

**THE EFFECT OF RAINFALL AMOUNT ON THE
SPATIAL STRUCTURE OF HILLSLOPE
SEDIMENT PRODUCTION IN WANALE
WATERSHED; UGANDA**

Wejuli Wesonga Wilber

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THE EFFECT OF RAINFALL AMOUNT ON THE SPATIAL STRUCTURE OF
HILLSLOPE SEDIMENT PRODUCTION IN WANALE WATERSHED; UGANDA

THE EFFECT OF RAINFALL AMOUNT ON THE SPATIAL
STRUCTURE OF HILLSLOPE SEDIMENT PRODUCTION IN WANALE
WATERSHED; UGANDA

by

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**INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION
ENSCHEDÉ, THE NETHERLANDS**

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THE EFFECT OF RAINFALL AMOUNT ON THE SPATIAL STRUCTURE OF HILLSLOPE SEDIMENT PRODUCTION IN WANALE WATERSHED; UGANDA

Abstract

The increasing vulnerability of hillslopes to soil erosion (sediment production) and its economic effects in Wanale watershed (Uganda) triggered several studies to improve its prediction, but with little success. The stochasticity of the factors and patterns of hillslope soil erosion suggests temporal instability in its spatial structure. This phenomenon is seldom recognised in existing models potentially compromising their prediction quality. This study aimed at improving the spatial prediction quality of hillslope soil erosion. Using measured soil erosion at 61 sample points, DEM hydrologic parameters, landuse, soil physical characteristics, surface cover and reflectance, we modelled and compared the soil erosion spatial structures for three rainfall event sizes (Low medium and high). Both the spatial structures and landscape factors were used to predict soil erosion (amount, patterns and uncertainty) by Ordinary Kriging (OK) and Kriging with External drift (KED). The results indicated that the hillslope soil erosion spatial structure changes at different event sizes, there is a positive relationship between soil erosion variability (CV %) and its spatial autocorrelation and soil erosion is a function of landcover, soil erodibility and the square root of slope. We also found that stochastic prediction with the soil erosion spatial structure improved predictions and that including landscape factors in stochastic prediction of soil erosion enhances the models' ability to reproduce the observed variability ($R^2 > 0.8$). We concluded that stochastic modelling improves predictions and the approach provides insights of the underlying factors. Additionally consideration for the change in the event sediment production spatial autocorrelation has positive implications for both packaging spatial information regarding the hazard and also for event-based modelling of hillslope sediment production. Further investigation is needed to determine the rainfall amount thresholds at which the sediment production spatial structure changes.

Key words: Spatial structure, Kriging, Stochastic modelling, Prediction quality, sediment production.

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DEDICATION

This work is dedicated to my beloved wife, Were Moreen

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1. INTRODUCTION

1.1. Background to the problem

Wanale watershed lies in UTM zone 36N (608412 to 636112E, 124890 to 145190N) in Uganda. The watershed lies on the fertile slopes of Mt Elgon and it receives wet bi-annual rainfall. These factors attracted human settlement and intensive agricultural activity which increased the vulnerability of its hillslopes to soil erosion (sediment production) with subsequent onsite and offsite problems (Bamutaze, 2005). Else where, Kok et al., (2007) related soil erosion to decline in soil productivity and other negative consequences to human livelihoods and welfare. Therefore interventions to the problem can be enhanced by providing spatial information regarding the hillslope soil erosion (Lal, 1984 ; Lal, 1998; Bagoora, 1993; Bamutaze, 2005; Okoba and Sterk, 2006).

Traditionally plot observations were used to provide insights on soil erosion. However plots do not provide spatial information over larger spatial scales and some deposition occurs in the plots. As such some studies apply plot data in models to provide insights of potential hillslope sediment production but most predictions are still poor (Nearing, 1998; (Aksoy and Kavvas, 2005) (See Figure 1.1).

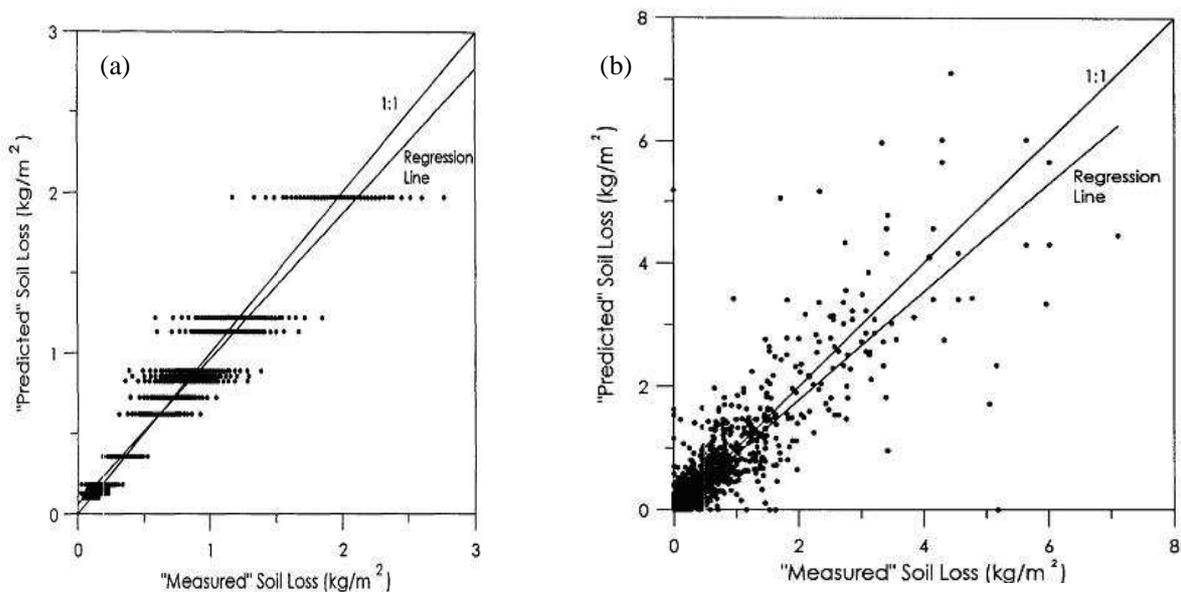


Figure 1-1: Poor predictions by deterministic (a) and physical model (b) (Nearing, 1998)

The dynamic and stochastic nature of soil erosion factors and patterns is a major cause for the poor predictions (Jetten et al., 2003). These factors cause high data variability complicating the predictions

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of both deductive and inductive models (Overmars et al., 2007). The high prediction errors complicate planning and positioning of conservation measures.

To enhance better spatial prediction quality of soil erosion, complex models were developed. However De Roo (1993) and Risse et al. (1993) comparison of the simpler models such as the Universal Soil Loss Equation (USLE) and Morgan-Morgan-Finney (MMF) (Morgan, 2001), with the complex Water Erosion Prediction Project (WEPP) showed that they performed equally well when they were tested for the same result (annual soil erosion). Moreover Jetten et al. (2003), explained that complex models may be prone to error from parameter uncertainty. Therefore the dynamic and stochastic nature of soil erosion factors is a major challenge to the several attempts to sufficiently capture erosion concepts in physical and empirical relations. As such current models only perform well for aggregated levels such as total annual soil erosion because some of the stochasticity is averaged out. Hill slope soil erosion at single rainfall events, here after called, event soil erosion is still difficult to predict accurately (Nearing et al., 1999; Nearing, 2000). While different studies have used different rainfall amount thresholds for categorizing rainfall events as low medium and high, they concede that soil erosion at smaller rainfall events is more difficult to predict than the soil loss from larger rainfall events.

The importance of rainfall event size can be visualized in terms of its high variability in the tropics, the fact that in some cases most of it is composed of low events and that the subsequent amount of soil erosion may enhance choice of more effective interventions. Therefore accurate estimation of event soil erosion is paramount (Bagoora, 1993; Kakuru, 1993; Okoba and Sterk, 2006; Carrera-Hernandez and Gaskin, 2007).

Bryan (2000), Jetten et al. (2003), Kok et al. (2007) and Overmars et al. (2007), suggested the use of more spatial information in event soil erosion prediction in order to improve the predictions of soil loss. Bryan (2000) and Jetten et al. (2003) explained that application of the soil erosion spatial structure in stochastic predictions may enhance the spatial prediction quality. Stochastic predictions provide several strengths such as the possibility to split the dependence on time and space so as to enhance modelling and prediction of complex spatiotemporal data (Sterk and Stein., 1997). The approach also enhances modeling of pure spatially-autocorrelated variability (Ordinary Kriging (OK)) and the prediction results can be enhanced by using secondary variables as linear feature-space predictors as well as residual spatial autocorrelation (Kriging with External Drift (KED)). It also provides clues to the underlying causes of the predicted process (Carrera-Hernandez and Gaskin, 2007; Perez-Rodriguez et al., 2007). Additionally the use of stochastic simulations can enhance kriging realizations (amounts and uncertainty) by possible patterns which can be used for different

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scenarios of intervention or even as other model inputs (Kyriakidis et al, 1999; Minasny and McBratney, 2007)

However the several studies which considered relationships between rainfall amount and soil loss explain the challenges of different rainfall event size data to soil loss modeling. For example Nearing, (1998), Nearing et al., (1999), Nearing, (2000) and Jetten et al. (2003), explained the difficulties in soil erosion modeling arising from the different influence of local and regional landscape factors to observed event soil erosion. They conclude that the low event soil erosion data has higher Coefficient of Variation (CV%) than the high rainfall event soil erosion (Nearing et al., 1999). This suggests a need to investigate such relationships prior to application of the soil erosion spatial structure in stochastic predictions. The fact that rainfall amount is inversely proportional to the soil erosion CV% may imply higher covariances for low rainfall events's soil erosion. This could imply differences in the sill (the total explained variance of the variable; see (Pebesma, 2004)) as well as differences in spatial autocorrelation between different event soil erosion. This may also have implications to the explained variability of the event soil erosion spatial autocorrelation model structure as well as its range of spatial dependence.

The possibility for different event soil erosion spatial structures should be considered to avoid similar complications such as in deterministic and physical models. Therefore simply applying the spatial structure in stochastic soil erosion prediction may only result into reasonable predictions for aggregated situations as the case is with current models. Therefore it may be useful to investigate the relative influence of the rainfall event size on the spatial structure of hillslope soil erosion (sediment production) prior to applying it in stochastic prediction of event sediment production. Sterk and Stein. (1997), recognized and applied the differences in the spatial structure to model and predict wind erosion. This implies that it is possible to apply similar logic to hillslope water erosion. Additionally several studies have applied the stochastic predictions using both the spatial structures and linearly correlated landscape factors to improve results (Carrera-Hernandez and Gaskin, 2007; De Cesare et al., 1997; Fetel and Caumon, ; Haberlandt, 2007; Wang et al., 2001). Therefore some of the empirical relationships between gross annual soil erosion with rainfall erosivity, soil erodibility, landcover and slope could be incorporated in stochastic predictions to improve prediction of hillslope sediment production (Renard, 1997; de Vente et al.). Moreover analysing the relative importance of the specific factors or combination of factors on event soil erosion may enhance the choice of model inputs; particularly the choice of landscape factors for use as secondary factors in prediction by kriging.

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1.2. Statement of the problem

Rainfall event size affects hillslope soil erosion variability and hence complicates its prediction especially at low rainfall events. However it is not known if the rainfall event size also affects the spatial autocorrelation model structure, range of spatial dependence and the explained variability of hillslope sediment production (soil erosion).

1.3. Aim

To investigate the relationship between rainfall event size and the soil erosion spatial structure and combine the spatial structure with landscape factors so as to improve the spatial prediction quality of hillslope soil erosion.

1.4. General research question

To what extent does stochastic prediction using the event spatial structure improve hillslope soil erosion prediction and to what extent does including landscape factors enhance the predicted result?

Table 1-1: Objectives research questions and hypotheses

Specific Objectives	Research Questions	Hypotheses
1. To model the relationship between the soil erosion variability and its spatial auto-correlation and to relate the spatial autocorrelation structure to rainfall event size	1. What is the relationship between the variability in soil erosion and its spatial autocorrelation?	1. The Coefficient of variation (CV %) is positively related to the event explained variability by the spatial autocorrelation model.
	2. How does the spatial structure of soil erosion vary with rainfall event size?	2. Spatial autocorrelation in soil erosion decreases with increasing rainfall amount.
2. To determine the influence of landscape factors to soil erosion at different event sizes.	3. Which factor or combination of factors minimizes the unexplained variability in soil erosion?	3. Soil erosion is a function of, land cover soil erodibility and the square root of slope.
3. To predict hillslope soil erosion using both the spatial structure alone and in combination with landscape factors	4. To what extent do KED and OK reproduce observed variability in soil erosion?	4. KED reproduces observed variability in soil erosion better than OK
4. To validate and explain the predicted soil erosion	5. What is the accuracy of the predictions?	5. KED is more accurate than OK
5. To simulate and discuss the implications of the results	6. What are the implications to modelling and management?	6. Stochastic prediction of soil erosion improves prediction accuracy

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1.5. Conceptual framework

The research concept is summarized in Figure 1.2. We sampled uncertain space; in this case the unknown but finite variability of hillslope soil erosion per rainfall event. A randomly distributed and large enough (sixty one) soil erosion sample was considered to be representative and to infer the unknown hillslope soil erosion variability in space and among rainfall events. The spatial structures were modeled by a covariance model/ spatial autocorrelation model, which were then used in stochastic prediction of event hillslope soil erosion; quantity, patterns and uncertainty. At the spatial scale (watershed) and temporal scale (One day steady state time steps) of modeling we assumed that all input data was continuous. The approach we apply in this study incorporates both the strengths of the event spatial structure and the use of known factors of soil erosion as secondary factors. The approach responds to the difficulties in understanding all the causes, the challenges in explaining sediment production variability; and the need for both predicted patterns and respective uncertainties for effective intervention in the hillslope soil erosion problem.

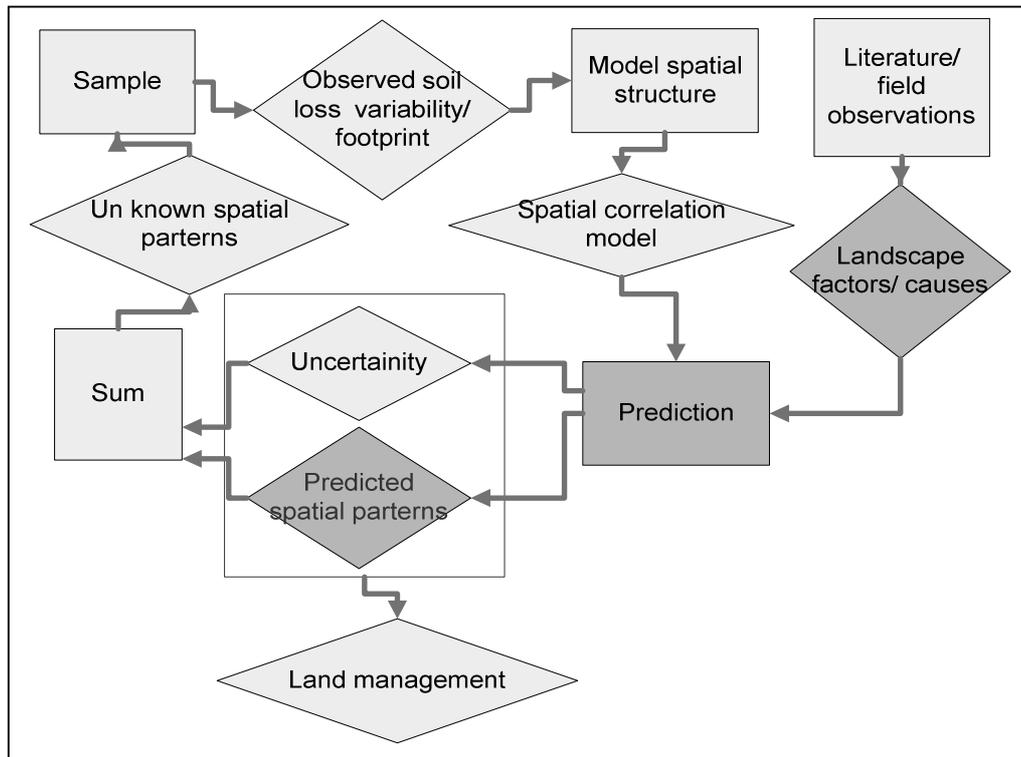


Figure 1-2: Conceptual framework

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1.6. Thesis structure

The thesis is composed of seven chapters.

Chapter two is a review of relevant literature so as to describe the need for spatial information regarding the hillslope sediment production problem and also to identify the challenges and recommendations therein. We focused on the possibility for event-based stochastic modeling to improve the spatial prediction quality of hillslope sediment production.

Chapter three provides the reasons for selecting Wanale watershed as a suitable area for this study and its location in Uganda.

Chapter four is a detailed description of the data methods materials as well as the scope and nature of the modeling approach. The analysis focuses on defining the soil erosion spatial structure and consideration for any evidence which might suggest its change as rainfall amount increases. The chapter ends with an explanation of the choice of landscape factors for predicting soil erosion as well as the procedure for soil erosion assessment and validation as applied in this study.

Chapter five includes visualization of both regional and local spatial dependence in observed soil erosion and presentation of the event and total annual soil erosion spatial structures. The results of predicting with the spatial structure and also in combination with landscape factors are presented in form of amounts, patterns, uncertainties, soil erosion hazard map and Gaussian conditional simulations.

Chapter six is a discussion on the basis of hillslope soil erosion as a watershed process and the implications of the results to both soil erosion modeling and its management. The chapter considers all the results and relevant literature to reject or accept the stated hypotheses and also to explain the limitations of the results.

Chapter seven is a response to all the research questions. The recommendations for future studies as well as for interventions are also stated in this chapter.

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2. LITERATURE REVIEW

Losses in annual food production due to accelerated erosion affect food security and human wellbeing (Kok et al., 2007). Additionally sediment delivery destroys human infrastructure, increases water pollution and threatens agricultural activities down stream (Rompaey et al., 2005; Verstraeten, 2006; Verstraeten et al., 2007). At the local level in Uganda, similar problems have been observed. Studies in Wanale watershed estimated that one tonne of sediment is removed annually from an nearby intake structure of water purification (Bamutaze, 2005; Nakileza, 1993). Therefore accurate estimation of soil erosion is essential in addressing such effects as well as for the prevention of costly and gross errors in land use planning decisions based on unreliable information (Jetten et al., 2003; Jordan et al., 2005).

The complication of model predictions is due to the relatively high spatial-temporal stochasticity in soil erosion factors and patterns (Jetten et al., 2003). This affects soil erosion variability and hence complicates soil erosion modelling. For example the high variance in the low events soil loss makes their prediction very difficult, yet they may constitute the largest magnitude of annual events in some areas.

2.1. Rainfall soil loss factors and the soil loss spatial structure

Both the rainfall kinetic energy and the runoff it generates cause detachment and displacement of soil particles. The rain water also changes the soil properties between and during rainstorms causing short term and long-term effects on soil erosion (Jetten et al., 2003; Van Roode, 2000). The changes in soil properties affect erosion response; specifically partitioning between rill and interrill; threshold hydraulic conditions for rill incision and rill network configuration (Bryan, 2000). The spatial temporal changes in the factors often lead to complex erosion patterns (Borah et al, 2004; Bruijnzeel, 2004) posing challenges in total explanation of single storm soil erosion variability. The erroneous predictions complicate the designing and positioning of interventions and hence they negatively affect the livelihoods and welfare of the community who depend on agriculture.

Van Roode (2000), considered the effects of vegetative barrier strips on surface runoff. The study showed that even uniform rainfall reaching the soil surface can be spatially variable due to interception by different vegetation characteristics. The study confirms the challenges of predicting soil erosion patterns from different event sizes. It also demonstrates the potentially different

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importance of land cover at different event sizes and its subsequent contribution to soil erosion patterns.

Nearing et al. (1999) compared pairs of adjacent plots and found that the Coefficient of Variation (CV%) increased with a decrease in event size. This is similar to several other study findings which applied experimental plots in investigating eventbased soil erosion (Nearing, 1998; Nearing et al., 1999; Takken et al., 2001a; Takken et al., 2001b; Yemefack et al., 2006). The studies universally state that it is difficult to accurately predict low events' soil loss. Hence investigating ways to predict the variable event sizes with better accuracy is desirable in enhancing community and institutional interventions. Some attempts to consider rainfall size and intensity in modelling have been made (Nearing, 1998; Nearing et al., 1999; Van Roode, 2000; Nearing, 2000; Pruski and Nearing, 2002; Michael et al., 2005 and Nearing et al., 2005). However, the studies neither predicted patterns nor uncertainty despite their importance in guiding interventions.

Focusing on the soil erosion spatial patterns was suggested by Bryan, (2000) and Jetten et al. (2003) as possible ways in improving the spatial prediction quality of erosion models. Nearing et al., (2005) and Maneta et al., (2007) explain the importance of mapping the spatial-temporal variability in soil erosion resulting from rainfall variability. Jetten et al., (2003), recognised that some of the factors are stochastic implying that stochastic approaches may perform better if applied in soil erosion studies. Moreover since most of the above studies were undertaken at plot scale, such predictions are unfeasible for interventions which often target larger areas (Renard, 1997). Therefore several studies recognise interrelationships between the underlying factors by conducting watershed research within complemented with process-based modelling (Bruijnzeel, 2004; Jordan et al. 2005; Krasa et al., 2005)

2.2. Spatial prediction quality of some erosion models

To account for the complexity of the interacting processes and to improve prediction of hillslope soil erosion, several models including very complex ones were developed. (Overmars et al., 2007) categorised and summarised the strengths and weaknesses of inductive and deductive models. Inductive models are reproducible but they can not handle discontinuities and are weak at handling scenarios yet they also can not guarantee causality. This may be due to the limited understanding of the physical processes involved (Refsgaard and Abbott, 1996). The deductive approach describes processes explicitly and it can therefore handle discontinuity better but they are not easily reproducible. Among the suggested options for future modelling are a structured and multidisciplinary approach (Kok et al., 2007) or stochastic modelling (Bryan, 2000). These are expected to improve predictions.

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Merritt et al., (2003) and Borah et al. (2004) reviewed several empirical, conceptual and physically-based models. Some empirical models such as USLE (Wischmeier and Smith, 1958) and the Revised Universal Soil Loss Equation (RUSLE) (Renard, 1997) show linear relations between soil loss and several factors but they can not predict for a specific year or storm. De Roo (1993) compared the lumped USLE and MMF (Morgan, 2001) models with the spatially distributed Areal Non-point Source Watershed Environmental Response Simulation model (ANSWERS) and the KINematic Runoff and EROsion model (KINEROS) and showed that they performed equally well when they were tested for the same result. Similarly Risse et al., (1993), tested the USLE and obtained an R^2 of 0.58 and 0.75 when comparing observed and predicted annual and average annual soil erosion values respectively. The values were higher than those attained by a much more complex and physically based WEPP model (0.54 and 0.68 respectively). This confirms the fact that the poor to moderate predictive capabilities of erosion models is due to the uncertainty in input parameters (Takken et al., 2001b). Modeling problems may benefit from more spatial information such as spatial autocorrelation and surface characteristics (Jetten et al., 2003). This is also recommended by Bryan (2000) Kok (2006) and (Kok et al., 2007).

2.3. Stochastic prediction with the spatial structure and landscape factors

Geostatistics can model processes as realizations of spatially autocorrelated random functions. The approach can use models of spatial autocorrelation to describe the spatial process structure (Hoosbeek, 1998). It has the capability to model the spatial temporal stochasticity in a process. The popularity of the approach is due to its relative ease to use a sample dataset to derive local estimates and their uncertainties at unknown locations and time (Goovaerts, 1999; Pebesma, 2004; Wang et al., 2001 ; Wang et al., 2002). It has been tested in modelling soil water content (Goovaerts, 1999; Western et al., 2004) and rainfall (Armstrong et al., 1993; Hohn et al., 1993). Other studies have applied stochastic prediction with secondary factors to evaluate and quantify uncertainty in hydrocarbon reservoirs (Fetel and Caumon), spatial prediction of soil properties (Minasny and McBratney, 2007), spatial temporal analysis of daily precipitation and interpolation (Carrera-Hernandez and Gaskin, 2007; Haberlandt, 2007) and uncertainty assessment of local nitrous oxide (van de Kastele and Velders, 2006).

Variogram models are essential for stochastic predictions by kriging. The variogram represents the average variance between observations separated by a distance. Variogram parameters include the 'sill' (the total variance of the variable), the 'range' (the maximum spatial extent of spatial autocorrelation between observations of the variable) and the 'nugget' (the unexplained error). The explained variability of a variogram function is quantified as the sill: nugget ratio; it represents the spatial autocorrelation in soil erosion (Pebesma, 2004). Empirical variograms are used to show the

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spatial autocorrelation between pairs of points in space as a function of their separation and hence to they can be used to model local spatial dependence of a process (Carrera-Hernandez and Gaskin, 2007). The use of stochastic prediction to provide estimates in unobserved locations can be enhanced by careful choice of an interpolation method. Spatial interpolation can be undertaken through the use of various algorithms such as Thiessen polygons, Inverse Distance Weight (IDW), Polynomial trend surfaces and Kriging. Kriging is a linear interpolator based on least squares technique that accounts for spatial autocorrelation (Goovaerts, 1999). The extent of this correlation is expressed by a covariance function (or a variogram model). Some kriging methods such as Simple Kriging (SK) and Ordinary Kriging (OK) do not use external variables while others like Kriging by Strata (KS), Kriging with External Drift (KED) and Cokriging (Cok) apply a secondary variable, as well as the primary variable, to predict. The Kriging method in general and multivariate Kriging with secondary variables in particular, yields more realistic spatial behaviour of processes (van de Kassteele and Velders, 2006; Verfaillie et al., 2006; Carrera-Hernandez and Gaskin, 2007; Carrera-Hernandez and Gaskin, 2007; Minasny and McBratney, 2007; Minasny and McBratney, 2007; Fetel and Caumon).

Kriging methods by their formulation minimize the estimation variance under certain stationarity assumptions. Three Kriging variants can be distinguished according to the way in which the trend is handled (Goovaerts, 1999): SK which considers the trend to be known and constant in the study area, OK which considers that the trend is unknown and constant on a specified search neighborhood and Universal Kriging or Kriging with a Trend model (KT) which considers that the local mean varies within each local neighborhood and on which the trend is modelled as a function of coordinates. KT is sometimes called Universal Kriging (UK) with local trend. KED is an extension of KT, but in this case the trend/drift is a function of one or more secondary variables (environmental covariables).

OK accounts for local variation of the mean as it gives higher weights to a neighborhood centered on the location being estimated. OK assumes that the modelled process is caused by a random spatially correlated process and also that the random process has a constant mean and variance (second order stationarity). However, some interpolation methods like KED are able to integrate a secondary “soft” information (Fetel and Caumon). This may improve prediction accuracy or to account for the underlying processes. KED evaluates the correlation between the soil erosion variable and the secondary variable within neighborhoods, providing information about the primary trend at locations (Goovaerts, 1999). The trend coefficients are constant within the search neighborhood. To apply this Kriging technique the relation between the two variables must be linear (if not an appropriate transformation of the secondary variable is needed) and the value of the secondary variable must be known on the whole (Carrera-Hernandez and Gaskin, 2007; Minasny and McBratney, 2007).

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3. STUDY AREA SELECTION

3.1. Relevant community and institutional development issues

IFPRI (2007), reported that land degradation, declining agricultural productivity, and poverty are severe and interrelated problems in Uganda. The study recommended land management and land use policies which can alleviate them and also increase agricultural productivity through sustainable use of resources. Declining soil fertility limits crop yields and it is linked to soil erosion. It implies that the success of such policies and compliance to regulations partly depends on accuracy of the predicted patterns and uncertainties of the soil loss. This study aimed at responding to this issue specifically by packaging spatial information to enhance interventions to soil loss in the Wanale watershed.

Uganda's economy and society is largely based on agriculture, and the Wanale community in eastern Uganda, in UTM zone 36N (608412 to 636112E, 124890 to 145190N on the WGS 84 datum (Figure 3.1), are an example of a community thriving totally on agriculture. The soil state affects yields, food security, and hence local livelihoods and welfare. This partly explains why the National Environment Management Authority (NEMA) strives to demonstrate the poverty and environment linkages through integrated ecosystem assessments. Additionally the (NEMA, 1999) soil policy highlighted soil productivity as a cross cutting issue which needs to be enhanced by better spatial information on related processes such as soil erosion.

3.2. Suceptibility to the soil erosion problem

Wanale watershed (Approximately 22,820 Hectares) was selected for this study for many reasons. Its location in the tropics on the foothills of a volcanic mountain influenced its geology and soil properties favouring agriculture and attracting a high population (Briggs et al., 1998). The population dynamics and intensive agriculture make the area vulnerable to the hillslope erosion hazard.

The climate of the area is classified as humid subtropical, dominated by seasonally alternating moist south-westerly and dry north-easterly air streams (Briggs et al., 1998). Wanale falls in the category of areas in Uganda with more than 90% probability of receiving over 1,000 mm. The total annual rainfall ranges between 1,500 mm to 2,500 mm, depending on altitude and aspect. The average annual precipitation amounts to 1500 mm and monthly values range from 61 mm during the dry season to 193 mm during the rainy seasons. Only 27% of storms are above 20 mm (Bamutaze 2005).

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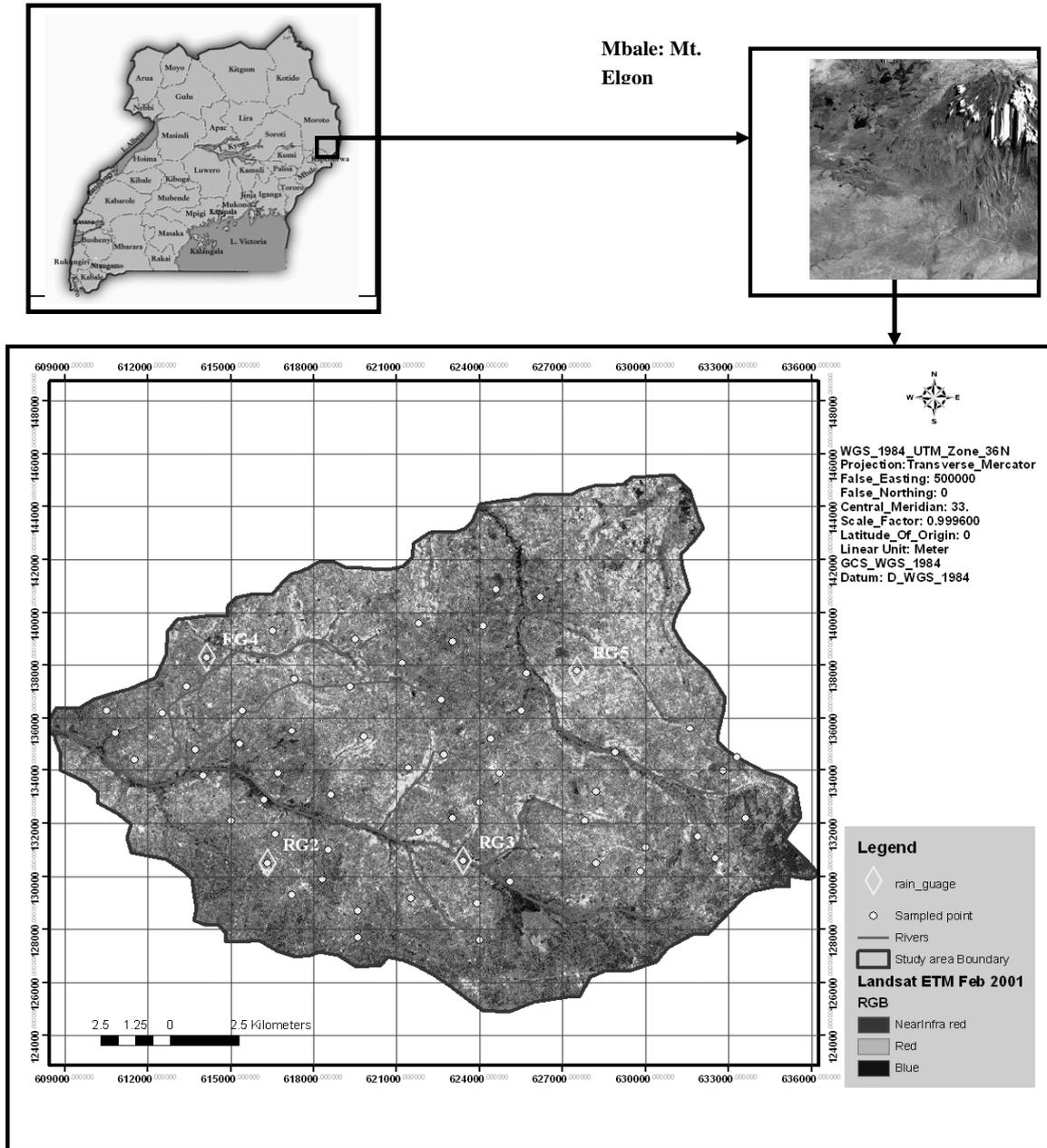


Figure 3-1: Location of Wanale watershed in Uganda

Bamutaze (2005) also found that the spatial variability of rainfall in the study area is not significant. However as rainfall increases, the size of raindrops and subsequent kinetic energy increases (Lal, 1984 ; Lal, 1998; Nakileza, 1993). The increment in energy results in more soil splash causing turbulence in runoff and increasing the capacity to scour and transport soil particles as explained by Hudson (1990) and Lal (1984). This phenomenon is higher in the tropical regions and so are the rates of soil loss (Lal, 1984; Brunner et al., 2004). The rainfall seasonality is bimodal with long rains occurring early in the year and short rains later. The combination of rains and hilly relief make

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Wanale watershed prone to soil erosion (Hudson, 1990). Most of this erosion is stated to be of hill slope rill and interrill type (Bekunda et al., 1994)

However Wanale watershed is still one of the most productive areas agriculturally and hence it attracted settlement and agriculture making it one of the most densely populated areas in Uganda. The high population density drives demand for land causing land shortage. The land shortage leads to more intensive use of the hill slopes resulting into soil exhaustion due to low or absence of fallow periods. These factors in combination with the biannual tropical rainfall increase the vulnerability of the hillslopes to soil nutrient loss and decline in soil productivity. The trend in continued soil productivity decline has also been attributed to challenges in the accurate positioning of the known conservation measures such as grass strips terraces and better tillage forms. These factors and the availability of soil loss, rainfall and runoff data, which was observed between 2001 and 2002 by Makerere University, made Wanale watershed a preferable study site for this study.

The Uganda government and local institutions have responded to the soil loss and related problems differently. An example is the protection of Mt Elgon forest as a National Park in 1991. Additionally the watershed is now protected by two regulations namely; the hilly and mountainous areas regulation of 2000 and the wetlands river banks and lakeshores regulation of 2000. Wanale watershed is hence of prime environmental concern, a factor which attracted a study of this nature.

3.3. State of soil erosion in Wanale watershed

The greatest geological influence on the Wanale environment is the nature of volcanic rock that comprises volcanic ash, soda rich agglomerates and tuffs extruded by volcanic activity (Briggs et al., 1998). In combination with a moderate to high rainfall these make soils relatively more fertile than the surrounding, areas (NEMA, 1999). However Briggs et al. (1998) reported that nutrient depletion due to hill slope erosion is increasing. They concluded that the magnitude of soil loss from the upper slope segment were significantly larger than the middle and lower segments, respectively. The variable land management and rainfall thus make the present study relevant in this area, especially following the revelation that the proportion of soil erosion has reached alarming levels (Brunner et al., 2004).

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4. METHODS AND MATERIALS

4.1. Data sampling design and strategy

The sampling design was determined by the Makerere University Geography department which established runoff plots in 2001 with funding from the National Environment Management Authority (NEMA). The aim of the project was to quantify soil erosion and enhance implementation of soil and water conservation in the area. The Geography department availed us with some of the data for this study. The plot locations in Figure 4.1 covered three land use types: annual crops, perennial crops, and trees. It also covered three slope positions: low, middle and upper. Sixty-one closed runoff plots (10 m x 15 m) were created to represent the heterogeneity in the area using Stratified Random Sampling Design (Freese, 1984). In the September 2007 fieldwork we strategically sampled from these very runoff plot locations to enhance comparisons.

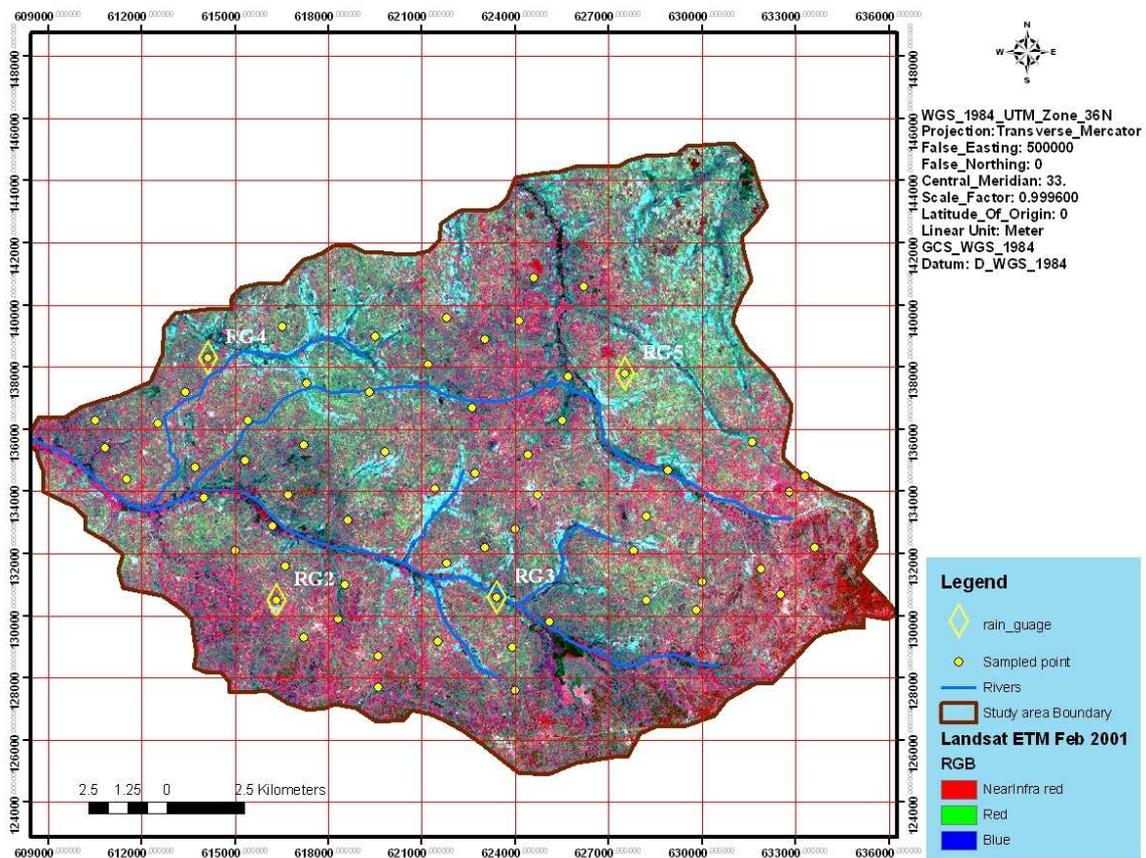


Figure 4-1: Distribution of the fieldwork samples

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4.1.1. Primary data collection

We undertook field observations at each plot for erosion features and existing conservation activities. We also measured elevation, slope angle, soil strength, canopy cover and surface cover. In addition we sampled soil for laboratory analysis and also collected landcover samples for the land use/land cover classification. A community focus group discussion with watershed residents and a guided interview of key informants were also undertaken to highlight social and institutional issues. Questionnaires and data sheets are in annex 0.3 – 0.4.

Although the primary objective of this study was to use closed runoff plots data to model and predict event hill slope soil erosion, we also observed rill and gully formations, cropping patterns, the current state of the runoff plot locations and current conservation practices. This contributed to secondary data evaluation and enhanced the discussion of the results.

Slope angle was determined by focusing the clinometer lens at the eye level of an object of the same height as the one focusing it, in the direction of the maximum slope. The separation distance of 15m which corresponds to the maximum length of the closed runoff plots was used. It also corresponds to the constructed DEM resolution. Elevation was collected by placing the altimeter on the ground. This was done to avoid errors during comparison with the obtained digital contours which represent the Digital Terrain Model.

Soil strength was measured from four random locations in a plot on the day after a rainfall event so as to ensure similar soil moisture conditions. The pocket penetrometer (Model 06.03 manufactured by Eijkelkamp, measuring range: 500 KN/m²) was pressed in the ground and the force was released at the first resistance. Measurements in Kg/m² were recorded on the data sheet.

Surface vegetation cover was monitored every two weeks at several locations within the plot and the monthly average percentage cover was computed. A FAO (1994) chart guide was used to visually estimate surface cover in the runoff plots. The chart has ten squares with four quarters in each square and a corresponding percentage value. The observations in the field treatment at a particular time were compared with the squares in the FAO (1994) chart to give the percentage value of the corresponding square. Canopy cover was estimated using a densitometer. We stood in the centre of the plot and counted the number of full squares and added them to half the number of the half squares. The sum was divided by 24 and multiplied by 100 to get the percentage canopy cover.

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At each plot we obtained soil samples from three representative locations randomly. A ruler was used to measure 0-15 cm and 15-30 cm depths from which soil samples were obtained for soil quality composting. The samples were thoroughly mixed and a composite sample of 1 kg was taken to Makerere University soil science laboratory for analysis.

For the landcover classification both a sample was collected for the training and accuracy assessment. Sixty (60) locations of pure land cover types within 15 m x 15 m area were geo-referenced with a Global Positioning System. The sampled landcover types included bananas, eucalyptus trees, maize, cassava and bare land, built up area, water, roads, coffee and other trees.

A focus group discussion was organised in the field; comprising of different age groups and gender in the same meeting. We facilitated the meeting in which farmers were asked to identify problems related to agriculture and prioritise them in order of urgency for intervention. The key informants were selected from related institutions. Questionnaires (See annex 0.4), were administered to 20 key informants from NEMA, Mbale Local government environment office, Makerere University and the Mt Elgon National Park management.

4.1.2. Secondary data collection

Soil loss and rainfall data were provided by Makerere University with consent of NEMA which owns the data. Details of the runoff plots' set up and data collection can be obtained from Bamutaze (2005) but a brief description is given here. The sites represented perennial annual and tree vegetation as well as slopes between 8-57%. The sites were geo-referenced and demarcated with iron sheets to maintain soil stability and avoid leakage of runoff. They were calibrated prior to recording runoff and erosion. The plot size was determined by previous studies hence maintaining the size was important for comparison. A plot frame and a divisor were used to measure and collect runoff. Runoff was measured after every rainstorm and when the divisor was full. Runoff samples of known weight were picked in one-litre bottles from tank and taken for drying and weighing. The average sediment concentration in each sample was multiplied by the total weight of the runoff collected at that treatment to give soil erosion for a rainfall event. The plot calibration coefficient accounts for differences in runoff generation owing to the different inherent soil characteristics at the different locations. This was taken into account while calculating runoff. Only erosive rainfall measurements were measured and recorded, from the four rain gauges distributed in the study area. An average rainfall amount was calculated and used as the respective day's rainfall amount.

Digital contours were obtained from the Department of lands and survey which is mandated to collect and archive cadastral and topographic data in Uganda. The data was digitized by the respective

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department staff in 1996. It was digitized from topographic maps as a measure to improve data storage sharing and processing in Uganda.

4.1.3. Secondary data evaluation

FAO (1993), recommends a search of secondary sources prior to primary data collection. However while there are benefits of secondary data, there are considerable shortcomings too. Hence evaluation was relevant considering that some data used for this study were collected between 2001 and 2002. Annex 0.1 shows the decision path followed in evaluation while Table 4.1 shows specific steps undertaken by this study. Particular attention was paid to definitions used, measurement units, missing values and the time span of the secondary data. we undertook geo-referencing of all runoff plot locations of 2001 in 2007 again, comparing coordinates in a standard spatial reference system, edge matching of administrative boundaries and river data, comparison of digital contours with field observed elevation and comparison of soil parameter values in Bamutaze (2005) with laboratory tests of 2007.

Table 4-1: Evaluation of secondary data

Questions	Answer
Does the data help to meet any of the objectives	Yes
Does the data apply to study area?	Yes
Does the data cover the time period of interest	No
Are the definitions, data collection methods and systems of measurements known and acceptable (can the data be revised?)	Yes
Is it possible to consult the original data?	No
Does the value of information exceed the cost of its acquisition?	Yes
Is the risk of bias high?	Yes

All the soil erosion and rainfall data was relevant basing on its spatial location but the period of collection was different (2001-2002) hence factors such as landuse change were considered. Similarly the digital elevation contours were relevant but they were collected at a different time. Therefore an accuracy assessment based on observed values was conducted. The data format collection method and measurement units were known and scientific and they could be reviewed using spatial tools. The identified limitations included, missing soil erosion and rainfall data and also geology and landuse. However the dataset could be used together with primary data, and careful choice of processing and analysis methods so as to achieve the objectives.

4.2. Data procesing

This section is an amplification of the conceptual framework shown in Figure 1.2. It represents the first step in data treatment including the procedure followed in handling the data as shown in Figure

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4.4. The section includes: 1) preprocessing steps aimed at putting data in more convenient formats for integration and further processing; 2).

Step 1: Storm selection procedure

The observed daily rainfall from four rain gauges spread over the observed period (annex 0.5) was available. Unfortunately, not all the corresponding soil erosion data was available for this study. The available soil erosion data was for three rainfall events corresponding to the first quartile (9.6 mm), Median (13.5mm) and third quartile (23.4mm) of observed rainfall. Therefore these events which had corresponding soil erosion data for the 61 locations were used in this study to represent a low medium and high event respectively.

Step 2: Creation of the prediction grid

To clip out the area for prediction and decide on the prediction grid resolution a catchment area boundary and the runoff plots size (15 m X 10 m) were used. The catchment area boundary was extracted using ILWIS 3.3 hydrologic parameter extraction tools. After loading the catchment area boundary in ArcMap we identified the extreme North, South East and West coordinates. Using these coordinates the grid was constructed using the `expand.grid` method of R (Rossiter 2007). The grid resolution was set at 15 m to enhance comparison with the closed runoff plots whose length was 15m.

Step 3: Digital Elevation Model (DEM) creation

This study also investigated a relationship between soil erosion and hydrologic parameters. To get these factors a finer resolution DEM was required. The DEM was constructed from digital contours. The digital contour data used in this study represents a Digital Terrain Model (DTM); hence it was visualised as such and field data elevation collection considered this factor. Figure 4.2 shows the specific steps of the DTM creation. Figure 4.3 shows the general procedure of contour interval change

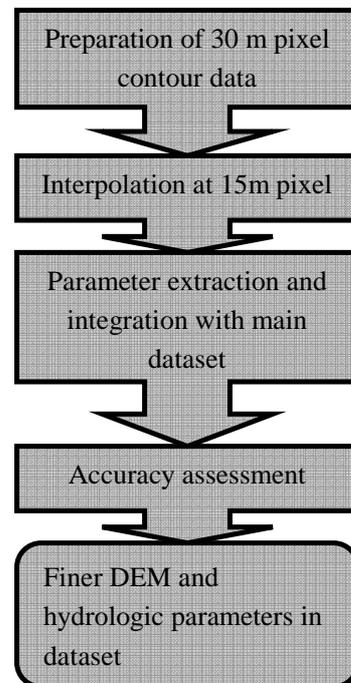


Figure 4-2: DEM construction

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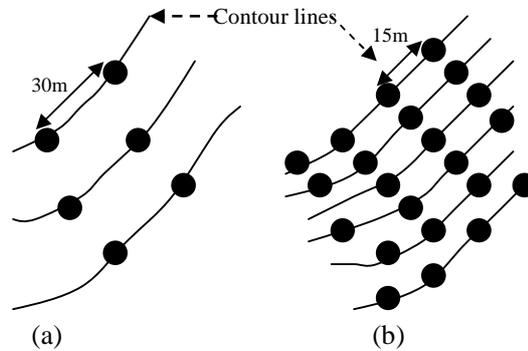


Figure 4-3: DEM construction from 30m contours (a) to 15m (b)

Preparation of data included the conversion of 30 m interval digital contours into 15 m interval, as shown in Figure 4.3. This ensured consistency with the runoff plots size. To visualise and interpolate using an appropriate geo-statistical model; the digital contour data was converted from polylines to points. The corresponding coordinates for the points were then retrieved. This procedure was undertaken using the spatial analyst function in ArcMap by: 1) conversion of line features to TIN; 2) conversion from TIN to points, 3) conversion from points to raster surface at 15 m pixel size using nearest neighbour algorithm. To extract elevation values at all coordinates, the constructed 15 m grid in Step 2 was used. The actual extraction was undertaken using the zonal statistics function in ArcMap. The elevation values were then joined with the coordinates of the interpolation grid. This enhanced visualisation, modelling and interpolation in the R project Graphic User Interface (GUI), since all the elevation values at this stage had their corresponding coordinates.

Step 4: Landuse/ landcover change detection

Given that some of the study data was collected in 2001 and the other part in 2007, it was vital to assess any changes which may affect the analysis undertaken in this study. This was investigated in two ways; first by interviewing farmers and observing at all previous plot locations if the general land use type had changed and if so to what. The other was to undertake a postclassification landcover change detection for the stated period. Due to the limitations of the available data, landuse change was not exhaustively achieved. This implies that the seasonal changes due to plant growth or periods between harvest and ploughing were not accounted for. However, the differences in landcover which are related to land use are accounted for. In order to classify, the Aster image of 28th August 2007 and the Landsat ETM+ image of February 2001 were georeferenced to the same spatial reference system and then resampled to a 15 m grid. This was because there was more information from Aster due to a finer pixel size than Landsat ETM+. Besides by resampling to a lower pixel size we reduced the mixed pixel problem of Land sat ETM+. Also this would enhance consistency with the other data at

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this resolution, such as the soil erosion data from the runoff plots. The images were radiometrically corrected for sun angle, haze and the atmospheric effect using the ATCOR extension in ERDAS IMAGINE 9.1. A random number was generated to represent each location sampled for landcover. Even numbers were used as training samples while odd numbers were used for accuracy assessment of the August 2007 Aster image. The geo-referenced landuse and landcover classes of 2001 were used for the training and accuracy assessment of the February 2001 Land sat ETM+ image. An accuracy assessment and a landcover/ landuse change detection were undertaken by the confusion matrix method in ERDAS IMAGINE 9.1.

Step 5: Pre processed parameter extraction and treatment

It is known that indices such as the Improved Soil Adjusted Vegetation Index (MSAVI) and the Optimized Soil-Adjusted Vegetation Index (OSAVI) can represent the bare soil. The Middle Infrared band is also a good indicator of bare surfaces because of its relatively high reflectance for soil. This study investigated the potential use of these indices in soil erosion prediction specifically as a way to reflect the potential for remote sensing in soil erosion modelling. The image band reflectance (NIR for R_{800} and Green for R_{670}) were extracted by zonal statistics and index computations were done in ArcMap. The calculations using equation 4.1 were undertaken using raster calculator tool while the extraction of the transformed values was undertaken using ArcMap zonal statistics function. A detailed correlation table of the different investigated parameters is in annex 0.7.

Improved Soil Adjusted Vegetation Index (MSAVI)	$MSAVI = \frac{1}{2} \left[2 \times R_{800} + 1 - \sqrt{(2 \times R_{800} + 1)^2 - 8 \times (R_{800} - R_{670})} \right]$	Qi et al. (1994)
Optimized Soil-Adjusted Vegetation Index (OSAVI)	$OSAVI = (1 + 0.16) \times (R_{800} - R_{670}) / (R_{800} + R_{670} + 0.16)$	Rondeaux et al. (1996)

Equation 4.1: Calculation of MSAVI and OSAVI indices

The major physical properties analyzed by the laboratory were soil texture (sand, silt and clay). The methods used for laboratory analyses were standard procedures from the Makerere University soil science laboratory.

The DEM was exported in TIFF format and then imported in ILWIS for extraction of all DEM hydrologic parameters using ILWIS 3.3. These included Elevation, Slope angle, flow accumulation, wetness index, stream power index and sediment transport index.

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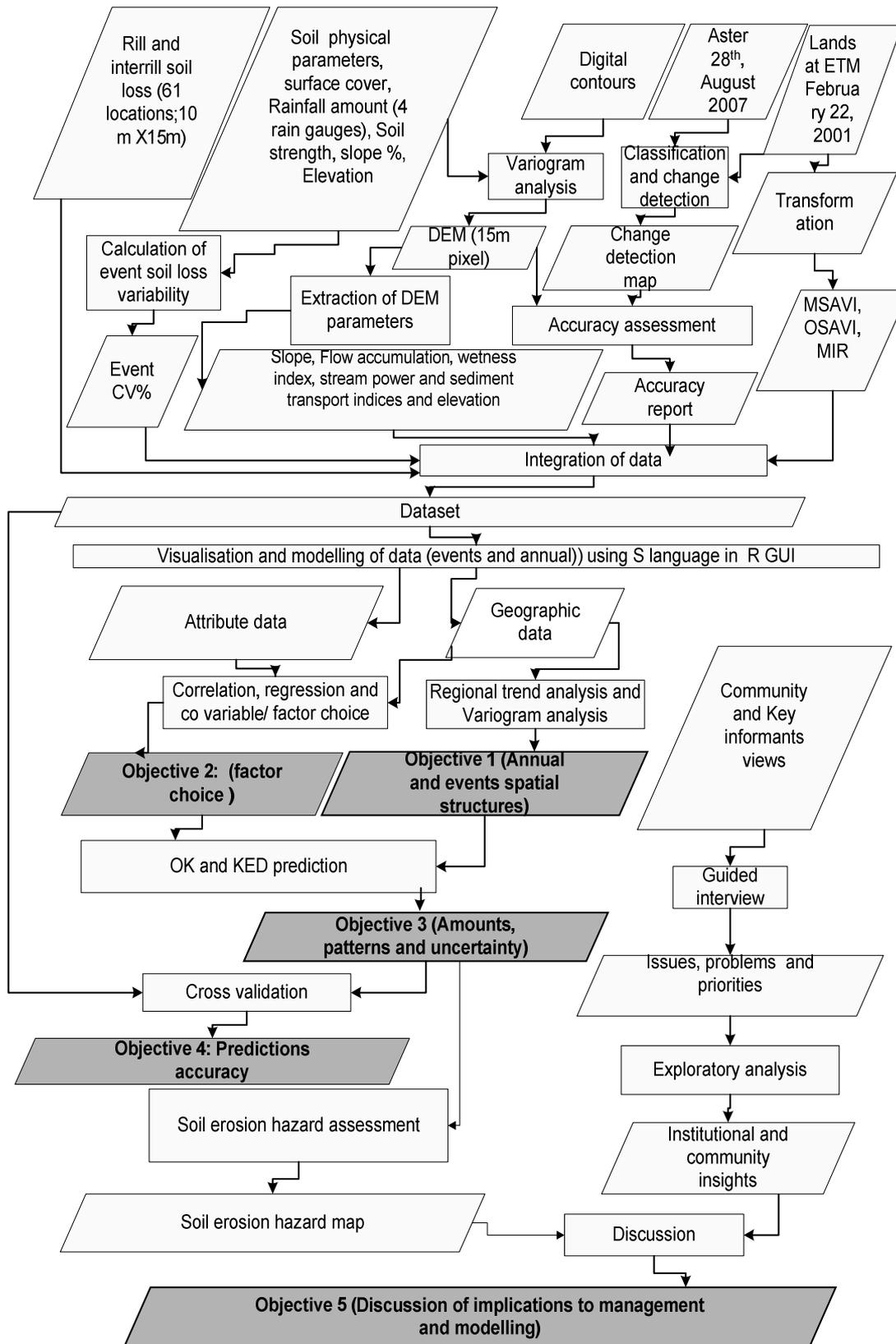


Figure 4-4: Flow chart showing detailed study procedure

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An average was calculated from the individual soil strength measurements for each plot location and the average value was used to represent the soil strength (against erodibility) at a plot location. The value reflects the soil resistance to particle detachment and subsequent transport. We used this measure instead of the erodibility (K) of RUSLE (Renard, 1997) because of its direct application to our study area. The K measures the inherent erodibility; it is a lumped parameter that represents an integrated average annual value of the soil profile surface reaction to a large number of erosion and hydrologic processes. For soils where the silt fraction does not exceed 70% an algebraic approximation of Wischmeier and Smith (1958) is recommended for computing K. However this K formula is based on soils in the US, which is why we chose to represent the soil erodibility by the observed soil strength. Soil erodibility was applied in two ways: 1) to get insights of the local soil erodibility and 2) to identify potential linear correlations between it and event soil erosion. This was vital for the application of KED. We could not use the RUSLE, LS factor for reasons similar to K factor. Instead we extracted slope angle from the constructed 15 m DEM and took its square root based on a similar slope power function (McCool et al. 1987; Renard, 1997). This was based on the fact that soil erosion is not linearly related to slope angle and also that in order to apply KED, the covariables must be linearised.

Erosion formulae are always based on potential erosion, which is then mitigated by cover and land management factors. For instance the RUSLE calculates potential erosion by multiplying the rainfall erosivity R (the driver) by the soil erodibility K (the strength). $R \cdot K$ gives the erosion in ton/ha/year. However given that we were not applying RUSLE but benefiting from the established physical relationships, we applied landcover directly in identifying and prediction of soil erosion. Therefore in this study we visualise the effect of cropping and management practices on erosion rates as observed differences in surface cover. While this approach does not represent the dynamic landuse changes it caters for the snapshot/steady state condition of particular landcover. Therefore 1-landcover is estimated and used. It is a simplistic perspective but it gave insights on community efforts in land management which could increase or reduce erosion hazard (the respective observed single storm soil erosion) and risk to humans, infrastructure or crop security at a particular instance.

Step 6: Data integration

This procedure preceded actual processing and analysis. Table 4.2 shows the complete list of data for this study. It was organised in an Excel spreadsheet before being exported to a database and CSV formats. The software applied in this study includes ArcGIS 9.2, ERDAS IMAGINE 9.1 ILWIS 3.3, S programming in R Graphic User Interface (R GUI), MS. Word and Excel. (Some scripts in annex 0.6).

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Table 4-2: Input data

Data name	Parameters	Time of data capture	Sampled locations
Soil properties (0-15cm&15-30cm)	Physical parameters of soil [leave out chemical, you are not using it anyway]	September 2007	61
Event soil erosion and runoff	Event Soil erosion and runoff in Tons/Ha/Yr	May 2001-May 2002	61
Landcover	Surface and canopy cover	September 2007	61
DEM hydrologic parameters	Slope %, square root of slope, elevation, Flow accumulation, wetness, stream power and sediment transport indices	September 2007	61
Soil strength	Soil strength in Kg/m ²	September 2007	61
Soil Erodibility	Soil Erodibility	September 2007	61
Classified images 2001& 2007	Medium infra Red reflectance, OSAVI and MSAVI indices, Land cover change (2001-2007)	September 2007	61
Rainfall amount	Daily event rainfall amount and averages in mm	May 2001-May 2002	119
Erosion observations	Notes on rills, gulley and conservation	September 2007	
Key informants and community views	Stakeholder problems, opinions, current projects and current development issues	September 2007	20

Step7: Nature and scope of the modelling approach

The modeling approach uses sampled soil erosion spatial patterns and landscape factors to predict event soil erosion on the entire grid using a stochastic method (Figures 4.4). The spatial structure is modeled from the observed patterns while the secondary variables are chosen based on the strength of the linear relationship with event soil loss as well as the structure of their residuals. The approach, hence, has the double advantage of deductive and inductive modeling approaches (Overmars et al., 2007). Specifically because we predicted soil erosion from both patterns (deductive) and also the causative factors such as soil erodibility, square root of slope and landcover (inductive). The landuse effect is indirectly represented by the soil erodibility and landcover factors. We attempted to understand and to quantify the large unexplained variability in soil erosion data so as to advance erosion modelling and improve prediction of low events. This was undertaken by considering 1) spatial autocorrelation and data variability as primary factors in modelling and prediction; 2) ensuring independent spatial autocorrelation models for different event sizes and 3) ensuring the capability of the modelling approach to predict both random/unexplained and explainable soil loss.

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Based on Kyriakidis et al. (1999), we visualised each event soil erosion variability as an independent hypothetical space which could be added together to achieve a longer period prediction. This was partly due to a relatively lower density of data in time than in space. In addition, a numeric integration of time to assume equal time steps of a day was used to simplify modeling. This is due to the highly variable durations of rainfall events. Figure 4.4 shows the details of undertaken steps.

To use this modeling approach for predicting annual total soil erosion requires categorization of the event as low medium or high; followed by the selection of an appropriate model of spatial autocorrelation and then predicting event soil erosion. Then the annual soil loss is calculated by summing up the product of the number of respective events and predicted soil loss at the event category.

It was not possible to model the thresholds for the spatial structure change with the sparse available data. Therefore annual average soil loss was modeled and predicted based on observed total annual soil erosion. Similarly we faced limitations to model and predict landuse change dynamics which may cause peaks in soil erosion during transitions in cover. For this study land use effect on soil erosion was visualized in terms of landcover and soil erodibility attributed to specific land management. The data could also not enable representing the seasonal dynamic effect of vegetation and crops to rainfall interception and infiltration rates. This is characteristic of normal temporal growth and subsequent change in vegetation density, surface cover and root depth but we did not capture it in totality. However among the factors which are implied in the observed soil erosion and also catered for in this model are: 1) variable management such as surface cover differences, 2) creation of runoff barriers by farmers 3) event based change in the soil properties and relative ability of runoff to cross barriers due to the event size and intensity.

We applied a multivariate stochastic prediction which incorporates the spatial structure with secondary variables. The data was visualized in R GUI with different extensions such as gstat, MASS, lattice and sp in order to enhance appropriate data exploration, analysis and graphic display (Rossiter, 2007). The scripting was done in S programming language (annex 0.6).

Both regional and local spatial dependence were visualized. Local spatial dependence models (variograms) were used to define the event spatial structures and also to predict soil erosion. A factor analysis based on the adjusted R squared and residual variogram plot was used to choose or drop factors for use as secondary predictors in KED. Validation was done by the Root Mean Square Error (RMSE), and comparison of the residual post plots.

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Step 8: Choice of an interpolation method

We chose Ordinary Kriging (OK) and Kriging with External Drift (KED) because the former can model pure spatially-autocorrelated variability while the latter can enhance prediction results by using secondary variables as linear feature-space predictors and residual spatial autocorrelation. The latter also provides clues to the underlying causes of the variability.

Alternatively we could have used Kriging with Strata (KS) on the assumption that the strata reflect all or most of the heterogeneity in the study area. The main problem with KS is that a variogram model is needed for each stratum which is not feasible with so few sample points. Cokriging is another alternative to KED but it requires a simultaneous spatial covariance model of both variables and the spatial cross-correlation. However Goovaerts (1999), found that KED can provide slightly better results than the more sophisticated coKriging yet it does not require a sophisticated model.

4.2.1. Ordinary Kriging and External Drift Kriging

OK assumes that the modelled process is caused by a random spatially correlated process and also that the random process has a constant mean and variance (second order stationarity). It has the advantage of modelling and predicting unexplained/random variability in the process by use of an empirical variogram.

KED models also the mean as a function of secondary data but this function is linear and its coefficients are estimated from the dataset itself. Consequently, KED was thought to be more suitable for this study. Besides KED has several favourable properties which could benefit this study, namely; it can handle n -dimensional problems it does not depend on a predefined regression model and it is able to represent complex and non-linear behaviour expected in spatial temporal processes such as soil erosion. KED assumes a non stationary random mean (first-order non-stationarity) and this is used to model along with the trend. For details about this approach see Carrera-Hernandez and Gaskin (2007). Both OK and KED were applied in this study.

4.2.2. Trend surfaces and Universal Kriging

Prior to application of the above prediction algorithms, the regional dependence of observed total annual and event soil erosion were investigated using trend surface analyses. This was to assess the possibility for using them in predicting and comparison of the predicted patterns. We visualized the regional spatial dependence by calculating the 1st, 2nd and 3rd degree trend surfaces. These trend surfaces were expected to represent the regional effect of topography broad land use types and even soil types on soil erosion. A third order trend surface was applied together with its residual spatial

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structure to predict the DEM. This was done by using Universal kriging. Local spatial dependence in the trend-surface residuals was examined by variogram analysis.

4.2.3. Modeling and prediction of the hillslope soil erosion spatial structure

The fitting of a variogram (curve) is an important step in the variogram analysis. We fitted the variogram iteratively attempting different combinations of cut off (Visualised/modeled distance in space) and bin sizes (width of the bin in Km) before fitting. The fitting was done by the `fit.variogram` method of `gstat`. Details of `gstat` computational methods can be seen in several publications (Goovaerts, 1999; Pebesma, 2004; Wang et al., 2001 ; Wang et al., 2002). Different event spatial autocorrelation model structures were computed for the whole explained range. Three spatial structures corresponding to the soil erosion at low, medium and high rainfall events were modeled and fitted. In addition one annual model corresponding to the observed total annual soil erosion was modeled and fitted. The variograms were used to represent respective spatial structures.

Prediction of the soil erosion was undertaken by OK, and KED. Amounts patterns and uncertainties were predicted for the whole area using OK and only at selected points for KED. The selection of predicted points for KED depended on the landscape factors' data availability. Gaussian conditional simulations were only applied on a part of the study area (615000 to 625000E, 131000 to 140000N) due to its computational demand on the computer system.

4.3. Data analysis

The analysis attempted firstly to define the soil erosion spatial structure at different event sizes, basing on their spatial autocorrelation. Secondly to relate spatial autocorrelation with the soil erosion variability expressed as the Coefficient of Variation (CV %). Thirdly to find if there is any evidence suggesting a change in the soil erosion spatial structure as rainfall increases. We also investigated means to choose from the available data, a combination of soil, topography and landuse factors which explains the largest amount of the variability in the observed soil erosion (sediment production).

The soil erosion data were fitted with different types of models on the basis of the shape which best fits it and also one which best describes the physical process. The spatial structures were defined by the shape of the fitted local spatial dependence models and the parameters (sill, nugget, range and explained variability). The comparison of the event spatial autocorrelation structures considered both the shape and model parameters. All comparison were computed on the same scale and also positioned side by side. In addition the percentage of the event Coefficient of Variation (CV%) was computed in Excel and then compared with the explained variability of respective spatial

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autocorrelation models. We compared the explained variability by the spatial autocorrelation model and the CV%.

To choose secondary factors for KED, the multivariate stepwise regression at 95% confidence interval, using the `step` method in R (Rossiter 2007) was applied. This procedure was selected because the least significant factor is dropped at each iteration. The combinations of factors which have the best linear relationship with soil erosion, as assessed by adjusted R^2 , and also a residual covariance structure which can be modelled were used to predict soil erosion using KED. Prediction by OK and KED yielded amounts, patterns and uncertainties and these were compared.

The predictions were computed at the same scale and displayed side by side to enable a qualitative comparison of the predicted soil erosion at different event sizes. Amounts, patterns and uncertainties were compared. The comparisons were done twice; first to compare differences in patterns and uncertainty at different event soil erosion predicted by the respective spatial structures and secondly to compare the ability to reproduce observed variability when we predict by the spatial structure alone (OK) and in combination with landscape factors (KED)

Owing to the difficulties of the runoff plots data to provide a total picture of the hill slope sediment production what we assessed is the potential hillslope sediment production. As such besides providing the sum of the kriged map of total annual and event soil erosion figures in Tons we categorized the predicted soil erosion map to provide a more reasonable picture of the hazard. This was to provide insights of the state of soil erosion in the study area. The categories used are: 0-5 no erosion, 5-10 slight, 10 -25 moderate, 25-50 severe, and > 50 very severe according to Bamutaze (2005). As the erosion hazard may imply high vulnerability of the community to related problems such as soil nutrient loss soil fertility decline in crop yields and subsequently low incomes and low welfare situations, this was to give a better picture in view of the locations which need intervention.

Gaussian conditional simulations were used to provide four potential patterns representing possible scenarios of soil erosion patterns in part of the study area. The simulations provide possible inputs in a model which applies hill slope erosion as an input and they can also be used to guide slightly different interventions in the soil erosion problem. Lastly the similarity in the simulation patterns gives insights of the robustness of the model used in the kriging interpolation.

The community interviews were used to provide insights on the vulnerability of the community to the erosion hazard, precisely to identify the different ways in which they may be vulnerable. The problems which are related to the erosion hazard and which the community faces were identified

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listed and prioritised with their help. The rest of the analysis was undertaken by exploratory statistics because the data was nominal. The institutional interviews focused on the institutional activities which are related to soil erosion, identification of the respective institutions as well as their problems and opinions in solving the erosion hazard within the watershed. The analysis attempted to respond to the spatial information issues raised such as packaging of soil erosion information to enhance institutional interventions.

Considering that there was a risk of error owing to the different time periods of data collection (2001/2002 and 2007) we investigated the possibilities of a landuse change by landuse change detection with specific consideration to the locations where data was compared. Similarly we undertook analysis for the possible effect of the spatial variability of rainfall on the soil erosion spatial structure. We investigated the potential effect of the spatial variability of rainfall on the soil erosion spatial structure by performing an Analysis of Variance (ANOVA) test between the four daily rain gauge values. The value was used to interpret significance of difference between the daily rainfall amounts. We also used ANOVA to test the landscape model's significance for use in KED.

Validation was undertaken by using the leave-one-out cross-validation (LOOCV). In LOOCV, the observed value is left out, because kriging is an exact predictor at known points, and so would predict the value itself, if that point were included. The the gstat package supplies a `krige.cv` for this purpose (Rossiter, 2007). We computed the Root Mean Square Error (RMSE) as well as the relationships between RMSE and the Standard deviation and the interquartile range. Another measure of model quality which we used is the Mean Squared Deviation Ratio (MSDR) of residuals with kriging variance (Equation 4.2)

$$\text{MSDR} = \frac{1}{n} \sum_{i=1}^n \frac{\{z(\mathbf{x}_i) - \hat{z}(\mathbf{x}_i)\}^2}{\hat{\sigma}^2(\mathbf{x}_i)}$$

Equation 4.2: MSDR

The kriging variance at cross validation point x_i , obtained during the kriging procedure (not the cross-validation) is used.

The MSDR is a measure of the variability of the cross-validation versus the variability of the sample set. This ratio should be 1. If it's higher, the kriging prediction was too optimistic about the variability.

We based on the results (amounts patterns and uncertainty) and the community and key informants' views opinions and problems to discuss the implications of the study to general hillslope sediment production and land management in Wanale watershed.

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5. RESULTS AND INTERPRETATION

5.1. Modelling and prediction with the event spatial structure only

This study is an attempt to improve the spatial prediction quality of the hillslope soil erosion at a single rainfall event by using stochastic predictions based on the spatial structure. To achieve this we investigated the relative influence of rainfall amount on the hillslope soil erosion spatial structure so as to define the spatial structures and also apply them in the prediction. The investigation is based on the principle of spatial autocorrelation; the value at any one point in space is dependent on values at the surrounding points. Positive spatial correlation means that similar values tend to be near each other. Considering that spatial autocorrelation can be shown regionally and or locally, we investigated both the regional and local spatial dependence in sediment production.

5.1.1. Modelling the regional spatial dependence

Table 5.1 shows that the soil erosion at different rainfall sizes demonstrates a very weak 1st degree trend at 6.93°. The 2nd, degree adjusted R² for the total annual erosion improved but the 3rd, degree trend surface did not improve for both annual and event erosion. Generally the regional trend is weak for both events and total annual erosion. The weak trends imply that the soil erosion in Wanale watershed demonstrates weak regional dependence and hence a weak regional spatial structure. This might implies a lower influence of regional landscape factors to the process. As such the local spatial dependence was investigated.

Table 5-1: Comparison of 1st, 2nd and 3rd degree trend surfaces for event and total annual soil erosion

Trend surface degree	First degree R²	Second degree R²	Third degree R²
Annual	0.34	0.44	0.44
High	0.34	0.23	0.23
Medium	0.34	0.27	0.27
Low	0.34	0.31	0.31
Direction	6.93	N/A	N/A

5.1.2. Modelling the local spatial dependence

Figure 5.1 shows the event spatial autocorrelation models. The event spatial structures are at the same scale. The total annual spatial autocorrelation structure (Figure 5.2) is at a different scale and different bins were used in its fitting. As such it is not directly compared with the event structures. The individual spatial structures including the total annual model are attached to this report as annex 0.12.

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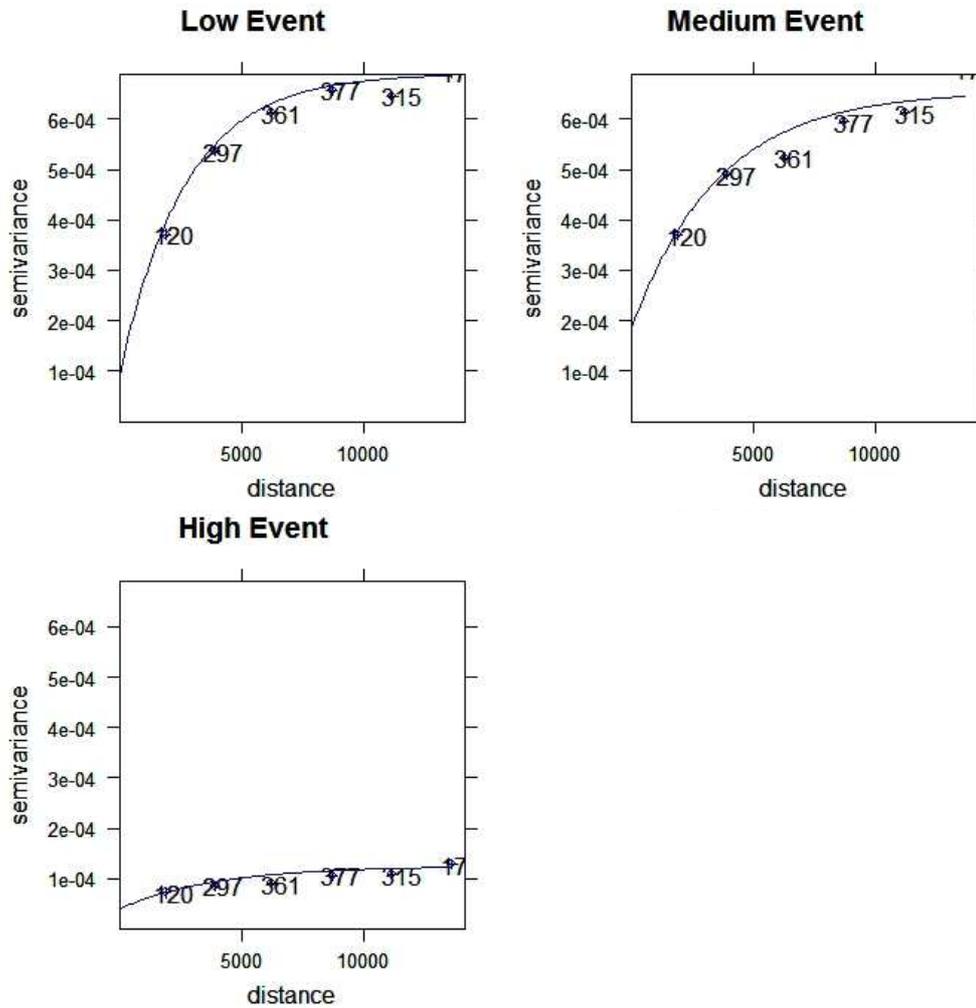


Figure 5-1: Comparison of event soil erosion spatial autocorrelation models

It is clear from Figure 5.1 that in all cases the semivariances reduce as the separation distance also reduces, implying that there is evidence of local spatial dependence in all modelled structures and hence they all demonstrate spatial autocorrelation.

Different model structures such as circular, Spherical, Gaussian and Exponential were fitted to all soil erosion categories manually and automatically prior to choice of the best fitting model. Therefore the exponential model fitted all the event soil erosion spatial structures.

The parameters (Range, sill and nugget) of the exponential structures for the event soil erosion may be attributed to the relative influence of local factors to event soil erosion. The local influence such as differences in soil erodibility characteristics leads to higher semivariances within shorter separation distances. The influence of local soil erodibility characteristics is expected to diminish as event size

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increases leading to smaller semivariances at longer separation distances between point pairs. This factor may be responsible for the steeper exponential model for the low event and a gentler exponential model for the high event. Table 5.2 also shows that the range of spatial dependence is higher as the event size increases and also that the sill as well as the explained variability (Spatial autocorrelation) are inversely related to the event size. The model parameters for different event soil erosion categories are different and this is also confirmed by Figure 5.1 which demonstrates differences in the shapes of the different fitted models for the respective event sizes. The differences confirm that the soil erosion spatial structure changes. It is also clear that as event size increases the spatial autocorrelation structure tends to a nugget model. This may have implications to modelling of high and extreme events.

The spherical model was fitted to the annual soil erosion at 1 km and 2.5 Km bin sizes. While a similar good fit was observed at the two bin sizes (1 Km and 2.5 Km) and while that is a sign that the spherical model is reliable, the zero nugget at 2.5 Km is unlikely to be true. Similarly an exponential model and a Gaussian model were dropped on account of a zero nugget and the fact that soil erosion is expected to vary closer to the nugget respectively. Zero nugget implies that 100% of the variability is explained at a point. However we observed some rill formations which imply that the models are unlikely to explain the total soil erosion. The 1 km bin size spherical model is shown in Figure 5.2. The small nugget may be the effect of averaging or the spatial separation of data points in the dataset which was large. With no close-spaced point pairs, estimating the nugget is difficult but the nugget value at 1Km bins was more acceptable, as compared to the zero nugget at the 2.5 Km bins basing on the field observations. The longer range of the total annual spatial autocorrelation structure may be due to the relatively higher regional effect as see in table 5.1 while the high sill is attributed to the larger data variability.

Table 5.2 shows a lower sill and longer range as rainfall event size increases implying that rainfall amount may affect both the data variability and spatial autocorrelation in soil erosion. The rainfall effect on the spatial autocorrelation can be seen in Figure 5.1 while its effect on the data variability is shown in Table 5.2. Therefore there may not be a single or definitive soil erosion spatial structure; but rather the possibility that different spatial structures define different event size soil erosion. The fact that the model explained variability (Spatial autocorrelation) is higher when the data variability (CV %) is also high may be because the explained variability by a spatial autocorrelation model is partly dependent on the differences in the data variability. This relationship may imply relative ease to model and predict highly variable data such as low rainfall event soil erosion by stochastic means.

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Table 5-2: Comparison of soil erosion data variability and autocorrelation model parameters

Parameter	Soil loss type			
	Annual	High event	Medium event	Low event
Sill	958.87	0.000085	0.000470	0.0006
Range (metres)	6883.23	3900	3550	2700
Nugget	37.80	0.00004	0.00020	0.00090
Model	Spherical	Exponential	Exponential	Exponential
Spatial autocorrelation	96%	68%	72%	87%
CV%	19.30	2.20	10.10	18.97

The inverse relationship between spatial autocorrelation and CV% may be explained in different ways. Firstly spatial correlation is different from uniformity. If data is uniform then there is no variability and perfect, albeit meaningless autocorrelation. Slight random deviations from uniformity then immediately lead to no autocorrelation (pure nugget variograms). This may also partly explain the relative difficulty to fit the high event model. The other possible explanation is that the low intensity events have low amounts of runoff that is strongly influenced by plot characteristics such as infiltration rate, surface roughness, vegetation, soil strength among others. So there is a larger variation which brings out the spatial autocorrelation better. Large events simply generate "a lot of runoff" everywhere which is less influenced by the environmental factors. Normally there would be more autocorrelation because large events cause more "connectivity" that means water flows from the divide all the way to the stream, so an accumulating effect occurs and autocorrelation may be present because of that (relation to stream network and topography). However these are distant closed runoff plots so the accumulation effect is unlikely, only local effects that are "drowned" because of the amount of water. Moreover, whether or not there may be an autocorrelation structure in a cumulative stream network can not be answered by this study, but the fact that both the runoff plot sizes and the minimum separation distance between them are large implies possibilities of capturing the real world situation by this modeling approach. In the 10 x15 m plots, processes such as rill erosion will be captured to a certain degree, but more severe erosion features such as gullies were not be part of the dataset. These circumstances are further discussed with the nugget effect on the soil erosion predictions and the model accuracy in chapter six.

5.1.3. The effect of rainfall spatial variability on the soil erosion spatial structure

Considering that variable rainfall amounts were received at different plot locations this, may result into different soil erosion values which can be mistakenly modelled and identified as the respective event spatial structures it is paramount to investigate this effect. The daily rainfall amounts were compared using ANOVA at the 95% probability level. The calculated F statistic was lower than the tabulated F (see Table 5.3). Therefore the differences between the mean daily rainfall for the four rain

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gauge values are not significant. This implies that based on the available data the spatial variability of rainfall is not significant in the study area (see Annex 0.5 and 0.8 for the data).

Table 5-3: ANOVA for four daily rain gauge measurements between May 2001 and May 2002

ANOVA					
SUMMARY	RG1	RG2	RG3	RG4	Total
Count	116	116	116	116	
Average	16.3	16.4	16.3	16.8	
Variance	88.7	94.5	83.2	94.3	
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>F crit</i>
Columns	17.0	4.0	4.3	0.01	2.4
Within	50320.6	575.0	87.5		
Total	50337.6	579.0			

5.1.4. Soil loss Prediction by the event spatial structure and comparison of patterns

This study aimed at applying the modelled and defined spatial structures to predict soil erosion amounts patterns and uncertainty. In Figure 5.3 amounts patterns and uncertainty are displayed at the same scale. The observed soil erosion is also overlayed in the brown circles to enhance comparison of the predictions with observations at the respective location. It is generally expected that larger circles should correspond with higher predictions on the prediction scale and vice versa. Despite slight over and under predictions, in most cases the observed variability was reproduced well even in the low event prediction. The better performance for the small event may be attributed to the better model fit. It is also clear that the scaled values of the low medium and high event soil erosion patterns and uncertainties are different for each event. This is a visual confirmation that the event soil erosion spatial structure changes. Low event soil erosion is more variable than the high event as expected. Additionally, the uncertainties are higher for the high event soil erosion and also for all positions where the predictions are higher or unobserved locations. However if the predicted values have corresponding high uncertainty and vice versa then the level of confidence in the predictions is also higher especially closer to the observed locations. The goodness of fit to show the model performance is shown in Figure 5.11 and annex 0.11

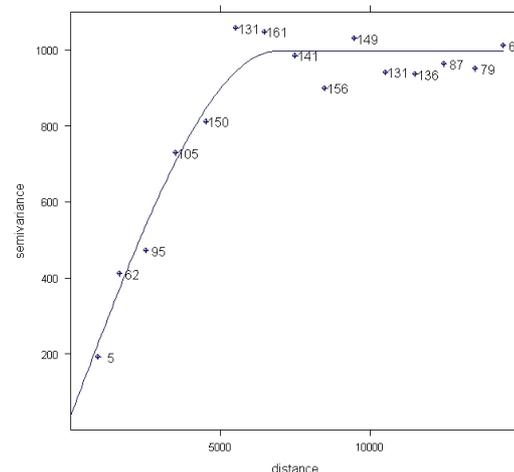


Figure 5-2: The total annual soil erosion spatial autocorrelation model

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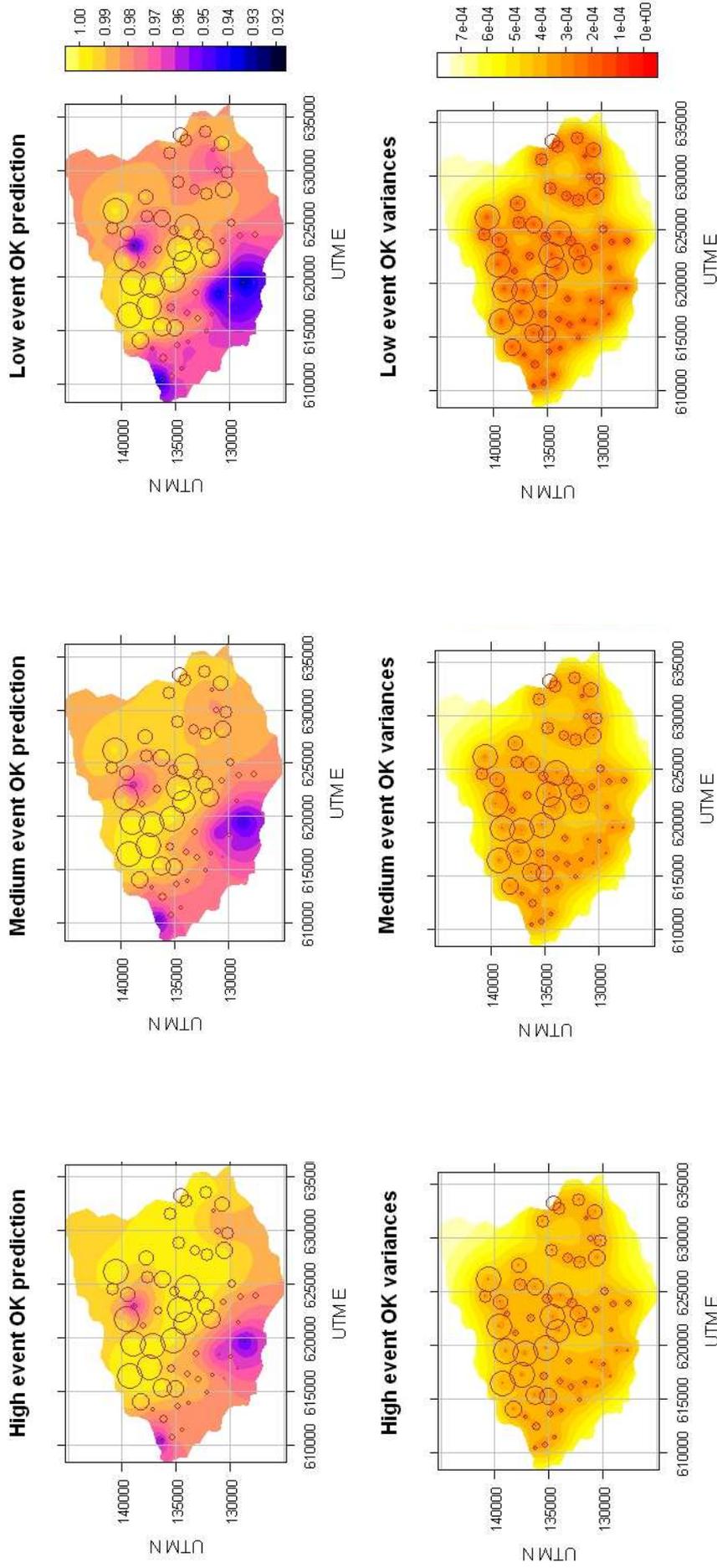


Figure 5-3: Comparison of spatial structure event soil erosion predictions (patterns amounts and uncertainty): Observations post plotted (Ton/Ha/yr)

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5.2. Modelling and Prediction with the structures and landscape factors

Since this study is an attempt to improve the spatial prediction quality of event soil erosion we also investigated possibilities for inclusion of secondary factors in stochastic prediction of soil erosion. Application of secondary factors in soil erosion prediction requires modelling of the drift which is provided by one or more secondary factors and a residual spatial structure. The residual spatial structure accounts for the unexplained variability while the drift accounts for the explained variability.

Among the investigated independent variables are image reflectances, observed landscape factors such as land cover, soil strength (erodibility) and DEM hydrologic parameters (see Figures 5.4). The Factors which showed very weak linear correlations and or absence of the residual spatial structure were dropped while the others were included in further tests as seen below. The full list of investigated parameters is annexed to this report (See annex 0.7). There is some positive but weak relationship between elevation and slope angle (see annex 0.2). Therefore higher areas are also expected to face some more soil erosion than lower ones.

5.2.1. Exploration of presumed soil erosion factors

In general Figure 5.4 shows that the Eastern part of the study area is higher than the West. The highest part of the study area is in the southeast closer to the Mount Elgon National park. This area is also composed of steeper slopes (annex 0.2). The adjusted R^2 of the predicted and observed elevation is over 0.9 (see annex 0.10). From the DEM several hydrologic parameters were extracted namely Slope, Wetness index, Stream Power index and Stream Sediment transport index (computations are shown in ILWIS 3.3). All the parameters were related with event and total annual soil erosion and the results

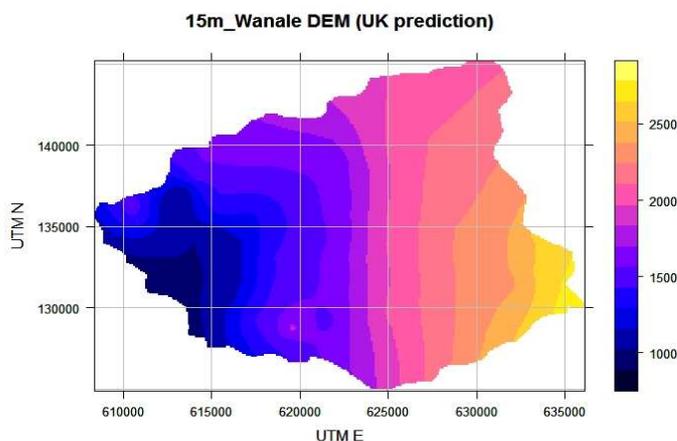


Figure 5-4: A 15 m resolution Digital Elevation Model (DEM) in meters A.S.L.

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It was important to explore a landuse change between the periods of data collection and to investigate relationships between soil erosion with both landuse and surface cover (Annex 0.9). The landuse change was investigated by postclassification landuse change detection between 2001 and 2007 (See Figures 5.5 to 5.7). This enhanced responding to questions such as if the land use type and or crops changed in all plots and to relate the landcover at the 2007 fieldwork with the landcover in 2001. This was important with certain results which may correlate better than with others such as surface cover percentage which may correlate better than others due to various factors such as variations at different crop seasons.

Figure 5.7 shows the postclassification landcover change detection for the period between 2001 and 2007. Classification accuracies of 89% and 91% for Landsat ETM+ and Aster image were achieved respectively, albeit with a quite small sample size (See table 5.4). Table 5.5 shows that in 30% of the area, the landcover did not change including at all plot locations; 52% of the area remained under agriculture but changed to another land use type such as from annual to perennial; 18% of the study area changed to built up area. However while the broad land use did not change the crop types and seasonal vegetation density changed. We have reason to believe that the change map is accurate given the high level of accuracy and a small difference in the classification accuracies. Two reasons were given by the interviewed farmers for the same land use type at the plot locations. Firstly they expected a project to be set up following the 2001 study; hence they maintained the plot cover and land use. Secondly, due to the land shortage it is unusual to change use of land from agriculture to others types. Therefore the landuse changes, specifically at the studied plot locations may not be significant for the time period between 2001 and 2007. This means that the analysis of the respective factors collected in the two different periods is valid.

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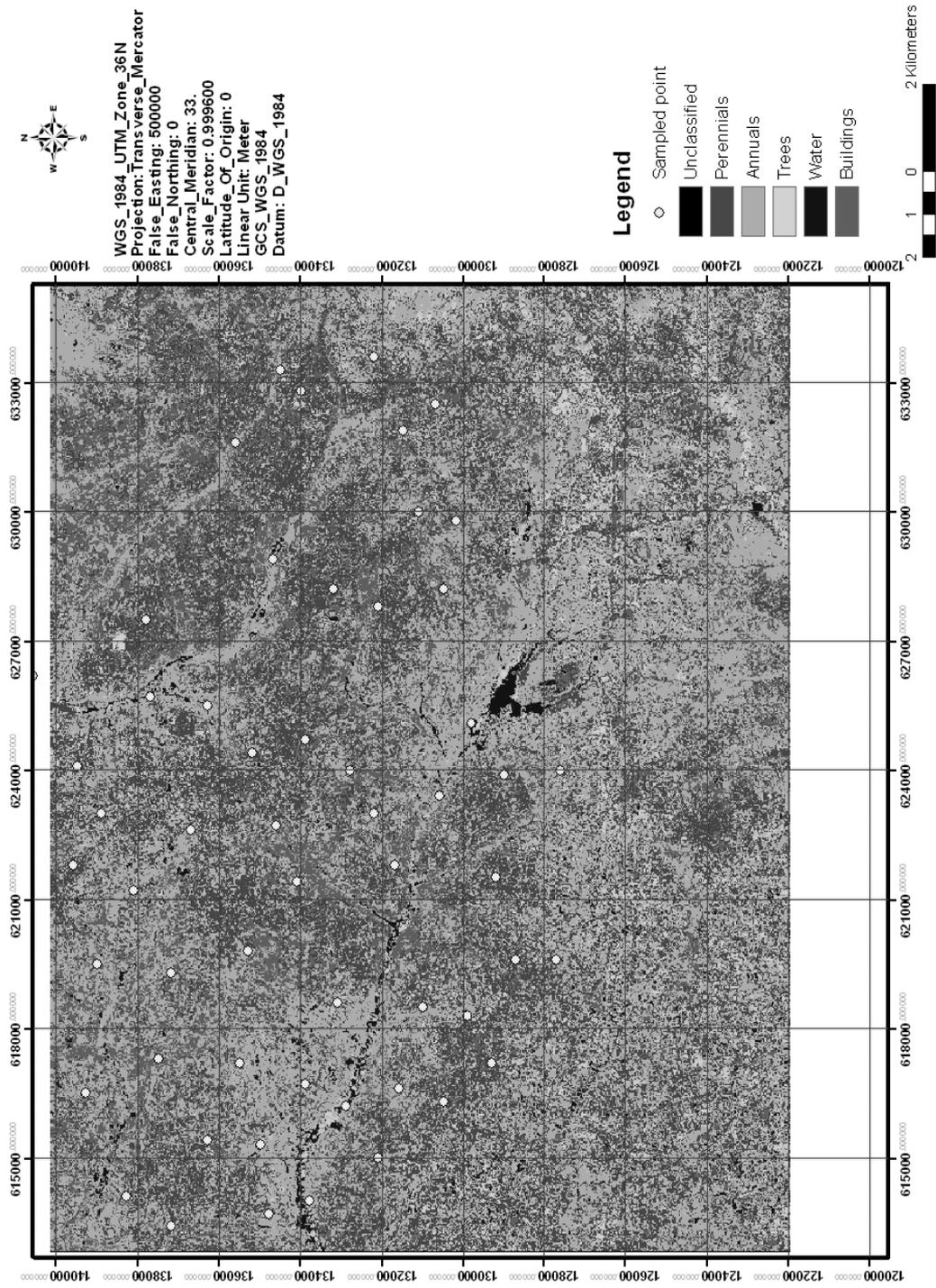


Figure 5-5: Land use/ land cover classification result for February 2001 (Land sat ETM+ image)

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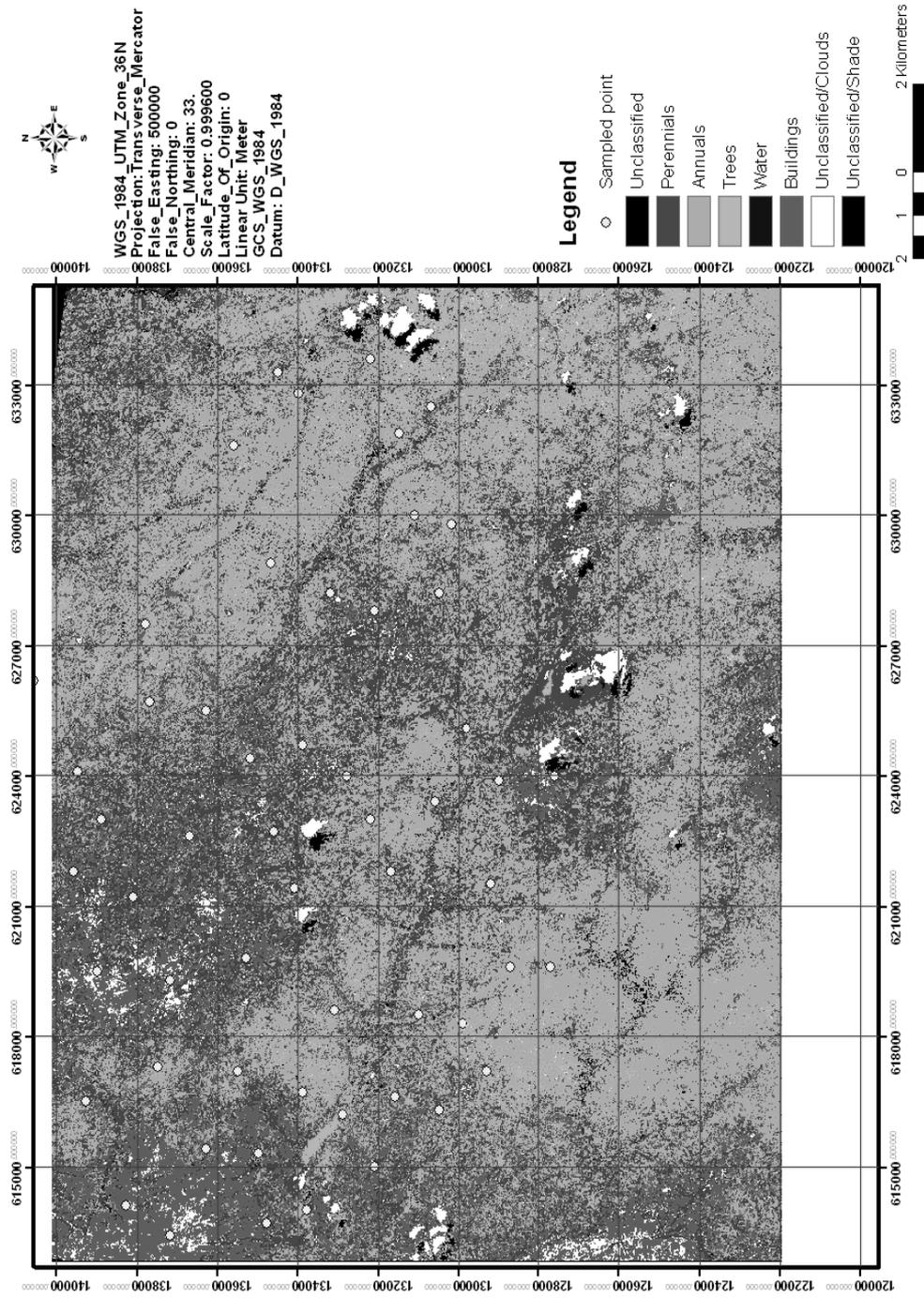


Figure 5-6: Land use/land cover classification result for August 2007 (Aster image)

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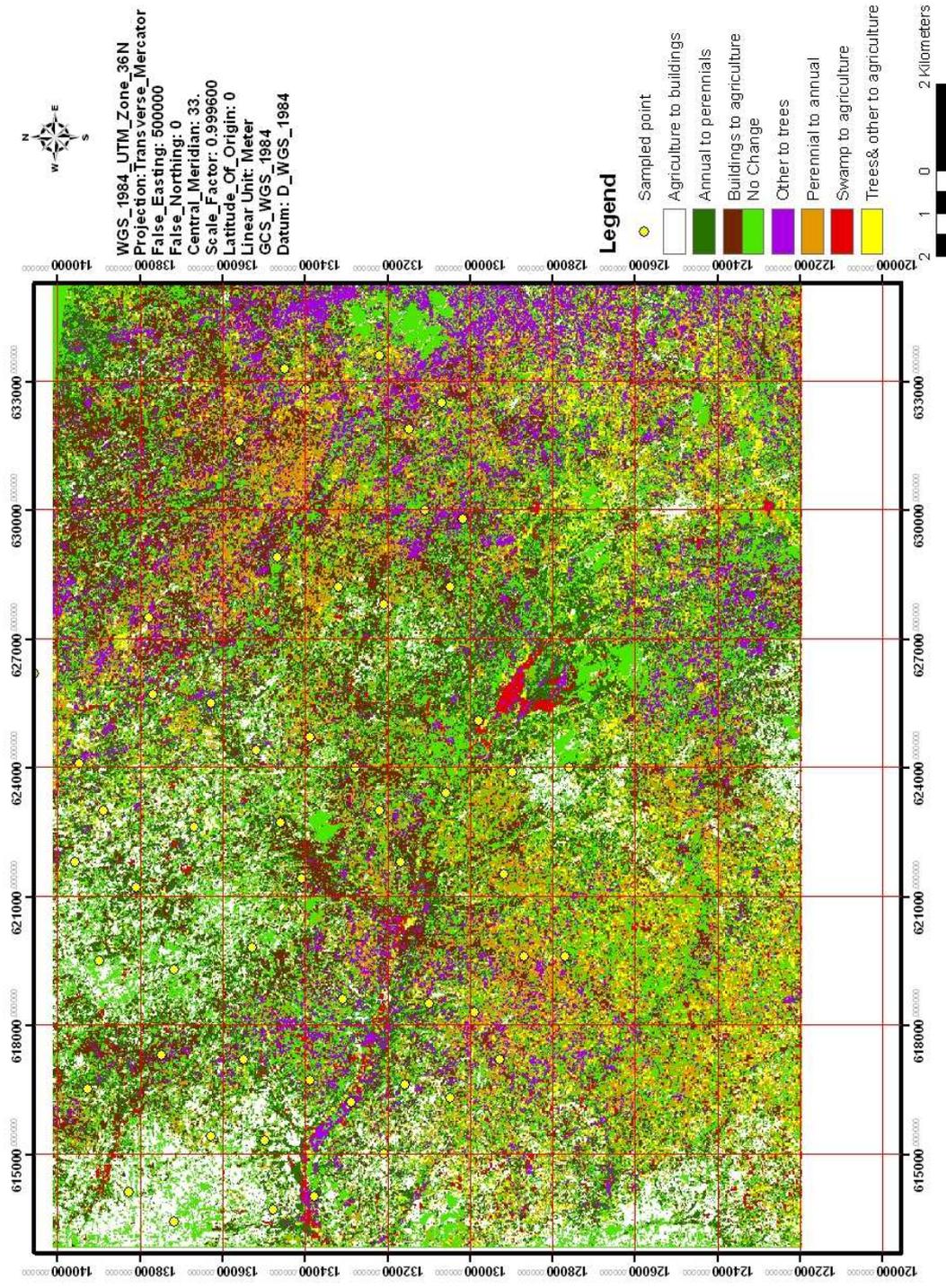


Figure 5-7: Land use change detection map 2001-2007

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Table 5-4: Post classification accuracy assessments

Image File : feb2001coverclasses.img					
Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
Perennials	5	5	5	75.00%	100.00%
Annuals	4	3	3	100.00%	100.00%
Eucalyptus	4	4	4	100.00%	100.00%
Water	2	2	2	100.00%	100.00%
Buildings	2	2	2	100.00%	100.00%
Clouds	4	3	3	75.00%	100.00%
Shade	2	3	2	100.00%	66.67%
Totals	23	23	21		
Overall Classification Accuracy = 91.30%					
Image File : feb2001coverclasses.img					
Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy
Perennials	4	4	3	75.00%	75.00%
Annuals	5	5	5	100.00%	100.00%
Eucalyptus	2	3	2	100.00%	66.67%
Water	2	2	2	100.00%	100.00%
Buildings	5	4	4	80.00%	100.00%
Totals	18	18	16		
Overall Classification Accuracy = 88.89%					

The similarity in the land use types between 2001 and 2007 enabled us to investigate several relationships between data collected at the two time periods. This enhanced the choice for landscape factors for inclusion in stochastic prediction of soil loss.

Table 5-5: Landuse/ landcover change detection between 2001 and 2007

CLASS_NAME	Hectares	%
Agriculture to buildings	2520	18
Annual to perennials	1757	13
Buildings to agriculture	2656	19
No Change	4096	30
Other to trees	1112	8
Perennial to annual	1104	8
Swamp reclamation for agriculture	153	1
Trees to agriculture	312	2
Summary		
No change	4096	30
Change to studied landuse (agriculture)	7095	52
Change to buildings	2520	18

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5.2.2. Modelling and choice of landscape factors

Having ascertained that no major changes in landuse occurred at the plot locations between 2001 and 2007 we investigated relationships between event and total annual soil erosion with the parameters collected in 2007.

The explained variability of a factor or a group of factors is represented by its adjusted R^2 value. These are shown in table 5.6. Generally the influence of several factors to soil erosion is different at different event sizes. The single factors explain less variability in soil erosion than the combinations such as the interaction of 1-Landcover and Squareroot of slope and also the combination of 1-Landcover (C), soil erodibility (K) and Squareroot of slope (SqS). This may be because soil erosion is a result of an interaction between several factors. The multiplicative model of $SqS*C*K$ explained most soil erosion.

Table 5-6: Linear regression R^2 values between soil erosion and soil loss factors

	1-Landcover (C)	Square root slope (SqS)	SqS*C	SqS*C*K
Annual	0.48	0.50	0.50	0.51
Low event	0.29	0.32	0.53	0.54
Medium event	0.33	0.37	0.48	0.47
High event	0.37	0.40	0.42	0.39

We also tested different model significances as shown in Table 5.7. This was to choose the best model amongst the ones with significant Adjusted R squared values (See table 5.6). Table 5.7 shows that the multiplicative model (interactive model) of landcover, soil erodibility and the square root of slope is the most significant at the 95% probability level.

Table 5-7: Testing landscape factor models' significance

Model	F	Pr(>F)
Model 1: Soil loss ~ Soil erodibility	3.07	0.08473
Model 2: Soil loss ~ Landcover	39.99.	7.568e-09
Model 3: Soil loss ~ Squareroot of slope	29.81	3.727e-08
Model 4: Soil loss ~ Landcover* Squareroot of slope * Soil erodibility	45.37	8.868e-08

5.2.3. Comparing the residual structures of soil loss factors

In order to apply KED we need both the landscape factors and the residual spatial structure. Therefore the residuals of the significant models were visualised for the spatial structure, the range of subtracted unexplained variability and the subtracted range of the unexplained variability. Some of the residual spatial structures are shown in Figure 5.8. We aimed at explaining as much soil loss variability as possible and this is attained by predicting using both the explained variability model (Table 5.7) and the unexplained /residual spatial structures (Figure 5.8). The spatial dependence in the residual

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structure (Green graph) is compared with the empirical variogram (Blue graph). The latter shows the total modelled unexplained variability while the former shows the amount of the random (unexplained variability) which still exists after application of the respective factor to predict soil erosion. 1-landcover, soil erodibility and the square root of slope showed some residual structure. If the gap between the two (green and blue) is large then the amount of the unexplained variability which is subtracted by application of the factor or group of factors is also large. It is clear that the gap between the multiplicative model (Interactive model) of 1-landcover, soil erodibility and the squareroot of slope is largest. This residual structure also subtracts the largest unexplained range as compared to the soil erodibility landcover or the square root of slope spatial structures alone.

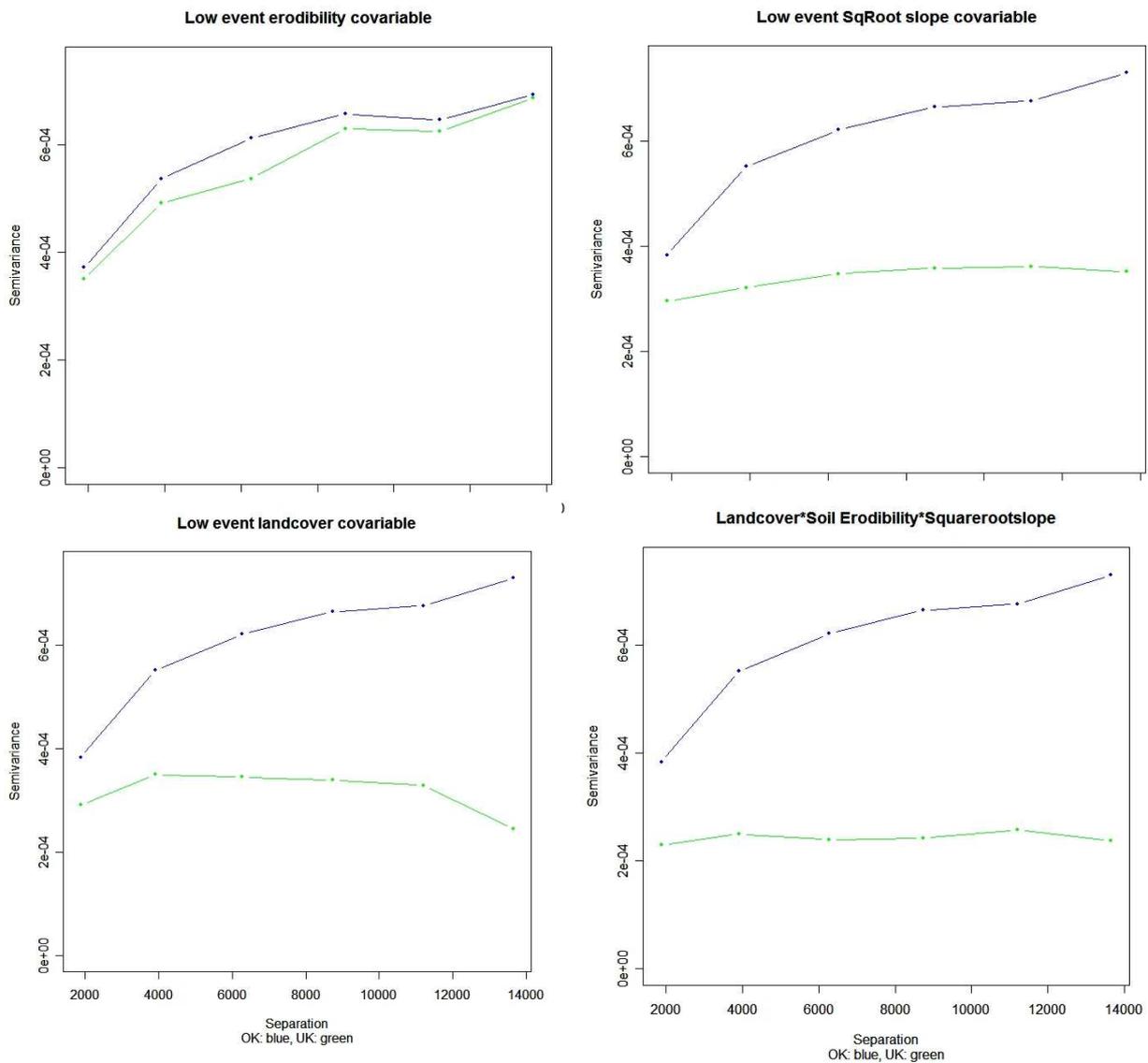


Figure 5-8: Comparison of landscape factor's residual structures

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5.2.4. Prediction using the landscape factors and the spatial structure

Save for soil erodibility and slope, we did not have the 1-landcover factor for the whole prediction grid hence we applied KED within the Leave One Out Cross Validation (LOOCV) method to predict at the 61 sample locations. LOOCV skips the predicted point when predicting at its location to avoid exact prediction of that point.

After choosing the factors to include in prediction soil erosion was predicted. The result of the Kriging with external drift using the LOOCV included a map and residuals showing the spatial variability of soil erosion and residuals when the landscape factors are applied in the prediction. The KED (prediction with landscape factors) result is compared with an OK (Prediction with the spatial structure alone) but this time the OK is also based on the LOOCV. The results are shown in Figure 5.9.

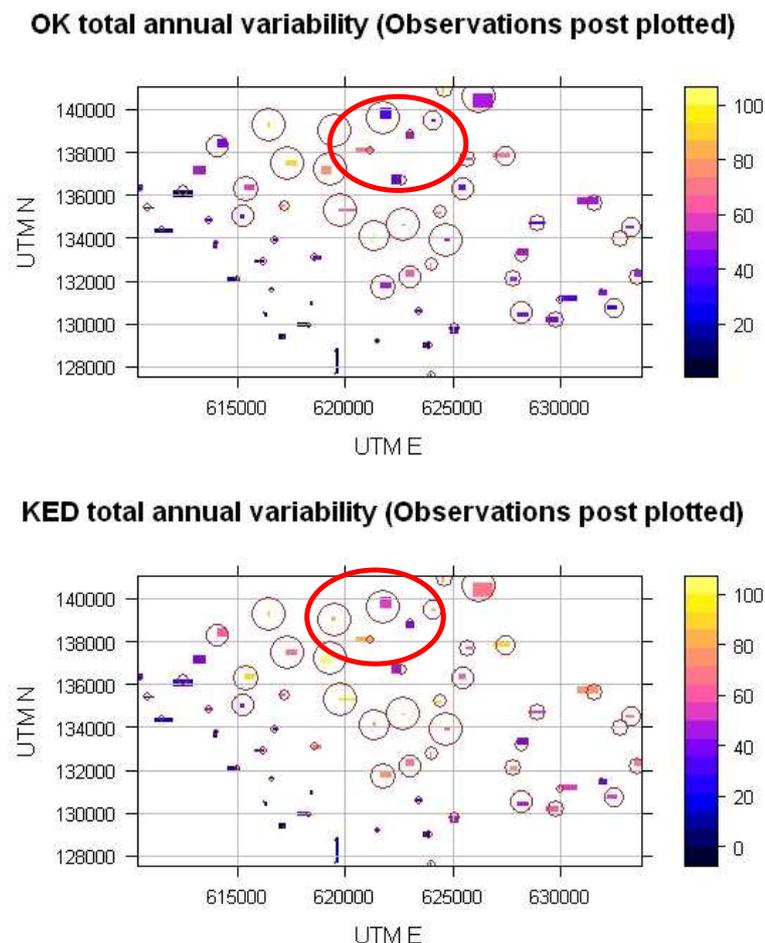


Figure 5-9: Comparison of KED and OK predictions (Tons/Ha/yr)

Figure 5.9 shows the OK and KED predictions with the observed values overlaid in brown circles. When the brown circle is large then the observed soil erosion value was also high. Large circles are expected to coincide with higher (yellow) predictions and vice versa. While most of the study area

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soil erosion variability was reproduced well by both methods, OK under predicts in the north and north western part of the study area as compared to KED. The use of landscape factors in KED should be the explanation for the relatively below ability to reproduce observed soil erosion variability.

5.3. Validation

Validation of the predicted amounts and patterns was one of the objectives of this study. Figure 5.10 shows the residual post plots of the OK and KED predictions.

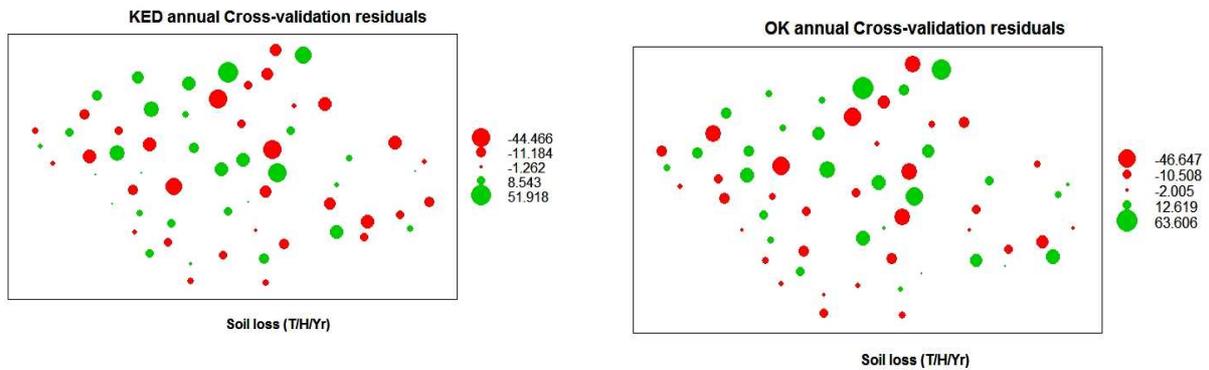


Figure 5-10: Comparison of OK and KED residual post plots

The Figure 5.10 does not show major clusters of positive or negative residuals implying that non of the interpolation methods systematically overpredicts nor underpredicts soil erosion.

5.3.1. Confidence intervals

The confidence interval states the range within which predicted values probably lie (See table 5.8). It was calculated using the student t test, at 95% probability level.

Table 5-8: Comparison of model performance using confidence intervals

	Ordinary Kriging				Kriging with External Drift			
	Annual	High	Medium	Low	Annual	High	Medium	Low
Confidence width	0.50	0.02	0.03	0.03	0.00	0.00	0.00	0.00
Mean (T/Ha/year)	46.97	1.4	1.22	1.12	46.97	1.4	1.22	1.12

The fact that the confidence widths are very low in comparison to the mean as shown by table 5.8 shows that both models performed well. The good performance of both modelling approaches may be due to the strength of ordinary kriging to model and predict random variability and the good choice of secondary factors used in the Kriging with external drift prediction. The good performance in all events shows that the explained variability of a model or the spatial autocorrelation may not be a good

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guide for determining the expected prediction result. Instead it reflects the maximum variability in event soil erosion which the model may totally represent.

5.3.2. Comparison for RMSE and MSDR

Table 5.9 shows that the OK mean error for the annual soil loss is 0.50 Ton/Ha/year which is about 1% of the mean soil loss value. The model precision is 21.5 Ton/Ha/Year, which is 73 % of the inter-quartile range and 48 % of the sample data standard deviation. Thus the validation precision is higher than in the sample data. The variability of the cross-validation versus that of the sample set (see MSDR value) is about 1.6. This is not a large difference therefore the model captures the variability fairly well. The MSDR is expected to be higher, with a lower nugget because the kriging variance would also be lower. This highlights the importance of a realistic nugget to capture the true small-scale variability. However considering that the sample data had large separation distances the relative difficulty in estimation of the true nugget may have affected the prediction accuracy. In general KED was better than OK (see RMSE values) and event MSDRs were better than the annual one.

Table 5-9: Comparison of model performance using prediction error statistics

Method	Ordinary Kriging				Kriging with External Drift			
	Annual	High	Medium	Low	Annual	High	Medium	Low
Mean	46.970	1.400	1.220	1.120	46.970	1.400	1.220	1.120
RMSE	21.495	0.009	0.021	0.022	18.493	0.010	0.021	0.018
RMSE/SD	0.730	0.946	0.905	0.896	0.628	1.051	0.897	0.750
RMSE/IQR	0.489	0.944	1.070	0.732	0.420	1.049	1.061	0.613

5.3.3. Comparison of the OK and KED prediction correlations with observations

Correlation plots along a zero intercept line were used to assess the fit of the predicted soil erosion and Figure 5.11 shows the results

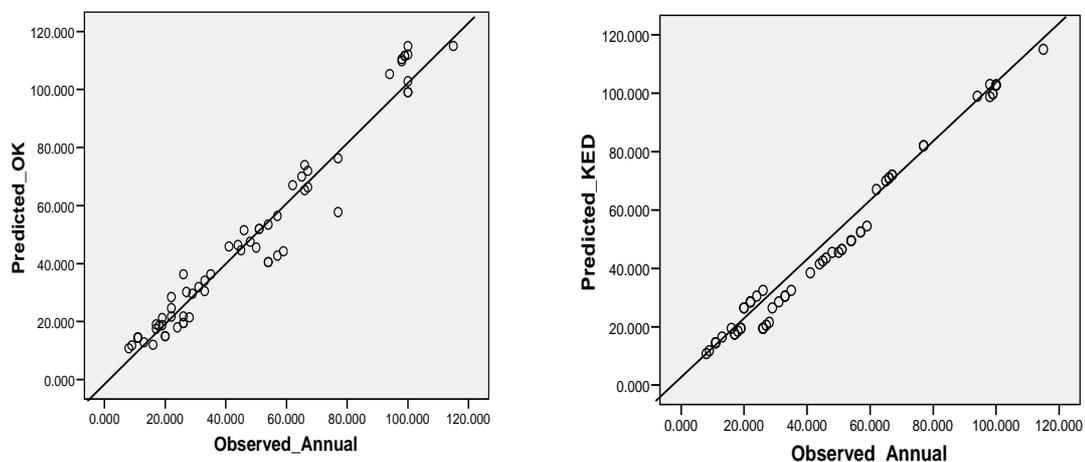


Figure 5-11: Comparison of OK (Adjusted $R^2=0.95$) and KED (Adjusted $R^2=0.98$) predictions

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Figure 5.11 shows that in general KED performs better than OK implying that predicting with landscape factors results into better prediction than without. The event correlation plots reflect a similar trend (See annex 0.11)

5.4. Soil erosion assessment and Simulations

5.4.1. Soil loss assessment

Table 5.10 shows that the difference in the mean predicted soil erosion is higher in the annual prediction than in the event soil erosion. This might be attributed to the relatively higher values and corresponding prediction semivariances. However for the events the mean predicted values are very similar to the actual mean values. Generally low events yield less soil loss than high events. However only 20% of the rainfall received in Wanale watershed is above 20 mm, therefore low events are equally important in terms of assessment of the soil erosion hazard. Annexes 1.5 and 1.8 show the daily erosive rainfall amount received within one year. Only OK was used in the soil loss assessment because of lack of data to cover the entire grid for KED. The total sediment production is only a possible amount as we did not have sufficient data to compute it and hence it does not represent the total hillslope erosion. This is due to some deposition which is expected in the plot. Therefore the predicted map (see Figure 5.12) shows the potential sediment production it is enhanced by a classification.

Table 5-10: Soil erosion assessment

	Ordinary Kriging (OK)			
	Annual	High	Medium	Low
SUM predicted (Ton)	1786161	48500	42151	38881
Predicted points	34560			
Predicted Mean prediction (Ton/Ha/Yr)	51.68	1.40	1.22	1.13
Observed Mean Sediment production (Ton/Ha/Yr)	46.97	1.40	1.22	1.12
Wanale watershed area (Ha)	22820			

5.4.2. Annual hill slope erosion hazard map

An erosion hazard map was produced from the Ordinary Kriging prediction result. Figure 5.12 show that the central as well as eastern and south eastern parts of the study area are more susceptible to the soil erosion hazard than the south-western part. These areas are also the highest steepest. In general the largest part of the study area faces soil erosion although it is very severe in the northern part which is also the most densely populated and with more intensive agriculture. This could mean high vulnerability of the community to problems such as soil nutrient loss soil fertility decline, decline in crop yield and subsequently low incomes and low welfare situations.

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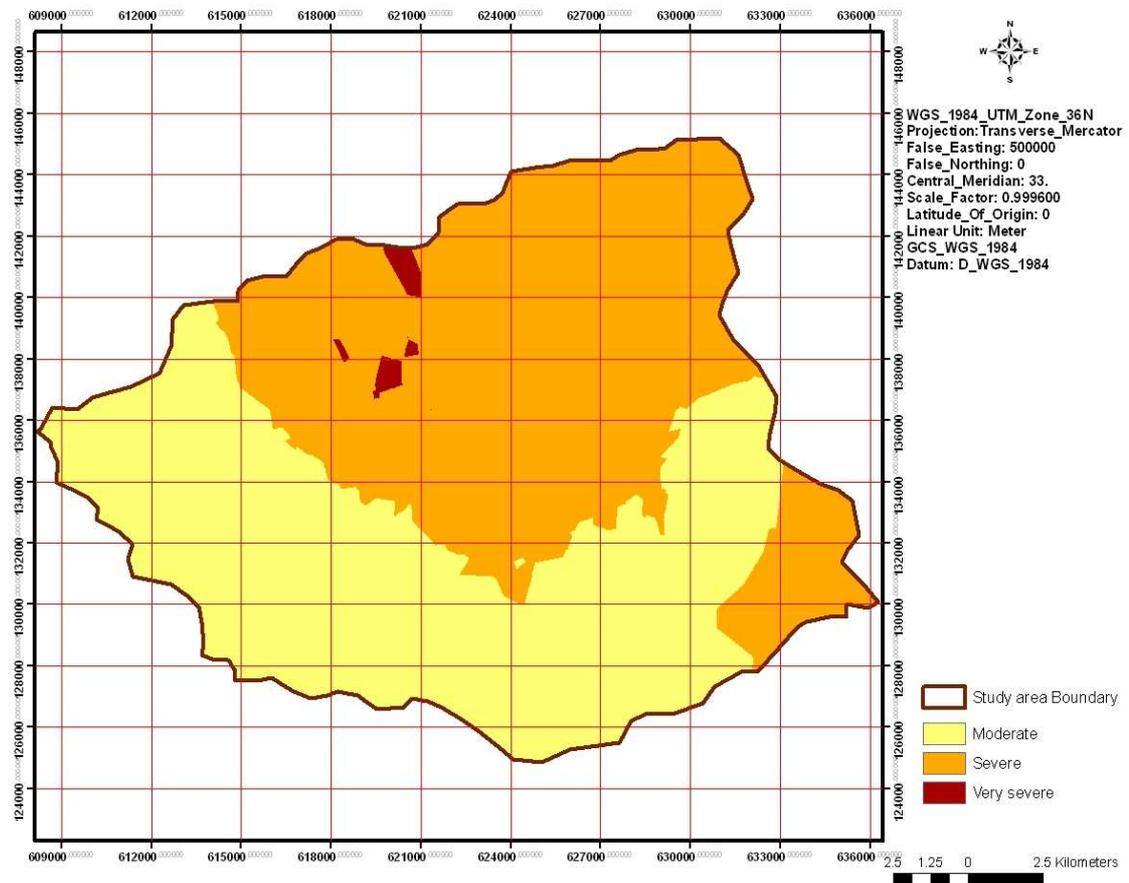


Figure 5-12: Wanale erosion hazard map

5.4.3. Gaussian conditional simulations

Kriging predictions portray some problems with respect to uncertainty such as: 1) Kriging is an exact predictor at known points, because all the weight is given to the known point; this is mathematically necessary but not realistic, since just away from the point the predictions are weighted. 2) Kriging prediction maps are by definition smooth, even if there is a nugget component to the model; the actual spatial field is usually much rougher. Therefore, a map produced by kriging may give an unrealistic view of the fine-scale spatial variability. We can recover this with conditional simulation: this shows one (or many) possible realizations of the spatial field as defined by the event spatial autocorrelation structure and as constrained by the known data values. Many simulated fields can be created, each equally valid, and they may be used as model inputs. The four simulations created for the low event soil erosion as seen in the Figure 5.13 can be used for different scenarios of interventions in the soil hazard or as inputs for other models. It is clear that all four simulations show a similar pattern to the kriging variability (see lower values at north east and south west). The data values of the simulations are also similar to kriged values.

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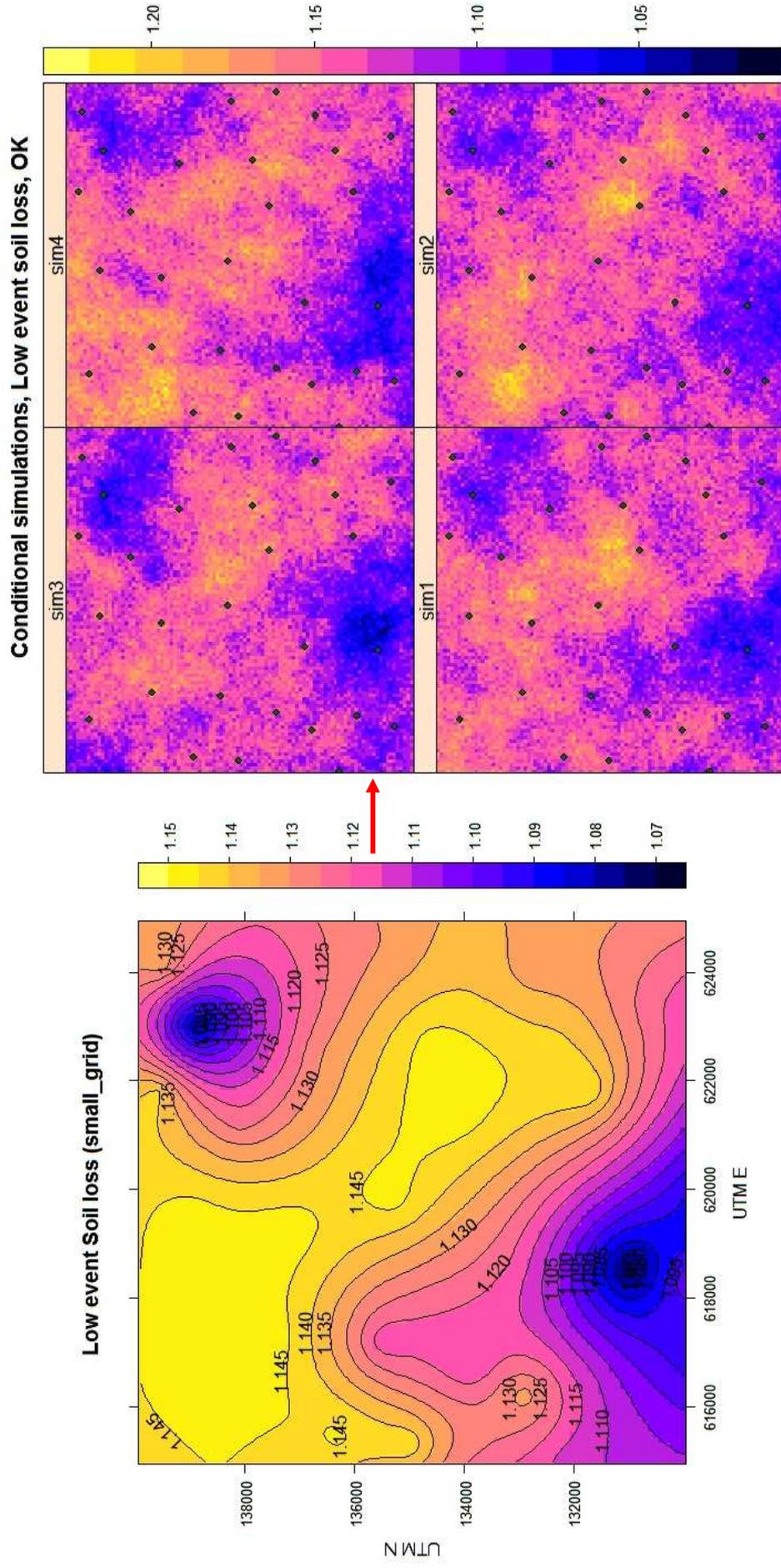


Figure 5-13: Simulation of soil erosion patterns (Soil erosion in (Tons/Ha/yr))

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5.4.4. Community and institutional problems and opinions

The community identified five problems related to agriculture namely, land shortage, low yields, soil productivity decline, low income, low agricultural prices/ fluctuations of especially coffee and carrot prices. The decline in soil productivity was ranked as the most acute problem. To mitigate this problem some of members of the community are also implementing soil and water conservation measures such as contour ploughing, terraces, grass bands (Napier grass), tree planting and mulching.

Key informants from institutions such as the National Environment Management Authority (NEMA), Mbale Local Government Makerere University and the Mt Elgon National Park recognised all the problems stated by the community and they are implementing several activities including research, monitoring and enforcement of environmental regulations. All the key informants recognised the soil productivity decline as a threat to agriculture and farmers' livelihoods in particular. They also linked it to increasing soil erosion which they attributed to poor landuse driven by increasing population pressure on land. The institutions also recognised poor packaging of results which makes them more difficult to interpret (40% of respondents), insufficient spatial information to guide interventions (100% of respondents); poor access to modern Information Technology (IT) facilities (30%) and insufficient processing skills for spatial data (100%).

Among the on going projects which could benefit from better access and packaging of spatial information are Payments for Ecosystem Services, carbon sequestration, Integrated Ecosystem Assessments and monitoring and enforcements through environmental audits and impact assessments. The different institutions intend to identify priority hillslope locations and to collaborate with the community in order to protect them. The institutions require maps showing the distribution of the soil erosion hazard and also guidance of the types of soil and conservation measures which can be easily implemented by the community.

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6. DISCUSSION

6.1. The hillslope soil erosion problem

This study recognised the fact that soil erosion is an environmental problem with several physical economic and potentially political problems (Aksoy and Kavvas, 2005; Amore et al., 2004). The latter is because the upstream effect on the downstream areas does not respect political boundaries. For example the 2007 floods in the drier flat areas of Teso region in Uganda were primarily due to the high rainfall amounts received on the Mt Elgon slopes. Similarly the high maintenance costs of the water supply stations in the lower Tororo and Mbale towns are offsite economic problems from the extreme sediment delivery by the Manafwa and Namatala rivers and whose source is in Wanale watershed. Globally, other erosion problems include losses in annual food and subsequent consequences to food security and human wellbeing (Kok et al., 2007) and damage of downstream infrastructure (Rompaey et al., 2005; Krasa et al., 2005; Jordan et al., 2005; Verstraeten, 2006; Verstraeten et al., 2007).

We focused on enhancing better predictive quality of hillslope soil erosion so as to enhance institutional and community management of the soil erosion hazard. We achieved this by visualising the watershed as a geographic space within which several processes and elements interact. The study also applied spatial analysis in a GIS based modelling approach (Bruijnzeel, 2004; Jordan et al., 2005; Krasa et al., 2005; Aksoy and Kavvas, 2005). We recognised the complexity of modelling the hillslope soil erosion (Jetten et al., 2003; Nearing et al., 2005), by seeking a better understanding of these relationships through applying stochastic modelling and prediction of the event hillslope soil erosion.

6.2. The implication of the results for hillslope soil erosion modelling

Some of the issues in soil erosion prediction and management are the reduction of costly and gross errors in landuse planning decisions based on unreliable information, limited ability to account for the dynamic underlying factors in modelling (Refsgaard and Abbott, 1996 and Merritt et al., 2003), the additional error resulting from parameter uncertainty (Jetten et al., 2003); and the phenomenon of predicting acceptable soil erosion with an incorrect pattern of the source and sink areas (Jetten et al., 2003; Takken et al., 2001a; Takken et al., 2001b).

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This study responded to these issues by implementing recommendation of Bryan, (2000), Jetten et al., (2003) and Kok et al., (2007) that better predictive quality of soil erosion models can be achieved by using more spatial information. In this regard we applied stochastic modelling and prediction with both the spatial structure alone and also in combination with landscape factors (Armstrong et al., 1993).

The results indicated that there is spatial autocorrelation in all event soil erosion categories (High, medium and low events) and also in the total annual soil loss. The spatial autocorrelation generally reduced with increase in event size and the range of spatial dependence increased with an increase in event size. While it would be expected that high events should depict higher spatial autocorrelation owing to their ability to average local conditions they actually depicted lower spatial autocorrelation. The difference between the high and low event soil erosion spatial autocorrelation could hence be attributed to a number of factors namely, the inherent data variability, spatial variability in rainfall, spatial and temporal differences in land management, the influence of regional factors on event soil erosion and the closed nature of the runoff plots which provided the data for this study.

The high data variability in the low events is expected to arise from the relatively larger influence of local erodibility factors (Michael et al., 2005) which are by definition in closer separation distances leading to higher sills and spatial autocorrelations in the short range than long range. This factor is also expected to explain the gentle slope of the higher event size soil erosion relative to low event soil erosion. Generally the spatial structure approached a nugget model as the event size increased. This may imply difficulties to model the soil erosion spatial structure of very large or extreme events.

Pruski and Nearing, (2002) explained the effect of rainfall variability on the soil erosion patterns. If the spatial variability of rainfall is significant it could also imply that the modelled and defined spatial autocorrelations in the event soil erosion are not definitive of the event soil erosion at a certain rainfall event but rather the differences in the received rainfall amounts at different geographical locations in the watershed. This study compared the daily rainfall observations for the entire study period and they were not significantly different. Therefore the modelled and defined spatial structures are primarily due to the differences in the received rainfall amount.

The fact that land management is attributed to landuse types and that this study did not have sufficient landuse data to ascertain the effect of land use dynamics on soil erosion and its spatial structure complicated the modelling and also the relationships between landscape factors with soil erosion. However owing to the fact that the observed patterns which were applied in this study are a function of several interactions in the soil erosion factors including land management, the modelled event

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spatial structures may reflect the several explainable and unexplainable interactions between soil erosion factors. Therefore modeling and prediction with the soil erosion patterns is a quicker and faster way of providing spatial information on the soil erosion problem.

Rodenburg et al., (2003), Wang et al., (2002) and Yemefack et al.,(2006) explained several regional factors such as slope, elevation and landuse type which can have an influence on soil erosion patterns. This may lead to regional spatial dependence. While the regional dependence in the modelled event soil erosion was generally low, the increase in the range of spatial dependence as the event size increased could be an influence of the weak observed regional trend. However this factor may also be due to the relative ability of the different events' runoff volume to create erosion. The high events generally have higher abilities to cross local barriers and also suppress the local erodibility characteristic in the final soil erosion patterns creating more similarity over a longer range. This implies that rainfall amount affects both data variability and the range of spatial dependence. Therefore highly variable data such as small event soil erosion can also be modelled with local spatial dependence (Hoosbeek, 1998).

The other possible explanation for the differences in the spatial autocorrelation between the event soil erosion spatial structures may be the closed nature of the runoff plots which affects the natural process of hill slope flow accumulation and soil erosion along hill slopes. Indeed the linear relationship between the soil erosion with the wetness index, flow accumulation and all the other hydrologic parameters was weak (See annex 0.7). This may be the effect of the closed runoff plots which may also cause the higher spatial dependence within the short range as opposed to the long range. However it is not clear how this factor may explain the dramatic differences in the other model parameters of the event spatial structures. For instance the sill and nugget were also higher for the low and medium event as compared to the high event. The closed runoff plots can not explain the relatively high accuracy of the predicted soil erosion by all the models including the high event one. The adjusted R^2 value for the total annual soil loss was higher than that attained by previous studies (De Roo, 1993; Risse et al., 1993), while the event soil loss predictions were also very well predicted with OK ranging from 0.5- 0.8 and KED from 0.8-0.9). The goodness of fit of all model predictions was also much better than Nearing (1998). While KED generally performed better than OK (See annex 0.11), stochastic prediction indeed improved the soil erosion predictions. The high prediction accuracy may mean that the differences in the model structure are true reflections of the inherent structure. This confirms the need for recognition of the change in the spatial structure of hillslope soil erosion while modeling and predicting it. This evidence is sufficient to accept the following hypotheses:

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1. The Coefficient of variation (CV %) is positively related to the event explained variability by the spatial autocorrelation model.
2. Spatial autocorrelation in soil erosion decreases with increasing rainfall amount.
3. KED is more accurate than OK
4. Stochastic prediction of soil erosion improves prediction accuracy

The analysis is also confirmation that the event soil erosion response to rainfall amount is different. The results confirm a change in the soil erosion spatial structure and also suggest that lack of consideration for this phenomenon may be responsible for the poor spatial prediction quality of hillslope soil erosion. The relationship between soil erosion data variability and spatial autocorrelation implies that there are limitations of the application of stochastic prediction for very or extreme events soil erosion. Particularly because it increasingly becomes more difficult to fit a covariance model as the data variability reduces.

6.2.1. Comparison of stochastic prediction with and without landscape factors

Comparisons of complex and simple models have been made regarding their relative performance in soil erosion prediction without reflecting better improvements by the former studies (De Roo, 1993 and Risse et al., 1993). This confirms Jetten et al.'s (2003) suggestion that the use of more spatial information and only dominant processes in a given landscape may reduce additional error resulting from introduction of additional parameters which often outweighs the improvement in prediction due to a better process description. Therefore we focused on identifying the combination of factors which yields minimum unexplained variability in soil loss and to guide the choice of input factors for stochastic soil erosion modelling and prediction in the future. A combination of the adjusted R^2 value obtained from the multivariate regression and the residual covariance model were applied for the factors choice. We applied the chosen factors in KED and compared the results with OK predictions and uncertainties.

The investigation resulted into a multiplicative model of landcover, soil erodibility and the square root of slope as the most significant interactive model that could explain the different event and total annual soil erosion. The multiplicative model was applied with its residual spatial structure to predict hillslope soil erosion. As a result the ability to reproduce observed variability was also higher for Kriging with the landscape factors. The results were sufficient to accept the following hypotheses:

5. Soil erosion is a function of, land cover soil erodibility and the square root of slope.
6. KED reproduces observed variability in soil erosion better than OK

The good performance of both methods can be attributed to OK's strength in modelling and predicting random variability, as well as a good model fit with high explained variability especially for the low

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and medium events. Predicting with secondary factors improved the results and also gave insights of the underlying factors. The fact that a multiplicative model of soil erodibility, landcover and square root of slope reproduced observed variability better shows their importance in soil erosion modelling.

6.3. The implication of the results for hill slope soil erosion management

This study also aimed at explaining the predicted soil erosion patterns in relation to community and institutional development issues in Wanale watershed. This is because NEMA, (1999) and IFPRI, (2007) reported that land degradation, low and declining agricultural productivity, and poverty are severe and interrelated problems in Uganda. These problems are linked to soil erosion which has been reported to be rampant in Wanale watershed. This study also confirmed large portions to be facing the erosion hazard. Therefore the success of the landuse policies and compliance to environmental regulations partly depends on accuracy of the predicted patterns of the hillslope soil erosion. The type of interventions may also be different for different amounts of runoff and soil erosion at the hillslopes.

We undertook developed four simulations which could be applied as different intervention scenarios. We also interviewed both the community and the key informants. The interviews provided qualitative information on the different ways in which the community may be vulnerable to the soil erosion hazard. This is the first step in assessing the risk of soil erosion within the watershed. In future scientific studies could base on our findings to quantify the erosion risk within the watershed. The results are a starting point for potential interventions in mitigating the hill slope soil erosion problem. The combination of amounts, patterns and uncertainties are also a better package of spatial information for the several institutions operating within the study area. The spatial information is timely for the institutions basing on the responses from the key informants. Currently some institutions are involved and the community has some efforts such as maintenance of grass bands mulching and many more but this study provides soil erosion patterns which can be used to prioritise interventions. Considering that Wanale watershed is targeted for integrated ecosystems analysis and the United Nations Environment Program (UNEP) which funded a poverty environment linkage project in Uganda, such means of packaging information may be useful to stakeholder institutions. Packaging of results and access to spatial information were stated as important issues by the stakeholder institutions in the Wanale watershed.

The community suggested a need for projects targeting improvement in agricultural productivity. These projects could benefit from the several possible prediction methods we have applied in this study as well as the several options of packaging results as applied in this study. We provided possible ways of spatial analysis basing on easily accessible remotely sensed data and introduced means for

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visualisation, modelling and construction of datasets such as prediction grids, Digital Elevation Model (DEM) and the maps which can be used for development projects in the watershed.

6.4. Limitations of the study

This study was limited by logistics and time. Additionally its scope could not handle most of the institutional, policy and legal issues surrounding the Wanale watershed management. Conversely, responding to the hill slope soil erosion problem depends on many factors. This calls for similar studies on other related issues specifically socioeconomic studies and quantification of the other watershed processes linked to hillslope soil erosion so as to account for the total sediment budget. This would enhance analysis of upstream and downstream linkages and to support stakeholder initiatives. Moreover, due to the limitations in the spread of the input data, it is important to be cautious about the application of this study results in a wider context.

We assumed that landuse had not changed in unobserved locations. The landuse change data used in this study was essentially a change in landcover and erodibility. Moreover landcover was primarily calculated from surface cover which is a simplification of the real situation. Despite the fact that landscape factors were only applied to predict at observed locations and for specific snap shots based on the corresponding period of an event, to make firmer conclusions about their effect in modeling and prediction would benefit from more detailed land use change information. This could be captured better by a dynamic process based model.

There were no significant differences in rainfall measured at the four rain gauges. However, the small number of rain gauges may not reflect the truth about the spatial variability in rainfall. We also did not obtain rainfall intensity data which may have an effect on soil erosion variability. Additionally, considering that we could only obtain a single value of rainfall per day we assumed a one day steady state time step. This is yet another simplification because the duration of rainfall is variable in time and space and this may affect soil erosion variability even for small events. Similarly antecedent moisture may be another important factor affecting runoff volume and erosivity of an event but it was not considered in this study. However we investigated the periods before and after the chosen storms. By luck, there were no high rainfall amounts before or after the selected storms, implying a lower effect of soil moisture levels on runoff generation and soil erosion.

OK and KED's performance, like several other kriging methods is limited by the number of data and the type of data it can handle therefore the relatively low number of points (sixty one) may have

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affected the model fitting and accuracy of predictions. However annex 0.11 shows from fair to very good results implying that the amount of data may not have significant effect to the results.

The data applied in this study was from closed runoff plots; these could not reflect the expected hydrologic process relationships such as relationships between slope length and soil erosion. For example, flow accumulation and wetness index were weakly correlated to soil erosion. While this may be due to the barrier effect of soil and water conservation measures in the area such as grass bands, it may also be due to the use of closed plots. Both can intercept runoff creating unexpected hydrologic relationships. It would be useful to undertake a similar study basing on non closed runoff plots data.

The large separation distance between observed soil erosion plots made it difficult to estimate the nugget. Yet the nugget is vital for estimates of model prediction precision. This might be the reason why some short range spatial structures (Soil erodibility and residual variogram of the 3rd degree trend surface for elevation) had lower explained variability. However the low event short range model and its high explained variability as well as the attained prediction accuracies imply that with careful model fitting this may be improved. Nevertheless it would be useful to apply similar studies with some close-spaced plots to better estimate the nugget variance.

We also resampled the Landsat ETM+ image to a 15 m grid. This can affect both the accuracy of the classification and also that of the landuse change detection. However the high classification accuracies we obtained may imply that the resampling did not negatively affect the results of this study.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

We responded to all our research questions by demonstrating the possibility to model define and compare soil erosion spatial structures at different event sizes. The soil erosion spatial structures changed at different event sizes. The spatial autocorrelation reduced with increasing event size while the range of spatial dependence increased with event size. Therefore rainfall amount affects the hillslope sediment production spatial structure, so that there is no definitive spatial structure for hillslope sediment production.

The implications for stochastic modelling include the relative ease to model and predict highly variable data including low rainfall event soil erosion, improved prediction accuracy and the ability to identify underlying factors when we model with landscape factors.

The implications for management include the relative ease for this approach to package essential spatial information such as amounts patterns uncertainties as well as a soil erosion hazard map. The approach also provides different scenarios of soil erosion patterns so as to enhance interventions to the soil erosion hazard at watershed scale.

7.2. Recommendations

Event-based stochastic modelling and prediction yielded good results hence it should be replicated to guide the watershed management. We recommend that management decisions be made on the basis of separating events' soil erosion and investigating their spatial structures separately prior to prediction. This could provide insights on the type of interventions. For example drainage channels may be better for high runoff and soil erosion while grass bands may be better for lower runoff and soil erosion situations.

We also recommend further research in the rainfall amount thresholds at which the soil erosion spatial structure changes if a large and long-term dataset of unenclosed and closely spaced data exists.

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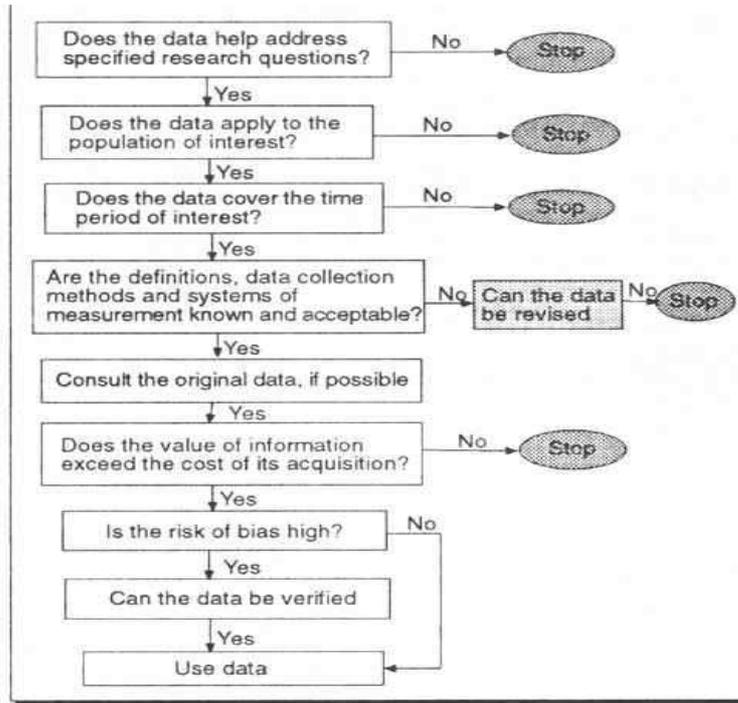
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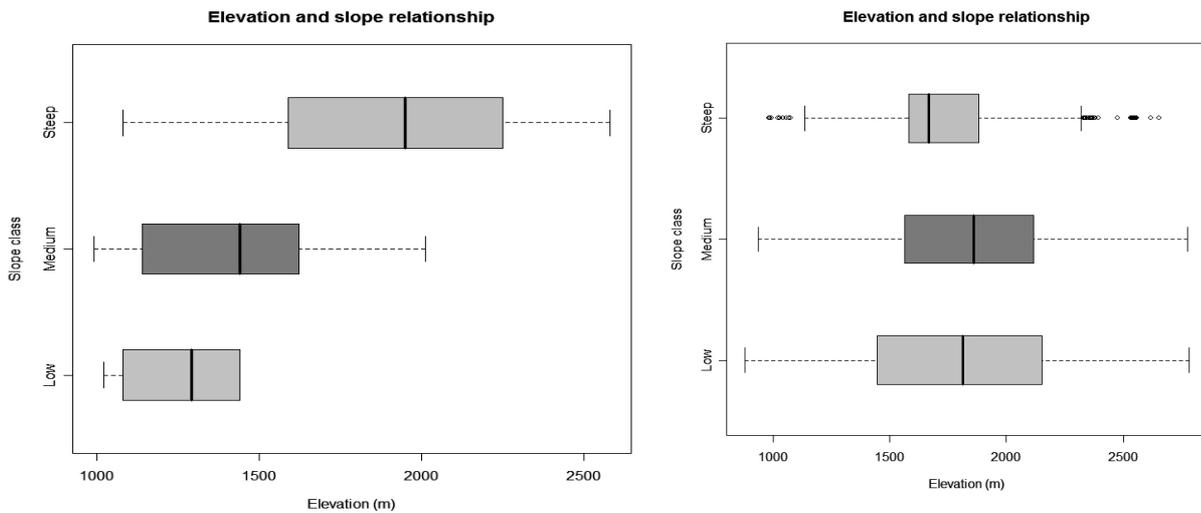
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ANNEX



Annex 0-1: FAO 1993 secondary data evaluation flow chat



Annex 0-2: Comparison between slope and elevation observed left and predicted right

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Annex 0-3:Field data sheet

Field data collection sheet											
Filled by:											
Date											
Data name											
Soil and other plot parameters											
Plot Code	GPS Code	X	Y	Top (0-15cm) label	Bottom (15-30cm) label	Soil strength (Kg/sq m)	Slope (%)	Elev(m)	Surface cover (%)	Canopy Cover %	Comment
A1											
A10											
A11											
A14											
A15											
A17											

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Annex 0-4: Field questionnaire for key informants

Data collection sheet 2; Key Informants in watershed management	
MSC. Research; ITC Enschede; The Netherlands	
Modelling and prediction of the effect of rainfall amount on the spatial structure of hill slope soil loss; Wanale watershed; Uganda	
Introduction	
Watersheds are sources of water for agriculture and drinking as such they are suitable areas for settlement. However settlement and subsequent land use types in the watershed may result into undesirable onsite and offsite effects such as increased soil erosion resulting into reduced soil productivity or increased sediment delivery to river channels. These have negative implications on livelihoods upstream and downstream and if unchecked they may be irreversible in the long term. It is hence important for natural resource managers to monitor and report on the watershed state in general and watershed processes in particular. This requires flexible, cost effective and adaptable systems and approaches in place. This study aims at examining the utility of geo-statistical models for characterizing the spatio- temporal variability of soil loss under different watershed conditions. This is expected to enhance decisions on erosion risk control at watershed scale. Hence your response to this questionnaire will be most useful.	
Date:	
Interviewer:	
Interviewee:	
Organization name	
Position	
City	
Head quarters location	
Question	
1	Briefly describe your organization's activities
2	Briefly describe your roles
3	If you or your organization undertake any activities/projects at watershed level list them
4	What are the issues of concern at watershed scale
5	How do you deal with these issues
6	What constraints do you face in dealing with the issues (if cost are involved state the figures)
7	How could these be solved
8	If you apply GIS and or Remote sensing in dealing with the issues explain how
9	Which specific improvements do you suggest for dealing with spatial data to enhance quicker and accurate interventions
10	How can quantification and location of soil erosion areas above the tolerance level assist in implementations of your activities
11	How can quantification of cost and impact (e.g. reduced sediment delivery) of interventions enhance the implementations of your activities
12	How can timely distribution of maps of sediment production/ soil loss enhance the implementations of your activities
13	Which other information and considerations are necessary to supplement the above in enhancing implementation of your watershed activities
14	Any other comments and suggestions can be stated below

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Annex 0-5: Daily rainfall data between may 2001 and may 2002

Date	Rainfall (mm)						
14/06/2001	5.4	19/06/2001	9.7	25/09/2001	13.4	16/04/2002	22.7
15/06/2001	5.5	10/05/2002	9.7	16/05/2001	13.5	16/09/2001	23.0
12/09/2001	5.6	01/11/2001	9.9	03/04/2002	13.7	13/04/2002	23.3
30/04/2002	5.8	03/08/2001	10.0	28/04/2002	13.8	29/08/2001	23.8
08/09/2001	5.9	23/08/2001	10.1	18/04/2002	14.2	15/05/2001	24.0
22/10/2001	5.9	09/09/2001	10.4	10/03/2002	14.3	26/10/2001	24.1
10/10/2001	6.0	05/11/2001	10.4	08/06/2001	14.5	17/04/2002	24.1
31/07/2001	6.2	09/08/2001	10.7	20/05/2001	15.0	28/10/2001	24.6
13/08/2001	6.3	31/03/2002	10.7	23/10/2001	15.2	13/11/2001	25.5
14/08/2001	6.3	29/10/2001	11.1	03/09/2001	15.6	19/07/2001	25.8
22/09/2001	6.5	22/10/2001	11.2	19/04/2002	15.6	25/10/2001	26.1
21/07/2001	6.9	11/11/2001	11.4	19/08/2001	15.8	01/08/2001	27.1
11/09/2001	6.9	07/05/2002	11.4	03/03/2002	15.9	07/05/2002	27.5
08/11/2001	7.0	10/11/2001	11.6	15/11/2001	16.1	12/04/2002	27.9
03/07/2001	7.5	17/11/2001	11.8	30/03/2002	16.9	11/08/2001	28.1
20/06/2001	7.6	23/09/2001	12.0	28/02/2002	17.0	13/05/2001	28.5
08/03/2002	7.6	05/10/2001	12.0	28/07/2001	17.1	08/05/2002	28.6
26/04/2002	7.6	06/11/2001	12.0	10/04/2002	17.3	12/11/2001	29.3
17/06/2001	7.7	17/09/2001	12.1	05/03/2002	17.5	20/04/2002	29.7
29/09/2001	8.2	22/11/2001	12.3	18/06/2001	18.2	21/09/2001	29.8
28/09/2001	8.8	24/02/2002	12.3	27/09/2001	18.3	02/06/2001	30.0
20/10/2001	8.8	08/06/2001	12.4	30/08/2001	19.4	22/04/2002	31.1
03/11/2001	8.8	22/08/2001	12.7	29/05/2001	19.5	02/10/2001	31.4
14/07/2001	9.0	08/10/2001	12.8	14/04/2002	19.9	30/07/2001	34.9
23/02/2002	9.1	13/10/2001	13.1	18/05/2001	20.8	06/05/2002	36.7
10/06/2001	9.2	16/10/2001	13.2	14/11/2001	21.1	28/05/2001	37.3
27/08/2001	9.4	18/07/2001	13.3	20/11/2001	21.3	28/06/2001	37.7
29/03/2002	9.5	23/07/2001	13.3	19/11/2001	21.9	24/04/2002	37.7
30/03/2002	9.5	24/07/2001	13.3	20/11/2001	21.9	25/04/2002	37.7
17/07/2001	9.6	26/09/2001	13.5	11/05/2002	23.4		

Source: Bamutanze, (2005)

Annex 0-6: Some S language Scripts

```

Loading and preparing a CSV file
#####
file.show("Lcalibset.csv")
file.show("Lpredgrid.csv")
anar1 <- read.csv("Lcalibset.csv", header = TRUE, sep = ",")
anar3 <- read.csv("Lpredgrid.csv", header = TRUE, sep = ",")
file.show("Ht.csv")
Ht <- read.csv("Ht.csv", header = TRUE, sep = ",")
while (is.element("package:gstat", search())) detach(package:gstat)
while (is.element("package:sp", search())) detach(package:sp)
while (is.element("package:lattice", search())) detach(package:lattice)
while (is.element("package:MASS", search())) detach(package:MASS)
library(sp)
library(gstat)
library(lattice)
library(MASS)
#####
Creating Geographic Objects
#####

```

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```

coordinates(anar1) <- c("X", "Y")
coordinates(anar3) <- ~ X + Y
coordinates(Ht) <- ~ X + Y
#####
Visualising Local spatial dependence
#####
v <- variogram(SL ~ 1, loc=anar1, width=1000, cutoff=15000)

plot(v, plot.numbers=T, main="Empirical variogram, Annual Soil
Loss", xlab="separation distance, m", col="darkblue", pch=20)

vm <- vgm(750, "Sph", 3850, 50)
print(plot(v, plot.numbers=T, main="Empirical variogram, Annual Soil
Loss", xlab="separation distance, m", pch=20, col="darkblue", model=vm))
#####
Automatic fitting of the variogram and computing explained variability
#####
vmf <- fit.variogram(v, vm)
print(vmf)
print(vmf)
vmf$range - vm$range
vmf$psill - vm$psill
sum(vmf$psill) - sum(vm$psill)
print(plot(v, plot.numbers=T, main="Empirical variogram, Annual Soil
Loss", pch=10, col="darkblue", model=vmf))
1-vmf$psill[1]/sum(vmf$psill)
#####
OK predictions; To predict at both known points and entire grid using ordinary Kriging
#####
SL_predOKpt <- krige(SL ~ 1, loc = anar1, newdata = anar1, model = vmf)
summary(SL_predOKpt)
summary(anar1$SL)
print(SL_predOKpt)
SL_predOKgd <- krige(SL ~ 1, loc = anar1, newdata = anar3, model = vmf)
summary(SL_predOKgd)
sum(SL_predOKgd$var1.pred)
#####
ANOVA and Model diagnostics
#####
anova(Erod, strength, Landcov, Slope, Slope_cov_str)
#####
anargrid1 <- SpatialGrid(GridTopology(c(615000 + 0.05, 130000 + 0.05), c(100, 100), c(100, 100)))
k.sim.4 <- krige(SL ~ 1, loc = anar1, newdata = anargrid1, model = vmf, nsim = 4, nmax = 256)
layout.2 <- list("sp.points", anar1, pch = 21, cex = 0.8, col = "black", fill = "darkgreen")
spplot(k.sim.4, zcol = 1:4, col.regions = bpy.colors(64),
main = "Conditional simulations, Annual soil loss, OK",
sp.layout = list(layout.2))

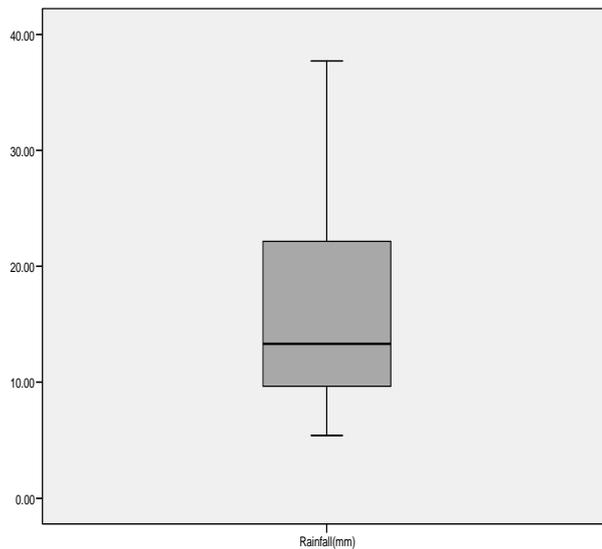
```

Where: **SL** is the observed total annual soil erosion at a plot, **anar1** and **anar3** are the calibration and larger prediction grids. **V**, **vm** and **Vmf** are the empirical variogram, eye fitted variogram and gstat fitted variogram respectively. **width=1000** represent the 1 km bin width while **cutoff=15000** represents a 15 km visualized soil erosion variability.

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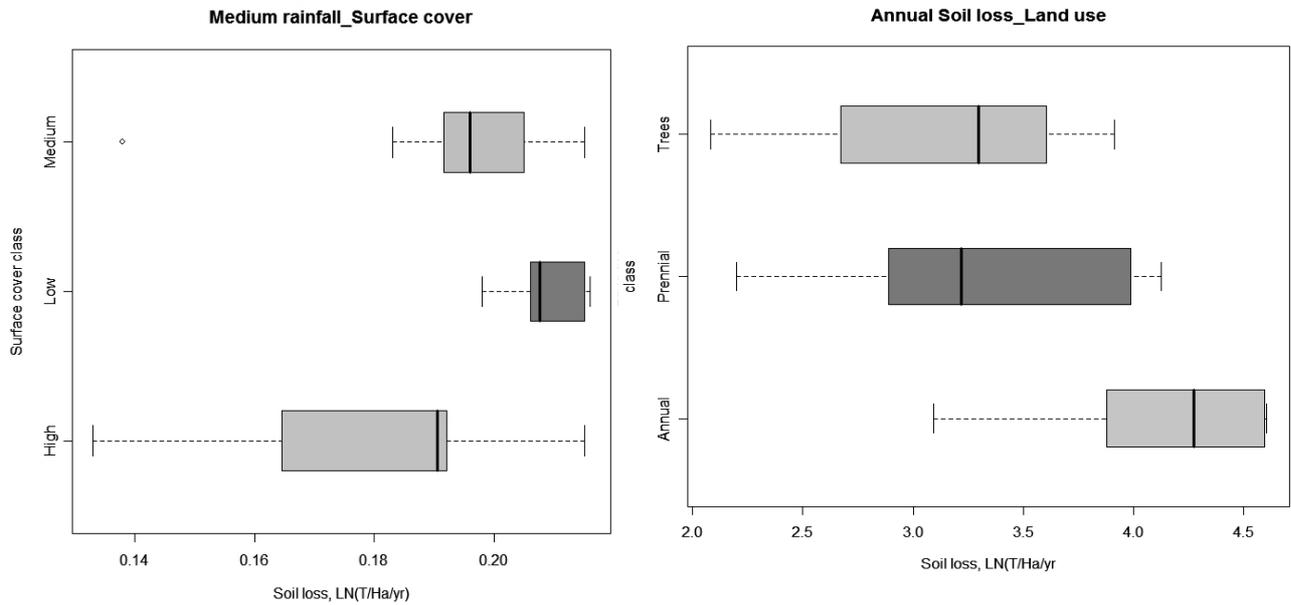
Annex 0-7: Linear correlation table showing R2 values

	Annual Total soil loss	Runoff	SLOPE	Surface cover %	High event soil loss	Medium event soil loss	Low event soil loss	Soil strength
Annual Total soil loss	1.00							
Runoff	0.85	1.00						
Surface cover %	-0.66	-0.68	-0.58	1.00				
High event soil loss	0.63	0.67	0.55	-0.63	1.00			
Medium event soil loss	0.72	0.74	0.60	-0.66	0.99	1.00		
Low event soil loss	0.81	0.80	0.64	-0.68	0.96	0.99	1.00	
SAND %	-0.05	-0.09	0.10	0.09	-0.14	-0.13	-0.12	
CLAY %	0.43	0.36	0.30	-0.47	0.36	0.37	0.39	
SILT %	0.44	0.55	0.56	-0.48	0.33	0.36	0.40	
Middle Infrared	0.19	0.11	0.12	-0.07	0.10	0.11	0.11	
MSAVI	0.10	0.20	0.17	-0.23	0.16	0.16	0.15	
OSAVI	0.09	0.17	0.15	-0.22	0.16	0.16	0.15	
Sediment transport index	0.22	0.16	-0.04	-0.18	0.13	0.15	0.16	
Stream Power Index	0.02	0.16	0.02	-0.19	0.02	0.02	0.02	
Wetness Index	0.22	0.29	0.25	-0.35	0.10	0.12	0.16	
Elevation	0.27	0.34	0.60	-0.52	0.25	0.26	0.26	
Flow Accumulation	0.16	-0.15	-0.16	0.08	-0.01	-0.03	-0.06	
Soil strength	0.22	0.10	-0.07	-0.20	0.21	0.22	0.23	1.00
Square root slope	0.64	0.70	1.00	-0.60	0.56	0.60	0.65	-0.05

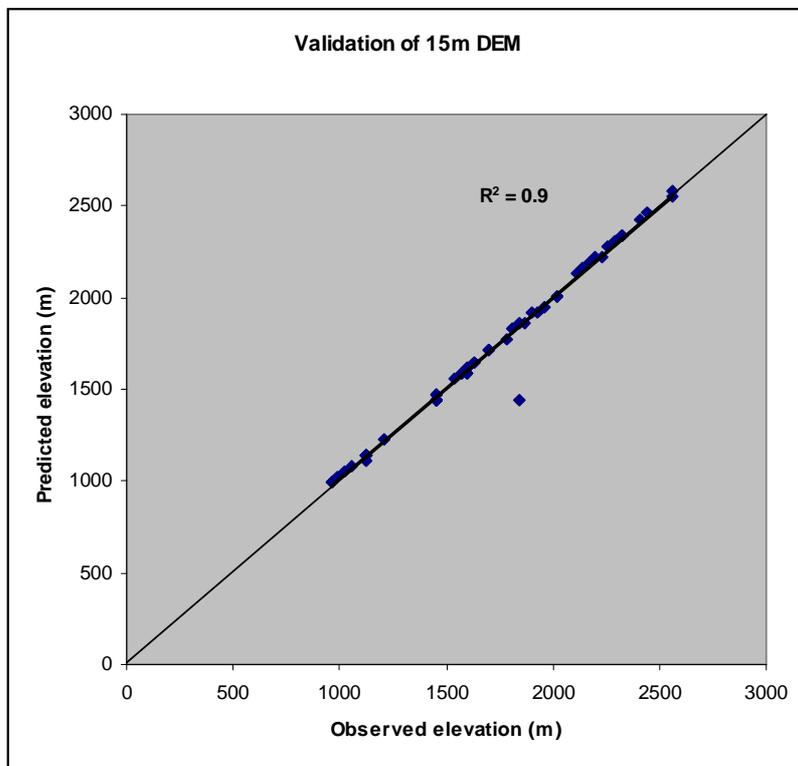


Annex 0-8: Box plot of the rainfall data between 2001 and 2002

THE EFFECT OF RAINFALL AMOUNT ON THE SPATIAL STRUCTURE OF HILLSLOPE SEDIMENT PRODUCTION IN WANALE WATERSHED; UGANDA

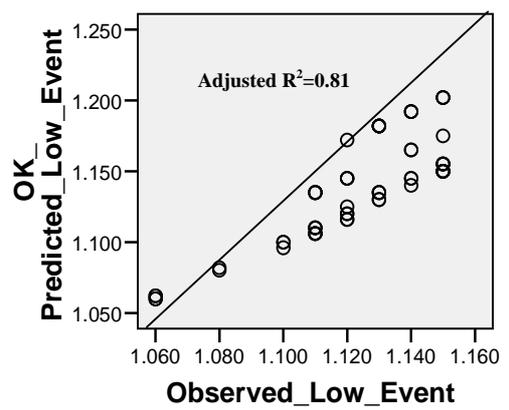
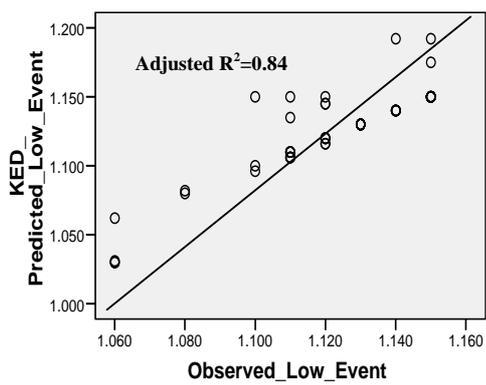
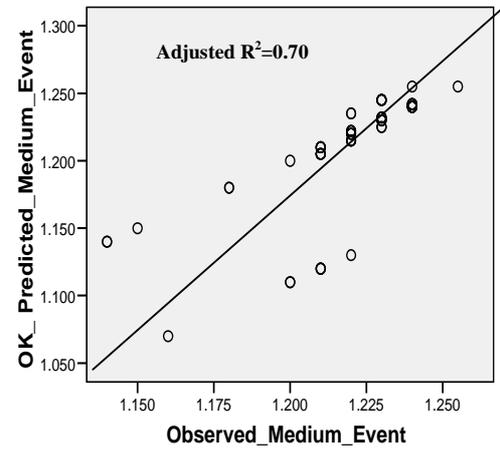
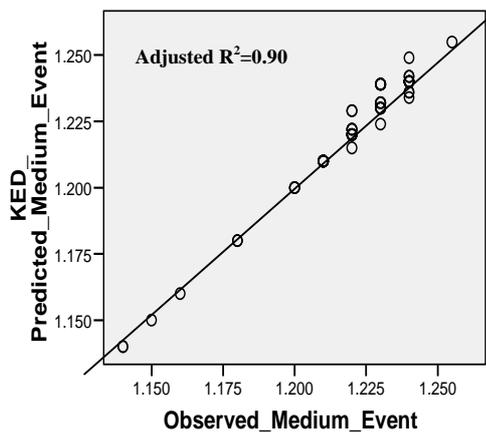
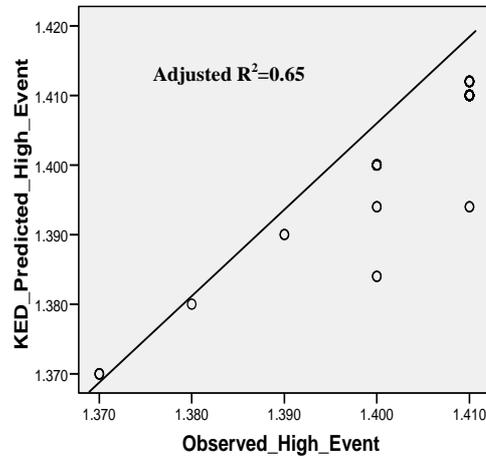


Annex 0-9: Relationships between soil erosion land use and surface cover



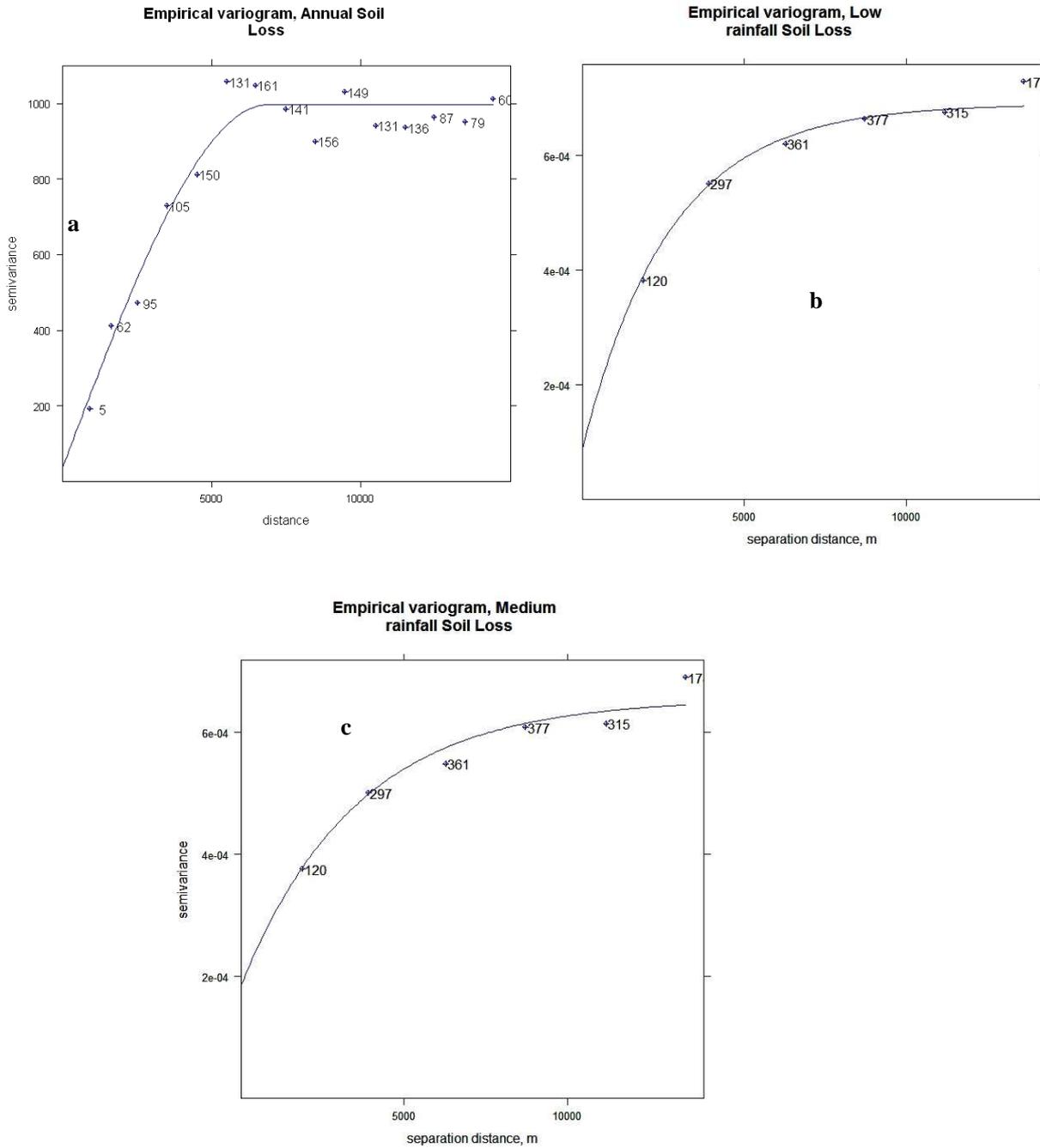
Annex 0-10: Correlation plot of observed and predicted elevation

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Annex 0-11: Comparison of OK and KED event predictions along a 1:1 line

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Annex 0-12: Total annual (a) low event (b) and medium event (c) spatial structures