 to 60%. Unusually high values of erosion were sometimes measured in some sites with cover conditions above 65% (Figure 7.1). Where erosion occurred in areas with cover conditions above 65%, slope appeared to be the dominant driver of soil erosion.

Slope

The next explanatory variable examined for relationship with soil erosion was slope. From Table 7.1 it is evident that slope had a significant positive correlation with depth of soil movement, depth of stem-washing, translocated surface litter, flow channels, depth of rills, and depth of root exposures. All these erosion features were found to have significant correlation (data in Table 7.1). The obtained results show that increase in slope is associated with increase in the level of soil erosion at the field-plot level. Figure 7.2 shows the values of the depth of soil movement plotted against 5% slope intervals for all the observations in the study area.

From the multiple correlation analysis shown in Table 7.1, slope and cover were considered appropriate for predicting the occurrence of soil erosion in the field plot. Figure 7.2 shows a plot of the depth of soil movement in the y-axis and slope gradient in the x-axis. From the figure, depth of soil movement is seen to increase gradually with slope. The high rate of soil erosion on the 0-5% slope is due to the fact that factors other than slope influence the occurrence of soil erosion. Erodibility, though a factor of soil erosion, showed no correlation in the multiple-correlation analysis and was therefore dropped as a predictor variable. For other areas other than Kiambu, the situation might be different and it is recommended that correlation analysis be carried out for all variables that are considered to influence soil erosion such as erodibility, length of field-plot, plot management, etc, if the data is available for selecting the predictor variables to be included in the logistic model.

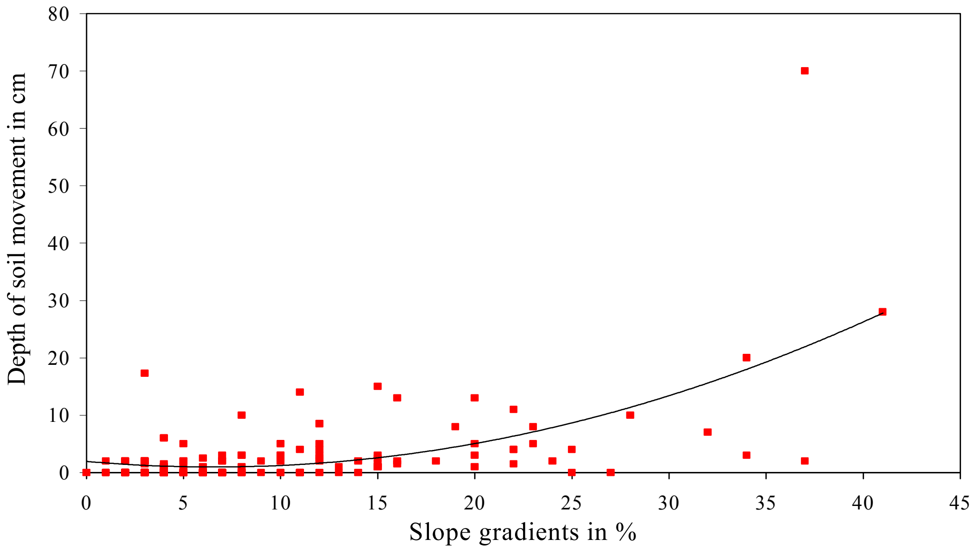

Figure 7.2 Values of the depth of soil movement plotted against 5% slope intervals for all the observations in the study area

7.1.2 Logistic regression

Due to the absence of soil erosion features in some plots, it was decided that logistic regression be used to predict the risk of erosion instead of the normal parametric linear regression models. In this process, slope and cover data retained their interval ratio scales of measurement (i.e. % values) for estimating the regression parameters. Table 7.2 shows the results of the estimated prediction parameters of the logistic regression. The measurements on the features of erosion were converted to 1 for presence and to 0 for absence. Prediction parameters that produced sigmoidal curves were considered to be the appropriate variables for fitting the logistic regression model. The model curve was considered to be sigmoidal if the predictor coefficients b_1 *and* b_2 and the constant did not produce a straight line curve. Two models were used for the prediction, the logistic prediction model and the logit model. The logistic probability model has response values ranging from 0 to 1 while the logit models produces values ranging from $-\infty$ to $+\infty$ (Neter et al., 1996). The logit model is a linear logarithmic transformation of the logistic probability model. The logit model creates a normal distribution of the transformed probabilities around the 0.5 value of the logistic probabilities. Logit values of 0 carry a probability of 0.5. Negative logit values are considered to be responses where the predicted erosion have a probability of less that 0.5. The normal distribution of the logit model stretches the range of the transformed probabilities and makes it possible to increase the class categories of the transformed probabilities and thereby separating areas with probabilities greater than 0.5 from areas with less than 0.5 probabilities. The two models support each other. The logistic model produces the expected probabilities that are constrained between 0 and 1, while the logit model stretches the probabilities by acquiring a normal distribution curve. The logit model therefore creates more log-transformed class intervals and helps highlight risk differences into two subclass ranges, i.e. those with less than 50% chance of occurrence from those with greater than 50% chance of occurrence. The stretch is applied to all predictor variables fitted in the prediction model. The logit response values are not quantitative values of the predicted risk but are more of relative linear quantitative probabilities. Probability meaning is obtained by taking antilogs of the logit values, which return the real probabilities that can be used for interpretations and decisions. The logit values can however be calibrated with actual field values such as soil loss values to give them quantitative value. The erosion risk predictions must therefore still be based on the logistic probability and the odds ratios. The logit transformation however, enhances the multi-variable spatial modelling that assists to optimise the probability classification intervals, and hence creates shorter normally distributed prediction intervals that are useful for targeted decision making.

7.1.3 Results and discussion

The prediction models

Table 7.2 Multiple logistic regression for all presence or absence of erosion features with slope and cover as the explanatory quantitative variables for the field-plot level data

Predictor variables	Logistic regression statistics parameters (maximum likelihood estimation) (165 cases included no missing cases)				
	Coefficient	Standard error (SE)	Estimated odds ratio	Coefficient/SE (t test for sigmoidal curve)	P* (significance of t test)
Constant *(b_0)*	4.18	1.13	-	3.69	0.0002•
Slope *(b_1)*	0.22	0.04	1.24	5.28	0.0000•
Cover *(b_2)*	-0.08	0.02	1.08	-4.96	0.0000•

Deviance test for goodness of fit of the logistic model

Convergence Criteria	No. of iterations	Deviance	P-value (χ^2) test	Degrees of freedom	Deviance/ Degrees of freedom
0.01	5	142.29	0.87	162	0.922 $^{H}{}_{0}$

• Significant t-test for the sigmoidal logistic regression curve. $^{H}{}_{0}$ = Conclude goodness of fit of the logistic model. * If P for the constant *(b_0)* is not significant then the curve is almost a straight line and not a sigmoidal curve as required for presence and absence data. The predictor parameter can therefore be dropped and new data sought. The closer to 0.000 the more significant is the result. Above 0.10 implies non-significant results. Deviance/degrees of freedom test provides the basis for concluding whether the model attains the goodness of fit. If values are closer to 0 and less than 1 then the conclusion is that the model is well fitted. Convergence criteria is the standard error obtained by the maximum likelihood estimation of the statistic parameters.

The parameters of the logistic regression estimated by the maximum likelihood estimation for the field-plot level data are shown in Table 7.2. Substituting the parameters of the model from Table 7.2 into the logistic regression equation 3.4 creates the logistic probability model for the field-plots shown in equation 7.1.

$$p = \frac{[exp(4.18 + 0.22 * slope - 0.08 * cover)]}{[1 + exp(4.18 + 0.22 * slope - 0.08 * cover)]} \qquad (7.1)$$

Substituting the same prediction parameters from Table 7.2 into equation 3.7 produces the logit model in equation 7.2.

*Logit linear predicted erosion = 4.18 + 0.22 * slope – 0.08 * cover* (7.2)

In order to use the two models in spatial modelling, the attribute structure of the tabular spatial database for which the predictions are to be made is modified to accommodate each of the two new variables, i.e. the probability and the logit fields. The variables are entered as floating point numeric data types. The thematic tabular database for predicting the expected erosion risk probabilities must beforehand have slope and ground cover numeric data in order for the computations to be possible. Equations 7.1 and 7.2 are then used to compute the logistic probability of erosion and the logit transformations.

The odds ratio

Other important elements in the logistic regression parameters in Table 7.2 are the estimated prediction coefficients b_1 and b_2. The interpretation of b_1 or b_2 is not the straightforward interpretation of the fitted slope in a linear regression model (Neter *et al.,* 1996) since they deal with predicting the occurrence of a certain response based on the starting point of the predictor variables. They describe the odds of obtaining a certain response. The reason is that the effect of a unit increase in the predictor value say *X*, varies for the logistic regression model according to the location of the starting point on the *X* scale. The risk of erosion for example is based on the initial conditions of the reference point such as the initial values of slope and cover in a field-plot. Erosion occurrence will be dictated by b_1 in the case of slope and b_2 for cover. The two are considered independent and the interpretation of one assumes that the second variable is a constant. The sign before b_1 or b_2 indicates the direction of increase or decrease in the expected occurrence of erosion. An interpretation of b_1 or b_2 is found in the property of the fitted logistic function that the estimated odds $(p/1-p)$ are multiplied by exp (b_1) or exp (b_2) for any unit increase in *X*. Exponential of b_1 or b_2 gives the odds ratio. The odds ratio provides a value for the rate of increase of the response variable with one unit of the predictor variable. In this case the increased risk of erosion with the increase in one unit of slope or the decrease of erosion with the increase of one unit of cover. Effectively, different locations will have different expected rates of increase in erosion risk depending on the initial prevailing slope and cover values. In general, the estimated odds ratio can be used to predict the expected change of the response variable when there are changes of a certain number of units of the predictor variables. For example, when the ground cover is increased by 20%, the occurrence of erosion will change according to the odds ratio computed by exp $(20*b_2)$. A positive sign before b_1 indicates that the predictor variable increases the response positively while a negative sign indicates the reduction of the expected response by the predictor variable. In this particular example, cover will reduce the incidence of erosion by the exp $(20*b_2)$. Therefore apart from the overall risk computed by the logistic or the logit model, b_1 or b_2 assists to obtain the rate of expected change just by obtaining its exponential. This can also be used for making management decisions based on which of the predictor variables can be manipulated to produce the desired effect.

Since the estimated logistic parameters produced a model with an accepted goodness of fit, the odds ratio obtained through the maximum likelihood estimations can be used for making erosion management decisions. The odds ratio for slope is 1.24 while the odds ratio for cover is 1.08. These values indicate that slope raises the probability for the occurrence of erosion by 24% while cover reduces it by 8% for a unit change of slope or unit change of cover. In normal practise, it is more difficult to change slope than it is to change cover. Cover can be changed by choice of crop or by instituting measures that minimise the exposure of the soil surface to the incidences of soil erosion such as mulching. Slope can only be reduced by putting barriers which accumulate material in the lower parts of the slopes such as planting of barrier hedges, riparian forests, terraces or by constructing bunds. Minimising landslides or mass soil movements entails changing the slope while minimising surface flow, and direct rainfall impact involves changing the ground surface cover. Table 7.3 is obtained from measurements of the mean percentage ground cover of different proxy types. From the table it is possible to identify the choice of proxy or cover types that can be used to increase the soil surface cover, thereby reducing the probability of the risk or erosion. The higher the number of units of cover that can be gained, the higher will be the amelioration factor depending on the number of units the specific proxy differs from the cover in the field plot of reference.

Table 7.3 Mean values of soil surface cover by the different land use or cover kinds

Land use/cover	% Mean Cover
Bare	10
Coffee	68
Fallow	70
Forest	92
Grass	73
Intercrops of annual & perennial crops	65
Coffee with macadamia	69
Tea	82

Logistic and logit predictions of erosion risk

The results of the spatial modelling of the soil erosion risk are shown in Figures 7.3 and 7.4 and in Figures 7.7 through to Figure 7.10. Figures 7.5 and 7.6 show slope and cover data that were used to compute the probabilities in the Gatwikira field plots. They are provided to show how the background data of the prediction variables contribute to the finally obtained predicted response probability and logit response predictions shown in Figures 7.3 and 7.4. Only the predicted probabilities for the encountered erosion proxies at the field plot level are shown in Table 7.4.

The computed probabilities showed that bare land had the highest probability of soil erosion at 0.87_{N35} probability. Vegetables followed with a probability of 0.75_{N13}. Coffee, open trees, and tea followed with 0.64_{N45}, 0.64_{N15} and 0.64_{N29} probabilities respectively. Maize with beans had a probability of 0.52_{N12} and Napier-grass a probability of 0.47_{N32}. The lowest probability was obtained for the grass plots with a probability of 0.34_{N11}. From the results, grass shows to be the best possible deterrent or disrupter of soil erosion. Napier grassed plots also faired well with probability values of 0.47. All the other crops and open trees have more than 50% chance of influencing soil erosion if not properly cared for. Napier grass also has a potential barrier effect. The data in the table are derived from sample areas located in different parts of the study area with many variations in individual slope and cover conditions. These lumped predicted probability values mask the predicted probabilities of the individual field plots whose results are enhanced in the spatial models. Figures 7.3 and 7.4 representing the spatial models of the logistic and logit predictions for the Gatwikira field plots are used to illustrate the benefits of the predictions of a spatial model.

Table 7.4 Probability of erosion risk at the plot level for the western portion field plots

Erosion proxies	*Computed probabilities*											
	Githiga plots (Slopes 1-37%)			Lynton plots (Slopes 0-40%)			Gatono plots (Slopes 1-40%)			Gatwikira plots (Slopes 1-34%)		
	N	AV	SD	N	AV	SD	N	AV	SD	N	AV	SD
Coffee	-	-	-	-	-	-	45	0.64	0.26	9	0.86	0.23
Coffee with trees	-	-	-	-	-	-	-	-	-	1	0.99	-
Tea	29	0.62	0.37	24	0.47	0.40	1	0.96	-	-	-	-
Young tea	6	0.82	0.20	-	-	-	-	-	-	-	-	-
Maize	45	0.62	0.26	-	-	-	8	0.71	0.29	31	0.71	0.24
Beans	1	0.64	-	-	-	-	-	-	-	-	-	-
Potatoes	1	0.64	-	-	-	-	-	-	-	-	-	-
Vegetables	13	0.75	0.28	-	-	-	-	-	-	2	0.22	0.09
Arrow root	-	-	-	-	-	-	6	0.62	0.36	7	0.18	0.13
Maize with beans	12	0.52	0.31	-	-	-	-	-	-	21	0.67	0.27
Maize & Potatoes	1	0.99	-	-	-	-	-	-	-	1	0.31	-
Maize & Fruit trees	1	0.97	-	-	-	-	-	-	-	-	-	-
Maize with tea	1	0.30	-	-	-	-	-	-	-	-	-	-
Maize with coffee	1	0.17	-	-	-	-	-	-	-	1	0.83	-
Maize with Napier	-	-	-	-	-	-	-	-	-	2	0.83	0.07
Maize with grass	-	-	-	-	-	-	-	-	-	4	0.65	0.16
Bare with maize	-	-	-	-	-	-	-	-	-	2	0.65	0.16
Maize with trees	-	-	-	-	-	-	1	0.99	-	1	0.23	-
Maize with shrubs	-	-	-	-	-	-	-	-	-	1	0.91	-
Homesteads & maize	2	0.57	0.08	-	-	-	-	-	-	4	0.52	0.25
Grass	11	0.34	0.22	1	0.53	-	8	0.65	0.31	31	0.61	0.29
Napier grass	32	0.47	0.31	-	-	-	6	0.54	0.23	26	0.61	0.31
Trees with grass	1	0.24	-	1	0.03	-	1	0.97	-	-	-	-
Avocado with grass	-	-	-	-	-	-	1	0.04	-	-	-	-
Avocado with herbs	-	-	-	-	-	-	1	0.82	-	-	-	-
Fallows	-	-	-	-	-	-	4	0.66	0.32	-	-	-
Shrubs with grass	-	-	-	2	0.67	0.0	1	0.98	-	4	0.58	0.34
Shrubs	2	0.99	0.0	6	0.62	0.45	3	0.73	0.45	1	0.61	-
Trees With herbs	-	-	-	-	-	-	1	0.94	-	2	0.69	0.62
Fruit trees	2	0.98	0.0	-	-	-	-	-	-	-	-	-
Trees	6	0.41	0.35	1	0.03	-	15	0.64	0.33	-	-	-
Woodlots	4	0.75	0.41	-	-	-	2	0.94	0.03	4	0.50	0.44
Forests	4	0.78	0.34	-	-	-	2	0.99	0.00	21	0.84	0.27
Bare land	35	0.87	0.20	3	0.98	0.32	14	0.83	0.26	29	0.88	0.19
Yards	1	0.77	-	-	-	-	-	-	-	-	-	-
Homesteads	28	0.55	0.32	-	-	-	18	0.76	0.23	22	0.67	0.28

N = sample size; AV = mean value; SD = standard deviation; - = absent

Figure 7.3 shows the logistic regression obtained by modelling the erosion probabilities using the logistic equation 7.1 while Figure 7.4 shows the logit transformation of the probabilities. The probability classes in Figure 7.3 show the field plots where different probabilities of erosion risk occur. Figure 5.9 in chapter 5 shows the distribution of the erosion proxies in the same field plots. The predicted probabilities follow the pattern of the predictor variables, slope gradient in Figure 7.5 and ground cover in Figure 7.6. The difference between the predictions using the logistic model in Figure 7.3 and the logit model in Figure 7.4 is illustrated by taking the example of a few field-plots planted with coffee. In Figure 7.3 the four out of the five selected coffee plots have a high probability of erosion risk (0.9-1.0). In Figure 7.4 more prediction differences are obtained with only one coffee field plot having very high-predicted risk compared to the rest. Three field plots have moderate predicted risk, while the field plot which appeared in Figure 7.3 as having slight probability of erosion risk is transformed to a no risk category in Figure 7.4. Both figures should be viewed to complement each other. The computed probabilities in Figure 7.3 show areas of different probabilities, while Figure 7.4 shows higher variation in the risk classes due to the log transformed probabilities. The logistic model in Figure 7.3, due to the constraint in the prediction range (i.e. 0.0-1.0), lumps areas with slight differences in slope and cover together, while the logit model stretches the differences within the same probability class by the bell-shaped normal distribution. The logit prediction model therefore increases the predicted probability range in Figure 7.3. Other examples of the predictions are shown in Figures 7.7 (logistic model) and 7.8 (logit model) for the Gatono field-plots and Figures 7.9 and 7.10 similar predictions for the Lynton field plots.

From the Figure 7.3 low probabilities are obtained on field plots on the valley floor and in field plots occurring on the crest of the interfluve. The shoulder and midslope positions have moderate and high probabilities. Some midslope positions and lower slope positions show high probabilities of the risk of erosion. Figure 7.4 shows a similar pattern but produces more classes and even places some low probability areas to no risk areas.

7.1.4 Conclusions

Odds ratio and erosion risk management

The odds ratios from the fitted regression model can be used to visualise the impact of the management options available and the socio-cultural, economic and resource implications associated with the management decision opted for. Changing one unit of slope to impact less on erosion risk would be more costly both in terms of time required to obtain satisfactory results and in terms of the resources, labour and energy required to effect the changes. Cover offers an easier management option though the gain in one unit of cover (8%) would be much less than the gain that could be obtained by reducing one unit of slope (24%). However, inputs into changing the cover conditions are much less, and it is easier to change more units of cover than units of slope just by mulching. Crops that have lower probabilities such as grass and closed trees can also be used to improve the net cover, thereby reducing the probability of the risk. Disrupters of erosion can be used to attain both slope changes and to create improvements in soil surface cover values as well.

Erosion proxies

The prediction of the erosion risk on the independent field-plots has shown that there is a variation of expected erosion on the erosion proxy, based on their property of cover and the slope position. The computed probabilities showed that bare land had the highest probability of soil erosion at 0.87 probability. Vegetables followed with a probability of 0.75. Coffee, open trees, and tea followed with a probability of 0.64. Maize with beans had a probability of 0.52 and Napier-grass a probability of 0.47.

The lowest probability was obtained for the grass plots with a probability of 0.34. From the results, grass shows to be the best possible deterrent or disrupter of soil erosion. Napier grassed plots also faired well with probability values of 0.47. All the other crops and open trees have more than 50% chance of influencing soil erosion if not properly cared for. Napier grass also has a potential barrier effect.

Spatial attributes

The spatial attributes which allow management of erosion include: the neighbourhood of each proxy object, the area affected by the predicted erosion, the location of the object and the availability and link of the objects with cover and slope data. Since most of these attributes can be displayed as visual object in a GIS, it is possible to identify target areas for action. The position within a selected watershed, the proximity to the streams or rivers, position of plot on slope, etc help to select appropriate intervention strategies. Soil conservation along the stream would be very different from soil conservation in the midslopes. Soil erosion management on cropland would also be very different from that in natural vegetation. The spatial data sets also enable the identification of the occupants of the field-plots that are most affected by the risk of erosion. They can therefore be included in erosion management decisions of field-plots in a particular area.

All biophysical information produced by the spatial prediction models can be availed to any group, which may be interested in managing any specific area. These products are important ingredients for the multidisciplinary teams discussed in Chapter 6, section 6.1.1. The distribution and neighbourhood analysis provides a pictorial view of the problem and the surrounding environment, providing a basis for targeted intervention action. The affected area provides information on the amount of anticipated work during intervention (i.e. energy, time, human, financial and other mechanical resources required for solving the problem). The location indicates the exact position of what needs to be tackled and the slope and cover data provide an idea on the type of intervention that might be required to solve the problem.

The prediction models

Both the logistic and the logit models produce prediction models that describe the variation of erosion risk in the field-plots in a manner, which corresponds to the distribution pattern of the explanatory predictor variables. When validated to posses accurate predictions, the models for the field plots can be recommended for adoption in other areas. Options for additional predictor variables that satisfy the production of logistic models with goodness of fit can be added to the prediction variable list. It is important to use both models in a spatial prediction since they support each other. The logit model optimises the logistic model, yet the logistic model provides the probability of erosion risk and the odds ratio. This conclusion is based on the observation that most erosion occurring in field-pots will be observed as presence or absence data in a random binomial distribution.

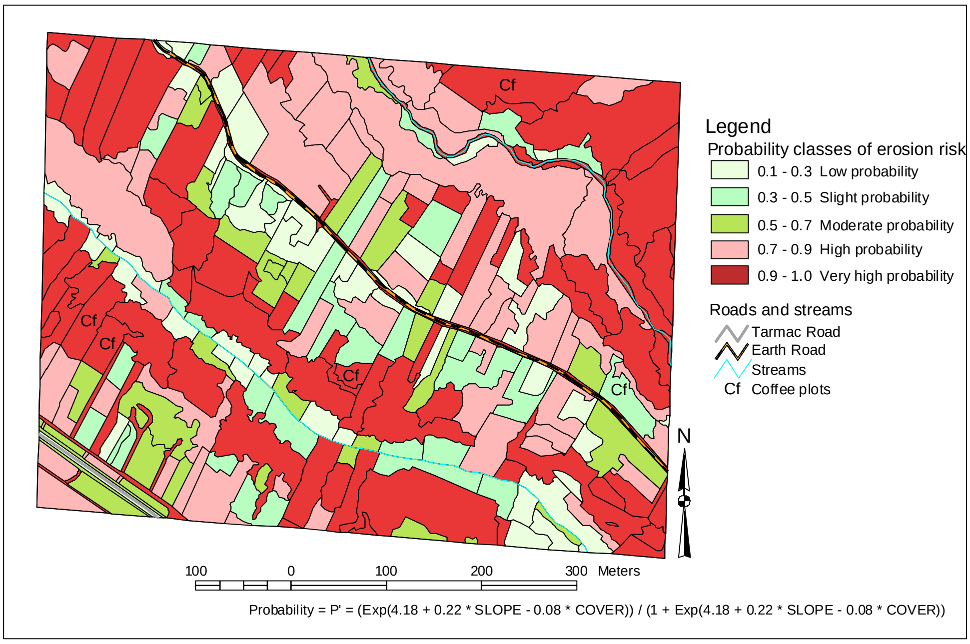

Figure 7.3 The predicted probabilities of erosion in Gatwikira field-plots using the model of equation 7.1.

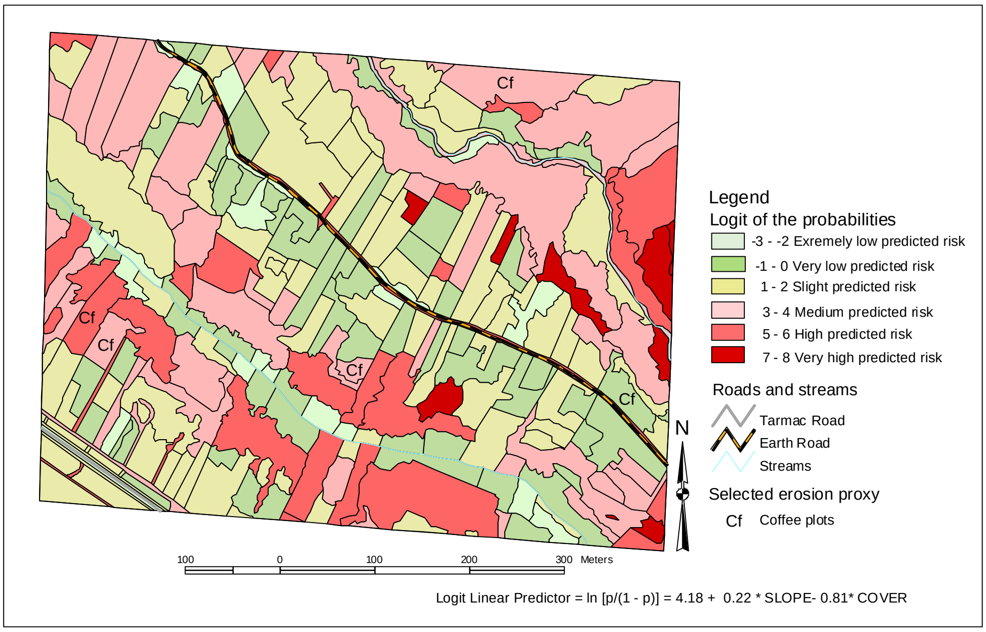

Figure 7.4 The transformed probabilities by the logit model of equation 7.2 for the Gatwikira field plots (annual, perennial, and mixed crops on small holder plots).

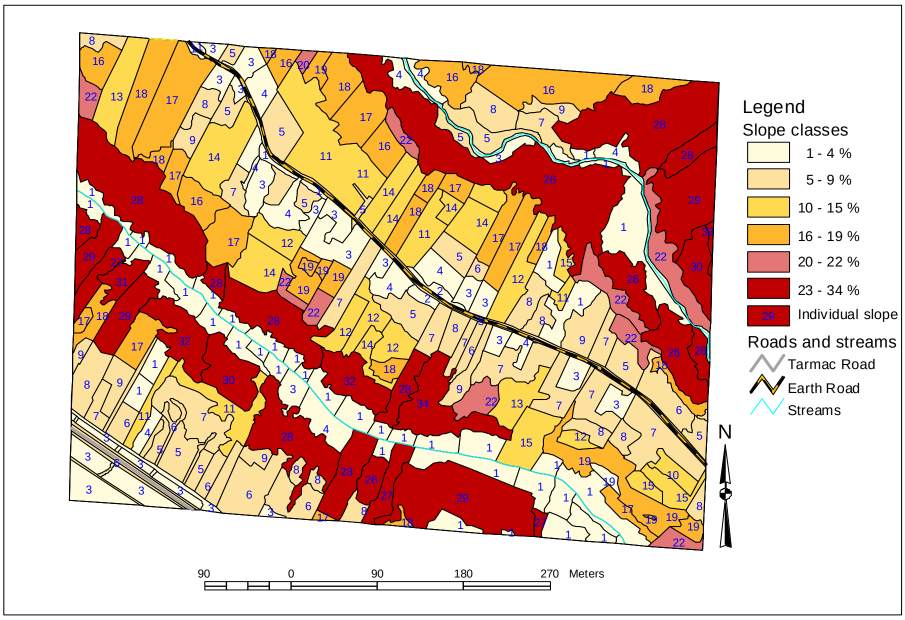

Figure 7.5 Slope values shown inside individual polygons while also grouped into different class categories.

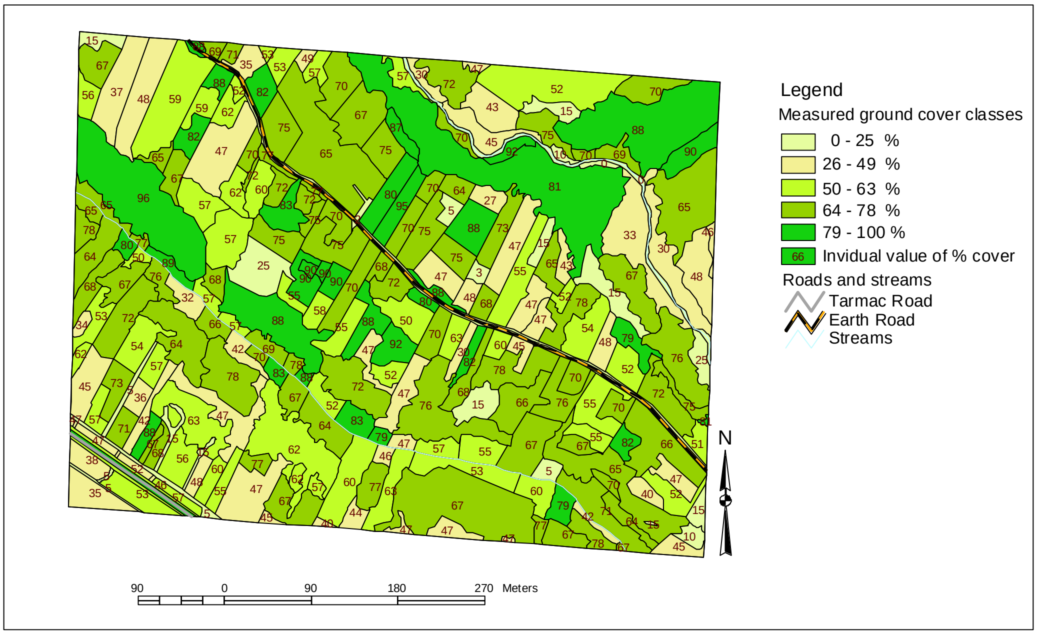

Figure 7.6 Cover values shown inside individual polygons while also grouped into different ground cover class categories.

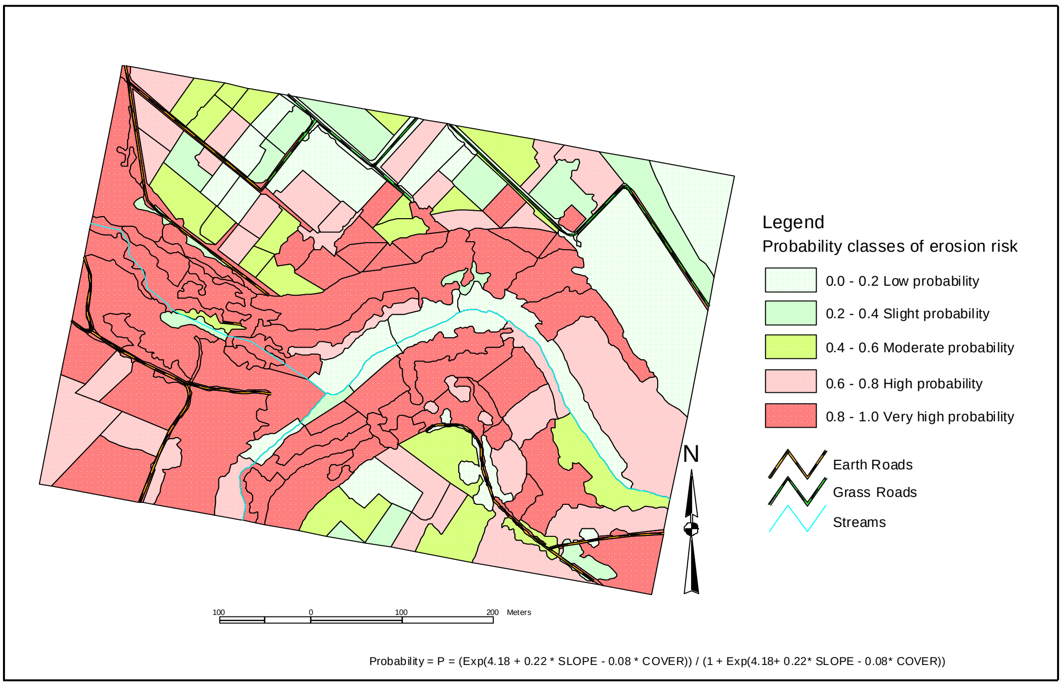

Figure 7.7 The predicted probabilities of erosion in Gatono field-plots using the model of equation 7.1.

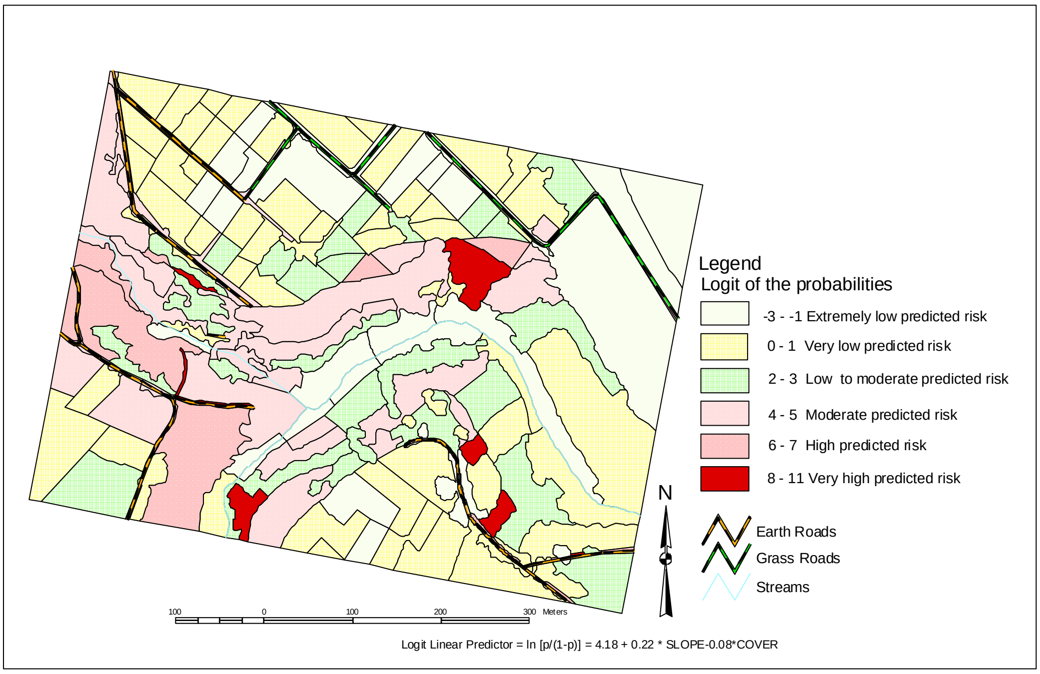

Figure 7.8 The transformed probabilities by the logit model of equation 7.2 for the Gatono field plots (annual, perennial, and mixed crops on small holder plots).

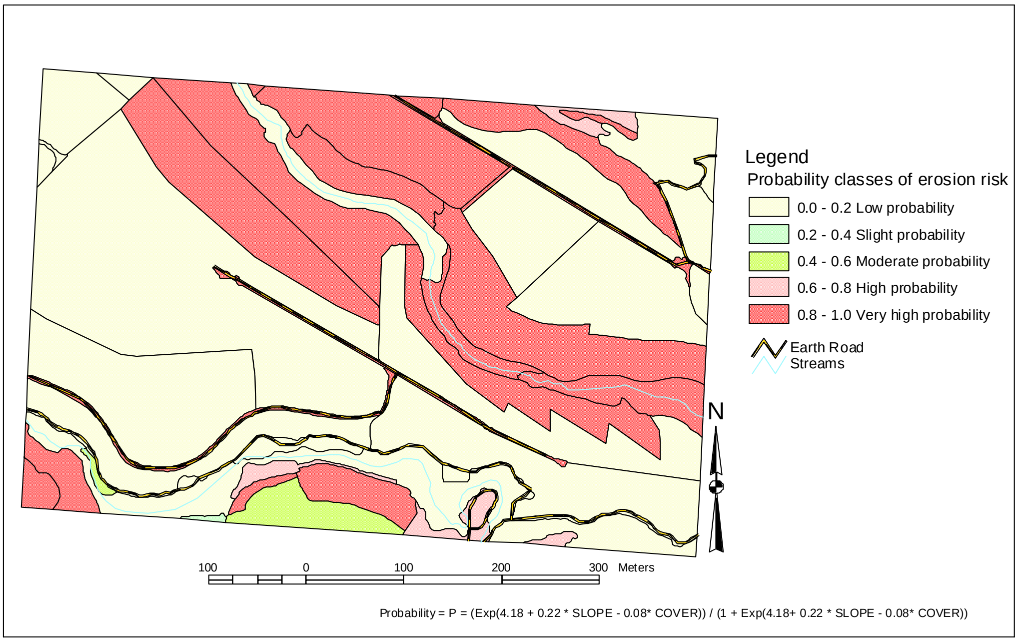

Figure 7.9 The predicted probabilities of erosion in Lynton field-plots (tea plantations) using the model of equation 7.1.

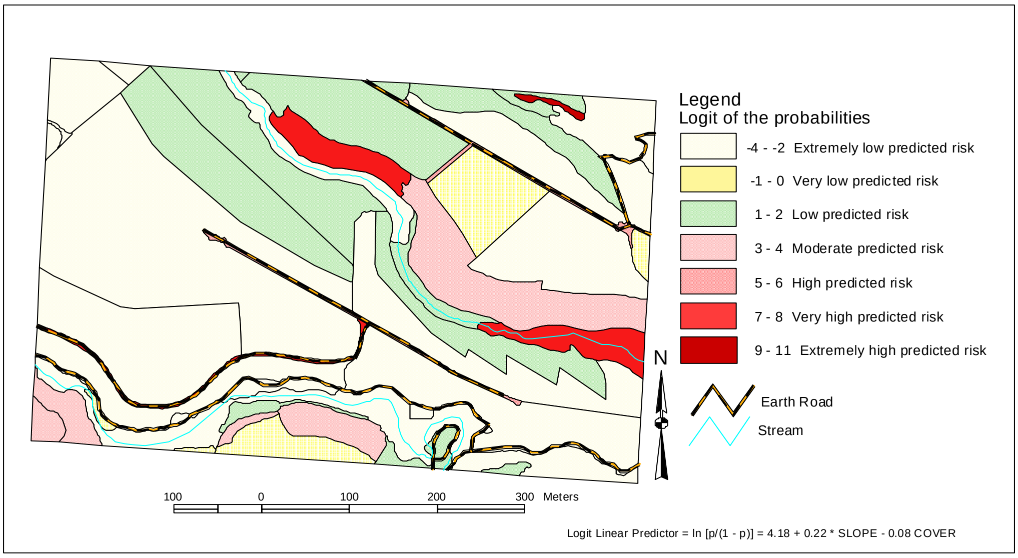

Figure 7.10 The transformed probabilities by the logit model of equation 7.2 for the Lynton field plots.

7.2 Results of the analysis and erosion risk prediction for the watershed holons

7.2.1 Correlation analysis

Results of the correlation analysis for the watershed level data are shown in Table 7.5. The response variables in the table included depth of deposition, depth of gully, depth of soil movement, depth of stem washing, depth of root exposure, depth of rills and summed up erosion. The analysed data had 76 degrees of freedom.

From Table 7.5, it is possible to see that slope had significant correlation with height of deposition, depth of soil movement, depth of stem washing, depth of root exposures and summed up erosion. Depth of soil movement, depth of stem washing, depth of root exposure and summed up erosion were significant at 1 %. Another significant correlation with slope was the height of deposition that had a correlation coefficient of (–0.2316), which was significant at 5%. The positive correlation with the features of erosion indicates that soil erosion increased with increase in slope. The negative correlation with deposition indicates that the height of deposition increased with decrease in slope.

On evaluating the correlation of soil erosion with cover, it was evident that cover correlated with the depth of rills. The depth of rills was significant at 10% while the summed up erosion was significant at 5%, all with negative correlation coefficients.

Table 7.5 Correlation analysis for the watershed level erosion data

Erosion features	*Multiple correlation analysis (78 cases included Missing 10 cases)*	
	Slope	Cover
Height of depositions	-0.23⚲	0.04
Depth of gully	0.17	-0.09
Depth of soil movement	0.64†	-0.13
Depth of stem washing	0.36†	-0.09
Depth of root exposure	0.53†	-0.12
Depth of rills	0.04	-0.22ƚ

* Refers to areas where all features of erosion were present and their depth values summed up. Height of depositions was not included in the summation. † Significant at 1%; ⚲ Significant at 5%; ƚ Significant at 10%.

7.2.2 Logistic regressions

From the results of the correlation analysis in Table 7.5, it was decided like for the field plots, due to absence of erosion in some of the proxies, to use logistic regression to compute the probabilities for the occurrence of soil erosion on the different proxies. Slope and cover were used as the predictor variables. Results of the logistic regressions are shown in Tables 7.6 and 7.7. Table 7.6 shows the results of the logistic regression using both slope and cover as the explanatory variables. Table 7.7 shows the logistic regression where only slope was used to produce the response parameters.

Table 7.6 Multiple logistic regression for all present or absent erosion features with slope and cover as the explanatory quantitative variables for the watershed level data

Predictor variables	Logistic regression statistics parameters (maximum likelihood estimation) (165 cases included no missing cases)				
	Coefficient	Standard error (SE)	Estimated Odds ratio	Coefficient/SE (t test for reg. curve)	P* (significance of t test)
Constant *(b_0)*	-1.33	0.39	-	-3.37	0.0008•
Slope *(b_1)*	0.30	0.09	1.34	3.27	0.0011•
Cover *(b_2)*	-0.07	0.16	1.07	-0.44	0.6572

Deviance test for goodness of fit of the logistic model

Convergence Criteria	No. of iterations	Deviance	P-value (χ^2) test	Degrees of freedom	Deviance/ Degrees of freedom
0.01	6	84.71	0.5192	86	0.985$^{H}{}_{0}$

• Significant t-test for a sigmoidal logistic regression curve. $^{H}{}_{0}$ = Conclude goodness of fit of the logistic model. * (See details in Table 7.2)

Table 7.7 Multiple logistic regression for all present or absent erosion features with slope as the explanatory quantitative variable for the watershed level data

Predictor variables	Logistic regression statistics parameters (maximum likelihood estimation) (165 cases included no missing cases)				
	Coefficient	Standard error (SE)	Estimated Odds ratio	Coefficient/SE (t test for reg. curve)	P* (significance of t test)
Constant *(b_0)*	-1.39	0.39	-	-3.64	0.0003•
Slope *(b_1)*	0.31	0.09	1.36	3.38	0.0007•

Deviance test for goodness of fit of the logistic model

Convergence Criteria	No. of iterations	Deviance	P-value	Degrees of freedom	Deviance/ Degrees of freedom
0.01	5	86.87	0.48	87	0.999$^{H}{}_{0}$

• Significant t-test for the sigmoidal logistic regression curve. ^{Ho} = Conclude goodness of fit of the logistic model. * (See details in Table 7.2)

Before the final model is decided upon, an examination was made of the results from the two tables. From Table 7.6 the p-test of the sigmoidal curve obtained for the cover was (P=0.6572) meaning that the contribution of cover to the sigmoidal curve was not significant. This requires that the predictor variable be dropped from the prediction list. This is primarily explained by the fact that most elongate or linear erosion proxies do not possess cover as an inherent property. Though the produced model attained the required goodness of fit with cover as an additional predictor variable, it was decided that the risk prediction be carried out only with slope, hence the production of Table 7.7. The estimation of the equation parameters was therefore carried out with slope as the only variable for obtaining the logistic parameters. Erodibility was not tested due to lack of data on soil erodibility. This is an important attribute of the soil, which might have had a contribution to the final model. The results of the prediction statistics are shown in Table 7.9. The same prediction parameters from Table 7.7 were fitted into equation 3.4, to compute the predicted probabilities and equation 3.7 to compute the logit linear erosion for the watershed level erosion proxies. Equations 7.3 and 7.4 were thus obtained.

The prediction models

Equations 7.3 and 7.4 were the two obtained prediction models. Equation 7.3 was used to estimate the logistic probabilities and equation 7.4 for estimating the logit linear predictions.

$$p = \frac{[\exp(-1.39 + 0.31 * slope]}{[1 + \exp(-1.39 + 0.31 * slope]} \qquad (7.3)$$

$$\textit{Predicted erosion} = -1.39 + 0.31 * slope \qquad (7.4)$$

7.2.3 Results and discussion

The odds ratio

The odds ratio from Table 7.7 was 1.36 meaning that an increase of one unit of slope increased the probability of erosion risk by 36%. This implies that if for any reason the slope was changed for construction purposes or changed by movements of the earth, such as in tremors or earthquakes, there would be a potential risk of 36% odds for the occurrence of soil erosion.

Logistic and logit predictions of erosion risk

Table 7.8 Computed probabilities of erosion for the western portion watersheds

Erosion proxies	*Computed probabilities*											
	Githiga watershed (slopes 0-37%)			Lynton watershed (slopes 0-40%)			Gatono watershed (slopes 1-40%)			Gatwikira watershed (Slopes 1-34%)		
	N	AV	SD	N	AV	SD	N	AV	SD	N	AV	SD
Bare plot boundaries	126	0.46	0.25	-	-	-	50	0.65	0.21	172	0.53	0.2
Bare footpaths	111	0.57	0.30	55	0.52	0.30	36	0.59	0.34	109	0.77	0.2
Grassed footpaths	16	0.84	0.20	-	-	-	-	-	-	6	0.81	0.2
Bare roadsides	24	0.41	0.15	-	-	-	-	-	-	31	0.20	0.0
Grassed roadsides	15	0.44	0.10	-	-	-	2	0.25	0.00	-	-	-
Hedges	160	0.43	0.24	-	-	-	7	0.26	0.04	154	0.49	0.3
Closed plot boundaries	21	0.46	0.27	-	-	-	74	0.32	0.17	33	0.20	0.0
Forest edges	88	0.56	0.33	-	-	-	13	0.39	0.28	193	0.38	0.3
Trees in a line	9	0.77	0.33	-	-	-	6	0.61	041	11	0.61	0.3
Access pathways	-	-	-	120	0.82	0.18	-	-	-	-	-	-
Wash stops in tea	-	-	-	103	0.25	0.00	-	-	-	-	-	-
Grassed boundaries	108	0.51	0.28	-	-	-	209	0.44	0.29	52	0.52	0.2

N = sample size; AV = mean value; SD = standard deviation; - = absent

Results of the computed probabilities are contained in Tables 7.8 and 7.9. The highest probabilities were obtained for the edges of the grassed footpaths of the Gatwikira watershed (0.84_{N16}), trees in a line (0.77_{N9}) in the Githiga watershed, bare footpaths in the Gatwikira watershed (0.77_{N109}), bare plot boundaries (0.65_{N109}) in the Gatono watershed, in that order. The influence of slope dictated the obtained results as portions of the bare footpaths falling on level terrain had low predicted probabilities. The lowest probabilities were found in un-dug or closed plot boundaries (0.20_{N33}) in Gatwikira area, bare roadsides also in Gatwikira (0.20_{N31}), on grassed roadsides (0.25_{N2}) and in hedges (0.26_{N7}) in the Gatono watershed.

The computed logistic probabilities were generally higher for the western portion watersheds than the eastern portion watersheds that were located on less sloping terrain. As the case was for the field plots, the lumped statistical averages do not provide a prediction of the individual objects, which is an important aspect for making decisions concerning the specific object. The spatial prediction analysis result is therefore better for showing and interpreting the results.

Table 7.9 Computed probabilities of erosion for eastern portion the watersheds

Erosion proxies	*Computed probabilities*											
	Bradgate watershed (0-10%)			Kitamaiyu Watershed (slopes 0-8%)			Ruiru Plain (slopes 0-1%)			Kenyatta Plain (slopes 0-5%)		
	N	AV	SD	N	AV	SD	N	AV	SD	N	AV	SD
Bare plot boundary	10	0.46	0.19	3	0.25	0.00	8	0.25	0.00	-	-	-
Bare footpath	5	0.24	0.02	-	-	-	-	-	-	29	0.2	0.00
Grassed footpath	6	0.35	0.11	7	0.23	0.03	-	-	-	-	-	-
Grassed roadside	12	0.35	0.12	4	0.30	0.11	14	0.25	0.02	15	0.26	0.06
Hedges	-	-	-	4	0.25	0.00	-	-	-	-	-	-
Closed plot boundaries	-	-	-	-	-	-	23	0.25	0.00	-	-	-
Grassed boundary	-	-	-	-	-	-	40	0.23	0.02	67	0.27	0.11

N = sample size; AV = mean value; SD = standard deviation; - = absent

Figure 7.11 shows the predicted probabilities of the risk of erosion in Gatwikira watershed on the elongate erosion proxies using the model of equation 7.3 while Figure 7.12 shows the predicted transformed probabilities of the logit model in equation 7.4 for the same area and erosion proxies. The erosion proxies occurring on the valley floor positions and those on the midslope position show slight to moderate erosion probabilities. From the logit model, the proxies on the valley floor are predicted not to posses any risk of erosion. The slight probabilities of erosion risk also occurring on the erosion proxies on the crest of the interfluve area are also transformed by the logit transformation to no risk situations. Footpaths and field boundaries on the midslope positions show the highest risk of erosion. Individual probability risk for each of the objects is clearly seen from the spatial distribution in the figures. Figures 7.13 and 7.14 show the individual features and the slope attribute values used for the predictions. The predictions were done for eight watersheds but only the distribution maps in two watersheds are included to show how the spatial distribution of the predictions. The predictions look appealing because portions of the footpaths, which are on the valley-floor, are predicted not to have any erosion risk by the logit model. The probability model reports slight probability. Though the data used for building the prediction models were collected independently, both the logistic model of equation 7.3 and the logit model of equation 7.4 have shown good relationship with variations in the terrain. From the two maps, it is possible to identify the positions and locations of the erosion proxies that require attention.

Where the modelled probability is high, immediate examination is required and if found to have existing erosion then appropriate intervention action should immediately follow.

7.2.4 Conclusions

Odds ratio and erosion risk management

The odds ratio for the fitted models indicate that for every increase in one unit of slope there will be a 36% risk of there being soil erosion. Sudden increase in slope can occur due to lowering of downslope positions by digging, construction, or due to landslides. If this happens, then there will be 36% more predicted erosion risk per unit increase in slope than if there was no change. Should this happen, immediate mitigation action should follow. From observations in the field, hedges along field boundaries, and paved footpaths seemed to have effectively stemmed soil erosion on the elongate features. The linear proxies that lie across the slope if properly dug out have good barrier effect on water flow and development of soil erosion. If the erosion barriers or disrupters can be built in the upper positions of the slope, there is a general possibility of reducing the slope gradient. The reduction of slope by one unit will reduce the hazard of erosion by 36%. The use of disrupters of erosion across the watershed slope direction is therefore highly recommended. Tree lines can also be used along the field boundaries to mitigate against soil erosion and to provide other alternative sources of income and protection of the environment as discussed in chapter 6.

Erosion proxies

The prediction of soil erosion on the erosion proxies though dependent on slope as the predictor variable showed good results. However, if other spatial attributes of the elongate proxies can be added into the predictions, there would be likelihood that good correlation is obtained between the effective proxies and those that are less effective. Such attributes still need to be identified. More research is therefore still required to find more attributes of the linear or elongate erosion proxies that have direct relationships with the risk of erosion and which can be included into the prediction model as additional predictor variables. Cover is unlikely to be one of the additional attributes since majority of the elongate erosion proxies lack cover as an inherent property.

Spatial attributes

As discussed in section 7.1.4, it is mostly the spatial attributes of the erosion proxies emanating from the results of the predictions that create handy tools for directed management of soil erosion. The spatial attributes that allow the management of erosion include spatial distribution of the predicted erosion on the proxies, the neighbourhood of each proxy object, the length of the spatial object affected by the predicted soil erosion and the location of the object. Other issues of consideration include the availability and link of the real-world erosion proxies with management structures such as barrier hedges, vegetated live fences, grassed boundaries, trashed boundaries and hillside cut-off ditches that can be used for preventing flow of water along the erosion-driving proxies. From the spatial distribution maps in the figures

(Figures 7.11 to 7.16) it is possible to visualise the areas which suffer the highest probabilities and for which immediate attention is required and other areas for which future conservation planning is necessary. Armed with these spatial data sets, it is possible to prescribe possible landscape management scenarios or patterns that will minimise soil erosion.

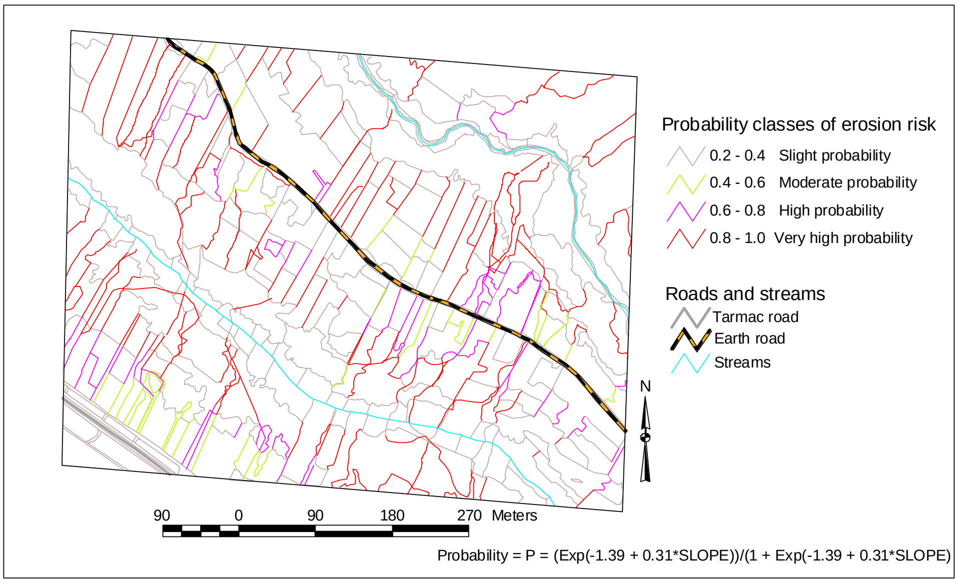

Figure 7.11 The predicted probabilities of erosion in Gatwikira watershed on the elongate linear erosion proxies using the model of equation 7.3.

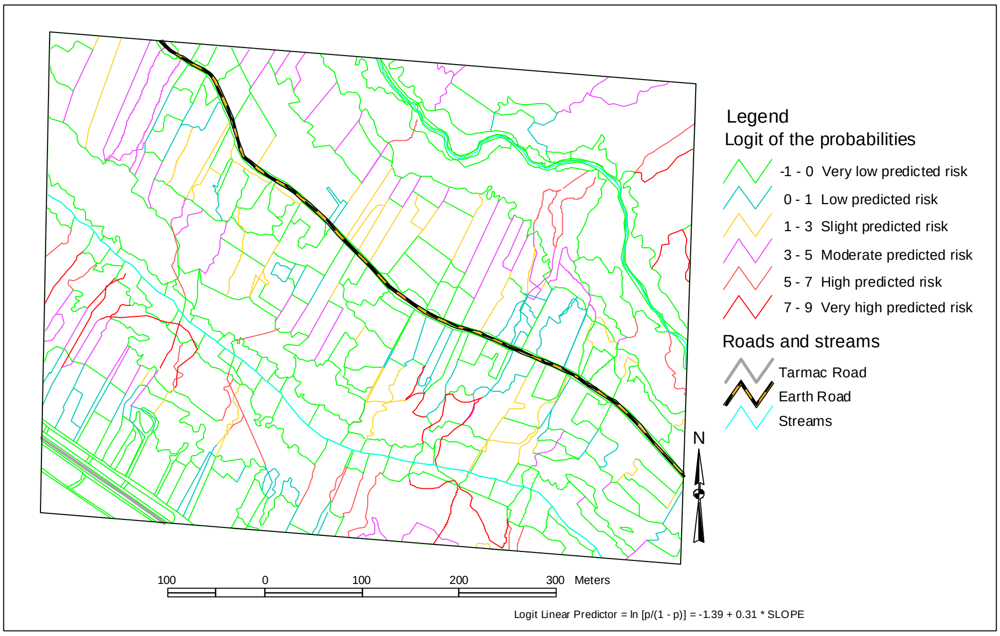

Figure 7.12 The transformed probabilities by the logit model of equation 7.4 for the Gatwikira linear erosion proxies.

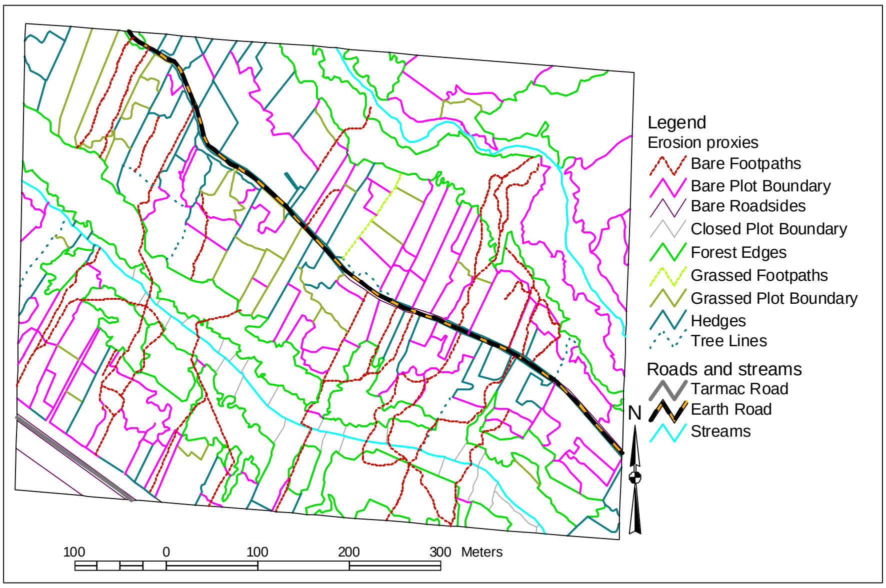

Figure 7.13 The linear erosion proxies of the Gatwikira watershed

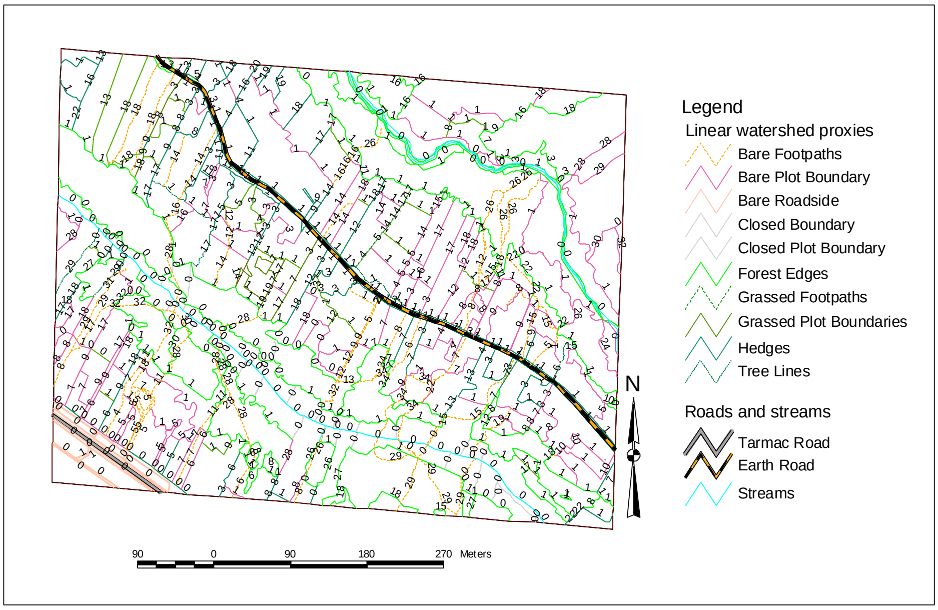

Figure 7.14 Slope values allocated to the different linear erosion proxies forming the basis for the spatial modelling using equations 7.3 and 7.4.

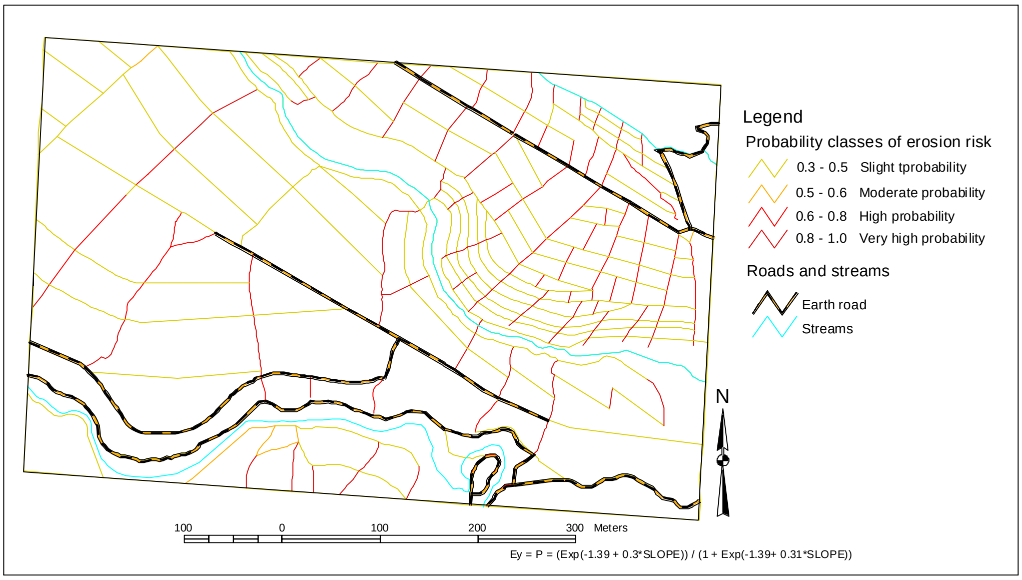

Figure 7.15 The predicted probabilities of erosion in Lynton watershed on the linear erosion proxies in tea plantations using the model of equation 7.3.

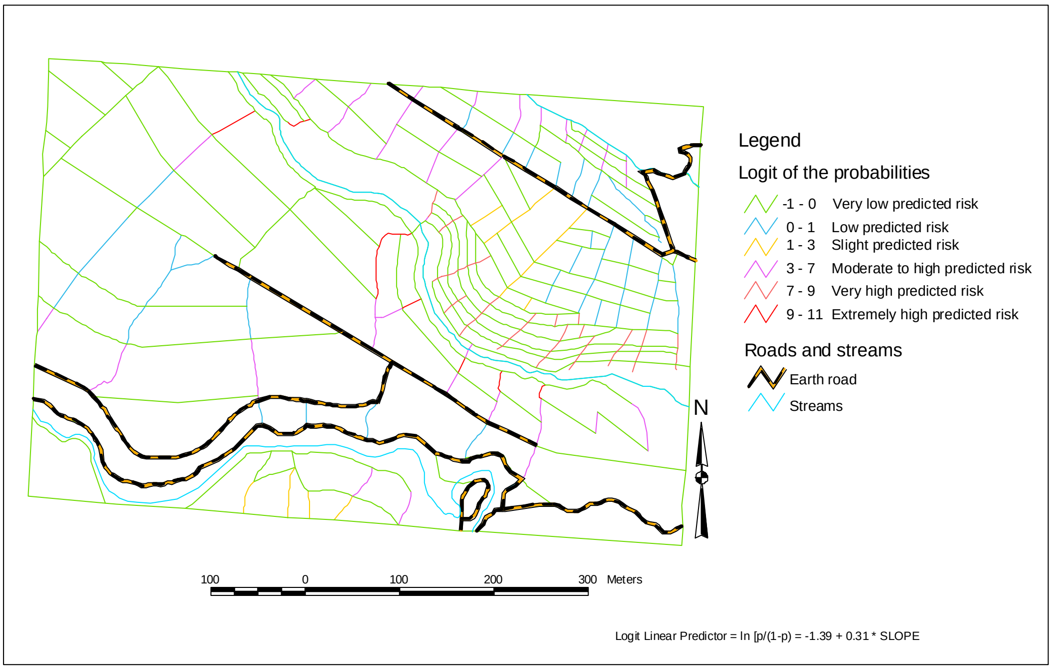

Figure 7.16 The transformed probabilities by the logit model of equation 7.4 for the Lynton linear erosion proxies.

If diversion ditches have to be dug, they should be paved with concrete or grass or other forms of vegetation planted in their course way all the way to the major stream or river draining the area. Trees species for planting on field boundaries together with crops in the East African region have been documented (Sanchez et al., 2001). The trees or hedges can offer shade, fodder and if properly selected can be used in carbon sequestration. Examples of tree species include *Tithonia diversifolia, Grevillea robusta, Calliandra calothyrsus, Sesbania sesban, Leucaena trichandra, and Leucaena diversifolia*.

The prediction models

Both the logistic and the logit models produce prediction models that describe the variation of erosion risk in the linear erosion proxies in a manner that corresponds to the distribution pattern of the linear features and their inherent slopes. The only weakness is that slope alone does not provide adequate prediction properties that exhaustively describe the linear features. Other factors that relate to soil erosion and which exhaustively relate to the linear erosion proxies should be in the future be identified for inclusion in the prediction models. This was not possible to achieve during this study. When the models are validated and found to possess accurate predictions, the models for the watersheds can be recommended for adoption in other areas. Options for additional predictor variables that satisfy the production of logistic models with goodness of fit can be added to the prediction variable list. It is important to use both the logistic model and the logit models in a spatial prediction since they support each other. The logit model optimises the logistic model, yet the logistic model provides the probability of erosion risk and the odds ratio. This conclusion is based on the observation that most erosion occurring in the watersheds will be observed as presence or absence data in a random binomial distribution.

7.3 Results of the analysis and erosion risk prediction of the landscape holons

7.3.1 Correlation analysis

The correlation analysis for the landscape level data is shown in Table 7.10. The variables corresponding to the measured erosion were: flow channels, translocated surface litter, depth of soil movement, depth of stem washing, depth of root exposure, depth of rills depth of gullies, width of gullies, and depth of mass movement. From the table, the degrees of freedom were 103.

From the data of Table 7.10, it is evident that slope had positive correlation with the measured erosion. Depth of stem washing, depth of root exposure, depth of gullies, width of gullies, and depth of mass movement bore significant correlation coefficients as shown in the table. Cover only bore significance correlation with the depth of rills, which were significant at 10%. Due to this single significant correlation, slope and cover were selected for the risk modelling. The correlation result obtained for cover is attributed to the fact that most erosion proxies of the landscape level were mostly human construction features having no cover. The river valleys however had cover data and if the fitted logistic model accepted cover as a possible predictor variable then its choice for prediction was valid.

Table 7.10 Correlation analysis for the landscape level erosion data

Erosion features	*Multiple correlation analysis (105 cases included)*	
	Slope	Cover
Flow channels	0.00	0.10
Surface litter translocated	-0.00	0.10
Depth of soil movement	0.12	-0.01
Depth of stem washing	0.36†	-0.06
Depth of root exposure	0.49†	-0.05
Depth of rills	0.02	-0.16ǂ
Width of rills	0.02	-0.15
Depth of gullies	0.17ǂ	-0.07
Width of gullies	0.23♀	-0.11
Depth of mass movement	0.36†	0.04

*Refers to areas where all features of erosion with vertical depths were present and their values summed up. Flow channels, surface litter translocated and width of gullies were not summed up. † Significant at 1%;
♀ Significant at 2%; ǂ Significant at 10%.

7.3.2 Logistic regression

The prediction models

The landscape level data was also converted into presence and absence data as already described in the preceding chapters for the field-plots and the watersheds. The data were thereafter manipulated in a statistical package using the logistic regression model to estimate the prediction parameters. The prediction parameters are estimated using slope and cover as the prediction variables whose results are shown in Table 7.11. The prediction parameters are thereafter introduced into equation 3.4 and 3.7 to create equation 7.5 and 7.6 which are used for computing the erosion risk probabilities and logit predictions for the landscape level erosion proxies. The two obtained equations are presented as.

$$p = \frac{[exp(1.07 + 0.83 * slope - 0.05 * cover]}{[1 + exp(1.07 + 0.83 * slope - 0.05 * cover]} \qquad (7.5)$$

*Predicted erosion = -1.07 + 0.83 * slope – 0.05*cover* (7.6)

From Table 7.11, the slope and cover data bore significant t-test for the sigmoidal curve as required by the maximum likelihood estimation of the statistic in a logistic regression model. The goodness of fit using the deviance fit had a value of 0.35, which concludes that the fitted model bore the requirements of a good and acceptable model for prediction modelling. Results of the logit predictions and the computed probabilities are shown in Table 7.12. The logit predictions are placed above the computed probabilities in the table. The total sample size is reported only once but includes both the logit predictions and the computed probabilities.

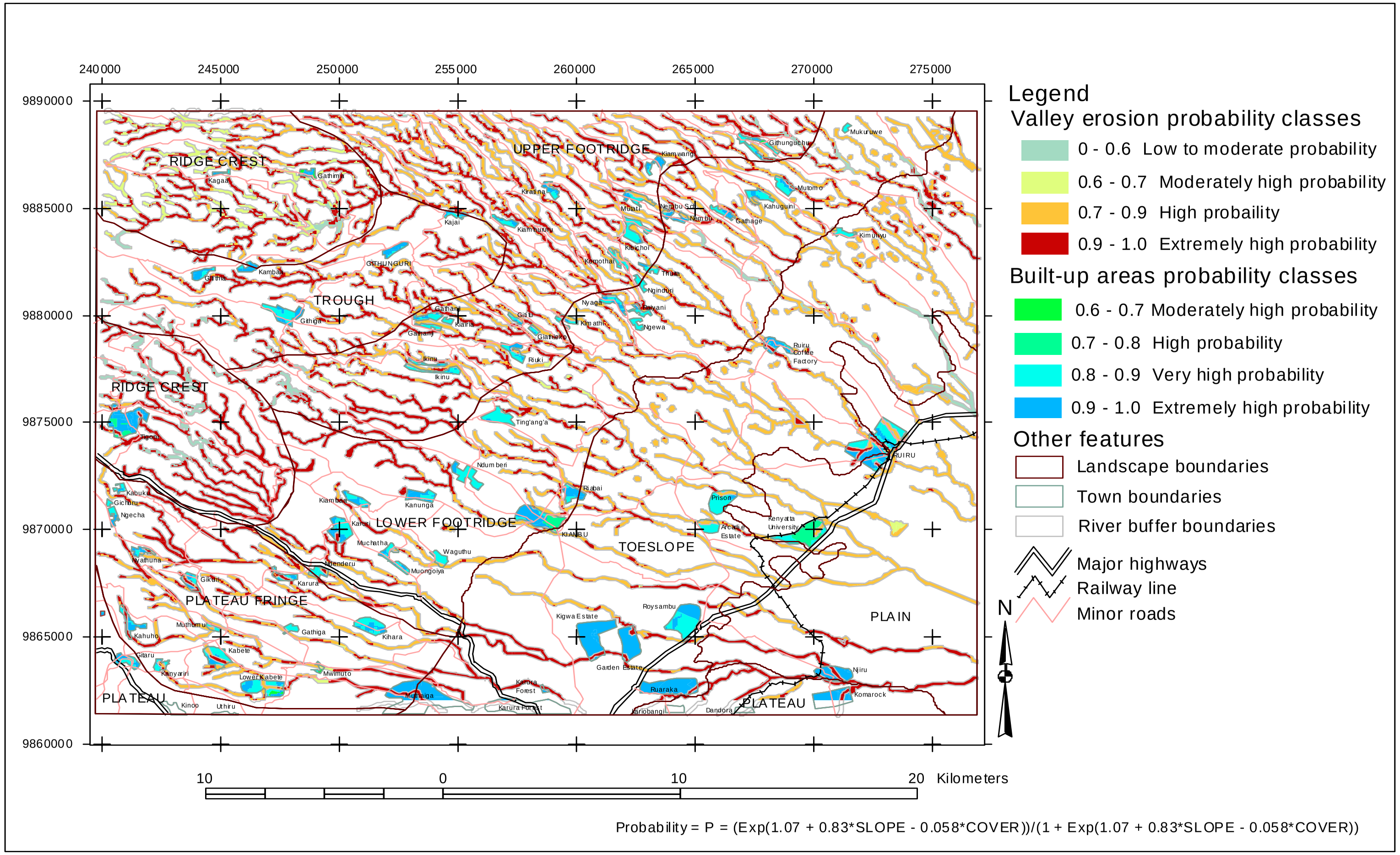

Figure 7.17 The computed probabilities of erosion in the landscape level erosion proxies using the logistic model of equation 7.5.

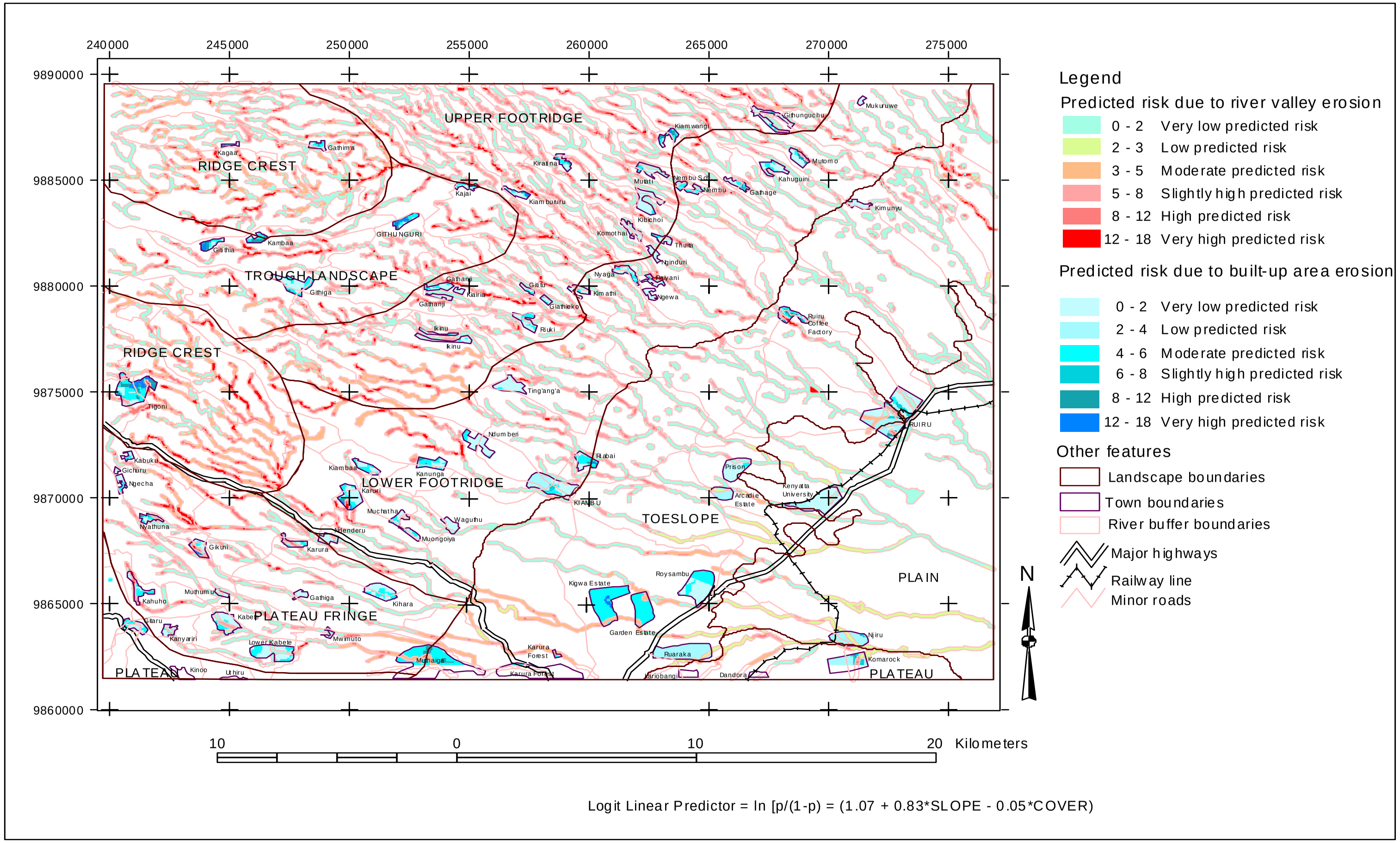

Figure 7.18 The computed risks of erosion in the landscape level erosion proxies using the logit model of equation 7.6.

Table 7.11 Multiple logistic regression for all present or absent erosion features with slope and cover as the explanatory quantitative variables for the landscape level data

Predictor variables	Logistic regression statistics parameters (maximum likelihood estimation) (165 cases included no missing cases)				
	Coefficient	Standard error (SE)	Estimated Odds ratio	Coefficient/SE (t test for sigmoidal curve)	P* (significance of t test)
Constant *(b_0)*	1.07	0.73	-	1.47	0.1429•
Slope *(b_1)*	0.83	0.40	2.29	2.07	0.0383•
Cover *(b_2)*	-0.05	0.01	1.05	-3.65	0.003•

Deviance test for goodness of fit of the logistic model

Convergence Criteria	No. of iterations	Deviance	P-value (χ^2) test	Degrees of freedom	Deviance/ Degrees of freedom
0.01	8	35.54	1.000	102	0.35$^{H}{}_{0}$

• Significance t-test for the sigmoidal logistic regression curve. $^{H}{}_{0}$ = Conclude goodness of fit of the logistic model. * (See details in Table 7.2)

7.3.3 Results and discussion

The odds ratio

Two odds ratio values were computed: one for slope and the other for cover to visualise how each one influenced the risk of soil erosion. The slope's odds ratio was (2.29) and that of cover was (1.05) (see details in Table 7.11). This meant that when cover was held constant, slope increase of one unit exposed the erosion proxies to 229% risk for the occurrence of soil erosion. When the slope is held constant, cover reduces the risk by 5%. This information on slope at the landscape level is frightening especially in an area where construction activities of new roads are going on from time to time. The high odds ratio is most likely attributed to larger features of erosion that were encountered on the landscape level erosion proxies.

Logistic and logit linear predictions of erosion risk

The computed probabilities of the landscape level erosion proxies are shown in Table 7.12. The computed probabilities of erosion were high in all the landscapes and all the erosion proxies having greater than 90% probabilities for the occurrence of soil erosion. The highest predicted probabilities of erosion on the proxies of the landscape were obtained for the valleys in the plateau landscape unit and the towns in the trough landscape unit with a probability of 0.97. The lowest predicted probabilities were those of the valleys in the plain landscape unit with a value of 0.91. The spatial distribution of erosion risk is shown in Figure 7.17 for the logistic model in equation 7.5 and in Figure 7.18 for the logit model in equation 7.6.

Table 7.12 Logit linear predicted erosion and probability of erosion risk at the landscape level

Landscape unit	*Predicted erosion probabilities on the proxies*								
	River valleys			Towns			Roads		
	N	AV	SD	N	AV	SD	N	AV	SD
Plain	245	0.91	0.08	54	0.95	0.05	68	0.92	0.06
Toe slope	1312	0.93	0.08	122	0.96	0.06	320	0.93	0.08
Lower Footridge	1957	0.94	0.08	172	0.94	0.07	556	0.93	0.08
Upper Footridge	3398	0.95	0.08	183	0.95	0.07	864	0.95	0.08
Trough Landscape	990	0.95	0.09	60	0.97	0.05	323	0.94	0.10
Plateau	92	0.97	0.02	20	0.95	0.06	72	0.94	0.07
Plateau Fringes	1038	0.95	0.07	146	0.94	0.08	363	0.95	0.07
Ridge Crest	2244	0.92	0.14	69	0.95	0.09	436	0.92	0.14

N = sample size; AV = mean value; SD = standard deviation; - = absent

From Figure 7.17, it is evident that most areas have moderate to extremely high probabilities. However, the river valleys in the Tigoni Ridge Crest landscape seem to be at the highest risk. Only a few of the valleys have low probabilities. Another landscape with high probabilities is the Upper Footridge covering Kibichoi, Komothai, Kiratina and Ikinu areas. The river valleys north of Kanunga are also seriously at high risk. They occur at the transition between the Upper Footridge and the Lower Footridge. River valleys of low risk are found in the Ridge Crest in the Kagaa and Gathima area. Some river valleys in the Tigoni Ridge Crest also suffer low probabilities most probably due less steeping terrain on which they occur. Most of the river valleys in the Lower Footridge, the Toeslope and the Plain landscapes suffer moderate risk. Only the river valley passing through Ruaraka, Njiru and Komarock areas have a high probability of erosion risk within the Plain landscape. Of the built up areas, Tigoni in the Ridge Crest landscape, Gitithia, Kambaa and Githunguri in the Trough landscape, Karuri, Kiambu, Kanunga, Kihara and Riabai in the Lower Footridges suffer high to very high probabilities. Muthaiga, Kigwa Estate, Roysambu and Ruiru areas in the Toeslope also suffer high to very high probabilities of erosion. Figure 7.18 obtained by the logit model in equation 7.6 stretches the probabilities into their log transformed values and produces finer details of the erosion risk domains. Though the erosion risk trend is similar to the landscape patterns as those obtained by the logistic model, it is possible to visualise and discriminate between areas that require less attention from the hot spot areas, which require immediate attention.

7.3.4 Conclusions

The odds ratios

The odds ratio for the fitted models indicate that for every increase in one unit of slope from any given point of reference, there will be a 229% risk of there being soil erosion. At this level and due to this high risk, it is recommended that tough policy is introduced for construction work since most of the landscape level proxies are created by human construction. The protection of riverbanks and river valleys must also be stressed and addressed by district or divisional soil conservation teams. This high erosion hazard is linked to the many gullies starting from trading centres in Kiambu and from the roadsides. Mass soil movements along valley sides are also attributed to this high hazard depicted by the odds ratio. For protecting the fragile areas with high erosion risk probabilities, the government must move swiftly to manage soil erosion in the hot spot areas (Figures 7.17 and 7.18) and to cure areas already suffering from gully erosion.

All the predicted probabilities of erosion in the landscape units were generally very high. This means that the erosion proxies selected for the assessment of landscape level erosion portend a high risk of erosion for the landscape units. Partly this was because all the proxies were drivers of erosion with none of them providing any barrier effect. Barrier effects can be achieved by erecting where applicable channelled water in built-up centres, trapped and channelled roof catchment water, paved roadsides, grassed roadsides, bushed or forested riverbanks.

Spatial attributes

As discussed in section 7.1.4, the spatial attributes emanating from the results of the prediction models are handy tools for the management of soil erosion. Spatial attributes that enable the management of erosion include: spatial distribution of the predicted erosion, the neighbourhood of each proxy object, the length or area of the spatial object, the location of the object and the availability and link of the objects with cover and slope data. Built up centres such as Kiambu, Githunguri, Githiga, Kambaa, Gitithia, Tigoni, Karuri, Kiambaa, Kanunga, Kiamwangi, Kiambururu, Ndenderu, Ruiru Coffee Factory, Lower Kabete, Kigwa Estate, Riabai, Ruaraka, Njiru, Komarock need immediate attention if the risk has to be controlled or managed. River valleys in the Upper Footridges, the Ridge Crests, the Trough Landscape and the Lower Footridges should be prioritised for conservation activities. These are the landscapes that the Ministry of Agriculture Soil and Water Conservation Branch should concentrate on. The logit prediction map should be used to discriminate areas that require immediate attention.

The location of the probabilities in the maps indicate the exact locations and areas where attention is required and the slope and cover data provide an idea on the type of intervention that might be required to solve the problem. All this is of course blended with societal needs and livelihood demands as discussed exhaustively in chapter 6.

The prediction models

The logistic and logit prediction models have shown that they are invaluable tools for predicting the risk of erosion without necessarily visiting those locations to map the spatial extent of soil erosion. The probability model provides a basis for ranking the urgency required for attention measures. As was the case with the field plots and the watershed proxies, the two models should be used in unison one to act as a warning, and the other to refine attention domains.

7.4 Validating the results

In order to validate the obtained prediction results, as has been described in Chapter 3, independent erosion data was collected in all the field plots to validate the obtained predictions. Due to obscurity of erosion by frequent cultivation and weeding, it was not possible to obtain data in smallholder field plots on annual crops and annual crops mixed with perennials. Nonetheless, it was possible to obtain erosion data in the large-scale perennial crops such as in large-scale coffee field plots an in tea plots. The obtained erosion from individual features of erosion were regressed with the logit linear predictions to establish the link between the features and the predicted erosion. Table 7.13 shows the results of the correlation analysis.

Table 7.13 Correlation analysis of the logit predicted erosion with measured erosion for the field-plots

Erosion features	*Pearsons correlation analysis*	
	Coffee plots (N=40)	Tea plots (N=12)
Flow channels	0.15	-
Surface litter translocated	-	-
Depth of soil movement	0.42†	0.80†
Depth of stem washing	0.12	0.49
Depth of root exposure	0.18	0.63♀
Depth of rills	0.12	-

† Significant at 1%; ♀ Significant at 5%

The predicted erosion on coffee plots erosion data yielded a significant correlation for the depth of soil movement. Tea plot data yielded likewise significant correlation with the depth of soil movement, and depth of root exposure. Soil movement appear to be good validation erosion features for the field plot level erosion, which confirms it high significance as obtained in Chapter 6 and Figure 7.1 and 7.2. The results indicate that there is a strong relationship between the predicted risks of erosion with some of the features of erosion. The prediction models are therefore proven acceptable for predicting the risk of erosion and computing the probabilities for the occurrence of soil erosion at the field plot level. The methods used for the assessment of erosion and modelling it are thus validated. The validation was limited only to part of the field plots. More work is required to validate the results of the watershed and landscape level predictions.

8

Discussions and Concluding Remarks

Discussions and concluding remarks

This chapter threads through the thesis examining what was proposed, the issues raised in the introductory chapter and what was achieved in subsequent chapters and subsections. The objectives raised are discussed on the basis of what was achieved and the utility of it. Weaknesses of the methodology, opportunities and future research opportunities are also presented.

8.1 Overview of the proposed objectives and what was achieved

The general objective of this thesis was to develop and present a method, which can be used to assess the risk of water erosion in different levels of the landscape system using spatial methods. The broad aim was to define relevant levels that form the basis for assessing soil erosion and managing its risk.

The specific objectives were:

(1) To conceptualize and define from the landscape continuum hierarchically ordered landscape elements whose internal characteristics and parts influence the occurrence of soil erosion and whose spatial extent and geometry enable their capture and modelling by remote sensing and GIS.

(2) To prove that there are spatial features *(erosion proxies)* which are part-of, and internally contained in the hierarchically defined landscape elements that can aid in soil erosion risk assessment and modelling.

(3) To demonstrate that the selected *erosion proxies* can be related to actual occurrences of soil erosion by statistical methods and similarly be differentiated as either drivers or disrupters of erosion.

(4) To demonstrate that prediction models can be derived from field data collected on the erosion proxies and the developed models used for modelling of soil erosion risk spatially in a GIS for each of the defined levels.

(5) To test and validate the method in Kiambu.

The following paragraphs describe how each of the objectives was approached, effected and achieved.

Specific objective (1)

Landscape systems, hierarchy theory, soil erosion theories and spatial modelling theories were explored. Specifically a functional hierarchical system was proposed based on the principles of hierarchy theory of asymmetry, emergent properties, principle of constraint, reaction time, principle of containment and the principle of indicators. A holon was defined as the basic unit of each individual level of the hierarchy. A generic conceptual model was postulated in chapter 2. It showed how from the landscape system, disaggregation could be used simultaneously with the hierarchy theories, spatial information theories, soil erosion theories to define and derive the levels of a functional hierarchical landscape system for erosion risk assessment and modelling. The concepts were actualised in chapter 3 and 5 where three levels of a functional hierarchical landscape system were defined. The field-plot, the watershed and the landscape unit were defined and extracted using aerial photography and satellite imagery.

Specific objective (2)

From the definition and disaggregation of the landscape system into hierarchically ordered landscape elements, it was possible to identify within the landscape system the holon types representing each level. The three levels of the hierarchy were represented by the field-plot holon types, the watershed holon types and the landscape holon types. The field plots were the lowest level members of the hierarchy while the landscape units were the highest level members of the hierarchy. Spatial features that are part of the holons were identified and classified either as the drivers of erosion or as disrupters of erosion. They were termed the erosion proxies. This categorisation of the erosion proxies was confirmed by the degree of occurrence of soil erosion features on the proxies as shown in chapter 6. The different erosion proxies occurring in the different holon types supported the hierarchy theory of new and emergent erosion risk properties for the different levels in the hierarchy. From the statistical assessment and analysis presented in Chapter 6, the different proxies proved to condition the occurrence of soil erosion features differently and can be used as indicators of soil erosion risk for each of the levels of the landscape hierarchy. Land use kinds and vegetation kinds occurred as the ideal erosion proxies of the field-plot level holon types while elongate linear features such as footpaths, field boundaries, hedges, etc. were ideal erosion proxies for the for the watershed level holon types. Riverbanks, roads, built-up centres, etc. emerged as the erosion proxies for the landscape level holon types.

Specific objective (3)

A soil erosion assessment method was developed which links soil erosion proxies with landscape holons. It was established that the erosion proxies are associated with observable and measurable soil erosion features as described in chapters 3 and 6. Clark's (1980) erosion features classification system was adapted for use in Kiambu and Nairobi areas with initial characterisation values by Clark (1980) adapted to match the observed erosion features in Kiambu and areas north of Nairobi. The features of erosion were used to quantify the severity of erosion on an erosion proxy. The quantitative link between the observed features of erosion and the erosion proxies was achieved in chapter 6 where descriptive statistics and the comparison of means was used to distinguish differences between the erosion proxies. The analysis of variance and Bonferroni's tests were used to determine difference between the means of the individual erosion features occurring on the different proxies. From this, it was possible to determine the erosion proxy that had significant differences among themselves from the computed means of the erosion features. These differences made it possible to separate the *'driver'* erosion proxies from the *'disrupter'* erosion proxies. Grass plots and forest plots were distinguished as the disrupters of erosion while tea plots, coffee plots, intercrops, coffee and macadamia plots were concluded to be the driving proxies of erosion in the field-plot. The assessment of the erosion proxies and erosion features in chapter 6 made it possible to relate each landscape holon with the specific erosion proxies and erosion features. Soil movement for example dominated the field plot level, flow channels, rills, exposed stems, and exposed roots were other predominant erosion features. At the watershed level, new features of erosion emerged which were earlier not observed in the field plots. These were gullies occurring on some selected erosion proxies in the watershed holons. Mass soil movement and larger gullies emerged as the new and emergent features of erosion for erosion proxies of the landscape holons. The features of erosion occurring in each level were explained mainly by differences in water-flow velocities in the erosion proxies of the different holon types. The statistical differentiation of the erosion proxies by the analysis of variance, produced mean results with high standard deviations attributed mainly to the difficulty of transforming zero values in the data into log transformed values with a bell-shaped normal distribution curve. The calculated means therefore had high values of standard deviation. Therefore a combination of non-parametric presence-absence data and ratio scale data were used to develop the logistic models for soil erosion risk modelling as described in chapter 7. Soil erosion as the response variable was converted to 1 for presence and 0 for absence while slope and cover retained their (%) ratio values. The presence-absence data for fitting the models had a binomial distribution curve, which limited the quantitative derivation of depth of soil erosion as initially measured from the features. However, the derived probability models fitted by logistic and the logit models proved to be good predictors of soil erosion risk for the spatial landscape objects. They are good for qualitative prediction of the presence or absence of erosion on the spatial landscape features with good estimates of the probabilities.

Specific objective (4)

Chapter 7 showed how the randomly collected data on erosion features was used to build logistic regression models that were used to produce spatial predictions of soil erosion risk. Objective 4 was therefore achieved as proposed. For each holon type and hierarchical level, correlation analysis and goodness of fit of the logistic model was used to select the predictor variables to include in the prediction models. Properties of the proxies, which are also factors of erosion namely, slope-gradient, surface ground cover, and soil erodibility were tested in a multi-correlation analysis to discriminate between the predictor variables to be included in the models. Kiambu being a localised area for which the spatial modelling was tested might not have had all requisite properties of the erosion proxies and other determinant factors of water or gravity erosion contributing to the prediction model. It should be considered more as a localised result. Other factors might prove more relevant in other areas so long as they contribute to a good fit in the prediction models and have spatial attributes with which they can be captured in a GIS for spatial modelling. Important outputs from the prediction models were the odds ratio, which provided quantitative values of how the erosion proxy properties influenced the risk of erosion. The field plot level had a unit increase in percent slope influencing an increase in the risk by 24% and a unit reduction of percent cover reducing the risk by 8%. Slope added to the risk while cover reduced the risk under constant slopes. For the watershed holons and proxies, unit percent increase in slope enhanced the risk of erosion by 36%. For the landscape level holons a unit increase in percent slope enhanced the risk by 229% when the cover was constant. A unit increase in cover reduced the risk by 5% when the slope was considered to be constant. These figures obtained by the odds ratio show the erosion hazard conditioned by each of the proxy types and for the different levels of the landscape hierarchies as defined in this thesis.

The spatial prediction data provided useful management opportunities. The spatial extent makes it possible to predict the amount of time and energy that is required to tackle the portrayed risk should resources be available. The spatial position attribute helps to precisely target intervention measures, while the distribution attribute shows the relative intensity of the risk in an area and the proximity of the risk to known locations or with known landscape features. The independently produced prediction models produced spatial patterns that corresponded very well with the predictor variables providing credence to the predictive power of the models. The logistic regression models showed the probabilities of erosion risk while the logit models refined the risk zones due to the transformation of the probabilities to a longer linear stretch by the normal distribution curve it attained. The logit models therefore provided a broader spectrum of the predictions making it possible to distinguish areas with less risk of erosion from areas with higher risks requiring immediate attention. The logit model was used by Sanders (1999) to determine environmental site factors that determined the occurrence of *Erica* and *Scorpodium* plant species in the De Weerribben nature reserve of the Netherlands. She concluded that *Erica* had a higher maximum probability of occurrence in De Weerribben than *Scorpodium* and that the logit model made it possible to distinguish areas of high or low probabilities of the occurrence of the two plant species. She used cross-validation to validate the regression model and compared the obtained results with actual species distribution. Using simple regression, the variability accounted for was 80% for *Erica* and 79% for *Scorpodium*. This further attests to the validity of using the logistic and logit models as used in this thesis for probability predictions.

Specific objective (5)

The framework of the methodology was developed as described in chapter 3 and tested in Kiambu district of Kenya as initially proposed. The predictions were validated to a limited extent as described in chapter 3 using correlation analysis involving the predicted results and newly collected data on soil erosion features occurring in the predicted areas.

8.2 Overview of the methodology

8.2.1 Relevance of hierarchical thinking

This thesis constructed three levels for assessing and modelling soil erosion in a multi-hierarchic landscape system. Dominant processes and features of soil erosion were identified for each of the levels and linked to soil erosion proxies. Important output was the opportunity the method provided as a basis for examining the soil erosion paradigm and risk in a multi-hierarchic landscape system. Issues emanating from up-scaling low level observations to higher levels through generalisation or smoothing were proved to be obscuring rather than enhancing landscape system knowledge. The prognosis here is that it might not be necessary to transfer information gathered at one level to a different level, considering that each level has its own indicator attributes and drivers of erosion. Generalisation of information is not favoured in this case because it causes loss of detail thereby losing value for use or application. The stress should be more on the relevance of information representation for application in planning and management at different levels rather than simplification by generalisation. Generalisation as one moves from a lower level to a higher level tend to obscure knowledge yet in systems thinking and in hierarchy thinking every level in a hierarchy is distinct with its own processes and distinct environment. Inflows and outflows can occur but the subsystems in the hierarchical structure still remain as stable distinct individuals. In this work, it has been shown that the spatial attributes of the prediction models offer opportunities for managing the risk of erosion and can be linked to specific action lines and for specific hierarchical levels.

The method differs from other methods such as that of Schoorl (2002) who used artificial cells to represent different levels of organisation in the landscape. The definition and construction of landscape features which can be recognised for their geographic properties and positions as used in this thesis creates more tangible and targeted means for real-life hazards that can be traced to existing landscape features for management or for conservation action. The definition of the holon as presented in chapter 2 and especially with reference to the constituent attributes of space, properties, time, energy, resources, intervention, and policy makes it possible to assess multiple attributes which possibly contribute to sustainable management of erosion risk in predefined landscape holons. The method agrees with Van Noordwijk et al. (1998) that the environment in which soil erosion occurs plays a big role in the acceleration and spatial redistribution of water and soil thus determining the fractal behaviour of erosion. According to them, soil erosion rates from a plot on a straight slope cannot be compared with the erosion from a complex topography such as a catchment or watershed. This according to them is not plausible because of different scales of measurement, and also because of wrong representation of the catchment. On larger sites, there are disturbances like local depressions, vegetation barriers and other landscape elements s that delay flow, create infiltration and deposition of eroded soil as opposed to a researcher controlled experimental plots. They use fractal-scaling factors to derive sediment yields emanating from an area. The fractal scaling factors take into account the filters such as vegetation barriers, local depressions, etc., which disrupt water flow and soil erosion. The method used in this thesis distinguishes landscape holons where erosion processes are contained within nearly homogeneous land areas with boundaries and for which comparisons in the manifestation of soil erosion can be made.

In summary, after ordering the landscape system into hierarchical levels, the holons in each level provided land regions for which soil erosion could be observed. Their internal parts *(erosion proxies)* provided biophysical conditions that stimulated the occurrence of soil erosion. Slope and ground cover of the proxies threaded through the three levels as properties of the erosion proxies that could be used in spatial modelling. The erosion proxies, due to their influence in the formation and as motors of soil erosion offer possibilities for soil erosion assessment and spatial risk modelling in a GIS. Their spatial attributes made them ideal for modelling the risk of erosion in the landscape and in a GIS. They also provided elements of the landscape system that can be used for soil erosion management and for future spatial process modelling.

8.2.2 Recognition of soil erosion features

Soil erosion features used in the assessment have been described in chapter 3. The assessment of past soil erosion offered opportunities for recognising soil erosion even in environments previously thought to be devoid of soil erosion. It removed the demand for determining current soil loss, which can be demanding both in time and resources, erratic (i.e. based on rainfall presence and fluctuations) and time consuming (requires a long period of time).

The use of soil movement, flow patterns, surface litter translocated, rills, gullies, streambank slump, mass soil movements, landslides, etc as evidence of soil erosion has made it possible to establish that erosion occurs beneath tea as well as coffee canopies. According to Stocking (1987), "such simple field measurements will never be fully respectable amongst the more technologically minded of the scientific fraternity, and some valid criticisms can be made of the accuracy of measurements so obtained. However, the very strength of field measurements lies in the possibility of taking large numbers. They are also not only cheap but can be carried out with the assistance of semi-skilled technical assistance, giving results that are probably more meaningful and visually impressive to the farmer and the extension worker than some super-sophisticated experimental facility at a distant research station". More often there is the assumption that field plots having mature tea plants suffer minimum or no erosion resulting to omissions in managing the hazard. The awareness created by assessing soil erosion in the manner done in this thesis has shown the occurrence of soil erosion in perennial cropping systems and beneath forests without undergrowth and in tea plantations. It also shows that tea and coffee plantations in sloping terrain require protection against erosion just like all other crops. Mulching might offer the best soil protection for beneath canopy soil erosion.

8.2.3 Managing soil erosion using erosion proxies and the landscape holons

Chapters 1 and 5 provided the definitions and descriptions of the different hierarchical landscape holons as used in this thesis. The definitions are clear and they remove the confusion in terminology such as that of the *'Catchment Approach'* terminology being used to target soil conservation in Kenya. In this context, it is better for the soil and water conservation teams in Kenya to use either the watershed or the landscape unit as soil and water conservation land units. Landscape units with lower risks of erosion will therefore demand fewer resources for management. Technologies will also be developed to countenance the type of expected soil erosion vertically or horizontally across the span of the hierarchies.

Managing soil erosion at the landscape level or any other level for that matter entails the use of both the biophysical and structural means. Biophysical refers to the use of physical barriers and vegetative cover. Structural means is the construction of structures on roadsides, riverbanks and in trading centres specifically meant for stopping erosion or controlling storm waters.

The holon forms a good management feature where knowledge can be integrated with space, time, energy, and resources to attain sustainable management systems. The management of erosion or its risk can also be more refined according to the level of the hierarchical structure and the holon type. Strategies will therefore be tailored to conform with the holon types their properties and other attributes such as resources, energy, interventions, people and time. The presented assessment and definitions in this work have also removed the problem of terminology especially in the definition of the holons as presented in Chapter 1 and 5. The watershed holon has presented itself as the best management unit for many members of a community and can be adopted by any organisation concerned with collective management of soil erosion. The field plot holon remains the preserve of a single farmer while the landscape holon requires more of State interventions and policy though community and other actors within it.

8.3 Implementation weaknesses in the methodology

Holistic glance of erosion risk

- The selective choice of the spatial landscape proxies for erosion risk assessment at different levels presents a selective situation of the erosion process in the landscape than its actual sum total if all the levels were all integrated and visualised simultaneously.

Spatial modelling

- The creation of the different feature objects for analysis and integration into a GIS environment suffers uncertainty and errors when compared to actual reality. There are errors associated with field data collection, digitisation, statistical errors and errors associated with lands use changes and dynamics that make the results useful within a short time frame when the land use situation remains unaltered.
- Interfacing GIS data sets with models still suffers the lack of an integrated interface for complex mathematical manipulation and analysis. It is also not possible to perform statistical analysis on thematic attribute data integrated in the GIS, it is therefore mandatory to export thematic data from the main GIS database to perform some statistics or make some complex computations before re-importing the data back to the main GIS database. This makes the method complex and time consuming to users with little knowledge in statistical analysis and database handling techniques.

Validation

- The models of predicted logit linear erosion and predicted erosion probabilities showed very good spatial distribution, which coincided very well with the existing landscape patterns. The plot level predictions turned significant correlation validation results with independently collected soil erosion features data. More work is still needed to validate the results and test the spatial models in the watershed holons and the landscape holons.

Erosion risk management

- Without working together with other technical disciplines, such as the social sciences and the policy innovators, the method might not add to the landscape system erosion risk management. People, the beneficiaries of the innovations of the method are an important ingredient to the success of its utilization. Their involvement was not taken on board and requires to be effected in order to test potential the method has for adoption.

8.4 Opportunities and important observations

Going through the chapters, the following opportunities come to the fore.

- Soil erosion assessment, management and control can be based on multi-level approaches.
- Disrupters of erosion can be used to filter and bar the development and perpetuation of soil erosion in a landscape.
- The drivers of erosion can be used to study erosion process resolutions in a hierarchical landscape system structure.
- Remote sensing data, aerial photographs with different spatial resolutions can be used to capture multi-level landscape holons for incorporation in a GIS for handling and modelling.
- The synergistic holon system concept can be used for studying and managing landscape system holons and processes from a multi-disciplinary strategy, where social scientists work together with the biophysical scientists in formulating sustainable systems that ensure sustainable livelihoods and environmental conservation.
- Soil and water conservation can be targeted to appropriate beneficiaries if the landscape system hierarchy as presented is formalised and adopted for use.
- Social scientists should critically examine the hierarchical landscape system structure to determine if there is a link between the biophysical landscape system structure and social strata as presented in this thesis and if the approach can aid in sustainable management of soil erosion risk.
- Policy makers should likewise research on appropriate policies that address soil and water conservation in tandem with the three level landscape hierarchy construction to supplement this work.
- It is evident from the data that no single descriptor of erosion, i.e. soil movement, root exposures, stem-wash, surface litter, depth or width of rills, depth or width of gullies or flow patterns adequately quantified the degree of erosion equally on all the proxies. This in effect means that all the features have to be observed and measured initially before conclusions are drawn on their appropriateness for the assessment of soil erosion in an environment.
- In extracting object data from aerial photographs and satellite images, the scale of the source data and spatial resolution determines the hierarchical level for which the data can be used. Larger higher-level landscape objects require satellite or aerial photography data at scales ranging between 1:50,000 to 1:100,000. Watershed and plot level data requires photographs at scales 1:10,000 or smaller. Other important attributes of the source data include spatial resolution, availability of the data, time of acquisition of the data, and visual quality.
- Correlation and logistic regressions are powerful tools for handling landscape data with presence or absence of the response data. In order to link the statistic models with the GIS data model, a statistical package and interfacing databases are a pre-requisite. The manufacturers of GIS software should team up with powerful statistical package developers so that most modelling modules and statistics can easily be coupled within the GIS operations.

8.5 Future research

Though the method has presented a framework for defining, constructing, analysing and modelling a landscape system for soil erosion risk management, some aspects of the landscape system with regard to soil erosion, landscape hierarchies and erosion proxies still need to be researched. Basically this research linked landscape and soil erosion knowledge with GIS technology and statistical analysis to produce prediction models. There are however some areas which were not tackled and which still need to be studied. They include:

- In depth social studies that link biophysical spatial properties of the landscape to the socio-economic and policy instruments for each of the levels of the landscape hierarchy and especially those that ensure sustainability of soil erosion management.
- Studies on process models that link to different levels of the landscape system hierarchy as defined in this thesis.
- Studies that link the field plot, watershed and landscape erosion to downstream sedimentation.
- Studies on other spatial predictor variables that can supplement those used in this thesis.
- Use of the management recommendations in this thesis for soil erosion management and control.
- Calibration of the prediction models in other parts of Kenya before they can be fully adopted for general use. As they are, they are appropriate for Kiambu.

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Summary

Though a lot has been done and achieved in erosion research and control in Kenya, most of the erosion research methods have in the past put emphasis more on quantifying soil loss or measuring soil erosion, rather than pinpointing to areas that are likely to suffer soil erosion. In most cases the erosion processes have been assumed to occur in a uniform manner at all levels of the landscape hierarchy, and hence the results of one level observation can be factored to cover other levels for which data was not collected. This has resulted in many people extrapolating site-specific point data to cover wider geographic regions, assuming uniformity of the erosion process over the region. Another interesting aspect of soil erosion is that though most attention is normally put on the negative effects of soil erosion, soil erosion has also some beneficial effects. For example, the deposition of eroded soil material to lower areas has sometimes improved the quality of the soil receiving the sediment, thereby improving agricultural productivity of the depositional areas. There have however been suggestions that the problem of soil erosion has been exaggerated and not proven to actually diminish crop yields against the background of improved crop productivity improvement techniques. All theses schisms makes it necessary to engage in soil erosion research, either to disprove the sceptics or to provide other means of assessing and viewing the problem of soil erosion.

The general objective of the thesis was to develop and present a method, which can be used to assess the risk of water erosion for different levels of the landscape system hierarchy using spatial methods. The broad aim was to define relevant levels that form the basis for predicting and managing soil erosion and controlling its risk. The specific objectives were:

(1) To conceptualize and define from the landscape continuum hierarchically ordered landscape elements whose internal characteristics and parts influence the occurrence of soil erosion and whose spatial extent and geometry enable their capture and modelling by remote sensing and GIS.

(2) To prove that there are spatial features *(erosion proxies)* which are part-of, and internally contained in the hierarchically defined landscape elements that can aid in soil erosion risk assessment and modelling.

(3) To demonstrate that the selected *erosion proxies* can be related to actual occurrences of soil erosion by statistical methods and similarly be differentiated as either drivers or disrupters of erosion.

(4) To demonstrate that prediction models can be derived from field data collected on the erosion proxies and the developed models used for modelling of soil erosion risk spatially in a GIS for each of the defined levels.

(5) To test and validate the method in Kiambu.

To address these objectives, concepts associated with hierarchy theory, landscape system construction, geographic information systems theories, and soil erosion theories were knitted together to develop a conceptual framework and a practical methodological approach to effect and realise the objectives.

Kiambu district was selected for testing the developed methodology due to its intensive utilisation for agriculture and its location in a rugged terrain in the upper footridges and footslopes of the Aberdare Mountains where below-canopy soil erosion is obscured by vegetation vigour and intensive cropping. Soil loss studies

through river sediment yields in the district, indicate that there are high amounts of soil lost annually by water erosion. These range from 20 t km^{-2} yr^{-1} in undisturbed forests, to 3000 t km^{-2} yr^{-1} in cultivated to grazing lands. Soil loss studies from runoff plots in Kiambu indicate that cultivated land loses between 20 and 30 t ha^{-1} $season^{-1}$ and bare soil loses more that 70 t ha^{-1} $season^{-1}$. Other justifications were prompted by the fact that soil conservation in Kenya has been focussed to the 'Catchment Approach' without necessarily defining what the catchment means. Perception of soil erosion by farmers was also biased to visible features of erosion such as gullies and tended to ignore the finer features of erosion like rills, interill erosion and other visible forms or erosion.

Recent developments in geographic information systems (GIS) technology have made it possible to model and represent geographical real world phenomena in computerised spatial databases through which they can be stored, analysed, and displayed. GIS can enable stepwise and ordered analysis of the landscape system components as deemed by the landscape researcher. Soil erosion is a product of the interaction of many geographical factors such as: soil surface cover, the erodibility of the soil mantle, the steepness and length of the eroding slope, the erosive energy of falling rain-drops and the specific management aspect of the eroding site. It can therefore be assessed and modelled in a GIS environment as is demonstrated in this thesis.

Concepts

The method integrates concepts, knowledge and implementation procedures. First there is *a priori* knowledge that is collated in order to facilitate the study of soil erosion in the context of a landscape system. Knowledge and practice are invoked to organise the landscape system into hierarchical levels through which equally ordered erosion processes can be studied, assessed and measured. The conceptual model revolves around the construction of hierarchical levels in a landscape system and how the landscape holons and their parts relate to soil erosion in terms of assessment, prediction and management.

Hierarchical construction of the landscape system allows an ordered organisation of the landscape components into superordinate or subordinate parts which correspond to process time-scales and their corresponding spatial extents. Such an arrangement of the landscape system allows relevant observations and measurements to be made of the ordered processes. The concept deviates from viewing the landscape as an agglomeration of parts in which processes occur presumably in a uniform manner, and where only size changes allowing for smoothing of measured results in a linear generalisation transformation. The method identifies *'individual'* landscape elements in each level of the landscape hierarchy in which processes occur within comparable time scales and for which data interchange and modelling can take place. They are termed *'holons'*. The holons are used to represent the levels in the hierarchy.

Methodology

The overall methodology comprised several parts involving first the definition of landscape hierarchies, followed by field observations, and then spatial data capture for erosion risk prediction. Statistical analysis and spatial modelling of erosion risk in a

GIS followed the first three steps. The first step mainly concentrated on defining the landscape hierarchies that could be used for assessing soil erosion risk spatially in a GIS. Landscape elements were identified to represent each level in the landscape hierarchy. These included the field-plot, the watershed and the landscape unit. The field observation part involved the collection of soil erosion data in a stratified and randomised strategy where 164 samples were collected for the field-plot holon types, 89 for the watershed holon types, and 104 samples for the landscape holon types. Maps were prepared for each of the levels before field data collection and data points plotted on them for field reference. Collecting soil erosion data involved measuring depths of erosion features formed by either water or gravity as agents of erosion. The erosion features included soil movement, translocated surface litter, visible flow channels, depth of stem washing, depth of root exposure, rills, gullies, and mass soil movement. Only the encountered erosion features on each proxy were observed and measured. Where there was no erosion, zero values were recorded. For prediction modelling, independent spatial data sets were prepared for the three spatial landscape holon types and their internally contained erosion proxies. Aerial photographs were used to capture the field-plot and watershed holon types while satellite images were used to capture the landscape level holon types. This was done in the spatial data capture part of the methodology. Statistical analysis involved confirming that the selected spatial erosion proxies influenced the occurrence of soil erosion, first by the occurrence of erosion features in the proxies and secondly by differentiating the contribution of each proxy to the overall erosion using the analysis of variance and the mean occurrence. The spatial modelling part of the methodology involved the production of logistic and logit regression prediction models from the initial random data, which were used to manipulate the newly created spatial data sets to produce erosion risk domains based on pre-defined erosion indicators, herein defined as erosion proxies for each of the levels. Properties of the proxies such as their slope-gradient, percentage ground cover and soil erodibility were used as the predictor variables after being tested for suitability as prediction variables by correlation analysis.

Results

It was possible to use large-scale aerial photographs to capture field-plot and watershed level erosion proxies. Their real-world positions in the broader landscape were located using a global positioning system, commonly known as a GPS. The extracted holon types representing each level and their erosion proxies captured from the aerial photographs and satellite images were digitised and stored in a geographic information system. Field plots with their lands use kinds represented the lowest level of the hierarchy. Linear features in the watershed such as field-plot boundaries, footpaths, hedges, fences, tree lines, stonewalls, forest edges, wash-stops in tea and closed field boundaries represented the second level of the hierarchy. The highest level of the hierarchical construction, the landscape unit had river valleys, roads, and built-up centres representing the highest level erosion proxies. All the levels of the landscape hierarchy represented by different holon types, i.e. field-plots, watersheds, and the landscape units were stored as area objects while the erosion proxies inside them were stored as either area objects or as line objects. The field-plots were stored as area objects while the linear watershed proxies were stored as line objects. The landscape level erosion proxies that included built-up areas, river valleys, and road networks were stored as either linear objects or as area objects.

From the descriptive statistics and analysis of variance it was possible to differentiate between the proxies that acted as the drivers of erosion as earlier postulated and those that acted as disrupters of erosion. The selected proxies for each of the levels and the frequency of their occurrences in each holon type supported the hierarchy theory of new and emergent erosion indicators for the different levels of the hierarchical organisation of the landscape system. Some proxies could be selected to act as the erosion indicators for each of the levels. Soil movement, rills, washed stems, exposed roots, flow channels and translocated surface litter occurred in all the field-plot level erosion proxies. Gullies emerged as new erosion features for the proxies of the watershed level while soil movement, rills, stem wash and root exposures occurred in one third of the watershed level erosion proxy types. Mass soil movement emerged as new erosion features for the landscape level proxies while rills dominated and occurred in all the proxies. Soil movement and gullies occurred in two-thirds of the landscape level erosion proxies.

Important outputs from the prediction models were the *odds ratios* that provided quantitative values of how the erosion proxy properties influenced the risk of erosion. For the field-plot level holon types, a unit percent increase in slope created an increase in the risk of occurrence of soil erosion by 24% while a unit percentage increase in cover reduced the risk of occurrence by 8%. Slope added to the risk while cover reduced the risk. The risk contributed to by slope assumes constant cover and similarly the reduction in the occurrence of risk assumes constant slopes. For the watershed level holons, slope enhanced the risk of erosion by 36%. For the landscape level holons, a unit increase in percent slope enhanced the risk by 229%. A unit increase in cover percentage reduced the risk by 5% when the slope is constant. These figures obtained by the odds ratio show the erosion hazard conditioned by each of the proxy types. Slope and cover of the different multi-level erosion proxies proved to be important variables for predicting the hierarchical risk of erosion in the landscape system.

The spatial data on predicted erosion risk provided useful information for erosion risk management. The spatial extent attribute made it possible to determine the amount of time and energy required for tackling the risk associated with any proxy. The object position helped in precisely targeting intervention measures, while the distribution showed the relative intensity of the risk in any given area and the proximity of the risk to known locations of the geographic feature space. The independently produced logistic and logit prediction models produced spatial patterns that corresponded very well with the predictor variables of slope and cover of the proxies. This obtained relationship gave credence to the predictive power of the models. The logistic regression models showed the probabilities of erosion risk in the proxies, while the logit models refined the risk zones due to the transformation of the probabilities to a longer linear stretch. The logit models therefore provided a broader spectrum of the predictions making it possible to distinguish areas with low risk from areas with very high risks of erosion that required immediate and prioritised attention.

Strengths of the methodology and conceptual model

The methodology seeks to establish a means by which soil erosion can be assessed and modelled at multiple levels in a landscape. It deviates from other single-level erosion assessment and risk prediction methods that are of common practice in Kenya and in many other parts of the world. It views the landscape as a medium in which water erosion processes are taking place in an intricate manner at different spatial hierarchies and which are also the entities for land use and erosion management. These spatial attributes offer the opportunity to predict and view the distribution of the risk of erosion on the broader landscape and at different attention levels. These create management opportunities are powerful tools for preventing or controlling soil erosion. The beneficiaries of the methodology outputs are seen as farmers, government departments, and other non-governmental organisations that are involved in soil and water management.

Weaknesses of the conceptual model

The following were the observed weaknesses during implementation:

- In intensive annual farming systems, the features of erosion are usually obscured by frequent tillage practices making their assessment only possible immediately after tillage and after the event of an eroding rainfall or during minimum tillage periods;
- The above reason means that temporal considerations must be embedded in the methodology where the observations in the field are timed to coincide with rainfall and field preparations; and
- Any organisations opting to use the method must be fully equipped with GIS facilities and technical capacity to manipulate the spatial databases and modelling their attributes. Technical capacity is also required in the fields of soil erosion assessment and statistical analysis. Remote sensing knowledge and data offer the best opportunities for capturing landscape objects for integration into a GIS. Acquisition of the data and capacity to manipulate the images both digitally and manually are unavoidable requirements of the methodology.

Overarching discussions and conclusions

After collecting data on soil erosion and analysing it statistically, it has been shown that soil erosion in the field plot holon, watershed holon and landscape holon can be distinguished according to different erosion proxies for each of the holons. This finding can be used to refine the erosion prediction models such that the erosion processes are linked to the landscape holons with which they are closely associated. Scientific observations and measurements can also be ordered according to the holon type such that any extrapolations are directed to equal levels within the structure of the hierarchy. Different holons represent different levels of the landscape hierarchy.
Due to the techniques of assessing soil erosion in the field as applied in this work, it was possible to show that soil erosion goes on even in tea plantations, coffee plantations and in forests. If erosion assessment is only based on farm fields, then the erosion in the in higher level holons such as watershed or the landscape unit will be masked somewhere during erosion impact evaluations. This thesis has also enhanced the recognition of soil erosion by using visible features to capture and measure incidences of past erosion. Soil movement, flow channels, translocated surface litter, are features of erosion, which are not usually discussed nor used for either assessing or quantifying soil erosion. Their use can now be integrated into further works. With the presented methodology of assessing soil erosion, more data will be generated and demonstrated to the farmers and other interested people on soil erosion and its hazard.

The presented assessment and definitions in this work have also removed the problem of terminology especially in the definition of the landscape features for studying and managing soil erosion. The watershed has presented itself as the best management unit for many members of a community and can be adopted by any organisation concerned with collective management of soil erosion. The field plot remains the preserve of a single farmer while the landscape unit requires more of state interventions and deliberate management policy.

Prediction modelling made it possible to assign a quantitative value to the risk of erosion. The landscape unit had the highest risk (229%), followed by the watershed (36%) and the field plot (24%). Resources and efforts must therefore be availed and directed towards addressing soil erosion risk occasioned by the landscape level erosion processes and proxies. Managing the landscape level alone will not have a net benefit if the two other levels are not also attended to since they equally suffer soil erosion risk. A holistic management approach will provide a more effective management approach to the soil erosion risk. Government priorities can be directed at the landscape level. Intermediate agencies such as Community Based Groups and organisations can tackle the watershed level risk while farmers and farming communities can tackle the field-plot and watershed levels.

Researchable areas include in depth social studies that link biophysical spatial properties of the landscape to the socio-economic and policy instruments for each of the levels of the landscape hierarchy, i.e., field-plots, watershed units and the landscape units. Others are studies that link these landscape system holons with soil erosion proxies and soil erosion processes especially on their relationships with sediment yields, etc. to confirm further the notion of landscape hierarchies and erosion process resolutions. Finally, calibration and further testing of the prediction models in other parts of Kenya are recommended.

Samenvatting

Introductie

Hoewel er veel is bereikt in Kenia, is het meeste erosieonderzoek gericht geweest op het kwantificeren van bodemerosie, in plaats van het aanwijzen van gebieden die waarschijnlijk onder bodemerosie (zullen) lijden. Licht chargerend wordt in het algemeen aangenomen dat erosieprocessen plaatsvinden op een uniforme manier op alle hiërarchische niveaus in het landschap. Als gevolg hiervan kunnen de resultaten op één observatieniveau worden benut om andere niveaus te bestrijken waarvoor geen gegevens zijn verzameld. Dit heeft geleid tot het extrapoleren van puntgegevens om uitspraken over grotere geografische regio's te kunnen doen. Hoewel over het algemeen de nadruk ligt op de negatieve effecten van bodemerosie, heeft bodemerosie ook enkele positieve effecten. De depositie van geërodeerd bodemmateriaal op lagere delen van de helling of (op stroomgebiedniveau) benedenstrooms, heeft op die plekken gezorgd voor een verbeterde bodemkwaliteit en daarmee een hogere agrarische produktie. Daarnaast wordt door sommigen beweerd dat het probleem van bodemerosie wordt overdreven en dat het niet is bewezen dat de agrarische productie daadwerkelijk afneemt, met name gezien de vooruitgang op het gebied van teelttechnieken. Al deze, soms tegenstrijdige feiten en denkbeelden rechtvaardigen een verdiepende kijk op het verschijnsel bodemerosie.

Het algemene doel van dit proefschrift bestond uit het ontwikkelen en presenteren van een methode, welke gebruikt kan worden voor de beoordeling van het risico van watererosie op verschillende hiërarchische niveaus in het landschap, daarbij gebruik makend van ruimtelijke methoden. Hierbij werd gezocht naar een 'niveau-specifieke' basis voor het voorspellen van bodemerosie en het beheersen van het risico.
De specifieke doelstellingen waren:

1. Het conceptualiseren en definiëren van het landschapscontinuüm, d.w.z. hiërarchisch geordende landschapselementen waarvan de interne karakteristieken en delen invloed uitoefenen op bodemerosie en die met behulp van ruimtelijke informatiesystemen en modellen (via Remote Sensing en GIS) tastbaar gemaakt kunnen worden.
2. Het bewijzen dat er ruimtelijke kenmerken zijn (erosie *proxies*), die deel uitmaken van de specifieke landschappelijke niveaus en die bruikbaar zijn bij het schatten en modelleren van het risico van bodemerosie.
3. Het d.m.v. statistische methoden demonstreren dat de geselecteerde erosie *proxies* gerelateerd kunnen worden aan bodemerosie, waarbij de *proxies* kunnen worden gedifferentieerd naar erosie-bevorderend (*driver*) en erosie-remmend (*disrupter*).
4. Het demonstreren dat voorspellende modellen kunnen worden afgeleid uit veldgegevens van de erosie proxies en dat deze modellen bodemerosie-risico kunnen voorspellen op elk hiërarchisch landschapsniveau, met gebruikmaking van GIS.
5. Het testen en valideren van de methode in Kiambu.

Om deze doelen te bereiken, zijn concepten op het gebied van hiërarchietheorie, landschapssystemen, geografische informatiesystemen en bodemerosie geïntegreerd.

Voor het testen van de ontwikkelde methode is het Kiambu district geselecteerd, vanwege het intensieve en gevarieerde landbouwkundige gebruik in de lagere, oostelijke delen en het geaccidenteerde terrein van de lagere hellingen van het Aberdare gebergte in het westen. Hier wordt bodemerosie aan het oog onttrokken door bos en meerjarige gewassen als thee en koffie. Ondanks deze laatste ogenschijnlijk bodembeschermende situatie, is aangetoond dat in het district jaarlijks veel watererosie plaatsvindt, van 20 t km^{-2} j^{-1} in ongestoorde bossen tot 3000 t km^{-2} j^{-1} in gecultiveerde graslanden. Bodemverlies gemeten op miniplots in Kiambu laten verliezen zien op cultuurgrond van 20-30 t ha^{-1} $seizoen^{-1}$ en op kale grond van >70 t ha^{-1} $seizoen^{-1}$. De laatste jaren heeft in Kenia de zgn. *Catchment approach* opgang gemaakt. Dit is een 'stroomgebied' benadering, waarbij participatieve actie centraal staat. Echter, de preciese definitie van 'stroomgebied' is niet voldoende duidelijk gemaakt. Ten slotte blijkt dat boerenpercepties t.a.v. bodemerosie grotendeels zijn geënt op goed waarneembare kenmerken in het veld, zoals bredere geulen en voetpaden die door afstroming zijn uitgehold. Smalle geulen en oppervlakkige afstroming worden veel minder vaak onderkend als kenmerken van erosie.

Met behulp van Geografische Informatie Systemen (GIS) technologie is het mogelijk om ruimte- en tijdsspecifieke patronen te modelleren via gecomputeriseerde ruimtelijke databestanden, waarmee opslag, analyse en visualisatie van de gegevens mogelijk is. GIS maakt het mogelijk een stapsgewijze en gerangschikte analyse te maken van componenten van het landschapssysteem naar de wens van de onderzoeker. Bodemerosie is een product van de interactie van diverse geografische factoren zoals: bedekking van de bodemoppervlakte, het erosierisico van de bovengrond, de steilheid en lengte van de eroderende helling, de eroderende energie van vallende regendruppels en de specifieke beheersaspecten van de locatie. Het kan daardoor worden beoordeeld en gemodelleerd in een GIS omgeving zoals gedemonstreerd in deze dissertatie.

Concepten

De methode integreert concepten, kennis en implementatieprocedures. Eerst is de a *a-priori* kennis ganalyseerd om de studie naar bodemerosie binnen de context van een landschapssysteem te vergemakkelijken. Kennis en ervaring zijn ingeschakeld om het landschapssysteem in hiërarchische niveaus te organiseren. Het conceptuele model draait om de constructie van hiërarchische niveaus in een landschapssysteem en om hoe deze niveaus en hun delen in relatie staan tot bodemerosie in termen van beoordeling, voorspelling en beheer. De hiërarchische constructie van het landschapssysteem laat een geordende organisatie van de landschapscomponenten toe in bovengeschikte of ondergeschikte delen, die overeenkomen met procestijdschalen en hun overeenkomende ruimtelijke omvang. Een dusdanige schikking van het landschapssysteem laat relevante observaties en metingen van de geordende processen toe. Het concept wijkt af van de beschouwing van het landschap als de agglomeratie van delen, waarin wordt verondersteld dat processen op een uniforme manier plaatsvinden en waar veranderingen in gebiedsomvang worden ondervangen door een lineaire, generaliserende transformatie. De methode identificeert 'individuele' landschapselementen op elk niveau van de landschapshiërarchie, waarin processen voorkomen binnen vergelijkbare tijdschalen en waarvoor gegevensuitwisseling en modellering kan plaatsvinden. Deze worden *'holons'* genoemd. Deze holons worden gebruikt om de niveaus in de hiërarchie weer te geven.

Methodologie

De algemene methodologie omvat ten eerste de definitie van de landschapshiërarchieën, gevolgd door waarnemingen in het veld en tenslotte de verzameling van gegevens voor het voorspellen van het erosierisico. Deze drie eerste stappen werden gevolgd door de statistische analyse en ruimtelijke modellering van het erosierisico in een GIS. De eerste stap concentreerde zich voornamelijk op het definiëren van landschapshiërarchieën die konden worden gebruikt voor het ruimtelijk beoordelen van bodemerosiegevaar in een GIS. Landschapselementen werden bepaald om elk niveau in de landschapshiërarchie weer te geven. Gekozen werd voor het 'perceel/veld', het 'stroomgebied' en het 'landschap'. Het veldwerk omvatte het verzamelen van bodemerosiegegevens volgens een gestratificeerde en vervolgens gerandomiseerde strategie. In totaal werden 164 observaties verricht voor het perceel/veld, 89 voor het stroomgebied en 104 voor het landschap. Voorafgaand aan het veldwerk werden kaarten gemaakt voor elk van de niveaus, waarop vervolgens in het veld waarnemingspunten konden worden ingevoerd. Het verzamelen van gegevens omvatte het meten van erosiekarakteristieken als gevolg van water of zwaartekracht, zoals verplaatsing van bodemdeeltjes en plantaardig materiaal, zichtbare afstromingspatronen, diepte van bodemverlies aan de basis van de plantenstengel, diepte van blootlegging van plantenwortels, kleinere en grotere geulen en massaal bodemtransport zoals in *landslides*. Waar geen erosie is aangetroffen is de waarde nul genoteerd. Ten behoeve van de voorspellingsmodellering zijn voor de drie ruimtelijke niveaus, met hun specifieke relevante erosie*proxies*, onafhankelijke ruimtelijke datasets gemaakt. Voor het niveau 'perceel/veld' en 'stroomgebied' zijn luchtfoto's, en voor het niveau 'landschap' satellietbeelden gebruikt. Statistische analyse werd aangewend om vast te stellen dat de geselecteerde ruimtelijke erosie *proxies* inderdaad een effect hebben op de mate van watererosie, ten eerste door het voorkomen van erosiekarakteristieken in de *proxies* en ten tweede door het differentiëren van de bijdrage van elke *proxy* aan de totale erosie. Hierbij werd gebruik gemaakt van variantieanalyse en het gemiddelde voorkomen. Het onderdeel 'ruimtelijke modellering' omvatte het produceren van logistische en 'logit' regressiemodellen met een voorspellend karakter, op basis van de primaire gegevens. De hierdoor ontstane nieuwe ruimtelijke datasets geven vervolgens voor alle hiërarchische niveaus, eenheden met een gelijk erosierisico, gebaseerd op a priori vastgestelde indicatoren, nl. de erosie*proxies.* Eigenschappen van de proxies zoals hellingsgradiënt, percentage grondbedekking en erosiegevoeligheid zijn, na te zijn getest op geschiktheid door een correlatie analyse, gebruikt als voorspellende variabele.

Resultaten

Het bleek mogelijk te zijn om erosie*proxies* op de niveaus 'perceel/veld' en 'stroomgebied' vast te stellen met behulp van luchtfoto's. Hun werkelijke geometrische positie in het bredere landschap werd vastgesteld met met behulp van een Global Positioning System (GPS). De verschillende holontypen, vertegenwoordigd door de drie niveaus met hun erosie*proxies* werden, na te zijn waargenomen op luchtfoto's en satellietbeelden, gedigitaliseerd en opgeslagen in een Geografisch Informatie Systeem. Het niveau 'perceel/veld' met zijn landgebruiktypen vertegenwoordigde het laagste hiërarchische niveau. Lineaire kenmerken op het niveau 'stroomgebied' zoals perceelsgrenzen, voetpaden, heggen , hekken, rijtjes bomen, stenen muren, bosranden, wasplaatsen in theevelden en afgesloten perceelsgrenzen geven het tweede hiërarchische niveau weer. Op het hoogste niveau, ‘landschap’, vertegenwoordigen grote ruimtelijke elementen als rivierdalen, wegen en bewonings- en bebouwingsconcentraties de erosie*proxies.* Alle niveaus van de landschapshiërarchie werden opgeslagen als ‘vlak’, terwijl de erosie*proxies* waardoor ze worden gekenmerkt werden opgeslagen als ‘vlak’ (perceel/veld), als ‘lijn’ (stroomgebied), of als een combinatie van beiden (landschap).

De beschrijvende statistiek en variantieanalyse maakten het mogelijk onderscheid te maken tussen de *proxies* die erosie in de hand werken of juist afremmen. De geselecteerde proxies op de drie niveaus en de frequentie van hun voorkomen bleken de hiërarchietheorie te ondersteunen, waarbij het erosierisico door verschillende *proxies* en in verschillende mate wordt verklaard. Sommige *proxies* waren op alle niveaus geschikt als erosie-indicator. Bodemverplaatsing, kleine geulen, blootgelegde plantenstengels en -wortels, afstromingsverschijnselen en verplaatsing van strooisel speelden in alle perceel/veld niveau *proxies* een rol. Grote geulen werden pas belangrijk op het niveau ‘stroomgebied’, terwijl bodemverplaatsing, kleine geulen en blootgelegde plantenstengels en –wortels voorkwam in éénderde van de *proxies* op dit niveau. Massale bodemverplaatsing kwam naar voren op het niveau ‘landschap’. Bodemverplaatsing en grote geulen kwamen voor in tweederde van de *proxies* op dit niveau.

Belangrijke output van de voorspellende modellen zijn de *odds ratios* die een kwantitatieve voorstelling geven van de relatie tussen de eigenschappen van erosie *proxies* en het erosie-risico. Voor het niveau ‘perceel/veld’ betekende een toename van de helling met 1% een toename van het voorkomen van bodemerosiegevaar met 24%, terwijl afname van het percentage grondbedekking met 1 het risico met 8% verhoogde. Helling doet het risico toenemen, terwijl grondbedekking het risico doet afnemen. Het risico-aandeel van helling gaat uit van constante grondbedekking en vice versa. Voor het ‘stroomgebied’ voorzag 1% meer helling in een toename van het voorkomen van erosiegevaar met 36%. Voor het ‘landschap’ leidde 1% meer helling tot een toename van het risico met 229% bij constante grondbedekking, terwijl 1% toename van de grondbedekking het risico met 5% deed afnemen.

De ruimtelijke gegevens van voorspeld erosie-risico zijn nuttig ten behoeve van het beheer van erosie. De kennis van de positie van de niveaus en hun onderdelen ondersteunt een preciese, ruimtelijk expliciete definitie van interventiemaatregelen. De onafhankelijk geproduceerde logistische en *logit* voorspellende modellen lieten ruimtelijke patronen zien die zeer goed overeenkwamen met de voorspellende variabelen van helling en grondbedekking van de *proxies*. Deze verkregen relatie gaf de voorspellende kracht van de modellen geloofwaardigheid. De logistieke regressiemodellen lieten de waarschijnlijkheden van erosiegevaar in de *proxies* zien, terwijl de *logit* modellen de risicozones verfijnden door een transformatie van de waarschijnlijkheden naar een langere lineaire schaal. De *logit* modellen zorgden daardoor voor een breder spectrum van voorspellingen die het mogelijk maakten gebieden met een laag erosierisico te onderscheiden van gebieden met een hoog erosierisico.

Sterke punten van de methodologie en het conceptuele model

De methodologie is gericht op het tot stand brengen van gereedschap, waarmee bodemerosie kan worden geschat en gemodelleerd op meerdere niveaus in een landschap. Het wijkt af van de gangbare erosiebeoordelings- en risicovoorspellingsmethoden die zich op slechts één niveau richten en die algemeen in Kenia en andere delen van de wereld worden gebruikt. Het beschouwt het landschap als een systeem, waarin watererosieprocessen plaatsvinden op een complexe manier en op verschillende ruimtelijke niveaus, die tegelijk de basis vormen voor landgebruik en erosiebeheer. Deze ruimtelijke attributen maken het mogelijk de distributie van het erosiegevaar op een breed landschappelijk niveau te schatten en te voorspellen. De zo gecreëerde beheersmogelijkheden zijn krachtige gereedschappen voor het voorkomen en in de hand houden van bodemerosie. De begunstigden van de output van deze methodologie zijn boeren, overheidsdepartementen en niet-gouvernementele organisaties op het gebied van bodem- en waterbeheer.

Zwakke punten van het conceptuele model

De volgende zwakke punten kunnen worden genoemd:

- Bij intensieve agrarische systemen met eenjarige gewassen worden de erosiekenmerken vaak verhuld door regelmatige grondbewerkingen, die een beoordeling alleen mogelijk maken direct na grondbewerking, na regenval of na periodes van afwezigheid van grondbewerking;
- De bovengenoemde reden geeft dat tijdsoverwegingen moeten worden meegenomen in de methodologie, dat wil zeggen dat de observaties in het veld moeten zijn afgestemd op periodes van regenval en landpreparatie voor het gewas;
- Iedere organisatie die van deze methode gebruik wil maken moet zijn uitgerust met GIS faciliteiten en de technische capaciteit om ruimtelijke datasets te bewerken en te modelleren. Technische capaciteit is ook noodzakelijk op het gebied van schatting van bodemerosie en statistische analyse. Kennis van Remote Sensing en de beschikbaarheid van ruimtelijke datasets zijn nodig voor het expliciteren van landschapsobjecten ten behoeve van integratie in een GIS.

Overkoepelende discussies en conclusies

Na het verzamelen van gegevens betreffende bodemerosie en de statistische analyse daarvan, werd het duidelijk dat bodemerosie op de holonniveaus ‘perceel/veld’, ‘stroomgebied’ en ‘landschap’ onderscheiden kunnen worden aan de hand van verschillende erosie *proxies* voor elk van de holons. Deze bevinding kan worden gebruikt om erosievoorspellingsmodellen te verfijnen, op een manier waarbij erosieprocessen zijn gelieerd aan het holon met welke zij het nauwst gerelateerd zijn. Wetenschappelijke observaties en metingen kunnen ook worden geordend volgens het holontype, dusdanig dat elke extrapolatie is gericht op gelijke niveaus binnen de structuur van de hiërarchie. De verschillende holons geven de verschillende niveaus van de landschapshiërarchie weer.

Dankzij de technieken gepresenteerd in deze studie was het mogelijk te laten zien dat bodemerosie een belangrijke rol kan spelen in theeplantages, koffieplantages en bossen. Als de erosiebeoordeling alleen is gebaseerd op agrarische percelen wordt de erosie op de hogere landschappelijke niveaus gemaskeerd tijdens erosie-impact evaluaties. Dit proefschrift heeft ook de herkenning van bodemerosie verbeterd, gebruikmakend van zichtbare karakteristieken om reeds plaatsgevonden hebbende erosie te meten. Bodemverplaatsing, afspoelingskenmerken en verplaatst strooisel zijn karakteristieken van erosie, die gewoonlijk noch bediscussieerd noch gebruikt worden voor beoordeling of kwantificering van bodemerosie. Met behulp van de hier ontwikkelde methoden voor het beoordelen van bodemerosie kunnen meer gegevens worden gegenereerd en gedemonstreerd aan boeren en andere in erosie geïnteresseerde partijen.

De gepresenteerde beoordeling en definities in dit proefschrift hebben ook het probleem van terminologie weggenomen, in het bijzonder in de definitie van landschapskarakteristieken voor de bestudering en het beheer van bodemerosie. Het ‘stroomgebied’ heeft zichzelf als beste beheerseenheid gepresenteerd voor vele leden van een gemeenschap en kan worden geadopteerd door elke organisatie die zich bezighoudt met beheersing van bodemerosie. Het ‘perceel/veld’ blijft voorbehouden aan de lokale boer, terwijl het niveau ‘landschap’ meer interventie van de staatsoverheid nodig heeft en een weloverwogen beheersbeleid.

Voorspellend modelleren heeft het mogelijk gemaakt een kwantitieve waarde toe te kennen aan het erosierisico. De landschapseenheid had het hoogste risico (229%), gevolgd door het stroomgebied (36%) en het perceel (24%). Op basis hiervan moeten middelen en inspanningen ter beperking van het erosierisico zich in eerste instantie richten op het niveau ‘landschap’. Het beheer op landschapsniveau levert echter geen netto winst op, wanneer niet ook de twee andere niveaus worden meegenomen. Een holistische benadering zal zorgen voor een effectievere beheersing van het bodemerosierisico.

Toekomstig onderzoek zou zich moeten richten op de relatie tussen de biofysische ruimtelijke eigenschappen van het landschap en sociaal-economische factoren en beleidsinstrumenten voor elk specifiek niveau van de landschaphiërarchie. Verder zouden de niveaus met hun *proxies* en erosieprocessen gekoppeld moeten worden met gemeten sediment. Ten slotte wordt het calibreren en verder testen van de voorspellingsmodellen in andere delen van Kenia aanbevolen.

Curriculum vitae

Peter Okoth was born on 7th July 1958 in Kisumu District of Kenya. He started his formal education in Flamingo Primary School in 1965 in Nakuru Town where he obtained a Certificate of Primary Education (C.P.E.) in 1971. In 1972 he proceeded to Menengai High School also in Nakuru Town where he obtained the East African Certificate of Secondary Education (E.A.C.E) in 1975. He joined Dagoretti High School in Nairobi for his Advanced Level Education in 1976 and obtained the East African Advanced Certificate of Education (E.A.A.C.E.) in 1977. In 1978 Mr. Okoth joined the University of Nairobi where he studied mathematics, chemistry and geology majoring in geology for his B.Sc degree in 1981.

After graduating Mr. Okoth joined the Ministry of Agriculture in Kenya as an Assistant Agricultural Officer assigned the duty of soil surveys in 1981. He later proceeded for a Postgraduate Diploma in soil surveys at ITC The Netherlands, which he obtained in 1983. In 1984 he was promoted to the position of an Agricultural Officer in the same Ministry. In 1987 he moved to the Kenya Agricultural Research Institute and was appointed as a Research Officer. In 1988 Mr. Okoth obtained an M.Sc Degree in soil surveys and pedology again at ITC in The Netherlands. Mr. Okoth has worked for the Kenya Agricultural Research Institute (KARI) since then till now. In his normal duties in KARI, Mr. Okoth has implemented a total of twenty projects in soil survey and agriculture related subjects and written several scientific papers that he has presented to conferences or published in journals. Mr. Okoth has won several research grants for different projects in KARI and won a meritorious award for the second best paper on crops presented to KARI scientific conference in 1998. He has also supervised M.Sc students from Wageningen University and Egerton University in the field. Mr. Okoth is a contributing author to the book titled '*Maize Technology Development and Transfer: A GIS Application for Research Planning in Kenya'. Edited by R.M. Hassan (1998).*

In this doctoral thesis, Mr. Okoth has presented a multi-level spatial modeling of soil erosion in which he has integrated landscape ecological theories, soil erosion theories, GIS theories, field methods and statistical methods with remote sensing to develop spatial erosion prediction models. Mr. Okoth intends to continue pursuing this area of research in his future scientific career and engagements.

Mr. Okoth is married to Mrs. Elizabeth Adhiambo Okoth and has two children, Newton Ochieng', a boy, and Marcella Anyango, a girl.

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