A Relative Potential Erosion Detection (PED) model for the upper Buff Bay catchment, parish of Portland, Jamaica: A Geographical Information System application

C.M.I. MacGillivray
(prepared for publication by S.K. Donovan)

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Catriona M.I. MacGillivray (deceased), formerly Department of Geography, University of Portsmouth, Buckingham Building, Lion Terrace, Portsmouth, PO1 3HE, England and Department of Geography & Geology, University of the West Indies, Mona, Kingston 7, Jamaica; Stephen K. Donovan, Department of Geology, Nationaal Natuurhistorisch Museum, Postbus 9517, NL-2300 RA Leiden, The Netherlands (donovan@naturalis.nnm.nl).

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This research introduces a Geographical Information Systems (GIS) model that predicts the location and relative susceptibility of humid subtropical hillslopes to sheetwash erosion. The extent of the erosion was based on the conservation potential of the existing vegetation cover. This is an original deductive and deterministic model (Potential Erosion Detection, PED) incorporating regionally applicable physical and land use factors thought to be influential. These were climate (agroclimatic zones), topography (aspect and slope angle), soil (texture, drainage, depth, aggregation), vegetation cover and land use (tillage activity).
The study looked at surface erosion as a perceived problem in a post-colonial economy. The processes, cause and effect of erosion were considered, and socio-economic factors discussed. Data collection and the design of the model recognised potential errors and uncertainties.
This research was initiated in the upper basin of the Buff Bay River (Portland) in the Blue Mountains of Jamaica. The results revealed a steep terrain, erodible soils and half of the watershed had little understorey and low litter levels. The dominance of coffee ensured that just under half of the research area had soils that were regularly disturbed. The model estimated that 30 % of the upper watershed had the potential for moderate to extreme erosion, contrasting with much higher previous estimates. The statistical dominance of each factor was analysed, showing that soil erodibility dominated the top erosion classes, followed by slope angle, then land use. Alternative soil and vegetative cover parameters for application of the model to other watersheds were also compared.
The reliability of the model was analysed using a number of local empirical relationships between erosion and influential factors. The erosion stake Cumulative Erosion Potential values were not significantly related to the PED model scores, but limited results differentiation weakened this approach. The research met two of the three objectives and provided an important preliminary conservation model for the local agencies involved in watershed management.

Contents

1. Introduction

This research introduces the premise that a Geographical Information Systems model (GIS) can be used to predict the location and relative severity of hillslope erosion. The area in which this research was initiated was in the upper basin of the Buff Bay River in the Blue Mountains of Jamaica. The research involved classification by overlaying a range of factors thought to be influential in determining surface erosion. The relative potential erosion of the parcels of land should be seen in terms of conservation and not development. A classification of high erosion indicates the potential situation should the vegetation be removed during watershed development.

Definitions of soil erosion and degradation

Soil erosion is taken to mean the removal of soil from an area by means of water (Philips, 1995), a definition which the FAO (1979) had used for water erosion, one of six processes of soil degradation. A limited definition of degradation is the change of a given soil type to one that is more highly leached (FAO, 1974b, 1976b). Degradation is also defined as a lowering of a surface by weathering and erosion, and deterioration as a result of leaching (Philips, 1995). A number of definitions were provided by Bergsma (1970), one of which is an additional element to erosion, that of material transported downwards. This leaves some original material in place to form new soil horizons through weathering, whilst the transported material may form a soil profile in its new location, on top of a partly weathered surface. Hence, erosion can complicate the task of assessing and classifying a soil profile. Erosion has also become a term for the breakdown of soil structure, surface sealing, and clay and colloid leaching to lower horizons. Degradation has become a byword for soils that have lost their fertility (FAO, 1974b, 1976b), a later redefinition of which was as a process which lowers the current and/or potential capability of the soil to produce goods or services (FAO, 1979).

In a review of soil erosion and land/soil degradation terminology spanning 25 years (MacGillivray, 2002b, appendix 1), the terms themselves were rarely defined. There were 38 references analysed, mentioning 49 terms. Eight authors used terminology which they did not define, while 15 authors defined the terms very specifically. Nine references used the terms and noted the consequences to the study area involved, whilst avoiding quantifiable definitions. There were 13 definitions that confused erosion and degradation according to the FAO (1979) definitions. The other terms were alternatives to erosion and degradation, namely deterioration, damage, worn out and loss of quality. Interestingly, each one was specifically defined. Table 1 shows an example from each category.

Even if definitions were often hard to find, the causes were specified in no uncertain terms. Degradation was variously referred to as an activity, a process, a state, or a condition from which the soil or land suffered. A negative impact or loss was implied. Soil erosion and land/soil degradation were considered ubiquitous, serious or needing to be reduced. The definitions almost always referred to degradation and soil erosion under the same vague explanation of a loss of soil in hillslope areas, through which agricultural production was threatened by visible signs of erosion ranging from topsoil loss to landsliding. The FAO (1985) mentioned degradation, loss of soil fertility and accelerated erosion as separate entities in one introductory paragraph and did not define any of them, using the general term 'erosion' in the following descriptions of group conservation activities.

One of the most useful degradation definitions was provided by Mitchell (1991), in which physical, chemical and biological degradation were treated separately. Physical degradation was defined as the loss of economic potential because of a decrease in porosity caused by compaction and pan formation. Chemical degradation involved chemical changes inhibiting production of economic plants, and includes acidification (pH <6, >10 % base saturation, decalcification), salinisation, alkalization and chemical pollution. Biological degradation referred to a reduction (>10 % annual decrease from top 300 mm of soil) in organic matter content inhibiting production of economic plants, removed by forestry, agriculture, pastoralism, erosion and drainage. Mitchell proposed that these processes could be natural or man-made, but that degradation was apparent only in economic circumstances.

The terms erosion and degradation have become confused because the definitions have come to include a range of processes. For the purposes of this research, the definitions of the FAO (1979) are retained. Soil erosion is presumed to involve the removal of soil particles downslope over (surface runoff) and through (groundwater or seepage runoff) the top of the soil profile, leading to a decrease in soil depth. This is one of six processes recognised as leading to soil degradation.

Relevance of a relative soil loss model

The need to develop simple methods for predicting areas of surface erosion is strong in many developing nations. The data that are available are often imprecise and input costs need to be kept low whilst producing accurate results (Mitra *et al.*, 1998). However, it is not always a lack of good data that thwarts the understanding of the erodibility problem. In an assessment of the erosion problem in Lesotho, Chakela & Stocking (1988)

Table 1. Examples of definitions for erosion and degradation (see MacGillivray, 2002b, appendix 1).

Category of definition	Erosion	Degradation	Alternative
Specific	Removal of soil	Loss of fertility	Structural deterioration and organic matter loss
Consequences instead of processes	Destruction of agricultural land	Non-reversible damage	
Confused	Lost productivity due to leaching and downslope transport of nutrients	Leads to erosion in form of gullies	

realised that the degree of the problem was poorly understood, despite a half a century of awareness of the erosion problem and rainfall records going back 30 years.

Erodibility and degradation indices have focused mainly on the physical properties of the soil, but have been constrained by those factors that can be observed easily in the field. Manpower shortages and time priorities have not supported the inclusion of socio-economic factors (McGregor *et al.*, 1998), despite the importance placed on them. However, the nature of the effects of many socio-economic factors have yet to be determined, as there is debate as to whether certain practices should be regarded as disbenefits, particularly by local inhabitants.

This research proposes a relatively simple, thematic GIS, watershed erosion model based on physical factors. Socio-economic issues are discussed, but only incorporated in terms of assumed tillage activity as it impacts directly on soil erodibility. The most appropriate activity for research is to focus on erosivity and erodibility at watershed level, emphasizing relative erosion classes rather than trying to pinpoint absolute classes of erodible and non-erodible soils. A brief review of physical models is included, a limited number of which include factors like land use, conservation and population pressure.

Contribution to the field of erosion – The Jamaican Natural Resources Conservation Agency was created under the Natural Resources Conservation Act in 1991. It included a Watershed Protection and Management Branch (WPMB) (MacGillivray, 1998a, b). The Watershed Management Committee was formed in 1995 to manage Jamaica's watersheds and to develop strategies to address deforestation. A 'treatment-oriented' land use classification (Sheng, 1972) had been implemented in western Jamaica, but despite this and other various development programmes, there was a general lack of knowledge regarding the present state of the watersheds. The following extracts (NRCA, 2001), five years after the Committee was set up, are revealing:

> "The policy will seek to address the most severe constraints to watershed management and will seek to employ strategies which will ensure the sustainable use and development of watersheds .... Rank each watershed and establish priorities for interventions: A reconnaissance survey, using remote sensing Geographic Information System (GIS) techniques, will be conducted to determine watershed conditions, problems, and management needs in order to prioritize each watershed and identify critical areas for interventions .... Proper land use is the foundation of watershed conservation work. Technical criteria for land capability classification will be established and used .... Given the resource constraints, research activities will focus on applied research. This will include determining erosion rates; identifying the most appropriate erosion control measures; studying farmers' and other land users' acceptance of conservation treatments; identifying incentive needs and effectiveness, etc."

The emphasis was on the development of the watersheds, GIS-based surveys and ranking for 'interventions', a new land capability classification and erosion rate research. Based on the Universal Soil Loss Equation, the local staff were considering conservation measures, despite the fact that it is not applicable in the tropics, where rainfall intensities, slope angles and soil types fall outside the range of conditions inherent in the index.

This research emphasizes the need for a relatively simple predictive tool using GIS. Using factors already acknowledged as influential in erosion (FAO, 1979), a methodology for capturing the data and categorising the array of values is presented. The model produces an image of the watershed in which areas of relatively high potential soil loss are identified given the conditions at the time of data capture. As new survey data are published or new factors are made available, the model can be rerun to give a more detailed analysis of erosion susceptibility.

The calculation of a natural rate of erosion is no longer possible, or perhaps even desirable, in environments where there is a history of subsistence or commercial agricultural production. To determine the potential erosion hazard of parcels of land, the conditions that give rise to high rates of natural soil erosion are combined with potentially erosive land use practices. Attempts to introduce effective soil conservation in Jamaica have been widely unsuccessful (Edwards, 1995), so it is difficult to see why conservation structures should be quantified as a factor offsetting erosion. Determining other influential socio-economic 'causes' of erosion are just as complex. Many of the political and socio-economic factors are regionally effective and intangible.

This research recognises both the limited manpower resources of Jamaican agencies as well as the enthusiasm and external financing available for advanced analysis techniques. For this reason, a model that is sensitive to this shift in investment is to be encouraged. The literature has not revealed a universal model that is this simple to use. The presentation of the resultant data in cartographic form allows these agencies (Natural Resources Conservation Agency and Forestry Department) to determine the potential watershed conditions in the absence of erosion rate data.

Objectives of this research – The purpose of the research was: to identify the climatic, vegetative, geomorphological and socio-economic factors that influence and determine hillslope susceptibility to surface erosion, at the watershed scale; to apply GIS cartographic and analytical modules to classify, map and combine those factors in a model that presents the extent and relative susceptibility of the watershed to erosion; and to initiate a simple field monitoring programme to measure actual hillslope erosion, for correlation and verification of the model results. The model is designed to facilitate watershed management and conservation, rather than development. It is a tool for identifying potential erosion when vegetation cover is not promoted or maintained. At the proposed scale, patches of high and extreme potential erosion are identified assuming the vegetation cover is retained. The need for plot demographics is not necessary until the patches are further analysed in the field for the development of conservation policies. Only then is land use at the farm level identified for contributions to conservation.

Constraints

It transpired, after being accepted for the research, that there was no evidence of Idrisi use by a current member of staff in the Department of Geography, University of the West Indies, Mona, where this project was initiated. A personally financed trip to Clark University in Boston, U.S.A. ensued, for a course in GIS and Idrisi.

Fieldwork was necessary to ground-truth the largely remotely sensed database and verify the current rates of erosion in relation to that proposed by the GIS model. Erosion and soil sampling sites had to be chosen close to the road since large tracts of land were inaccessible or dangerous (specifically drug gangs). Family relocation occurred after two and a half years, curtailing fieldwork. Subsequent visits to Jamaica were not possible because of financial constraints; this entire programme of research was undertaken without grant support. On transfer to the University of Portsmouth, the research philosophy was extended to include a literature review of the socio-economic problems of the Caribbean region and the philosophy of classification to investigate how the physical and socio-economic factors might be incorporated in the model.

The 1:50,000 topographic map was used as the basis for contours, roads, water courses and settlements. Soil boundary information came from a consultancy report, but, without grid references, the watershed boundary was used to match the map to the topographic map. The parameter data for soils were qualitative, the quantitative details of a Dutch consultancy survey (CRIES, 1982) having been mislaid by the Rural Physical Planning Department. Samples were taken for physical analysis, but no facilities were available for chemical analysis. Unfortunately, attempts to procure a cadastral map of the area were unsuccessful and it is not yet known what parameter data are available with boundary information.

The decision to use specific hardware and software combinations for GIS analysis were driven by availability. The raster-based programme, Idrisi (Eastman, 1997, 1999), was the only GIS available. A Summagraphics A3 format digitizer was available in an affiliated department in Mona.

The list of constraints seems endless and it has certainly determined the initial simplicity of the model. However, this project is more concerned with developing a usable model for decision making than identifying precise data sources and actual soil loss. It is to be hoped that a Ministry would have certain powers to acquire data and local manpower with access to areas that are unsafe for graduate students.

Structure

This volume consists of eleven chapters. In the first chapter, surface erosion is defined and discussed as a perceived problem for developing countries in a post-colonial economy. The philosophy of land element classification is included since determining erosion patterns is a form of land evaluation. Chapter 2 describes the processes of erosion, from the mechanics to the identification and measurement of erosivity and erodibility. Cause and effect are identified for physical parameters, but socio-economic factors are also discussed. Chapters 3 and 4 are a literature review of conventional and GIS research that has described soil erosion from the purely descriptive through to process modelling. The Buff Bay watershed is the focus of Chapter 5, with relevant history, physical and vegetative aspects, and an analysis of socio-economic factors relating to local perceptions of erosion. In Chapters 6-8, data collection and the design of the model are described and discussed. The parameter values for the factors included in the model are presented with potential errors and uncertainties. Chapters 9 and 10 present the results of the model run and fieldwork, and Chapter 11 the discussion. Relevant appendices are to be found in MacGillivray (2002b, pp. 235-263).

Challenge of classification: social constructs or natural kinds

The philosophy of land element classification is important for the insights it reveals regarding the political aspects of land evaluation and specifically soil erosion. The purpose of any classification is to create an organisation of the properties and relationships of objects. The process involves the formation of classes by grouping the objects on the basis of their common properties (Cline, 1949). Put more succinctly, the activity of classification involves placing individuals together in mutually exclusive groups defined in terms of one or more attributes of the individual (Higgins, 1977). Classification is an abstract representation of the situation in the field using well-defined diagnostic criteria (FAO, 2000). The diagnostic criteria are required to be scale and source independent.

When the classification of a continuum, like land, is carried out, it is difficult to conceive of discrete forms, although they may appear well delineated in the field. Geomorphology has historically classified land on the basis of a morphological (attributes, form, type) or functional framework (behaviour, suitability, erodibility, productivity). Using these frameworks, researchers have developed classification systems of individual land elements or forms, homogenous entities that differ and can be delineated. Functional classifications have been almost exclusively developed for resource evaluation. Morphological classifications, on the other hand, have been driven by more academic objectives, such as the relationship between form and process. The classification systems Land Systems Analysis and Agro-Ecological Zones have been developed for military and agricultural planning, respectively, whilst some of the physiographic and parametric studies of landform have had purely academic objectives.

The philosophy of classification has helped scientists to understand the concept of landforms. Morphological classifications have assumed discrete categories, the taxonomy of which is refined on the basis of investigating both process and geohistorical occurrences (Rhoads & Thorn, 1996). However, the recognition of 'natural kinds' has introduced a new element of philosophy into geomorphology. Landforms can be viewed as either an objective entity or a social construct according to the philosophical orientation of the scientist. The former, the objective, suggests that individual objects are naturally divided into distinct classes by virtue of intrinsic properties, existing without human intervention. The latter, the social construct, assumes that all objects are brought into existence by human practice (Hacking, 1999), carried to extremes in universal social construction in which it is said that nothing has reality until it is talked about.

Objectivity is essential and assumed in geomorphological classifications, but the results of such classifications are now recognised as reflecting the society of the scientist producing that classification. Research methods are not predetermined. In terms of landform taxonomy, the categories might resist the form given them. For research to progress, this resistance has to be accommodated or the classification modified. The publishing of results is even more susceptible to construction, since the networking efficiency of a scientist will affect the way his proposal is received and accepted as the 'right' model. Therefore, it is essential to uncover the way in which the world is structured independent of human thought, because it forms the foundation of many theoretical generalisations. It is the goal of science to discover the theoretical real essence, causal mechanism, power or process, and to reveal the true structure of the natural world, independent of the context of the enquiry (Rhoads & Thorn, 1996). The question remains as to how pure the essence of theoretical proposals can be.

Hacking (1999) referred to 'indifferent kinds' within natural kinds. This refers to those that might be affected by what a scientist does to them during an experiment, but not because they are aware of the nature of the experiment. Within geomorphology, the experiments using plot boxes to simulate runoff have led to classifications regarding the erodibility of the soil, but extrapolation to other scales of process have had to recognise the indifferent, but affected, nature of the response of soil to plot box conditions. Not all philosophers agree that natural kinds are determined by essential processes, depending as they do on the context of enquiry (Rhoads & Thorn, 1996).

Morphological properties cannot provide the basis for classification because the properties vary in detail among landforms of the same type. This means that existing landform categories are socially constructed, not natural kinds, because beaches, mountains and valleys, for example, do not have real essences and cannot provide theoretical generalisations. The classification of landforms might therefore be regarded as merely a nominalistic exercise, since the basis on which discrete landforms are identified is constructed, rather than determined on the basis of the real essence of natural kinds. The way forward for analysing the landscape, therefore, is on the assumption that surfaces are continuous, that any boundaries are socially constructed and that natural clustering needs to be determined on the basis of the causal processes responsible. Mitchell (1991) was aware of the subjectivity of developing parametric classifications for landforms, especially in the absence of preliminary process studies. In fact, he advanced the idea that a parametric classification of the terrain of a region might highlight process differences.

As if to illustrate the concept of constructs, classification systems may follow one of two approaches. The *a priori* approach is an abstraction of the objects or types occurring, based on class definitions before any data collection has taken place. There is a certain scientific arrogance in apportioning a natural kind to a type before it has been observed. Commonly used in soil science, the classes are standardised independent of the area and methods used, but also rigid, since field samples may not fit into assigned types. The Land Cover Classification System (LCCS) (FAO, 2000) designed a new classification system based on *a priori* principle, with the aim of making it mappable (standardisation and clear boundaries).

The *a posteriori* system has no preconceived notions, since the objects are observed and then classified on the basis of groups of similar attributes. There is less generalisation, but also less standardisation, making it useful for local, but not universal, systems. With this reference framework, the research undertaken here involved classifying land according to the relative potential erosion of the soil. Empirical data were used to determine the upper and lower attribute ranges, but accepting that the process of erosion produces a spatial and temporal continuum of soil loss means that classifying the relative erosion potential of a parcel of land is socially constructed. The literature has revealed some threshold values that can be used to suggest boundaries to the classes, just as previous research has been cited in the determination of processes. However, classifying the resulting values into ranges of relative erosion is an entirely local phenomenon. The model results can be related to fieldwork which not only verifies the classification of relative erosion, but provides the quantitative soil loss ranges within the factorial parameters. That is, its flexibility in adapting to local conditions is the benefit of an *a posteriori* system. In the absence of definitive fieldwork results, the model results can be used to identify areas of potentially high relative erosion in the watershed that might benefit from further investigation. The interpretation of the results is socially constructed since there is a range of reactions to the existence or relative importance of soil erosion.

The problem of soil erosion: development and consequences

It is often difficult to single out the effects of human activity on erosion and sedimentation rates from other variable factors including climatic change and ongoing natural processes. In hillslope regimes there is a level of natural soil degradation that is rarely considered, which is the most complete form of degradation because it depletes nutrient rich horizons, reduces rooting depth and water reserves (Lal *et al.*, 1989). Natural solution has accounted for surface lowering in natural environments, leading to the conclusion that there has been water erosion, whereas the process can be more accurately described as chemical degradation. The prevailing ignorance regarding natural degradation for most environments has led to over-estimates of man-induced degradation. Unfortunately, in these environments it has been practically impossible to measure the natural processes, since so few places in the world have been left uncultivated. Even when an area is designated with some form of protection, such as a wildlife reserve or site of a recreational activity, there is still the former land disturbance to be considered as well as off-site inputs to and outputs from the designated area.

Natural erosion – Lal *et al.* (1989) were strong proponents of the importance of background or natural erosion, and identified a number of natural pedogenic processes occurring in the humid and sub-humid tropics that lead to degradation, including laterization, leaching and acidification. Hamilton (1995) found that natural surface erosion also occurred in forests on steep slopes. The study of gap dynamics (McDonald *et al.*, 1994) of Jamaican tropical moist forests after Hurricane Gilbert concluded that natural surface erosion was low despite frequent and intense rainfall, shallow litter and ground vegetation.

Soil erosion is an essentially natural process in which rainfall, soil conditions, slope and vegetation are the governing factors (Stocking, 1978), but it is difficult to evaluate at the watershed scale because of the modification of most such environments by human activity. Stocking (1978) recognised that man controlled the system by upsetting the steady state. In the era of watershed modelling infancy, when deterministic models were just being proposed, he felt it necessary to test emotive assumptions about the ubiquitous influence that man had on erosion, especially with the complex pattern of local conditions, climatic change and agricultural history in some countries.

As Stocking (1978, p. 129) stated, "Man has long been recognised as an important control variable in the erosion process." However, he was sceptical that all erosion or degradation had to be laid at the feet of indigenous farmers. In a study of population pressure and gully growth in Tribal Trust Lands in Rhodesia, he found no firm historical or statistical evidence that man had caused severe erosion or high rates of gully advance. He cited paternalism for the blame that natives were ruining soil through bad farming, despite an awareness of the erodible nature of the soil and gully formation as a product of natural processes. Man may have aggravated the conditions, "but he was not the principal cause" (Stocking, 1978, p. 130), leading to the contention that other forms of erosion (e.g., tunnel erosion) were natural responses to soil types found.

Accelerated erosion and land degradation – Erosion is termed normal when vegetation cover helps to maintain the natural processes of erosion at the same rate as the weathering processes that replace the soil. Erosion becomes accelerated when the normal balance of this soil system is disturbed. Once vegetation cover is removed under conditions of climate and topography that normally trigger erosion, positive feedback occurs. The soil surface is no longer protected, it is splashed and washed downslope, leaving a difficult environment in which growth can regenerate. Fertile topsoil becomes thinner providing a reduced nutrient base for plants, runoff increases when surface sealing increases and the reduced infiltration can lead to a water supply problem for remaining vegetation.

When an area of productive land is subjected to accelerated erosion, reduced drainage, declining organic matter or disruption to soil fauna and flora activity, degradation may follow. The point at which this occurs is termed the critical limit, or the point at which the soil becomes economically unproductive or unable to support subsistence production. For most agricultural situations, the critical limits of the soil properties are so variable that degradation cannot be predicted. Not only is the level of organic matter critically affecting soil structure unknown, but the most critical property for crop growth is also not known (Lal *et al.*, 1989).

Recent research has found evidence for both natural and man-induced erosion. Ahmad & McCalpin (1999) found significant correlation between deep landslide activity and proximity to fault zones, whilst shallow landslides correlated strongly to proximity to roads. Larsen & Parks (1997) delineated a swathe of land either side of mountain roads in which the highest frequency of landslides occurred. However, such research has tended to simplify the complex nature of hillslope erosion by highlighting the statistically dominant factor accounting for the number of landslide events. At the other end of the scale, laboratories and plot research have been important for identifying both natural and man-induced processes and thresholds, but cannot be used reliably in extrapolation to watershed scales. Meanwhile, few watershed scale studies have taken into account the level of inherent natural processes, or fully incorporated the history of local land use practices, except to describe them in preliminary chapters. An exception was the study of Mejia-Navarro *et al.* (1994), who incorporated a factor called historical record into their algorithm to predict debris flow susceptibility.

Development statements focus on sustainability, for example, the "[agrosystem] ability to meet evolving human needs without destroying, and if possible improving the resource base on which it depends" (Committee on Agricultural Sustainability in Developing Countries, 1987). However, land resources are so unevenly distributed on a global scale that assertions that a minimum of 0.5 ha arable land per capita is necessary for survival become meaningless, especially in the face of present estimates suggesting that available land resources will be 0.23 ha arable land per capita by the year 2000 (Lal *et al.*, 1989). Blaikie (1985) determined that natural and accelerated rates of soil loss should be distinguished so that political-economic conflicts about the causes of erosion could be resolved. A model in which the potential for natural erosion was predicted would be an important tool.

Rates of hillslope erosion are commonly cited as extrapolations from field experiments, with all the dangers of interpretation that involves. However, a natural rate of erosion would be no more useful in determining the suitability of land for agricultural production or even subsistence farming. For example, Lal *et al.* (1989) derived the magnitude of soil erosion from croplands for Jamaica of 90 t/ha/yr. The Universal Soil Loss Equation (Wischmeier & Smith, 1965) was applied in Jamaica in the Yallahs Valley (GOJ/UNDP/FAO, 1982) and a range of 160 to 280 t/ha/yr calculated. As McGregor (1988) suggested, the wide variations in soil loss estimates can only lead to general indications of plot-based erosion, at about 120 t/ha/year from agricultural land, which is not a reflection of catchment-wide rates. Such figures, even for international comparisons, have little practical application. Even the relatively detailed approach of sediment delivery ratios (SDR) does not identify the areas in a watershed that are eroding, depositing and maintaining a fragile equilibrium, since the SDR represents only the net results of all the processes going on upstream. In a more accurate, but no less alarming, analysis, nearly a thousand tons of suspended sediment was estimated from the Rio Pedro watershed (Sheng, 1986). Only 12.5 % of the watershed was being cultivated under annual crops (the rest under forest, food forest and grassland) and further analysis revealed that 60 % of the sediment was from the crop area.

A factor that features in some analyses of soil erosion is the 'Tolerable Erosion Rate'. This is the maximum rate of soil erosion while still permitting sustainable, high level productivity. This rate is equal to soil formation which varies considerably according to climate, geology and biotic activity. The 'Tolerable Erosion Rate' is not set for Jamaica (McGregor, 1995), but soil formation rates act as a surrogate. Sheng (1986) quoted a soil formation rate of 10 t/acre/year whilst McGregor (1995) suggested 10 t/ha/year. Since 1 acre is 0.33 ha, it is a significant difference. Interestingly, 10 t/ha/year was quoted for Costa Rica (Hall, 2000). It is hard to imagine, along with other 'national erosion statistics', what is the purpose of such a figure and from whence it was extrapolated. Morgan (1986) suggested that soil losses of 25 t/ha/year were 'sustainable' in areas of mountainous terrain with high rainfall. Sheng (1986) also stated that any conservation measure that could reduce erosion to that rate would be considered acceptable and appropriate for development, and McDonald *et al.* (1996) certainly considered that hedgerow intercropping brought erosion rates (4t/ha/yr) to below stated 'acceptable' estimates. This in itself is further evidence of a scientific approach to a much more complex socio-economic problem. Firstly, average figures are applied to areas of intense fragmentation and complexity. Secondly, the needs of the farmer, who may have no evidence of erosion on his plots, are more likely to be related to farm supplies and transport to markets. Thirdly, it is assumed that the quality of the weathered soil is the same as the soil lost, with no account of the non-linear development of soil. Finally, the subsequent land use classification takes no account of the intangible value of the plot to the farmer, that of social status or family inheritance.

Issues of sustainability in developing economies – It has taken the failure of technical soil conservation innovations to encourage researchers to look for deeper-seated causes of erosion. Since the available practices have proven ineffective in many extension aid projects, Hudson (1981) reasoned that they must be inappropriate. Soil erosion is controllable by reducing the effects of rainfall, topography or maintaining vegetative cover, so the problems caused by soil erosion must be socio-economic (Stocking, 1983). Both Stocking (1972, 1983) and Blaikie (1985) commented strongly on the 'current conventional wisdom' about soil erosion and the 'blinkered exclusion' of political systems. Meikle (1998) noted that decision making processes of farmers were poorly understood and extension agencies were seen as saviours rather than consultants.

The dimension of socio-economic concerns for small island independent developing states (SIDS) has tended to fall outside the sustainability debate, partially because of the complexity of an uneven and discontinuous economic geography in Caribbean territories (Douglas, 2003). There were major objections to the assumptions regarding sustainable development for future generations. Firstly, island peoples were socially and economically differentiated and excluded, and hence there was no consensus. Secondly, the low income and subsistence base of many of the population led to income differentiation, so that resource usage was exploitive or extractive rather than sustainable. Thirdly, the concept that present generations pay compensation to future generations by reducing consumption was irreconcilable with the status of the present generation which had less than was being proposed for future generations. This often involved clearing land to create employment opportunities, provide food and improve the infrastructure, many of which damaged the environment to secure a sustainable socio-economic structure. The concept of sustainable development was not only influenced by the status of the present generation, but by external ownership, markets and economics. Hall (2000), among others, has asked if sustainability can be applied to tropical nations, with their history of exploitation and consequent impoverishment that came from paying for imports. Attitudes still prevalent in some SIDS include an acceptance of public debt, the need to earn foreign exchange, the desire for non-sustainable imports, particularly food, to the detriment of the home production system and even the dependance of ecotourism on non-sustainable cheap flights (Hall, 2000).

The 'colonial' model and market economics – Stocking (1983) conceded that, whether intentional or not, the farming methods, conservation acceptance and encouragement to produce a marketable surplus were all factors that had a major role to play in determining the extent of soil erosion. In Zambia, he highlighted the gap between the entrenched poverty of subsistence farming and the strained economics of commercial farming in a classic developmental conflict between capitalist strategies of concentration of limited resources to well developed productive enterprises and socialist policies of spreading the benefits of development to the poorest. After independence, the new government withdrew the preferential conservation treatment for European farmers and dismantled the legislation applied to African farmers. One environmental consequence of the colonial model (Blaikie, 1985) was that monocropping of maize and cotton were particularly vulnerable to soil erosion because of the poor plant cover properties. In contrast, the traditional village garden interplanted with vegetables was relatively safe from soil erosion (Wiersum, 1984).

Interestingly enough, commercial farmers motivated by highest yield for lowest cost had little environmental perception outside the immediate dangers of loss of fertility and erosion (Meikle, 1998). Subsistence farmers, on the other hand, were generally aware of resource conservation and applied methods to lessen personal risk (Davis-Morrison, 1998). This suggests that where soil conservation measures are more likely to be maintained where they have a tangible benefit to the individual farmer.

The Jamaican situation – In Jamaica, attitudes to the land are either market driven or based on individual survival. Since the 1950s Jamaica has received a range of assistance from bilateral agencies, which Blaikie (1985) asserted originated from the colonial rulers' political and economic interests. As the pressure on agricultural land in Jamaica has increased it has become necessary for farmers to cultivate more intensively, both legally and illegally. This further marginalised subsistence farmers who were then blamed for the erosion. Land that was formerly recognised as erodible was reclassified as vulnerable (Sheng, 1972), in recognition of the need to cultivate it, but with conditions of use attached. However, the conditions imposed by various agencies have proven to be overwhelming for small farmers. The terracing and drainage structures seen in many projects have rarely been maintained after the initial financial incentives have disappeared, mostly as a result of labour shortages and fragmentation, rather than indifference to their usefulness (Spence, 1989).

An analysis of the history of cultivation on Jamaican hillsides has revealed a varied rate of soil loss, but it is generally agreed that the coffee estates of the eighteenth century lost all their topsoil and traditional yam cultivation produced losses of between a quarter and a half an inch a year (Edwards, 1995). The land use problems of Jamaica were occurring because the land capability limits were being ignored (Sheng, 1972). Land that could be protected by prescribed structural measures was cultivable if treated accordingly, although such land could be released for less intensive use, but not overused as cultivated forest. Land that could not be treated (because of severe erosion, stoniness, wetness) was classified as forest, pasture or agro-forestry, but all land over 30° (and between 25° and 30° with problems) was classified as forest. As a result at least one valley with a high proportion of steep slopes under annual crops was experiencing severe erosion, which could have been avoided if the project policy had followed the criteria. The tradition of clean cultivating the land for subsistence crops had been passed down the generations. Sheng thought the solution was to help farmers protect and improve the land, rather than move them off it. He was circumspect in noting that removal of farmers was neither likely nor feasible.

This system produced a very fragmented map of suitable land use in western Jamaica which Sheng did not attempt to correlate with the tenure boundaries since the squatters were being resettled and had no ownership. Activities such as agroforestry, horticulture and animal husbandry commonly produce returns near subsistence levels, whereas the forest, coffee plantations and small farmers are competitive for the Blue Mountain area, and these activities were not complementary to those of the Water Commission. The pressure from agencies to intensify these activities might be feasible within the physical constraints and improvements suggested by Sheng, but not the socio-economic constraints of these environments.

Edwards (1998b) cast a rather different light on the proceedings with the first phase of soil conservation (1950s to the 1970s) promoting relatively simple practices, not capital intensive structures. Sheng (1972) argued, from a Taiwanese background of high population pressure and another cultural framework, that Jamaica could not indulge in keeping away from steep slope cultivation and a land capability classification, which involved capital intensive measures to make the steep slopes cultivable. Hence, Edwards saw Sheng as introducing non-sustainable concepts to the development and erosion control of Jamaican hillslopes, while Sheng regarded these concepts as essential to the survival of the country economically.

Review – The 'colonial' model that Blaikie (1985) described is exemplified in the Zambian and Jamaican histories of conservation extension. Unfortunately, many of the projects being adopted recently have shown similar trends (MacGillivray, 2002b, appendix 2). The 'colonial' model, which Blaikie vilified, saw the land user as ignorant and the State as neutral, whereas each State was partisan by nature (Blaikie, 1985). Soil erosion was proposed as an environmental, not a socio-economic, problem. Additionally, the bilateral agencies always had narrow aims and were steered towards benefitting the State, not the individual farmer. This agrees with the assessments of Hudson (1981) and Edward (1998b) of 'clientelism'. One other major assumption of the model is that the objective function of land is capital accumulation or profit-oriented. There is no room for subsistence economics.

As far as Blaikie was concerned, the soil degradation and erosion prevalent in many developing economies could be explained in terms of surplus extraction, that is, cultivators in the colonial setting producing crops for cash. He also pointed out that spatial marginalisation of the type that occurred in Zambia and Jamaica seldom occurred on their own, but were accompanied by other forms of subordination and disruption. In the two cases mentioned by Edwards (1995) and Stocking (1983), this could be seen in 'setting aside' Crown lands, tourist development on previously agricultural land, protecting steeplands by reserving forest areas and only offering assistance to 'exporters', further marginalising subsistence farmers. In the bilateral aid project taking place in the Rio Grande in Jamaica (Meikle, 1998), aid was only available to those with secure tenure and those participating in banana or dasheen for export experiments.

2. The identification of erosion processes

> "Erosion hazard is not a survey of actual erosion; it is simply a way of describing the natural propensity of an environment to allow soil erosion to happen" (Stocking, 1987).

Designing a model to predict where soil erosion is going to occur requires three theoretical steps. The first involves the mechanics of erosion, the process of soil particle detachment and transport. The second step is to review how traditional and modern methods have identified and presented the spatial pattern of soil erosion. The third step is concerned with the factors that trigger soil erosion. Land that has been modified by man may be managed in such a way as to accelerate or reduce soil erosion. When the most influential factors are isolated they can be included in a model. Some work has been done in isolating these factors and some research carried out to test their relative importance. This research is also reviewed below.

A common definition (FAO, 1976b) of erosion implies that sufficient vegetation cover maintains the balance of erosion and weathering so that no net loss is experienced. This research presumes that this applies to soil budgets at larger scales, like the watershed. There may be areas in the watershed, like banks and slope toes, where there is a net loss, but higher on the slope topsoil can be increasing, a net gain. By inference, vegetation cover only has to be sufficient for the local conditions of climate and topography. However, measuring these conditions is very difficult. Under natural conditions of cover it takes 300 to 1000 years to generate 25 mm of topsoil (FAO, 1976b). However, some bedrock types under tropical conditions might weather faster, providing that water penetrates to the bedrock face and is not lost to runoff on high angle slopes. A weathering rate of 10t/ha/yr has been quoted for the tropics (Hall, 2000), the equivalent of 0.6 mm/yr, taking less than 50 years for 25 mm of soil to form.

The mechanics of tropical soil formation and soil erosion

Erosion is a product of erosivity and erodibility. The potential ability of rain to cause erosion is called erosivity, whilst erodibility is defined as susceptibility or vulnerability of the soil to erosion. Erosion encompasses a number of activities, from surface wash to mass erosion like landsliding. This research concentrates on surface or sheetwash erosion, as a product of surface runoff.

Surface wash is the term that describes the processes of sheetwash and sheet erosion, defined by Bryan (1991) as “the removal of soil from extended surface areas without apparent concentration along surface drainage lines.” This type of erosion by water involves the particles of soil becoming detached by raindrops and then transported by running water. There are forces that promote and resist these activities. These are variously referred to by researchers as the erosivity of raindrops, tractive force of running water and the surface resistance of soil particles. Since surface wash rarely takes place over an homogenous surface, it has a variable depth, to the point where it becomes rill erosion, thought to be the most common situation on most hillslopes (Bryan, 1991). However, not all surfaces develop a rill or gully system, suggesting that although erosion may be active, the balance between the resistant and tractive forces is such that defined channels do not develop. There is also a temporal factor which includes the changing cohesive nature of the soil surface within a rainfall event, as well as over longer periods, and the ongoing agricultural activity on many hillsides that effectively replaces a rill pattern with an unpatterned one during the tillage activities.

Defining and measuring erosivity

The intensity and frequency of rain events are more important than annual or monthly totals in terms of erosivity. Erosivity is expressed as the kinetic energy of the rainfall, which is a function of intensity and duration of the event as well as the mass, diameter and velocity of the raindrops (Morgan, 1979). Potential and kinetic rainsplash energy released by raindrops causes the dispersion of soil particles and the destruction of aggregates. Raindrop energy, for example, is proportional to the soil detached and transported in runoff (Morgan, 1979). Clay disperses and seals pores causing absorption to decrease and overland flow (in conditions of negative pore pressure) to occur. In such a situation, the degree of erosion may be detachment limited, where crusting limits the entrainment. Alternatively, it may be transport limited where loosened soil is left by insufficient volumes and velocities of runoff. Various studies have investigated the relationship with varying degrees of complication (Hudson, 1965; Kinnell, 1995). Characteristics that are often used as surrogates for energy are intensity, raindrop mass and terminal velocity. These can be determined from drop mass and size, size distribution and direction, rainfall intensity and rainfall terminal velocity. Govers (*in* Bryan *et al.*, 1989) referred to the debate about whether rainfall kinetic energy rainfall momentum, or yet another property, determined its capacity to detach soil particles.

Raindrops are potentially more erosive than overland flow, but friction plays an important part, limiting expended energy on erosion to 0.2 % for raindrops and 4 % of runoff (Morgan, 1979). The terminal velocity of raindrops is reduced by interception by vegetation, whilst runoff encounters surface roughness. In a review of surface flow and sediment yield in forested tropical areas, Thomas (1994) noted that sediment was not always entrained by rainsplash because canopy and litter cover rendered raindrops ineffective. Splash erosion occurs if water forms a layer more shallow than raindrop diameters; otherwise, energy is dispersed in deeper flows. Rainsplash compacts bare soil on impact, but causes particles on the periphery of the drops to dislodge and disperse, which in turn disperse others. There is disagreement as to whether it is fine- or medium-grained sand particles that are detached, since clay particles are chemically bound and resist such forces (Morgan, 1979). Where the dominant particle size is less than 0.5 mm, erosion velocity flow exceeds fall velocity (Thomas, 1994). These fine-grained particles are easily mobilised by low flow, whereas larger particles (>1 mm) are transported as bedload.

Runoff erosivity concerns the transportation of loose material by turbulent water. Rain infiltrates into the soil during the initial period of many rainfall events. The capacity of the soil to absorb water decreases until it becomes less than rainfall intensity (Bergsma, 1970). Surface storage exceeds surface retention capacity and surface depression storage, and runoff begins, which can start and stop many times during unsteady rainfall events. The only situation in which this does not happen is crusted or sealed surfaces. Since the surface is usually rough, the water flow is braided, the nature of which can be represented by Reynolds (Re) and Froude (F) numbers. The more turbulent (Re>500) and rapid (F>1), the more erosive the flow. The essential element is velocity since it is proportional to the size of grains entrained. Merel & Farres (1998) showed the importance of recording soil aggregates and rock fragments as factors in surface roughness and subsurface soil protection. The runoff coefficient (or coefficient of impermeability) is the ratio of the amount of rainfall which runs off a given surface. Grassland (5-30 %) and woodland (1-20 %) have fairly low ratios. However, these figures are influenced by antecedent soil moisture, slope and internal depth to bedrock (which at a depth of 100 mm can result in 95 % runoff coefficient). Thomas (1994) reviewed a number of forestry studies, finding a range of runoff coefficients from 0.5 % (pine forest, 14° slope, 2000 mm annual rainfall) to 47 % (forest, 19° slope, 4000 mm annual rainfall).

There are disagreements about patterns of runoff (overland flow), and the extent and distribution within a watershed under different vegetational environments (Table 2). Horton (1945) described an overland flow pattern during the peak of a storm, based on infiltration capacity exceeded, the rate of which was determined by soil structure, texture, vegetational cover, soil moisture content and soil surface condition. The crest of the watershed was free of erosion within a zone downslope until sufficient volume and velocity had been reached to initiate rills, after which more than two thirds of a slope would be experiencing infiltration capacity overland flow. Morgan (1979) suggested that, under close vegetation, overland flow was more closely related to soil moisture capacity being exceeded than infiltration rates. Runoff and erosion are also affected by the shape of the slope, but occasionally results are unexpected. In the Belgian Loam Belt (Vandaele *et al.*, 1996), most severe erosion (surface lowering) occurred at the top of a slope and on the convexities, whilst deposition occurred at the bottom of the slope, on the concavities and the concentration line. This was not expected from water erosion processes and tillage was suspected as the cause.

Table 2. Arguments for and against the presence and causes of overland flow.

For	Presence and causes of overland flow	Against
	Surface detention and overland flow rare on steep slopes	Bryan (1989)
Horton (1945)	Infiltration capacity exceeded	
Morgan (1979)	Soil moisture capacity exceeded	
Chatterjea (1989)	Perched water table despite rainfall interception	
McGregor (1988)	Upper horizon higher soil moisture (perched water table)	
Hamilton (1995)	Impeded internal drainage and surface sealing	

Bryan *(in* Bryan *et al.*, 1989) suggested that sheetwash could not be the dominant process since surface detention and Hortonian overland flow were rare on steep slopes under natural vegetation, although the relative frequency of surface wash under natural conditions was lower, not absent. Chatterjea (1989) found evidence in the rainforest of Singapore to the contrary and in support of Horton. Treefalls occurred on steep slopes due to considerable surface and sub-surface water, which occurred despite high levels of rainfall interception. He found that during high intensity storms, a temporary or perched water table emerged to become saturation overland flow. This research was not contrary to Morgan, since Chatterjea admitted that the closed canopy precluded ground cover and high slope angles had no leaf litter. McGregor (1988) found that sandy lower horizons (rapid throughflow at depth) and deeper soils seemed to coincide with a perched water table, although runoff totals were not particularly high.

Since Bryan *(in* Bryan *et al.*, 1989) referred to a significant volume of research regarding the importance of subsurface flow, the conditions to which Chatterjea referred may be unique. The nature of the vegetation is certainly important in these various studies. The difference between agricultural and non-agricultural soils can be seen mainly in the top horizon where the latter exhibits a better developed structure with a higher proportion of void ratios. The properties of agricultural soils differ from each other depending on parent material, tillage and crops, but it was generally stated by Bryan *(in* Bryan *et al.*, 1989) that the original open structure of the upper horizons was replaced by less stable secondary aggregates, fewer macropores and a prevalence of sheetwash. Initial surface entrainment forces were resisted on disturbed soil by primary and secondary aggregates, rather than the whole surface under natural conditions.

Bryan's argument that an increase in infiltration is higher and, hence, surface flow rare in non-disturbed soils is persuasive, but the research of Chatterjea was also supported by Hamilton (1995). He referred to overland flow resulting from impeded internal drainage under natural forest, during high intensity or prolonged storms. The absence of ground cover and the coalescence of raindrops had sealed the surface, whereas canopy cover, leaf litter and deep root systems tended to protect the hillslopes from gullying and shallow-seated mass erosion. Remote sensing would have recorded the area as close vegetation and surface flow would not have been inferred. Certainly, Fournier (1967) found that six years of groundnut cultivation led to decreases in the soil stability and permeability, showing the importance of cohesion and stability of soil aggregates as factors affecting runoff and soil erosion. This suggests that, unless well cultivated soils have porosity restored by tillage and sustainable land use techniques, overland flow and, hence, erosion is common on slopes with agriculture. Hortonian overland flow is also not unknown under natural conditions, without the need for high levels of antecedent soil moisture. There is evidence to suggest that surface wash occurs in non-disturbed, closed canopy conditions, not usually thought to represent a hazardous erosion environment (Hamilton, 1995). The vegetative structure of forests, and particularly understorey presence, is an important aspect in this respect.

A problem particular to the use of rainfall in erosion prediction is its spatial variability. This makes interpolation particularly unreliable since weather is observed only at specific points (weather observation stations), yet certain characteristics of weather need to be quantified at any point in the evaluation area. Numerous studies have attempted to quantify this using sophisticated measuring devices and complicated mathematics (for example, Reyes & Gayle, 1995). There have been recent advances in sensors and data processing aimed at complete area weather knowledge. The NEXRAD weather radar in the U.S.A. operates continuously, covers the entire lower 48 states and is calibrated to give reliable rainfall amounts on a grid size of about 1 km^2. Geosynchronous ('stationary') weather satellites can already provide cloud cover data and some information about cloud type continuously on a 16 km^2 grid. These continuous and relatively high resolution data present significant problems of information storage and processing. Simulated rainfall cannot mirror the complex internal turbulence and angle of rainfall, hence the relatively simple measure of timed intensity, on which many indices of rainfall erosivity are based. For example, local topographic conditions in tropical steeplands with a paucity of rain gauge equipment make both the temporal and spatial climatic factor highly unpredictable.

The estimation of rainfall at a point or for a region not sampled can be interpolated on the basis of the nearest sampling station, but, of course, the station network may not be very dense in some countries. Information from the stations with a record can be manipulated four different ways. The easiest method is to assume the rainfall is the same at the unsampled point as the nearest station. The second method is to take an unweighted average of nearby stations that are presumed to have the same rainfall regime. There is a third method in which a weighted average of nearby stations is taken and, finally, it may be possible to construct an isohyetal map and interpolate the value for the point between the isohyets. The advantage of isohyets is that they can be drawn both from station records and from knowledge of terrain, including elevation, aspect and local effects, such as lakes and gaps. The disadvantage is that they require specialist knowledge (Rossiter, 2000).

Direct measurement – Direct measurement involves observing how much erosion is caused by a particular storm using experimental plots. The elimination of soil factors is a prerequisite to obtaining erosivity relationships. For assessing 'splashability', that is, the ability to cause detachment, Ellison-type splash cups were recommended (Hudson, 1977). A carefully controlled series of experiments in Africa showed an equally precise correlation obtained between erosivity and erosion, whether measured by splash alone, splash and run-off (Free-type soils pans) or field erosion plots. Another method involved simulated rainfall, measuring raindrop size, terminal velocity and raindrop intensity to calculate momentum and kinetic energy, since kinetic energy increases with rainfall intensity (Hudson, 1977).

Indirect measurement (from existing rainfall data) – Fournier (1967) proposed the relationship p^2/P between annual rainfall (P) and rainfall of the wettest month (p). He regarded indices dependent on calculations of the erosivity for each storm (and the total of all events or an annual value) useful for research, but less accurate as a guide to actual annual rainfall. He developed this guide to annual erosivity which was still empirical and not reliable outside the region where it was devised. Chakela & Stocking (1988) found it necessary to verify the relationship between rainfall quantity and energy, and apply the relationship to mean annual rainfall data. Once the mean seasonal energy was calculated directly for four stations representing lowland, foothills and mountains, it could be applied to the isohyetal map of the country. Despite lower rainfall erosivity in the mountains, where drizzle and light rains were common, the erosion hazard was very high. Steep slopes, high quantities of rain, poor lithosols and average vegetational cover accounted for this, which reiterates the point that erosivity indices are not always the most appropriate measure.

Monthly precipitation has also been used in place of the erosivity index from the Revised USLE (RUSLE), for countries where long term rainfall intensity data are not available (Renard & Freimund, 1994). The important process was establishing a relationship between the calculated RUSLE erosivity values and the monthly totals. For example, the correlation between RUSLE and annual average precipitation was not significant at rainfall stations on the coast of the U.S.A., whereas the correlation was better at inland stations. Stations exhibiting a uniform annual precipitation or dominated by summer precipitation showed very high correlations. In another example, the lack of rainfall stations with intensity data led Yu (1995) to use daily rainfall amounts in the wet season saturated watersheds in the west tropics of Australia. The relationship between his modified erosivity factor and erosion was found to be close when comparing annual sediment yields for two river basins.

Wischmeier & Smith (1978) developed EI_{30} on the basis of multivariate field-plot data in the U.S.A. to determine soil loss in terms of rainfall. It required the identification of the greatest average intensity in any 30 minute period during a storm. The relationship was empirically derived from regression analysis and EI_{30} merely gave the best fit. It was a function of the kind of storm and not applicable elsewhere, and required a considerable network of automatic rain gauges. Cooke *et al.* (1998) developed EI_{15} & $EI_{7.5}$ specifically for tropical situations because of the shorter intense periods of rainfall. Harden (1990) referred to research in Ecuador which showed that tropical rainfall amounts were highly variable, whilst the duration of relatively intense storms (I_{30}>20mm) was typically less than 15 minutes, an event not preserved in rainfall data. Lal (1976) developed AI_mV for tropical instances similar to EI_{15}. A is the amount of rain in a storm with maximum intensity I_m, while V allows for the increased terminal velocity of rain accompanied by wind.

Hudson (1965) noted that rain falling at intensities > 25 mm/hour was the threshold at which point erosion started to occur, hence the index KE>25. Research had shown that African conditions varied considerably from temperate regions (where 10 mm/hr was later determined as the critical threshold by Morgan, 1979). Later work by Hudson (1971) compared the intensity and kinetic energy relationship for thunderstorms; a sharp rise in kinetic energy was found for low intensities to around 50 mm/hr, after which the rise in kinetic energy tapered off.

Review – The surrogates for rainfall energy that have been reviewed take account of the historical temporal rainfall patterns where records exist. Cooke *et al.* (1998) highlighted the shortcoming of some of these indices in their reliance on automatic rainfall gauges, which are few and far between in tropical areas. Where they are available, they are often stored on strip charts that are difficult to interpret. They developed a computer modular programme to digitize existing rainfall charts to determine breakpoint rainfall (important for determining intensity periods). Morgan *et al.* (1984) took into account factors like annual rainfall, number of rain days, rainfall intensity, percentage rain intercepted and evapotranspiration, thus increasing the importance of the climatic factor considerably. However, at the watershed level and in areas where automatic gauges are not available, the most appropriate index for the tropics has to be based on rainfall quantities, annual, monthly or daily, according to the supply of data.

With the advent of geographical information systems, advances have been made in the use of other surrogate parameters for mapping erosivity. For example, Goovaerts (1999) used elevation (from a DEM) and geostatistics to map monthly and annual erosivity in Portugal. As an indicator of antecedent soil moisture status, and hence runoff potential, potential evapotranspiration (PET) was calculated for eleven locations around Jamaica and showed a linear relation with altitude, which was then extrapolated to the other stations (Batjes, 1994). Since long term monthly averages showed a linear relationship with temperature (measured at only 22 stations), extrapolation was also carried out to the other stations. Monthly rainfall data were collected from stations with continuous observations for a minimum of 20 years and an algorithm for normalizing skew rainfall data was incorporated for low rainfall areas with some extreme events.

Defining and measuring erodibility

Erodibility is defined as susceptibility or vulnerability to erosion, the reciprocal of resistance to erosion (Hudson, 1977). Care should be taken when using this term, since it can refer to the soil entity, the sensitivity of an area or the management factors affecting erosion. The four main factors involved are soil texture, soil structure, slope and cultivation. There are many factors influencing the nature of physical soil properties and the change in these over time. Many properties are intrinsic and assumed in many studies not to vary significantly in time, whilst others, like the hydrological properties, are dynamic and transient. Bryan *et al.* (1989) suggested that erodibility was a practical rather than theoretical concept which was poorly defined as a result. Since the typical soil erosion experiment has involved shallow slopes, agricultural soil and field scale, the dominant subprocesses of sheetwash and rainsplash had been incorporated, to the detriment of others and hence limiting the usefulness of any resulting index.

Direct measurement (runoff plot and plot box) – Bryan (1991) reviewed the many runoff plot experiments in the U.S.A., Africa, South America and Europe, and concluded that a number of problems arose from them. Firstly, the conversion of collected soil weight into an erosion rate was at best an estimate since the source and bulk density of the original soil was not known. Secondly, the construction of plot boundaries meant that sediment replacement from upslope was ignored, leading to the presentation of each plot as erosional, not depositional, and causing overestimation of the rate. Thirdly, the use of simulated rainfall made such research only strictly comparable with other plots under simulated and not natural rainfall, although inappropriate comparisons did occur. Hudson (1965) concluded that with the exception of the extensive USLE studies carried out in the U.S.A. during the 1930s, runoff plot studies were only applicable to the particular soil under local conditions and not only represented a short time period, but also a restricted spatial one, with little opportunity for extrapolation or prediction.

Boardman & Favis-Mortlock (1993) referred to the inability of plot studies to reproduce the conditions found in fields. This was emphasised by the severe erosion occurring on agricultural land as a result of relatively low rainfall intensities, which isoerodent maps based on the USLE failed to predict. Rainfall intensity appeared to be less important than quantity and erosion was commonly the result of low intensity rainfall. A log-linear relationship was observed between the RI and soil loss, and total soil loss for each of the erosion seasons measured. The timing of rainfall events turned out to have an important influence on the fit of the regression line, a factor rarely incorporated into other indices, but important where seasonal vegetation cover varies considerably in the ground cover (and sowing and cropping techniques employed) provided by the crop. The weighted RI was good at predicting the number of sites at which erosion occurred and the total soil loss, whilst the maximum daily rainfall produced the highest correlation with median soil loss.

A considerable body of plot box research has been carried out in Leuven in Belgium, on the basis of field studies in Africa. Bryan (1991) reviewed this and Australian research, noting how the researchers came from quite different directions to collectively provide information regarding rill initiation. With regard to the general state of plot box research, Poesen *(in* Bryan *et al.*, 1989) named the lack of standardization as one reason that soil erodibility experiments were not comparable. The plot box size determined the interrill-rill relationship, the intensity of the erosion processes, the mean splash distance, water losses from the box by splash and the sediment output. One of the most meaningful variances between experiments was soil depth. The evolution in the soil surface moisture through time was dependent on the depth to plot box bottom (and the effect this had on capillary pull at the moist front), and would cause serious errors if the soil loss results were extrapolated to field soils with greater depth.

Indirect measurement – The indirect method of measuring erodibility involves soil property isolation in the form of an index. Hudson (1977) suggested that it was unlikely that any one measure of erodibility would account for the separate properties of resistance to splash (detachability) and resistance to surface flow (transportability). Field experiments could not control variable erosivity, whilst laboratory experiments could not emulate the nature of the soil in the field with all the external factors of water table, soil moisture in adjacent plots and the drying effects of turbulence, leading Renard (1997) to state that it was unlikely that a few soil properties would accurately describe K values for each soil.

The texture and structure of the soil is more complex than an index can imply. Theoretical data are not easily measured in the field and the slopes in a watershed are complex. There is a mix of surface grain sizes, heterogenous surfaces and complex soil moisture patterns. However, research has highlighted some basic tenets of soil physics which can be used as indicators of erodibility. The following division of research into soil property themes is arbitrary and a degree of overlap is unavoidable.

The texture of the soil influences a number of processes, such as infiltration, moisture content, cohesion, pore pressure and nutrient availability, and hence other factors such as vegetation type, root structure and, ultimately, erodibility. The texture of the soil on a slope will also change over time at the different horizons, due to the downslope movement of transportable fractions. The positive feedback mechanisms that are thought to accelerate erosion are related to soil texture.

Fournier (1967) recognised from his own research in Africa that extensive fieldwork had not enabled him to draw any conclusions on the erodibility of soils. However, he identified a number of soil parameters, namely structural stability, permeability and texture, that he thought pertinent to erosion studies. Sandy soils were known to erode given sufficient runoff, because their structural stability was low. Declercq & Poesen (1992) predicted higher erodibility for coarse textured soils with higher organic matter (OM) content. This was explained as the water repellent effect of OM on very sandy soils. However, Merzouk & Blake (1991) found that soil loss decreased with soil material > 2 mm on the surface. This was thought to be partly due to high infiltration rates in the coarser-grained soil, but also the protective mulch-like property offered by the larger aggregates. However, the indicator with the highest correlation with erosion was the textural term (% soil material > 2 mm + % sand).

Fine textured soils are dominated by clay particles (<0.002 mm) which can resist erosion to the same extent as particles of 10 mm, due to chemical cohesiveness. Bryan (1968) concluded that although fine aggregates could be moved by low velocity runoff, dispersed materials were more easily eroded, such as those with a high silt content (Morgan, 1979), specifically those with 40 to 60 % silt (Richter & Negendank, 1977). Sharma *et al.* (1995) found soil detachability was inversely related to clay content due to the effect on soil strength and aggregate stability. However, sediment transportability increased linearly with clay content. Where clay content was less than 30 % they found significant differences, the detachment rates being higher for sandy soils. This was attributed to particle redistribution within the interrill area, whereas the transport mechanism was efficient in removing fine textured soils.

The USLE measure of erodibility is based on the percentage of silt and fine-grained sand, higher values of which give high erodibility values. The equation is not feasible for silt content higher than 70 % and in well aggregated soils. The K factor developed by Declercq & Poesen (1992) took aggregation and textural extremes into consideration by calculating K(Dg) which was based on geometric mean particle size (GMPS). This correlated highly with OM, so that if OM and GMPS were known for a soil, the model became much more accurate.

Bryan (1968) reviewed soil dispersion properties in terms of usefulness as a measure of erodibility. The silica-clay ratio is a general index used by the FAO (1976b) to indicate the structure. Clay absorbs water and links particles, leading to the conclusion that older soils erode less, having a more weathered and hence higher clay content. However, clay soils crust which increases surface runoff, the volume and velocity of which increase entrainment of fine-grained particles like silt.

The dispersion ratio (DR) (Middleton, 1930; Cooke & Doornkamp, 1990) in which silt plus clay in an undispersed sample is compared as a percentage with that in a dispersed sample was developed around the concept that only dispersed material can be eroded. Erodible soils gave values of above 15 %, but Bryan disliked the reference to non-erodible soils, preferring relative erodibility. He also criticised the lack of consideration for dispersal by raindrop impact and that sandy soils were poorly represented.

Clay ratios, as a measure of material binding, were also devised (Bouyoucos, 1935), but found to be unreliable when compared to field observations, whilst Bryan (1968) criticised the clay ratio for instances when clay content was low and because OM was not considered as a binder. By the 1950s, many studies were focussed on aggregate size, rather than formative-dispersive properties and many ratios were devised. If aggregates were low in important textural components then certain indices would give poor correlation to erosion. In the 1960s it seems that parent materials as an influence on the dispersion ratio were once more popular, but the order of erodibility was different to that given by the surface-aggregation ratio.

The need to combine soil dispersion properties with soil water-transmission properties was proposed by Middleton (1930) based on the assumption that erosion is caused by runoff, which is directly related to the ability of the soil to transmit moisture. This was measured indirectly using the colloid content/moisture equivalent ratio. When this was combined with the dispersion ratio it gave the resulting erosion ratio the advantage of taking two of the most important properties into account (Bryan, 1968). Chorley (1959) reported an impressive correlation between soil permeability indices and relief forms in Oxford, observing the importance of runoff and erosion in shaping the top part of the catchment, with mass movement important lower in the basin.

The role of soil saturation and pore pressure is related to rainfall intensity and position on the slope (Morgan, 1979). The status of the soil water prior to rainfall events is directly related to the infiltration capacity of the soil and the onset of runoff or overland flow. However, Temple (1972) noted that measuring susceptibility to erosion in terms of runoff was highly dependent on rainfall, and that, perhaps, the rate of percolation was more suitable since this showed greater consistency and was a more significant index of moisture conservation. However, he added that moisture was not necessarily the better index for erosion, although it was not plot-scale limited.

Since porosity is one of the best guides to structural condition, the complex relationship between soil moisture, storage and transmission needs to be understood if overland flow and erosion are to be modelled accurately. Scatena & Lugo (1994) compared ridge and valley positions in a study of subtropical wet steepland watersheds in Puerto Rico, and concluded that valleys had more landslides and treefall gaps, and richer soils than ridge areas, due to the downslope transfer in water (increasing pore pressure and treefall uproots) and nutrients.

Chatterjea (1989) concentrated on the process of surface wash in the rainforest of Singapore. Two important observations were directly related to processes occurring during high intensity storms. A temporary rise in the water table occurred soon after the onset of prolonged and intense rain, and emerged to become saturation overland flow. It was also noted that surface flow was evident when soil at depths of more than 280 mm was recording positive suction. The negative suction of the upper horizon was thought to represent a perched water table, especially since the sand percent decreased and the clay percent increased with depth.

In his research in the Peak District in Derbyshire, Bryan (1968) repeated the experiments of others who had developed erosion indices. The subtle variations in erosion meant that he had to devise more sensitive measures of actual erosion, so he placed small plots of soil in the laboratory under artificially simulated rainfall, arguing that the process of erosion under simulated rainfall was essentially the same as sheet erosion under natural rainfall. The test was carried out on 18 groups separated on the basis of slope angle, aspect, vegetative cover, parent material, altitude and soil type. The indices which showed correlation coefficients above 0.5 (the most efficient indicators) for the group 'all soils' were the erosion ratio, % weight water soluble aggregates (W.S.A.) > 0.5 mm, and the modified and original surface-aggregation ratio.

On the basis of the correlation coefficients, he considered the most efficient index to be the % weight of W.S.A. >0.5 mm; the next four most efficient involved either a direct or indirect measure of aggregation. However, a number of indices showed very high correlations for particular soils, supporting the view that no universal index needs to be devised (Table 3).

Table 3. Indices efficiency according to sample group (derived from Bryan, 1968). Key: * = limestone parent material and 233 to 295 m in text, but shale parent material and 141 to 233 m in table and graph.

Within sample group	**Most efficient index**	**Comparison between sample groups**
—	Modified clay ratio	Gritstone and limestone parent material
Gritstone parent material, altitude > 295 m	W.S.A. > 3 mm	Low and high altitude
Shale parent material, slopes over 20º, 141-233 m altitude*	Modified surface aggregation	Average and high angle slopes, woodland and grassland
Slopes 0-5º, low and average angle slope, grassland, limestone parent material	Erosion ratio	Low and high angle slopes, north and south aspect, limestone and shale parent material
Slopes 5-20º, south aspect, woodland, 233-295 m altitude	W.S.A. > 0.5	Low and high angle slopes, gritstone and shale parent material, low and medium + medium and high altitude, brown and podzolic soils + horizons A and B horizons

Clay content and organic matter (measured as % weight of W.S.A. > 3 mm) correlated negatively and strongly with total soil loss. The index % weight W.S.A. > 3 mm was the only index that reflected the order of erodibility accurately and the most significant differences between the classes, hence the most useful. Bryan noted that water stable aggregates may be unstable under high velocity rainfall and the water-drop rather than wet-sieve technique should be used in future research.

The aggregate stability concept proposed by Bryan (1968) was challenged by Igwe *et al.* (1995) in a study carried out in southeastern Nigeria to compare various indices. The Clay Flocculation Index (CFI), Clay Dispersion Index (CDI) and USLE K were suggested as giving a better estimation of simulated soil loss than other indices. Since the soil loss was determined from analytical rather than empirical data, it was suggested that unexpected results might occur, for example, the negative correlation coefficient of Dispersion Ratio (DR) with soil loss. This was explained by the authors by the unusually high organic matter content of the soils so that chelation might be considerable and erosion occurring. Also, one of the authors had carried out empirical research which supported a result of positive correlation coefficient between soil loss and DR. The Geometric Mean Diameter (GMD) indicated that their rankings were not related to texture or clay content. All the indices correlated well with Fe_2O_3 except the diameter ratios, suggesting that it was influential in flocculation, but not aggregate size.

The surface-aggregation ratio involved measuring the total surface area of particles larger than 0.05 mm (on the basis of mean diameters) and the quantity of aggregated silt plus clay (from total silt plus clay minus dispersed silt plus clay). The quantification of particles as spherical and using mean values opened the ratio up for criticism, including the use of silt as a binder with no supporting evidence. Indeed, Bryan (1968) discovered a negative correlation (r^2 = -0.4) between silt content and total soil loss. Further work along the same lines involved water stable aggregates (W.S.A.) at various diameters.

There are a number of factors that promote aggregation. Aggregated particles are resistant to erosion because of their size. However, the water stability of aggregates is important because of the action of rainfall that disperses non-stable aggregates. Clays, for example, with a high exchangeable sodium percentage are easily dispersed as are smectites, non-crystalline allophanes and halloysites (not kaolinitic). Erosion is significantly enhanced by lime, which disperses aggregates (Merzouk & Blake, 1991). Aggregating elements include humic and argillaceous colloids, with organic matter levels greater than 2 %, iron oxides, and living roots and fungal hyphae stabilised by microorganisms (Thomas, 1994).

Misra & Rose (1995) found intra-aggregate strength to be one of the most important parameters in determining the magnitude of erodibility, especially in relation to the breakdown of large aggregates by rainfall impact. Although their study concentrated on cohesion of the soil as related to shear or tensile strength, they also considered the slope position of the soil. The erosion rate was strongly influenced by the cohesive strength of the soil in situations where the soil was only partially covered by deposited sediment.

Merzouk & Blake (1991) related forty-two individual soil properties to soil loss using regression analysis. Soil loss was well correlated with active $CaCO_3$, a function of the instability of large aggregates in the presence of $CaCO_3$ causing crusting, pore space sealing and, hence, lower infiltration and higher runoff. A stepwise multiple regression analysis was performed to create a simple relative erodibility index. It included textural, active carbonate and electrical conductivity parameters. Contrary to the findings of Bryan (1968), Merzouk & Blake (1991) found that % WSA (i.e., aggregate stability) was positively correlated with soil loss, but not only was there the limitation of the small plot used to obtain the data, they also used simulated rainfall impact, which gave a more predictable result of unstable aggregates correlating with soil loss. Bryan (1968) had suggested as much in his recommendations for further research and Merzouk & Blake (1991) realised that the smectitic nature of the clay soils in the study area accounted for this factor. Therefore, % WSA was an inappropriate index in their region of Morocco.

Review – The use of quantitative indices of erodibility based on a number of parameters, such as texture, soil dispersion, soil moisture, aggregate stability and shear strength, has a long and contentious history. The basic assumptions of soil loss from the literature were that erodible soils had one or more specific characteristics (Table 4).

Table 4. Indicators of soil erodibility according to various authors.

Parameter	Notes	References
Textural		
Clay content (9 to 30%), high dispersed clay content	Small particles entrained	Evans, 1979; Sharma *et al.*, 1995
High silt content (40 to 60%)		Richter & Negendank, 1977
Sand	Low structural stability	Fournier, 1967
Dry, loose surface	Wet compacted surface has an erosion rate ten times lower	Govers, 1989
Soil moisture		
Low infiltration, slow rate of percolation	Increased runoff quantity	Morgan, 1979 Temple, 1972
High antecedent soil moisture	Increased runoff	Morgan, 1979
Aggregation		
Low stability of aggregates and low % weight, >0.5 and >3 mm	Dispersed materials transportable	Bryan, 1968
Poor intra-aggregate strength		Misra & Rose, 1995
Chemical		
Aggregates with smectites	Dispersion under raindrop impact	Merzouk & Blake, 1991
Low levels (<2%) of organic matter	Increasing OM content lowers erodibility except sand	Declercq & Poesen, 1992
Low humic and argillaceous colloids	Act as silt and sand binder	Fournier, 1967
Presence of $CaCO_3$	Aggregate instability	Merzouk & Blake, 1991
High exchangeable sodium percentage (ESP)	Dispersive soils	Thomas, 1994
Absence of iron oxides	Iron cements clay particles	Thomas, 1994

Another factor for consideration is the effect of land use. On undisturbed soil, increased macroporosity is assumed (with exceptions) to be higher than on disturbed soil, making infiltration capacity an important factor (Bryan *in* Bryan *et al.*, 1989). Aggregate indicators, on the other hand, might be used more effectively on disturbed soils, except that the soil will develop surface crusting with significant raindrop impact. As soil surface coherence develops, as with undisturbed soil, the aggregate stability indices proposed by Bryan (1968) become less effective and indices which reflect crusting susceptibility are needed. This change in conditions is very difficult to predict. No single soil crusting property (except high proportions of silt and clay) has been identified, but surface cohesion is thought to be an important property governing rill erodibility (Bryan *in* Bryan *et al.*, 1989). In some soils, rills develop as a result of subsurface rather than surface water concentration, so there will be no universal index that indicates rill erodibility, despite the claims of the USLE to the appropriateness of the K factor in this regard.

Since none of the indices displayed the necessary parameters to be universal, Bryan (1968) suggested that no such measure can probably be found. Further research into aggregate stability and distribution offered the most fruitful research in his opinion. The index developed by Merzouk & Blake (1991) was in this vein, but applicable only in the limited soil series found in their research area.

In marginal hilly agricultural areas, where intensive, non-mechanical farming is temporally interspersed with extensive or fallow techniques, the appropriate indicator would be invalidated by the changing conditions. This might also be said of agricultural soils since the difference between newly tilled (non-coherent) and long term rain impacted (coherent) soil is significant (Bryan *in* Bryan *et al.*, 1989), according to changing shear strength with sealing of the surface. The temporal element has been studied by Govers *(in* Bryan *et al.*, 1989) who, with others, has recognised this dynamic factor that makes a constant like the USLE K factor ineffective. Antecedent moisture is very time dependent, and is known to influence crusting and rill formation, such that a wet compacted surface has an erosion rate ten times lower than a dry, loose surface (Govers *in* Bryan *et al.*, 1989). Therefore, erosion is not only time dependent, but spatially variable within a soil type, providing yet more limitations to any one index being developed to quantify the erodibility of the soil, especially in situations where either basic soil properties or remotely sensed data are available.

The original K-factor developed by Wischmeier & Smith (1978) was based on field experiments spanning 20 years, since such a long period would ensure that variations in antecedent soil moisture, surface conditions and other hydrological variations would be reduced. Subsequent research reviewed here has shown that the reliability of the index is compromised by ignoring these factors, whilst an attempt at universality is inappropriate given the spatial and temporal variations in these factors that defy prediction within watersheds.

Bryan (1991) summarized the five most important factors in the contribution of surface wash processes to landform evolution, and the control exerted by both soil erodibility and soil surface behaviour:

1. Variability of initial textural and aggregation character.
2. Spatial and temporal change caused by selective erosion.
3. Temporal changes in erodibility related to changes in soil moisture content.
4. Time-dependent evolution of surface crusts in response to rainsplash and other activity.
5. The role of soil fauna in disturbing crusts and providing sediment for entrainment.

There is no one index that can represent the erodibility of the soil, or take account of the other environmental processes like soil moisture conditions, macroporosity, coherence/crusting, and organic matter content and state. Since time plays such an important role, both in short term changes in moisture conditions and long term changes in vegetation, it is doubtful whether an index would be able to take these into account and remain reliable. The decision to use an index for any one watershed, for example, is most likely to be influenced by the available data, rather than the most effective measure of aggregate stability, soil moisture content or determination of surface coherence, none of which can easily be determined in the field. Observer objectivity is an important issue in choosing factors and indices, since the social construction of such activities presumes that the observer is influenced by contacts and literature.

Identifying cause and effect relationships

The energy that can be measured during tropical rainfall events is used as a predictive factor in erosion studies. The intensity and duration of individual events have been measured in a number of studies, to determine the threshold for certain erosion features. Wischmeier & Smith (1958) showed that EI_{30} could be used to estimate soil loss, but Ahmad & Breckner (1974) disputed this for tropical climatic regimes. They concluded that no single rainfall factor correlated very highly with soil loss in Tobago and that only the maximum 15 minute intensity factor seemed to correlate with one soil type. Therefore, they considered that the R-factor was not applicable to West Indian conditions. This was in part due to the lack of provision for wind (affecting energy and angle of impact). Also, the USLE intensity equation was based on rainfall no heavier than 50 mm/hr. They maintained that higher intensities were known from the region. Intensities of 150 mm/hr and 97 mm/halfhour have been recorded in the tropics (Nwosu *et al.*, 1985). Nwoso *et al.* (1995) looked at the relation of soil erosion to rainfall erosivity in southeastern Nigeria, especially in areas with limited rainfall intensity monitoring. The laboratory results showed only slight soil agitation at intensities of 50 mm/hr, the USLE maximum, whilst extreme turbulence occurred at 200 mm/hr, although results for soil loss were not significantly different from intensities of 100 mm/hr.

Much of the research has involved simulated rainfall to identify basic principles, but by its very nature rainfall is highly variable; simulations, although useful, cannot replace the real events (Hudson, 1977). Chakela & Stocking (1988) admitted that errors were inherent in using an isohyetal map at 1:500,000 scale since rainfall was known to be spatially variable in type and amount especially in mountainous areas.

Topography: slope and aspect – A number of authors have proposed the use of terrain models to quantify erosion using time series analyses (Dymond & Hicks, 1986; Merel & Farres, 1998; Vandaele *et al.*, 1996). There have also been a number of empirical studies that concluded that soil material loss rises exponentially as slope steepness increases. This was certainly identified by Fournier (1967), unless, as in Guinea and the Ivory Coast, the soil was so poorly protected that erosion was intense whatever the slope angle. The intense rainfall in subtropical areas was found to be the trigger for erosion, whilst the slope angle controlled the extent of erosion. Bryan (1968) assumed that slopes less than 5° were depositional and slopes greater than 20° erosional. Although this assumption was stated in research in a temperate region, it was thought to hold true generally.

Under uniform rain, the runoff on a steep slope (>40°) will be faster than on a gentle slope, but the same volume of rain will give a thinner sheet of water on the steep slope (Bergsma, 1970). Presumably this reduces the size of particle that can be entrained since water erosivity is reduced. Finer soils are eroded from steep slopes, leaving sand particles behind. Erosion will become supply limited, not unlike a crusted surface. The sand particles will give a rough texture that might further reduce surface runoff velocity.

El-Hassanin *et al.* (1993) studied soil loss on different angles (8 to 30 %) of slopes in Burundi, concluding that increasing slope gradient significantly enhanced soil and runoff losses. Liu *et al.* (1994) noted that data for assessing the effects of slope on soil erosion concentrated on slopes up to 25 %. They found that soil loss was linearly related to the sine of slope angle on the loess plateau in China (silty and silty clay loams) for slopes from 9 to 55 %. Gachene (1995) evaluated soil erosion susceptibility in Kenya for slopes from 25 to 48 %. Soil loss increased logarithmically with increasing slope gradient and slope length. Steep convex slopes over 30° were most susceptible to erosion.

Two studies found that this simple relationship was not always applicable. Ahmad & Breckner (1974) found that soil loss on the 30° slope was less than that on the 10° slope on two of the three soils studied. The soil properties were not regarded as the cause. Instead, both the effective slope length (shorter for steep slopes assuming vertical rain) and the exposure of the sites (prevailing or leeside) were presumed to have caused the inverse relationship of slope and soil loss. Cut slopes tend to be more unstable than natural ones and removing the soil upsets the equilibrium of the slope. In an area of deeply weathered sedimentary rocks in southwestern Nigeria, Odemerho (1986) found the greatest soil loss per hectare was in the 7.5 % slope class and the least in the 22.5 % slope class. By fitting a simple exponential regression equation to each class, a lower exponential rate was suggested for steeper slopes (17.5 %) than for gentler (7.5 %) slopes. This negative relationship for steeper slopes meant that soil loss decreased as slope steepness increases. Odemerho concluded that a simple regression equation was inappropriate even for straight slopes.

Another topographical element considered in some research is aspect. Larsen & Torres-Sanchez (1998) found that landslide frequency was twice as high on hillslopes facing the prevailing winds, and noted that, due to the latitude of the tropics, the difference in temperature between north- and south-facing slopes was less marked. The diurnal patterns of cloudiness and prevailing wind determined soil moisture, which in turn influenced erosion when the rain began to fall in greater volumes on the prevailing wind slopes affecting both landslide and sheetwash activity. Maharaj (1993a), working in the Blue Mountains, Jamaica, also found that landslide frequency was related to aspect. Slopes facing east and south were most susceptible. The eastern slopes received rain first and in greater quantities; although the same slopes received more sun, it was at a time of day when ambient temperatures were lower. The higher resulting pore pressure triggered slope failure at times of high intensity rain. The analysis of erodibility carried out by Loch & Pocknee (1995) revealed that the contribution of rainfall-driven processes to erosion was higher than that of overland flow where slope angle (hence, stream power and rill formation) was low. However, soil strength became an important factor in determining the onset of erosion during the process of runoff where slopes were steeper.

Vegetative cover – According to Fournier (1967), the theory that there is no natural environmental equilibrium in tropical zones is incorrect. Since the level of equilibrium was low (particularly on light soils), human intervention had to be considered carefully. Vegetation cover was regarded by Stocking *et al.* (1988) as the most important factor in erosion processes in the region. Where cover was poor, erosion of 100 t/ha/yr was common, but very low erosion rates were recorded irrespective of other factors where it was 60 to 100 %. Therefore, vegetation plays an important role in erosion control as undergrowth decreases the kinetic energy of drops reaching the ground, canopy intercepts rainfall, runoff velocity is decreased, soil strength is increased by rooting activity and transpiration dries the soil.

Elwell & Stocking (1976) measured the percentage cover of common Rhodesian crops over a ten year period and found the protection differed significantly. Soil loss and runoff did not increase rapidly until total vegetative cover fell below 30 %. Elwell & Stocking (1982) developed the experimentally-derived curvilinear relationship of vegetal cover with soil loss, since vegetation gave the soil better crumb structure and improved infiltration, as well as stems retarding runoff and organic matter accumulation on the ground.

One of the most defining pieces of early research carried out in Southern Rhodesia showed that gauze erected 100 mm above a bare plot reduced erosion to the level detected under a cover of Digitaria (Pangola grass) (Hudson & Jackson, 1959). Since the gauze and grass had similar results, the important factor was the reduction in the raindrop kinetic energy by grass and gauze rather than the retention of soil particles within the plot by the grass. Fournier (1967) also found that grassland was very effective as a ground cover, especially if growth was dense, giving complete protection. Many studies have shown a tenfold difference in erosion between plots with grass (Hudson & Jackson, 1959; Temple, 1972; Alleyne & Percy, 1966). The grass cover had a higher rate of infiltration and percolation than bare ground and low runoff generation characteristics. Of particular note was the almost negligible soil loss under grass, despite some runoff. Results from a thicket plot showed low soil and water loss even on steep gradients, but water was lost in transpiration (65 %) and evaporation (35 %), so only 5 % of rainfall was left to feed springs (Temple, 1972).

The issue of forest cover is more complicated than that of grass. The general opinion is that forest cover protects the soil. For example, Fournier (1967) concluded that forest, combined with the presence of undergrowth, was considered the best soil protection, the canopy absorbing the kinetic rain energy while the undergrowth held and protected the soil from splash and transportation. Another study of tropical forest (Nortcliff *et al.*, 1990) looked at complete and partial clearance of forest in northern Brazil. The most interesting result was the canopy removed plot which compared favourably with the natural forest. The natural forest yielded an average of 5 kg soil loss and the canopy removed plot 10 kg. However, the cleared plot yielded over 90 kg for the same period, supporting the assertion that clearance of the understorey, not the canopy, was the important factor in erosion and that the rate of regenerating ground cover was as important as the original deforestation.

One of the most important results in terms of erosion has been the identification of raindrop fall required to attain 95 % of terminal velocity (Cooke & Doornkamp, 1990). It was found that the larger the raindrop (mm), the higher the terminal velocity until a ceiling of around 9 m was reached, although air turbulence affected terminal velocity in natural rainfall. Concentration of rain on the leaves led to coalescence and drop sizes of around 5 mm, whereas open sky rainfall drop size was nearer 2 mm. High intensity rainfall has smaller drops (Hudson, 1971), whereas Hellstrom (2000) reported that, at storm intensity, raindrop size could be higher than under a single canopy. The high closed canopy that was previously thought to afford considerable protection to the soil was a popular myth according to Hamilton (1995). Unless there was close understorey cover or litter, a canopy higher than 9-10 m afforded no more protection than open bare ground, and if there was raindrop coalescence, erosivity (in terms of raindrop kinetic energy) might be higher (Morgan, 1979).

Douglas (1968) noted that dense forest vegetation in Australia, Malaysia and Singapore provided a protective cover against mechanical processes like raindrop splash and slope wash, but favoured chemical attack. The increased CO_2 given off by the vegetation and the other acids in the soil enhances weathering, allowing a soil depth of 30 m to develop. At an altitude of 2000 m, there was only a single 7 m storey canopy, easily penetrated by raindrops and the erosion had reduced the soil depth to 5 m. A belt of forest at the margin of the forest had dense shrub and ground flora, preventing erosion better than the rain forest. But in the adjacent open woodland, where nutrient levels were poor, the trees were widely spaced so that the canopies did not meet and grass cover was discontinuous, so that erosion was significant and the streams were rapidly discoloured by sediment during a storm.

Teak was being established in Trinidad as a pure crop to improve quality by the 1920s. Bell (1973) looked at the effect of pure cropping on soil erosion. Although an evergreen understorey had been advised, the teak trees were planted close enough to create deep shade, suppressing the undergrowth. This left the soil bare to the heavy rains, affecting soil depth and fertility. In the three year period, runoff did not differ significantly between natural and teak areas, but erosion in the teak plantation basin was an average five times higher. Hellstrom (2000) looked at the relationship between canopy and soil erosion in India. His results showed that thick crown cover was related to severe erosion, that bush cover correlated with lower levels of erosion, but that tree height was not related to erosion, although the fewer the trees in a plot under closed canopy, the more likely erosion would be severe.

Land use – Soil loss in cultivated areas is extremely variable, according to tillage practices, sowing and cropping seasons (in relation to the main rains), and efforts at soil conservation. It was found that cotton as a crop was not responsible for the high erosion in southern Africa, but the tillage practice and presence of erodible soils was (Elwell & Stocking, 1982). Fournier (1967) found that the preparation of the soil in some African countries favoured erosion, because mechanical methods, in particular, destroyed root structures, and ploughing took place just in advance of highly erosive rains. Temple (1972) highlighted the fact that cultivated plots needed less runoff to carry away the same amount of soil than compacted bare plots. Consistent with runoff observations, the cultivated plots at Cinchona, Jamaica, showed higher erosion than bare plots, associated with loosening the topsoil prior to cultivation. However, El-Hassanin *et al.* (1993) concluded that cultivated crops contributed less soil loss than bare fallow watersheds.

The experiments reviewed by Temple (1972) showed runoff, but not soil loss, was high under clear weeded coffee where rainfall intensities were as high as 76 mm/hour. Banana crops lost 15 times more soil than grass, maintaining cover throughout the year (perennial). Lal (1976) concluded that land clearance and crop residue disposal by fire allowed raindrop compaction of the soil surface and hence greater runoff. Conversely, plantation crops and those providing continuous cover were found to cause less erosion. Lal (1984) reviewed the effects of deforestation, grazing and fire from empirical studies throughout Africa. He highlighted the increases in surface runoff and sediment yields as a result of deforestation. Like Fournier (1967), he determined that traditional methods and manual tools caused least erosion, whilst mechanised agriculture caused erosion several orders of magnitude greater.

Morgan & Rickson (1988) noted that the use of a single coefficient for the effects of vegetation on erosion control could be misleading. The influence of vegetation ranged from the erosion-inhibiting interception of rainfall to the erosion-enhancing plant-induced roughness on surface flow. Even rainfall interception could be interpreted as giving linear decrease or increase in erosion according to the height and percentage cover of vegetation and raindrop size. Okigbo & Lal (1977) found that mulching combined with a minimum or no tillage system preserved the structural porosity of the soil, and reduced surface sealing and crust formation.

The reasons given for the almost complete protection offered by grass cover vary from energy reduction to the significance of infiltration properties made possible by the grass. The research by Temple (1972) brought many other important points to light, most significantly the necessity for dense cover in combination with crops and, perhaps, just as importantly, social issues regarding sustained protection and grazing factors. These factors are further discussed below, in which quantified soil loss is used to determine the relative importance of land use activities.

Socio-economic factors involved in soil erosion

Collier & Collins (1980) stated that considerable evidence existed for crop and land management as the most influential aspect on soil erosion rates. Hudson (1977) quantified the influence that variation in the erosivity of rainfall, erodibility of the soil and modification of the slope had on the rate of erosion, and concluded that any variation in erosion rates due to crop and land management was a factor of 2000 more significant. Land use was not taken into account in the only study of erosion hazard in the Buff Bay watershed (CIDA & Forestry and Soil Conservation Department, 1993), which based its results on soil and slope only. It is appropriate to review some of the social factors which could influence land use and hence soil erosion, given the results of both Hudson and Collier & Collins.

Deforestation – Hamilton (1995) considered the ambiguity surrounding deforestation, suggesting that the term be abandoned, or at least more carefully defined and qualified with adjectives indicating the nature of post-deforestation conversion. Of the activities that represented deforestation, such as fuelwood cutting, commercial logging, tree removal for annual cropping or absence of the trees, none was as important as the activity that replaced the trees (Table 5).

This conversion activity was particularly significant in the humid tropics where the regrowth rate was spectacular after natural deforestation events. Hamilton (1995) also mentioned the terraced padi of Bali, a deforested area, where neither erosion or other hydrological problems existed. Not all alterations and conversions led to erosion, but the way in which they were carried out can involve a reduction in soil shear strength (trees not pollarded), or compacting and gullying (tree removal and road excavation).

Table 5. Erosion under different land uses (adapted from Wiersum, 1984).

Vegetation type	Median erosion t/ha/yr
Multi-storied tree garden	0.06
Shifting cultivation, fallow period	0.15
Natural forest	0.30
Forest plantation undisturbed	0.58
Tree crops with cover crop/mulch	0.75
Tree crop clean weeded	47.6
Forest plantation burned/litter removed	53.4

Cultivation – A considerable range of soil loss can be seen in the many land use activities seen in tropical environments (further discussed in Chapters 6-8). Estimates of erosion based on field experiments and guesswork should be used as an indication of relative erosion, not for extrapolation. In Sri Lanka, Stocking (1992) carried out extensive field research into land use types and erosion. Table 6 shows the erosion results for rainfall regimes of 1900 to 3000 mm.

Table 6. Land use and soil loss in Sri Lanka (based on Stocking, 1992).

	Slope %	t/ha/yr	Condition of soil surface
Mainly tree cover			
Grass prepared for pine	42	240	Clean-weeded strips
Pinus caribaea	30	40	Thin layer pine needles, crusted surface
Grass cover			
Grass on old tea estate	25	none	Old tea land 95 % cover
Grass for dairy farm	30	none	Continuous grass cover
Tea lands			
State-run seedling tea	40	200	< 40 % cover, degraded stony surface
Seedling tea	58	10	60-80 % cover, good surface litter
Annual cropping			
French beans	50	> 200	Surface gravel, intensive fertilizer
Weed fallow after beans	50	< 10	Variable cover % weeds

Established tea plantations had well prepared land, but high erosion occurred under <40 % plant cover, just as seedling tea on small-holdings, with lower planting densities and lower cover. The land was cleared for new plantings, a very erosive phase in the crop cycle, with four months of bare soil. Clean weeding for pine and French beans caused high erosion, but weed presence and litter layers protected the soil.

McDonald *et al.* (1996) looked at both yearly and event-based erosion (Table 7). Event based rates gave unusual results compared to established theories, due to the crusting of a bare surface, or the preparation or harvesting of an annual crop prior to the rain event. Event

Table 7. A comparison of event and yearly-based erosion results (based on McDonald *et al.*, 1996).

(tonnes/ha/yr)		(tonnes/ha/event)	
Forest	< 1	Forest	0.021
Calliandra	4	Bare	1.47
Agriculture	7.5	Agroforestry	1.612
Bare	11.5	Agriculture	2.158

based statistics should therefore be avoided for long term modelling.

Collier & Collins (1980) identified marked differences between the methods of cultivation practiced on small scale peasant farms and large scale commercial farms, even under the same continuous crop. The main differences seemed to be the percentage of pure stand, woodland, grassland and ruinate, significantly higher in large scale operations. However, percentages of total acreage in mixed stands, food forest stands and fallow were higher for small farms. This means that the soil management was dependent on scale of operations. If erosion were related to this difference in cultivation practice, scale of operations could be used as a factor in an erosion model. Land use type is used in the research model, although there are problems of identification of activity which are discussed in Chapters 6-8.

Land tenure – Land ownership and land rights have a complex history in many developing nations. There are exceptions to the rule, but a developing nation's need for international trade tends to govern the allocation of unfragmented fertile areas for export production. In India, the land for all policy led to allocations to small farmers of 1 ha on 40° slopes with a top soil of 50 mm.

There are conflicting views regarding tenure and management of the land, some believing that private ownership gives an incentive to manage well (Blaikie, 1985), whilst others (Davis-Morrison, 1998; Meikle, 1998) have found no difference in the treatment of land whether owned or squatted, with the exceptions that owned land showed evidence of food forests and squatted land contained more annual crops. A relationship between land tenure type and erosion cannot be iterated on the basis of the Jamaican literature.

Fragmentation – The fragmentation of agricultural land concerns either the subdivision of farm property into smaller units or the composition of one holding of many non-contiguous parcels, spatially dispersed over a wide area, intermixed with the parcels of other farmers (King & Burton, 1982). In the introduction to many articles these definitions are loaded with negativity. King & Burton (1982) used the terms 'poorly organised agricultural land', 'undersized' units, too small for 'rational exploitation'. Floyd (1970) concluded that "half [the population engaged in agricultural activity] are eking out an existence on scattered, diminutive hill plots [in the Yallahs Valley, Jamaica] ... the result of fractioning of individually-owned holdings over many years... hardly a basis for creating a viable and prosperous agricultural community." It was also noted that "the most readily apparent constraint to the development of agriculture in the project area is the small size and fragmentation of the farms" (Interim Agricultural Development Plan, 1983, p. 23). Just under 70 % of the farms were less than five acres and 41 % of respondents farmed on more than two parcels of land.

Some of the indices used to measure an individual farmer's level of parcelization were reviewed by King & Burton (1982). One of these was an attempt by Igbozurike (1974) which, although ignoring the number of plots and having one or two methodology flaws (concerning units and distance measurement), it did use mean plot size and aggregate round trip distance to quantify the dispersal problem, and the inefficiency that this produced in operational terms, a common theme in the criticism of fragmentation. Floyd (1970) pointed out that journeys of between two and eight miles between home and main plot area were not uncommon for around 20 % of farmers. However, as King & Burton (1982) pointed out, farmers made adjustments to their operations to maximise their time, in terms of intensity of cultivation, with more extensive, less labour-intensive crops grown on the provision ground or remote plot that is more than 2-4 km away.

The main criticism of fragmentation has been the time wasted commuting and the inadequacy of total farm sizes when the fragmented plots were added up. King & Burton (1982) noted that there was little opportunity to rationalise operations, involving irrigation, drainage and soil conservation measures. Most importantly for some Caribbean farmers, it has been the marginalised, subsistence farmer on fragmented land that cannot benefit from extension aid, because of the lack of export crops on the plots and tenure insecurity (not always the case), but also because holdings less than two hectares are not considered sustainable. In an assessment of the Integrated Rural Development Project II (Edwards, 1995), one of the reasons for project underachievement was the use of soil conservation measures that were too capital intensive or technical (not repeatable by farmers) and therefore not appropriate for fragmented plots. A contiguous farm should be easier to maintain in terms of contour barrier/hedge construction and maintenance, especially if farm labour is minimal.

Thomasson (1994) found that gardeners traditionally cultivated a fragmented holding because the kitchen garden and the provision ground (at higher elevations) complemented each other nutritionally and seasonally. There is evidence from both Montserrat (Thomasson, 1994) and Grenada (Brierley, 1991) that the kitchen garden economy sustained both the national and local economy in difficult times. King & Burton (1982) found three reasons for fragmentation not to be “universally ... condemned,” despite the negativity of their introductory definitions: that fragmentation might be a logical response to soil and crop variations; small plots and a mixed crop system might prevent pest and disease epidemics, and provide protection from wind and soil erosion; and the endemic nature of the system suggested that it had utility and relevance to have lasted so long. This was what Igbozurike (1970, p. 322) had suggested, that the personal and social forces which induced fragmentation in the first place “must have been so overriding, and the momentum which has sustained it so pervasive, that the probability of a reversal to an earlier unitary land status is quite low.”

Contrary to the popular belief that tropical agriculture suffers from fragmentation, it has been found that production per unit is not necessarily smaller than for consolidated farms and that fragmentation is not always a retrogressive form of agriculture. Joint ownership is a common adjustment to fragmentation in intensively cultivated land, for example, irrigated land in Taiwan. Sheng’s (1972) insistence that the erosion problems of the hillslopes of Jamaica was almost entirely due to the land capability limits being ignored, would have been coloured by a cultural framework in which fragmentation had been effectively consolidated by socio-cultural adjustment. Hence, larger units of land could be more effectively protected by prescribed structural measures than the relatively fragmented Jamaican hillslopes. Two main points of opposition arise concerning consolidation in certain rural environments. The first is the heterogeneity of soil, land type and climate in hillslope regions which fragmentation exploits. The second is the socio-cultural benefit for farmers in areas of subsistence agriculture in which enforced consolidation would be seen as bureaucratic interference with the pre-existing system.

The problem of fragmentation in relation to erosion seems to be the disjointed nature of the plots from the house and each other, rather than the size of each plot or the total farm size. This warrants further investigation as it might also explain the problems that agencies have found with farmers accepting erosion control measures. There has been some research on field boundary erosion (Bergsma, 1978) and presumably the fewer the cross-contour boundaries, the better the erosion control. If fragmentation were linked to erosion, in terms of lack of conservation measures or increased and intensive use of pathways (conduits), then an index based on that of Igbozurike (1974) could be used in an erosion model. However, plot entities are not considered in the author's model, since the watershed scale is presented as the analytical framework, and farm dynamics would be part of a post-model phase once high and extreme erosion patches had been identified.

Traditional Caribbean agriculture – Despite a history of degradation caused by plantation agriculture and exacerbated by some poor practices by smaller scale farmers, many Caribbean hillslopes are home to a system of traditional agriculture which is not thought to cause soil erosion or fertility loss (see Table 5). These former slave provision grounds have become a major tradition, the most notable form of which has been the food forest, agroforestry area or tropical mixed garden. This system has only recently gained recognition as a form of sophisticated, ecologically sustainable agriculture which internal and aid agencies are keen to develop and support.

This mixed cropping system is now known to encourage different rooting depths, optimising the use of soil nutrients and water. Organic matter is routinely added to the soil if animal manure is readily available, keeping nutrient levels and yields high, and presumably reducing erosion. The vulnerability to pest and diseases epidemics is significantly reduced in these ecologically stable environments (Hills & Iton, 1983). Although mulching has always been encouraged by external organisations for both moisture retention and rainsplash protection, local farmers believe it encourages pest and fungal growth. Hence, it is not a stubbornness against new techniques that is often reported, but a rejection of an unsuccessful technique based on experience.

Review – Research into erosion mechanics is not always conclusive as a result of incomplete knowledge of particle size and distribution in natural environments. Many threshold and graphic relationships have been determined for energy functions regarding rainsplash and overland flow. It is difficult to apply these to an area of soil type based on the central class concept, given the issue of homogeneity. Once surface heterogeneity and vegetative cover are taken into account, erodibility becomes very difficult to quantify. There is no one universal aspect, since texture, structure, soil moisture, vegetation and cultivation have to be taken into account. Erosivity, as the review has showed, is just as difficult to interpret and interpolate. This review of soil field and laboratory research shows that much is known about soil types, whilst remote sensing has expanded the knowledge of soil surface conditions and cover at specific times. There remain many unresolved issues including temporal limitations, cloud cover, understorey identification, sampling resolutions and disagreements about processes and thresholds. If extensive fieldwork is viable, accuracy will prevail, but in the limited development budgets usually available, relative rather than quantitative results are perhaps a more appropriate objective.

Biophysical problems of erosion can be overcome, but the socio-economic factors require immense effort to be surmounted. Amongst others, there is tenurial uncertainty, fragmentation with its multiple potential boundary conduits, replacement of traditional sloping land management with maladapted ones and political chicanery. “Gravity seems almost conquerable given these other formidable foes” (Hamilton, 1995, p. 10).

3. Review of conventional assessments of erosion

Surface erosion is one of the more visible geomorphic processes. Not only can the results of an event, like a storm, be recorded directly in terms of sedimentation and landslides, but many of the mechanisms, too. Rainsplash, the formation of rills and other soil surface changes can be observed at microrelief scale using photogrammetry (Merel & Farres, 1998). These data give the researcher an insight into the spatial patterns and functional processes, but at a very small scale. The larger the area being studied, the greater the number of assumptions, in part because the observer cannot be everywhere, but also because remote recording of a heterogenic surface is only a snapshot in time.

Maps are used to present the evaluation of the spatial relationships between variables. Cartography has developed from a tool for communication to a presentation of spatial patterns as models. Descriptive models present existing conditions for specific locations, similar in nature to conventional cartography. There is an increase in complexity in producing predictive or deterministic models. They allow the user to determine the factors that are important in explaining the spatial patterns, but are dependent on the determination of verifiable causal relationships. Therefore, there is an element of hypothesis and assumption with predictive models that need to be verified with the original descriptive basis. The user can describe erosion for an area and go on to predict it, but the model of prediction has to have some element of time series verification for it to have an application.

A descriptive model of erosion would show the areas where erosion has already taken place, using Morgan’s (1979) indicators, sedimentation depths in reservoirs and landslide mapping, to name a few examples. A prescriptive map would take this one step further, for example, using as an assumption the idea that erosion is worst on steep slopes. The map would then present the slope steepness of an area to prescribe where erosion ought to occur and, in a relative sense, to what degree. However, this already assumes that the causal relationship is straightforward and, in fact, slope steepness is not regarded by all to be proportionally related to erosion (Ahmad & Breckner, 1974; Odemerho, 1986; Liu *et al.*, 1994). A well known and complex example is the USLE. In developing a model for the assessment of soil erosion risk, Morgan *et al.* (1984) used parameters that were observable or determined empirically for field-sized areas.

By the end of the 1970s, geomorphologists and soil scientists started looking at ways to predict erosion hazard, rather than just measure existing problem areas. In general, research was often carried out under the auspices of conservation and extension, and there was an increasing interest in quantifying cause and effect relationships. Predictive models are dependent on verifiable causal relationships being determined and are therefore empirically based. There is a considerable body of literature concerning what causes erosion. The quantification of erosion parameters has kept researchers publishing and led to process-based models. A number of studies analysed soil erosion taking account of one factor only, the univariate approach. This had the advantage of determining the extent to which that factor was influencing erosion. One method involves uncontrolled conditions, concentrating on one factor that is thought to influence erosion, whilst acknowledging that other factors are important, but not controlled. This should not be seen as less scientific, for this method allows the examination of the data in the most natural environment possible and without creating the conditions to be studied. Alternatively, conditions can be controlled by creating experimental plots. These 'plots' can be in the field or laboratory. In the field situation, the land is somehow modified so that the measurements only refer to the area of ground studied. The area is typically protected at the boundaries to prevent runoff and soil from upslope entering the plot. Vegetation may be modified, rainfall simulated and slope lengths altered. It is important to minimise the variation in the influencing factors not being studied, so that the remaining factor can be studied in relative isolation. The alternative to univariate research is multivariate research.

Descriptive research: soil erosion from empirical evidence

Extensive research involving plot-based experiments is still carried out to ascertain soil types, erodibility and fertility, as well as larger scale land use and management factors. Accurate measurements of runoff and soil loss on natural hillslopes are difficult to obtain and interpret because of the complexity of the operating controls and influencing factors (Temple, 1972). Hence, much of this verification has been, and still is, carried out on experimental plots.

Qualitative soils survey and soil loss descriptions – The practical purpose of a soil survey is to determine the pattern of the soil cover by dividing this pattern into relatively homogeneous units and to map their distribution, enabling the soil properties over an area to be predicted. The map and legend are not the final objective of the soil survey, but, rather, the use that will be made of them. The final part of the survey distinguishes the mapped units in such a way that useful statements can be made about their land use potential and response to changes in management. The fundamental problem is that only a tiny fraction of the soil is observed directly in a survey. This sampling (by auger or shovel) is destructive, that is, once it is sampled the original characteristics at a site are destroyed. Some properties of the soil can be identified non-destructively (ground-penetrating radar, airborne imagery of the soil surface). In practice there is a reliance on associated characteristics. Of the many international systems used, some are based on soil genesis and processes, others are mutually exclusive, and most have been referenced to the USDA and FAO to provide international correlative frameworks.

Hardy (1942) described soil erosion in Trinidad and Tobago, using qualitative descriptions like suffering sheet erosion and downhill dragging of the soil. The negativity implied in the descriptions was occasionally reversed when the beneficial effect of deep erosion was recognised. The removal of a considerable amount of old surface soil and leached subsoil had exposed 'rotten rock', the mineral rich parent rock from which a new soil was regenerated when sugar cane highlands had reverted to secondary forest.

Plot-based runoff and erosion measurements – Such qualitative analyses have been replaced with more quantitative approaches. The soil conservation manuals of the 1950s and 1960s contained important details of the factors involved in soil erosion by water, as well as methods to control runoff and conserve soil. Soil surveys in some (sub)tropical areas were typically carried out as part of the colonial interest in export agriculture; "In view of the importance of agricultural production in supplying food for the Africans and as a source of wealth, special attention should be devoted to soil conservation, taking account of the need to cultivate the land... developing a rational method of farming the land to ensure that it retains its production potential" (Fournier, 1967, p. 54). Good farming practice, rational land use, and efficient management of soil, crops and livestock was meant to result in sustained high yields, which were commonly believed to coincide with minimum soil erosion (FAO, 1974a).

In the 1960s, severe soil erosion was identified in Africa, "Senegal is sounding the alarm... In other parts good land is becoming rare and is being fought over..." (Fournier, 1967, p. 54). Soil Conservation Research Stations had been set up in Africa in 1954 for measuring runoff and soil loss, studying the factors involved in runoff and erosion, and measuring the conservation value of plants and cultivation techniques and systems. Experimental plots were set up to measure the quantity of soil displaced by raindrops and the soil lost from the field. These plots were necessary to understand the structural stability and permeability of soils to devise conservation locations and measures. It was readily admitted that measurements at this scale were not applicable to regional interpretation since the environment of a field was defined with precision, whereas the natural environment was variable.

Although the history of the soil might be known in qualitative terms, the rate of change in chemical and physical properties, and varying depth to bedrock are not recorded over longer time scales. The influence that this history might have on water transmission properties, cation distribution and textural proportions is unknown for most soils, and, therefore, the rate of erosion is dependent on some factors which cannot be measured, let alone predicted. This temporal aspect has also been addressed by a number of researchers (Bryan *et al.*, 1989; Misra & Rose, 1995), in which the temporal heterogeneity of antecedent soil moisture, hence soil cohesion and erodibility, was such that no one index could represent the conditions in the field or laboratory.

Review – Quantitative soil surveys have recorded the amount of soil loss for crop yield analysis, but not the contributing factors. Plot and catchment scale measurements of erosion (see Chapter 2) have added immense understanding to soil erosion causal and process research, but have been unreliable for extrapolation and prediction. The next section reviews research in which absolute soil loss is used as a basis to predict erosion.

Predictive research: linking cause and effect using empirical evidence

Where descriptive research provides essential research input data to soil erosion, predictive research is that which will happen in a model (Whittow, 1984). It is used to describe research involving the use of factors influential in soil erosion, in an index or model, in which those factors have a direct empirical basis. Although not process modelling, predictive indices take some processes into account, like erosivity or erodibility, founded in empirical research.

Universal Soil Loss Equation (USLE) – One particular multivariate model that has gained widespread acceptance is the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978). The USLE is empirical by nature and does not represent the physical forces that cause soil erosion in a process based index (Hall, 2000). The USLE incorporates the factors rainfall erosivity (R), soil erodibility (K), slope angle (S), slope length (L), vegetation cover (C) and conservation practice (P). The USLE is an important component for calculating long term soil losses from specific areas with particular crops and management systems. The values in the equation are taken from charts and graphs, based on extensive plot based experiments in the U.S.A. in which the loss of material from plots of standard dimensions on a slope of 9 % on different soil types was measured. A number of studies have calculated the USLE for field scale erosion as originally intended, but techniques of data capture and storage have advanced since the index was first developed to allow for watershed scale studies. Stephens *et al.* (1985) developed a system of mapping erosion units from air photos (1:60,000) and then calculated the expected soil loss per field by averaging weighted soil loss values for erosion units represented in that field. The average annual soil loss estimates were 72 % accurate, suggesting that a detailed soil map (1:20,000) was necessary for accurate photo-interpretation.

The USLE represented the major factors involved in erosion and it was thought that transferring it to locations throughout the world required only the determination of appropriate values for the different factors (Renard & Freimund, 1994). One example from Malaysia (Kamaruzaman & Baban, 1999) computed the USLE using mean annual rainfall for the USLE R-factor, a small portable rainfall simulator for the K-factor and an unspecified manipulation of the DEM for the LS-factor. The land use/cover map was produced from Landsat TM images using a stratified supervised classification and ground referenced data. The factors were converted for use in the USLE equation and overlain in Idrisi to show the distribution of soil erosion assessment. This map (with 30 m resolution) was compared with a friction map (with 1.7 km^2 resolution) produced from fieldwork.

Some authors doubt if the nomographic value ranges were applicable to the humid tropics (Gachene, 1995; McGregor, 1995) or anywhere outside the U.S.A. As a result, alternative models were devised for many aspects of the USLE. The factor values were recently revised following the analysis of thousands of new measurements, with a significant slope calculation modification resulting in the Revised USLE (RUSLE) (Renard *et al.*, 1991), whilst Pilotti & Baucchi (1997) devised a slope model to make the USLE applicable to complex slopes. Gachene (1995) modified the USLE for the K-factor in Kenya taking the dispersion ratio, percent clay, organic matter and bulk density into account. The C-factor was modified for Burundi when it was noted that dividing soil lost from vegetated plots by that from fallow plots (Cr) overestimated total soil loss in, whilst the plant cover (Cp) factor gave similar results to the USLE (El-Hassanin *et al.*, 1993). Liu *et al.* (1994) found that their results of soil loss fell between those predicted from the USLE and RUSLE. Torri *et al.* (1997) carried out a comparison of global field studies in which K values had been calculated under a variety of conditions and of which only a third of the studies met the broad criteria for calculating K values in the first place. The authors concluded that the large scatter was due to varying definitions of the erosivity factor, topographic corrections, differing antecedent soil conditions and short-term nature of experiments, rather than the inability of the parameters to predict K values.

Many attempts to improve the range, applicability and tolerance of the variables for locations outside the U.S.A. were plot-based, but factors varied considerably from year to year. Experiments needed to last at least five years, thus making direct measurement costly and time consuming (Renard, 1997). Of all the modifications, slope complexity transcends this limitation because it alters the nature of the variable fundamentally, rather than merely extending the range, like soil texture or rain intensity. Seventeen years after the original rainfall erosion index had been presented, Wischmeier (1976) replied to criticism on the erosion index by restating some of the conditions under which it should be used. Foremost amongst these were recommendations for areas where it should not be used, namely regions where the factors could not be accurately evaluated, complex watersheds and specific rainfall events.

Model for assessment of soil erosion risk – Based on many of the concepts of the USLE and a precursor to process-modelling, the model proposed by Morgan *et al.* (1984) involved separating the soil erosion process into a water phase and a sediment phase. The latter phase was then further divided into a detachment and a transport phase, allowing the analysis of situations where erosion was restricted by a lack of erodible material of sufficient runoff. The model was validated using published data from Europe, Africa and southeast Asia. Morgan *et al*. (1984) could not sufficiently validate their model for very low and very high rates of erosion, but found that, between rates of 0.1 kg/m^2 and 20 kg/m^2, their model was robust enough to predict soil loss in 70 % of test sites, which rose to 90 % if field-based soil properties instead of estimated values were used. The model was a response to the complex methods available and its relative simplicity (14 parameters) enabled soil loss to be predicted from fields on hillsides. However, it still required an estimate of rainfall intensity and a calculation of moisture storage capacity (using four precise field-based measurements). In terms of applicability, it could use USLE-based crop management values, which other authors (Bocco & Valenzuela, 1988) have determined with varying degrees of success from remotely sensed data.

Prescriptive research: indices and models

Prescriptive research is defined as that which ought to happen in a model (Whittow, 1984). The large amounts of data necessary to service predictive models, like the USLE, are beyond the scope of many countries, hence grey box systems have developed in which the most important variables are incorporated and the system not fully understood.

Soil-Loss Estimation for Southern Africa (SLEMSA) – Over a period of nearly 25 years, Elwell, Stocking and others developed SLEMSA (Elwell, 1978) for savanna and semi-arid environments. It is included here for the pioneering analysis in vegetative cover and erosion. In the early 1970s, a simple factorial scoring procedure for erosion hazard was developed (Elwell, 1978) which was a basis for building soil loss models to provide the best estimate of annual soil losses from sheet erosion on arable lands in southern Africa. In the mid 1970s, extensive fieldwork in Zimbabwe enabled relationships to be determined between vegetal cover and soil loss. The model comprised four physical systems in its framework; crop type, climate, soil and topography. Soil erodibility was gathered from field experiments based on soil depth, crusting and infiltration. The model developed from field based studies, in which soil loss was measured in t/ha/yr, to a country level methodology in which soil loss hazard was presented in Erosion Hazard Units (Stocking *et al.*, 1988; Chakela & Stocking, 1988).

Elwell & Stocking (1976) criticised the USLE because of the indefinite number of possible combinations of crops, rotations, tillage and other practices which the cropping management factor (C) had to take into account. They suggested that vegetal canopy was a major influence in determining erosion and adopted percentage area of soil protected by vegetation as a soil-loss estimation parameter. A further development was driven by the shortcomings of the USLE (Abel & Stocking, 1987) using the simpler, but important, threshold of 30 % vegetative cover for a reduction in soil loss to be identified. For wider application of the model a single figure of vegetation cover was abandoned and mean seasonal interception of rainfall was derived (Stocking, 1987), recognising that several land uses might occur in one square (Table 8).

Table 8. An example of a SLEMSA cover type calculation.

Vegetation type	Proportion of square	Interception %	USLE - C	Proportional C
Woodland	0.4	70	0.053	0.021
Grazing	0.3	30	0.17	0.051
Cropland	0.2	20	0.3	0.06
			Final C-value	**0.132**

The vegetal cover databank was further modified for research in Tanzania (Ndyetabula & Stocking, 1991) so that each land use type could be distinguished on the basis of two energy interception models. The original objective of combining simplicity, economy and accuracy to extrapolate to unmeasured conditions was no longer a goal, and it was replaced by increased accuracy. In this way, SLEMSA was starting to develop attributes for which the authors had criticised the USLE, namely the indefinite number of land use combinations.

The erodibility of individual soils, F_b, posed a problem since the local dynamics of surface crusting and loss of organic matter made soil series ratings inaccurate. Adjustments were made on the evidence of current erosion, management practices, soil depth and claypan presence. By 1993, the SLEMSA approach had been applied in Namibia (Stocking & Chakela, 1993), using the FAO map, which obscured important soil differences, a recognised major weakness of the model, but soil was considered to be overshadowed by vegetation and slope.

Elwell & Stocking (1982) claimed that the SLEMSA approach would have widespread relevance, but not universality. The authors recognised that although each factor in the model had equal weight and importance (although tropical soils are more sensitive to vegetation changes), the erosion process might not reflect this. Neither did they allow for the exponential relationship known to exist between vegetative cover and erosion (change in cover from 10 to 20 % is more effective in reducing erosion than

70 to 80 %). Since the intention was to produce a semi-quantitative estimate of hazard, these problems were not thought to be serious.

Index of land degradation – The 'data-hungry' approach of the USLE, the need to incorporate socio-economic data in land condition studies and the inappropriateness of the existing erodibility models (FAO, USLE) to subtropical conditions persuaded McGregor *et al.* (1998) to develop their own index. The Degradation Index (DI) was specifically designed for the Jamaican hilly, marginal areas. Although Sheng (1972) (see 'Review of conventional research,' p. 44, below) had developed a classification for agricultural suitability, erodibility was not considered as a limitation to productivity, merely an historical result of inappropriate land use. McGregor *et al.* (1998) realised that soil conservation programmes had largely failed and wanted a different classification in which the state of the environment, not the potential, was recognised.

The index was based on unpublished work by Stidwell (1993), and more loosely on the USLE and FAO (1979), and relied solely on attributes that could be identified easily in the field. The indicators were split into five groups; soil, erosion signs, topography, vegetation and management. At each site the indicators were scored on a nominal scale and a DI number allocated from arithmetic aggregation for each sample point. Weighting was introduced to reflect assumed importance, slope by angle and management by conservation measures (FAO, 1979). The most degraded site was in an area of coffee cultivation on a steep slope, with no land management evident. The broad categories of relative degradation contained considerable internal variation, and the weighting was abandoned because it caused false levels of variation and masked subtle patterns. The index was then applied to distinctive agricultural conditions of plots of yam and tree garden, and the new results showed lower standard deviation.

As a measure of degradation, the index had a degree of subjective assessment and relied on extensive field indicators and erosion evidence. The authors wanted to develop it beyond an academic exercise to include a wider range of agroecosystems, and were dissatisfied with the simple field indicators and the subjective nominal classification. However, it was the only index specifically designed for this kind of environment, which had been verified by evidence of erosion indicators.

Social factors incorporated in indices – In Chapter 2, the discussion considered the activities of man as factors that might influence erosion. Vegetative changes (deforestation, plantation, cultivation) and tillage techniques are not always negative, nor is there necessarily a linear relationship between the effects of cultivation and soil loss. Neither is land tenure type or fragmentation a reliable indicator of erosion.

One research project looked at determining if contemporary erosion was aided by population pressure (Stocking, 1978). The rates of gully head cut erosion were compared between catchments of differing population densities. The main assumption was that each land user had an equal effect on the extent of erosion, an assumption that Stocking already knew to be incorrect from observations of adjacent plots and their varying degrees of declining fertility. However, the averaged effect was thought to be sufficiently acceptable and density varied considerably with village proximity to arable land and watershed boundary roads. Both vegetation cover and population density were eliminated at the early stages of the regression because they were nearly randomly correlated with gully growth. Stocking concluded that either density was a poor measure of pressure or that pressure was not a controlling factor in gully growth, and he favoured the explanation that gully growth was a natural phenomenon.

Hudson (1981) put together a forceful argument for extending research and solutions beyond the strictly technical, concluding that the important constraints on soil conservation were political, social and economic, together more significant than deficiencies in techniques. Stocking (1983) pointed out that placing farming systems and environmental degradation in the context of political and economic aspects was essential for explaining the causes and consequences of deterioration.

The definition of a land quality indicator sets out the "measures, or values derived from variables, that provide estimates of the condition of land relative to human needs, changes in this condition, and human actions which are linked to this condition" (Pieri *et al.*, 1995, p. 8), in terms of their social and economic equivalents, GNP or human life expectancy. The first indicator of pressure was the rural/agricultural population density in relation to agroclimatic zone and soil type, since an increase in human fertility could be at the expense of soil fertility. Secondly, the cultivation/fallow ratio and ratio of cultivated to cultivable land was suggested. This indicated the limitations of agricultural resources. Finally, the ratio between monoculture and multiple cropping or crop rotation was listed to indicate the level of capital resources for inputs as well as the appropriateness of soil management.

Review of conventional research

Soil modelling has developed significantly since the first qualitative descriptive surveys, but none of the direct or indirect measures can be applied everywhere with any degree of accuracy. A list of problems common to parametric indices are noted by Rossiter (2000); a misleading sense of accuracy, arbitrary choice of factors, factor ratings without validation and assumed catalytic interactions in factors. Too many factors led to lower average ratings and severe error propagation, and arbitrary subjective weighting was not always reinforced with empirical testing. However, the authors of SLEMSA and the DI were open about the shortcomings of their indices and traded the non-universal status for accuracy. The problems associated with extrapolation affect both predictive and prescriptive research. In the former, the use of empirical data necessarily ties the model to the original area of research. In the case of the latter, an inadequate model will not sufficiently reflect the causes of soil loss and be unreliable.

Some attempts have been made to quantify the natural susceptibility of land units as well as taking socio-political factors into account. Usually, the physical data on soil loss have to be combined with a fairly detailed knowledge of land use and its history if the human activities that contribute to erosion are to be reliably estimated over large areas (Blaikie, 1985). The review of land quality indicators (Pieri *et al.*, 1995) gives an alternative to the complex data sets required for some indices, but also introduces a new level of subjectivity. The ratio of rural population to productive potential of agroclimatic zones assumes that there is consensus about that potential, whereas classifications of land capability can vary widely according to the current ideas and financing for structural improvements of sloping land.

The use of qualitative and quantitative descriptive research has rather fallen out of favour in the wake of computerised models and indices, as researchers struggle to discover the 'how and why' instead of merely the 'where'. The data capture and analysis techniques have advanced beyond what original practitioners could have foreseen, but their field experience is still invaluable and essential, a factor that is not always appreciated (MacGillivray, 2002a).

Classification of land elements and activity

The necessity to classify terrain was originally driven by limited access to field verification in military operations. It is important to review these classification methods where projects are being considered using secondary data. Although an important point to take into consideration, air photography alone is not sufficient to produce accurate soil survey maps (Beckett & Webster, 1969).

Land systems analysis – The identification and classification of land systems for military purposes developed in the 1960s, although it was recognised that a general purpose classification would be more applicable. A physiographic system, the Land System Classification (LSC), was recommended in preference to a parametric one (Becket & Webster, 1969). Various field trials (the Oxford trials) tested the homogeneity of the units identified, a necessary parameter for extrapolation. The limits for tolerated variability for soil water variance and soil strength were defined, and reasonable separation between the classes was confirmed.

The mutually exclusive themes of recognisability (using a large enough scale to recognise certain key elements) and reproducibility (producing a map at a small enough scale to cover a region economically) were examined. The common drawback to the system was found to be the intricacy of the terrain, with large changes in soil and microrelief within relatively short distances. The scale had to be increased to recognise and map the features, but this presented a problem for reproducing the maps at a manageable scale.

Other terrain models – A comprehensive review of physical regionalization was carried out by Mitchell (1991). The physiographic units were based on relief, land use type and features. Geometrical classification systems for smaller landforms were also reviewed, using a morphometric approach to express microrelief. A number of techniques for slope measurement, morphological mapping and recognition of surface irregularities were developed in the 1950s. The quantitative data enabled researchers to carry out form and process correlations, for example, the morphometric techniques used in karst relief and process analysis in the Caribbean (MacGillivray, 1996).

Parametric and physiographic systems can be regarded as complementary (Mitchell, 1991). Whereas the parametric is objective and does not assume a hierarchy, the physiographic allows for local subjective expertise and a weighting of parameters for any particular process (Table 9). However, the parametric may highlight differentiation between sites or processes that were not obvious in landform description, whilst using a language that is universal for comparison. An example is a DEM analysis, in which elevation, aspect or slope angle clusters may be revealed.

Table 9. Comparison of parametric and physiographic systems.

Parametric	Physiographic
Language specialised, but universal	Terminology expressive, but not exportable
Objective	Allows local subjective expertise
Non-hierarchical/no weighting	Grading relative importance of attributes
Intersite comparison/small scale differentiation	Causes of differentiation given
Quantitative/statistical correlation/variance	No computational analysis
Scale sensitive based on sample density	Composite, clearly divisible/land use fragmentation identified
Specific attributes for temporal extrapolation	Changes in morphology = temporal analysis
High density sampling for spatial extrapolation	Extrapolation / inferences of unsurveyed (soil profile)
Scanning; attributes automatically quantified	Regional classification quicker (fewer parameters)

Another consideration in classification is the issue of mapping boundaries. Many features are mapped with hard boundaries which are, in reality, fuzzy. This is an indistinct or gradual change from one category to another, where an object has a degree of membership with both adjoining categories. Gradation between categories raises the problem of where to draw the line and whether to divide the area so that the graded area becomes a new category. Naesset (1998) researched the positional accuracy of boundary lines for clearcut and mature forest. Compared to groundtruthed data, interpreters located boundaries inside mature forest stands by 1-3 m. Tree crowns and shadow were partly responsible, but the subjectivity of the interpreter in fixing the absolute limit of the stand was considerable (Naesset, 1998).

When Bergsma (1983) carried out a classification of erosion in central Java, he combined morphological (type and intensity of present and past erosion features) with functional (erosion hazards) classifications, based on lithology and the presence of aggradation and degradation features, hydrography, horizons in soil profiles and intensity classes for sheet erosion.

Land cover – Land cover encompasses the “vegetational and artificial constructions covering the land surface” (Burley, 1961). The Land Cover Classification System (LCCS) (FAO, 2000) stated that “land cover is the expression of human activities,” although strictly defined as the “observed (bio)physical cover on the earth’s surface.” Vegetation is commonly used as a key to recognising landform and soil types on air photos, but because it does not necessarily mirror the boundaries of landform or soil type, researchers use it primarily as a diagnostic tool, for example, as a protective effect in reducing erosion or landsliding.

There are a number of vegetation indices that present the vegetative aspect of satellite imagery. The contrast between the amount of reflected energy in the red and near-infrared regions of the electromagnetic spectrum has been the focus of developments for a quantitative index of vegetation condition. The Normalized Difference Vegetation Index (NDVI) (Rouse *et al.*, 1974) separated green vegetation from the background soil using Landsat MSS data. Non-vegetated surfaces, like water, had a negative value and zero represented no vegetation or bare soil.

Heyligers (1968) carried out a reconnaissance survey of the Aitape-Ambunti region in New Guinea to determine not only a division between native gardens, plantations and regrowth, but also seven categories of natural vegetation and, eventually, homogenous units within the major vegetation types. The study revealed a query about the extent to which the invisible features (understorey and litter) correlated with forest type. Subcanopy cover, for example, ranged from 50 % in open tall forest to 35 % in old regrowth forest.

Land cover/use hybrids – Many land cover classifications have tried to incorporate human activity in the system. The objective of the Land Use and Land Cover (LULC) classification system (Anderson *et al.*, 1976) was to provide systematic information on land use and land cover occurrence and patterns. The criteria stated that "the categorisation should permit vegetation and other types of land cover to be used as surrogates for activity" (Witmer, 1977). Problems of identification were often solved by the minimum mapping size, so that distinguishing the nurseries and ornamental horticulture from citrus groves was avoided since the entities were all smaller than 16 ha.

The Rural Land Use and Cover Classification (LUCC) was developed (Gils *et al.*, 1991) to be universally applicable to temperate and tropical conditions, based on FAO definitions of land use and the World Land Use Survey (LUS-1). It aimed to solve the conceptual difference between use and cover without resorting to crop type or field size, since LUS-1 did not distinguish between use (e.g., pasture) and cover (e.g., grassland). A specific cover class could have different uses so that woodland (cover) could have grazing, forest, or conservation uses or be unused. Certain combinations of cover classes led to conclusions regarding land use. For example, buildings near fields indicated processing operations like coffee or tobacco, because of drying sheds close to picking points.

The Land Cover Classification System (FAO, 2000) was designed to accommodate any land cover using independent diagnostic criteria to distinguish eight major land types. The cover type was fine-tuned in a hierarchical set of classifiers and not a class name. The LCCS included land use (termed artificiality of cover) within the cover system. In the humid tropics, the small kitchen garden sustains the family in vegetables, is limited in size and is therefore horticulture. However, the same crops are grown elsewhere in agricultural systems. The LUCC used complex mapping symbols for 'mixed ' subclasses, for example, successional crops in one field or agroforestry.

One of the earliest applications of the LUS-1 in the humid tropics was carried out by Collins (1966), because the "considerable variation in the [Jamaican surveys and census] statistics throws doubt on their reliability. Furthermore the absence of maps, which have the immediate advantage of revealing omissions and overlaps, makes the statistical evidence ... of limited value". Collins noted that both coffee and cocoa were grown under shade with a likely identification as dense woodland. Sugar cane exhibited a very wide tonal range and could be confused with banana, and the tobacco crop could not be identified because it had been harvested, with a classification of 'cleared' if drying sheds could not be located.

Land use – Land use is the pattern of society's exploitation of its environment (Mitchell, 1991). Land without inputs rarely possesses productive potential, since the collection of wild produce requires labour and the conservation of natural wilderness requires measures for its protection (Higgins, 1977). Subsistence and commercial farmers grow the same crop giving an identical morphological system classification, but the nature of management would be different in a functional system.

One early project (Harnapp & Knight, 1971) focused on providing an agricultural classification system based on landscape and socio-economic features, defined in terms of elements, pattern and phase. The elements were observable as patterns in the landscape whilst sequential photography provided evidence of the phase. This was important for providing information regarding farming practices tested in a Puerto Rican setting. Commercial sugar cane production was classified as 'commercial continuous' because three film types showed a range of hues and tone suggesting different phases, a similar finding to Collins (1966). The key identifiers of peasant multi-crop (gardens) were an area associated with the village, with small plots of cultivated land. The authors concluded that their recognition of the landscape as an expression of human behaviour presented a (functional) system classification rather than a (morphological) land-use key.

Collier & Collins (1980) developed a specific classification of land use because most of the existing tropical land use classifications took no account of the scale of activity, a determinant of agricultural practices. Since crop and land management were thought to be more important than slope, soil type or rainfall intensity in determining the rate of erosion, the normal usage of the land needed to be identified. The research focused on agricultural systems on two different scales in the parish of St. Catherine, Jamaica; large scale plantations on the gently sloping alluvial plains (farms > 100 acres, 97 % pure stand) and intensive small scale cultivation (farms < 5 acres; 45 % pure stand) mixed with large scale agroforestry. Only coconut stands were readily identifiable, common to small and large scale cultivation. The undercropping was essential in determining erosion, since pure stand coconut cultivation showed no signs of erosion, but clean-tilled annual undercrops did. However, they did not define a threshold acreage at which small scale became plantation, leading to misinterpretation if small scale operations started operating plantation techniques in the hilly areas (coffee growing areas of Portland). Also, land fragmentation (see 'Socio-economic factors involved in soil erosion', p. 32, above) may confuse the interpretation of small and large scale. Brierley (1991) has shown that the expansion from subsistence to commercial operations can happen to one owner over a period of years (mean age of semi/commercial farmers was near 57 years). This may be enabled by profitable kitchen gardening, which finances the acquisition of new parcels (and commercialisation), whilst precipitating fragmentation.

Land quality – Once economics are introduced to the land classification debate, views on what constitutes the role of man take a polarized form. A number of classifications are based on numeric or ratio indices. The methodology is to combine single numeric factors (usually values of land characteristics) to reach a final numeric rating. Either each specific land use is evaluated separately, so there is a range of suitability (excellent to poor) for a specific use, or an arithmetic ratio scale is adopted, that is, land rated 80 is twice as good as land rated 40. Land quality is defined as "the condition of land relative to the requirements of land use, including agricultural production, forestry, conservation and environmental management" (Pieri *et al.*, 1995, p. 7). There is no single index for land quality because of a lack of information regarding sub-indices for changes in soils, water resources, forests and rangelands, which would be added to economic and social indices already available (GNP, Gini coefficient, life expectancy, infant mortality and literacy).

The land quality indices proposed by Pieri *et al.* (1995) looked at the issues of human resources impact (e.g., population density, access to markets), land quality (e.g., soil fertility, erosion indices, land cover), agricultural impacts on biodiversity, and land use and practices (e.g., major land use, conservation adoption) in the steeplands of Latin America.

Land capability and suitability – In the middle of the land classification debate sit the proponents of optimal land use in which land capability classification is the foundation of proper land use (Sheng, 1973). At one end of the scale are those who advance maximum land utilization in which the use of fertilizers is the most important single factor in good soil management except where soils are particularly susceptible to degradation (Greenland, 1981). At the other end of the scale are those who are concerned about the condition, not the exploitation of the land (McGregor, 1988). One of the drawbacks to land capability classification is the assumption that economic returns must be maximised, regardless of the motivation for cultivation.

Different soil classification systems have different objectives. Morphological systems (FAO Soils Map of the World, World Reference Base, Soil Taxonomy) identify the soil type according to horizon composition and colour, whilst functional studies analyse the properties of the soil in relation to the suitability for a particular activity. In suitability classifications the soil profile is used as the base, the major determinant for which is climatic zones. In early soil mapping surveys, individual properties were recorded at each observation point. Sets of properties were found to vary proportionately with each other, which led to the recognition of classes of soils. Comprehensive general schemes to explain the distribution of major classes developed from these early single attribute systems based on clay or humus content to the natural classification developed by the Russians in the 1920s. Soil Taxonomy (USDA, 1983) was designed to group soil series in general interpretive groups. The World Reference Base and its predecessor FAO Legend were designed to identify pedological structures and their significance, and understand and organize global soil geography (Rossiter, 2000). The French emphasized horizons, in which a horizon sequence can have more than one classification. Indigenous people living on and using the land often have a classification based on perceived differences that are important to their uses.

The classification of this capability of the soil employs both terrain analysis and an economic assessment of return, although there is considerable variation in the relative importance placed on physical and socio-economic elements. Soil classifications minimise the diversity of topsoil characteristics in determining homogenous areas, although topsoil can change fairly rapidly under human influence. Soil suitability classifications are grouped by specific properties important for a land use or set of land uses.

The USDA Land Capability Classification (LCC) (Klingebiel & Montgomery, 1961) was based on detailed soil surveys (at 1:20,000 scale) with a view to ranking the capability (from best to worst) of a soil to produce crops and pasture. The soil had to sustain the crops without deterioration over a long period of time, assuming the presence of moderately high management practices and the removal of non-permanent limitations.

The LCC only considered relatively permanent land characteristics (e.g., stoniness), with reduced weighting for chemical parameters (e.g., pH). No attempt was made to determine profitability by including factors such as distance to market or location within a farm.

In the early 1970s, there was growing dissatisfaction with the existing land classification that ignored socio-economic aspects of land use. There was an early recognition that some factors could not be quantified like an inter-generational transfer of wealth. These 'non-economic' preferences were expressed as absolute or partial barriers to economic behaviour (Rossiter, 2000). Societies that were not motivated by wealth accumulation were included since most preferences could be given a monetary value. Subsistence agriculture was quantified (calories, grams of protein, labour time and intensity) on the basis of consumable foodstuffs, fibre, wood and animal products. In market-oriented societies, both benefits and costs were expressed by price measures.

The FAO recognised the need for an economic input to land evaluation (FAO, 1976a) that is not used in the U.S.A., where domestic methods and modelling approaches are more popular (Rossiter, 2000). Suitability for each use was assessed by comparing the required inputs (labour, fertilizer, access) with the products, production calendar, markets and other external influences. The main advantages were in meeting the shortcomings of the LCC, giving a range of suitability for a specific use; there are no bad land areas, only inappropriate land uses. From this it is possible to infer that "there are no difficult lands, only incompetent land users" (Rossiter, 2000, p. 9). Many European countries based their classification systems on the FAO.

Another method, agro-ecological zones (AEZ), involved dividing the land into homogeneous areas with respect to the physical factors that were most important to crop (or other plant) production. Crops were grouped according to their photosynthetic pathway using factors like moisture (from rainfall and soil storage), temperature, radiation and photoperiod. Soil requirements of crops included internal (e.g., soil temperature, moisture, aeration, fertility, depth, stoniness, salinity and other toxicities) and external requirements (e.g., slope, micro- and macro-relief, occurrence of flooding during the growing period, accessibility and trafficability) (Rossiter, 2000).

One simple watershed rating system was proposed by Sheng *et al.* (1997). Classification criteria for a management rating of the watershed were based on watershed problems, whether they were physical (floods, landslides, severe soil erosion), sustainability related (steep land cultivation, deforestation, overgrazing, downstream interests) or socio-economic (poverty, unemployment, agricultural, tourist potential). If government policy was protection oriented, then the classification prioritised watersheds with physical problems and downstream interests (i.e., steep slopes, necessary protective vegetation cover, soil erodibility). The priority of a watershed was based on points awarded to factors according to an arbitrary class system.

In the second part of a survey undertaken by Collins (1966), land potential was mapped in Jamaica. The Land Capability or 'crop potential' of every soil had been determined according to its composition, environmental condition and ground slope (Collins, 1966). The land use data showed that the uplands were being used far more intensively than the prevailing soil/slope conditions could support, causing erosion. Collins saw the only solution as a considerable reduction in crop farming, and the extension of grassland, tree and forest uses, but also recognised that farming communities operated at subsistence levels with intensive methods, so extensive methods would not be feasible.

Sheng (1972) was also dissatisfied with the LCC, realising that it was poorly adapted to hilly areas where both commercial and subsistence agriculture were essential activities of the economy. Farmers were being refused extension to cultivate coffee, banana and food trees on land officially classified as pasture (slopes steeper than 21°). Despite the USDA classification these areas were under cultivation, but without the necessary improvements, leading to erosion. He devised a classification that encouraged the appropriate soil conservation measures so that land 'suitable for cultivation' was not limited to 8° slopes, agroforestry was encouraged, and intensive and extensive cultivation alternated according to local fallowing practice. The only limit was for slopes steeper than 25° where permanent tree crops using manual labour and forest were prescribed (Table 10).

Table 10. Assumptions used by Sheng (1972) to develop a suitability classification.

Assumptions mirroring the USDA-based systems	Additional assumptions
Agricultural suitability not 'crop specific', productivity or profitability rating	Any land safely cultivable by hand is classified as suitable due to socio-economic pressures
Physical permanent limiting factors: soil, slope and erosion elements (improvement costs excluded)	Soil conservation is a pre-requisite in lands to be cultivated
High level of management and most intensive tillage possible presumed, not present use	Management and land improvement presumed
Class homogeneity based on degree of hazard, not physical characteristics	
Economic classifications carried out separately	
Reclassification of land after reclamation or new technique necessary	Classification based on expected results of improvement

The most important limiting factor was slope, because cultivation intensity and convenience were dependent on it, but it was one factor that could be modified with consequent reclassification on the basis of expected results. In view of the implied intensity of use proposed, only very poor or very steep land would have been left for forest or unused. The simplicity of classification, intensity of use and the release of treated lands to cultivation made the system popular in Jamaica. The practicality of the scheme was demonstrated in western Jamaica, a hilly marginal area, where half of the proposed resettlement area was cultivable with treatment, with a quarter for food trees and pasture, and the rest forest (Sheng, 1972). Previous classifications had discouraged any cultivation. Sheng insisted that an economic classification of lands should be a separate activity, ignoring the costs of treatment that could affect the implementation of such a classification.

Batjes (1994) presented the results of an island-wide agroclimatic and crop zoning study of Jamaica using JAMPLES (Jamaican Physical Land Evaluation System) and the FAO methodology (1976a). Variability of rainfall was introduced into the crop zoning procedure using the concept 'dependable rainfall' (R75), the minimum rainfall exceeded in a specified time period in 75 % of years. The 'dependable growing period' (DGP) was defined as the number of months when R75 was greater than 0.5 × PET. The R75/

PET index was used to present the 'moisture availability' zones of the island at a scale of 1:250,000. The model defined thresholds when field preparation and planting could safely take place, although that period also included humid months when extreme events could cause severe runoff and erosion. However, the model assumed that soils were freely drained and deep, with a maximum holding capacity of 100 mm, whereas soils in very steep areas are rarely deep, so the usefulness of the model may be restricted in marginal areas.

Review of classification systems – The development of tropical agriculture has benefitted from remote sensing techniques since the 1960s (Collins, 1966; Heyligers, 1968) whilst air photo compilation keys (Harnapp & Knight, 1971) and classifications specific to tropical environments (Sheng, 1972; Collins & Collier, 1980) have aided local agencies in identifying land evaluation issues. Parametric indices, like the NDVI, have a regional application and a potential for process-based modelling.

Physiographic systems, like the LSC, were based on the rigorous homogeneity of facets, whilst the LUCC allowed mixed classes for complex pixels and the LCCS used classifiers to determine boundaries. Those systems incorporating a seasonal element in terms of vegetation phase or complex mapping symbols were similar to the USLE and SLEMSA indices, and more useful to a soil erosion model than those which identified the activity at a fixed point in time. Sequential data were useful for a seasonal element to indices, but could not predict changes in land use where there was short or unstable tenure or for products for which demand might change rapidly (export markets). The significant terrain management inherent in certain classifications (LCC, Sheng) took the future use of the soil into account, but did not incorporate an economic evaluation of the techniques involved. The LUT, on the other hand, regarded a cost-benefit analysis as essential in classifying the land. Measuring the capability of land resources requires a quantification of potential use, not merely current occupation.

The concept of boundaries has always been an issue in classification (Beckett & Webster, 1969), particularly in natural kinds. Boundaries of a natural feature are a social construct, and a problem for analysts of continuous data in both raster and vector information. The range of values that represent a soil type classification indicate a point at which one soil series becomes another. Within one series, homogeneity is assumed, despite a considerable value range. Foussereau *et al.* (1993) solved the boundary issue by resampling the variability of the soil data, using a method called bootstrapping, and presenting alternative maps. Very few soil profiles in a soil mapping unit actually meet all the specifications of the classification unit according to Burrough (1991), although Lopez (1991) demonstrated that physical properties were very homogeneous within certain geopedological types, thus validating the use of some properties for extrapolation.

4. Review of GIS assessments of erosion

Despite the limitations of conventional methodologies, they have been successfully applied, conducted manually for many years before the advent of GIS. The definition of a GIS is necessarily broad, describing as it does a tool, developed simultaneously by many institutions, to automate certain geographical techniques. The term "geographical information system" is European, but it is not universal (DeMers, 1997), although the acronym is generally recognised. The definition has also changed with the development of new packages and imaging software. GIS deals with space-time data with subsystems for spatial data input, storage and retrieval, manipulation and analysis, and reporting (DeMers, 1997). However, a GIS is reliant on its input. It does not make data more accurate or reliable, it does not challenge incorrect sources, and there are considerable assumptions involved in converting and interpolating data points. Like statistics, a GIS can produce an attractive output that may have a spurious input and analytical basis.

The first phase is the production of a base map on which the analysis can be presented at an appropriate scale and simple enough to communicate the spatial location without causing confusion when overlay data are added. The same issues arise for GIS analysis as for traditional procedures. Firstly, a mapping entity (terrain mapping unit, hydrological response unit, hillslope response unit or pixel) presumes a degree of homogeneity within the chosen unit, for which scale is important. Secondly, the thematic classification still has boundaries, class intervals and representation to be considered. Analog, conventional cartography has benefitted particularly from GIS tools in the field of predictive analysis. The GIS environment can save time, but input activities, correction and groundtruthing are often underestimated. Traditional thematic map production was compared with a GIS analysis of the same information (DeMers, 1991) in which vegetation notebook data were converted into a GIS database (DBMS in ArcInfo) to produce more accurate maps. The analog method obscured pertinent data in the soils map that the DBMS showed clearly. If the field notes were already available, the GIS approach could always be more easily produced and respond better to the concept of different uses of the same data.

The power of the computer is in measuring, comparing, interpolating and describing the contents of the database. Therefore, the art of producing a useful GIS model is clean input data, transparency of analytical methods and simplicity of reporting. If data cannot be included because it is unreliable or unpublished, then such information should be left out of the model until it can be more rigorously tested.

The GIS-related research reviewed here is arranged according to type. The direct approach to analysis involves mapping the existing features and interpreting each of them on the basis of its location, requiring little more than data input, manipulation, storage and presentation, but is often the basis from which more complex models are developed. A descriptive or qualitative GIS analysis involves the combination of control variable maps using subjective rules. It represents an attempt at identifying causal mechanisms. Predictive or deterministic research uses primary or derived data to construct causal models. The next generation of deterministic models involves statistical analysis. Rather than the deductive approach of most deterministic models, statistical research uses inductive reasoning, in which the data layer of the known feature is overlain with factors known to be influential in the initiation of the factor.

Direct approach

Direct analysis assumes that future activity of the mapped features is based on past activity, with no attempt to determine potential future activity based on cause and effect. One of the first projects involved habitat changes in traditional marsh pastureland in the Broadlands of eastern England (Baker & Drummond, 1984), in which the boundaries of vegetative zones and their centroids were digitised from air photos and integrated with Landsat MSS data. This time series analysis identified the trend of marsh towards pasture. Vandaele *et al.* (1996) produced two digital terrain models for 1947 and 1991 to calculate the difference in z (vertical) coordinate to compare with convex and concave entities. The results bore little relation to previous water erosion models of slope processes and tillage practices were suggested as the alternative influence.

Direct analysis is simple and quick, but only gives a limited description of the dataset with some descriptive statistics. The time series analysis of Baker & Drummond (1984) and Vandaele *et al.* (1996) showed neither cause and effect nor process, and the interpretation depended on hitherto unseen factors.

Descriptive research

Soil erosion hazard may be described in terms of the present morphometry of a drainage basin. Casasnovas (1995) defined erosion classes by assessing five properties; drainage density, eroded area ratio, crenelation ratio, depth and erosion activity level. The hydrographic properties were mapped and aggregated to assess the erosion class. Alternatively, the spatial nature of an individual factor and the potential extent of erosion can be the goal of descriptive research. Lopez (1991) applied the adiabatic lapse rate to a DEM allowing a mean annual temperature map to be constructed. He could establish when the soil was saturated since the rainy seasons and the annual rain per season were known.

Another approach is to measure the temporal change in a factor thought to influence erosion. Meijere *et al.* (1988) modelled land use change and erosion under certain cultivation practices. Physical, infrastructural and legal aspects were combined into attractiveness classes. Population growth, derived average farm sizes and observed agricultural practices were combined to show the areas of less suitable and accessible land that would be under pressure of development. Claure *et al.* (1994) generated a DEM for topographical elements, and then used an overlay of geology, soils, land cover and slope gradient to determine overall hazard. The relative weights were drawn up to reflect the relationships these factors had with erosion (see Chapters 6-8).

Qualitative systems tend to be developed when there is inadequate data or software limitations. The subjective weighting in some GIS models may have a basis in empirical studies (Claure *et al.*, 1994), but each of these reviewed examples contained subjectivity at more than one level. Meijere *et al.* (1988) had to assume cultivation practices would not change in a decade and that attractiveness was limited to three factors. Casasnovas (1995) used five variables to determine erosion class to classify the land area with a subjective ranking (see above). Lopez (1991) based mass movement hazard on the seasonality of soil saturation and bioclimatic zones; Claure *et al.* (1994) presumed geology, slope and soils were the only positive effects on landslide hazard.

Despite these assumptions, each of these studies produced useful research for the areas concerned even though they were hampered by a lack of data. Therefore, the main advantage is that such research is relatively quick, not requiring abundant or detailed geotechnical data.

Predictive or deterministic research

Deterministic research assumes causal relationships, based originally on both Newton and Darwin for which there is occasionally empirical evidence. Cause and effect research is still a common theme in geography despite having been relegated to the historical section. Models and data collection have enabled generalisations about the environment to be made, making prediction possible. Predictive techniques identify the potential activity of a feature or hazard using algorithms, extrapolation and simulation.

Karnielli (1991) developed a soil moisture accounting procedure in which hydraulic conductivity had been based on bare soil hydraulic conductivity, and percentage ground and canopy cover. Schmidt *et al.* (1995) had empirical research to support the assertion that soil carbon and nitrogen content were highest on north-facing slopes at a high elevation in a densely populated watershed in Nepal. When Worosuprojo *et al.* (1992) used a combination of the USLE and GIS in erosion hazard mapping, the factors were directly observed in the field and through laboratory tests of soil samples, not using remotely-sensed data.

There are several models that simulate watershed characteristics, attempting process-based modelling. AGNPS was developed to analyse non-point pollution in agricultural watersheds (Engel, 1996). It simulated runoff, sediment and nutrient characteristics for each cell, and routed the data according to downslope movements. AGNPS modelling has been combined with GIS software (Bishr & Radwan, 1995; Lo, 1995) using climate, hydrology, soil, elevation, slope angle, aspect, land use and cover. Another approach was that used by Sauchyn (1993), coupling a water erosion risk map with the USLE estimations to evaluate the empirical basis of the USLE.

Critique of deterministic analysis – Deterministic models assume there is sufficient knowledge about the processes that explain the spatial patterns of the feature. The GIS component can operate at all scales, and produce (Sauchyn, 1993) a relative estimation of soil hazard locations relatively quickly and cost effectively. None of the research reviewed here extrapolated the data outside the research area, but those projects using the USLE factors are extrapolating American empirical field evidence, which is thought not to apply to the tropics (McGregor *et al.*, 1998). The development of laws and models of general application are popular, so it should be no surprise that the USLE has not only gained so much favour, but been used outside the boundaries of applicability. It is also said that the study of unique occurrence is the domain of the social sciences. However, it is necessary to understand the results that do not fit the generalised model in order to improve the model or abandon it altogether. In the next section, 'unique conditions' is one of the methodologies encountered.

Statistical research

The data layers in a GIS can be assessed in a number of ways to determine factorial completeness and influence. This might take the form of error matrix generation, but temporal determinism or causal research is also useful in linking modelling with an empirical database. The analysis can use statistics to establish weights for the factorial layers associated with the model results or feature. These may be uni-, bi- or multivariate.

Multiple regression, discriminant analysis, cluster analysis, unique conditions and logistical regression have been used in landslide studies, a common focus of statistical analysis.

Thurston (1997) chose stepwise overlay to produce a landslide hazard map using GIS in Derbyshire. All the factorial layers were divided into classes of erosion contribution and each pixel had a cumulative score. Each pixel had a unique condition, or combination of scores that gave that score, weighted with a map of current erosion. Once the accuracy of any factor in predicting the final erosion score for any pixel was known, each subsequent factor could be added to improve accuracy, until there was a diminishing return. Slope angle gave 69.4 % accuracy, which when added to geology gave 76.7 % accuracy. Aspect was added to the overlay to give 77.6 % accuracy, but distance to river was rejected since accuracy diminished to 76.8 %.

Mejia-Navarro *et al.* (1994) incorporated a range of environmental factors, preclassified into ten classes of influence, in an algorithm to estimate hazard susceptibility and land use suitability. The stability of geomorphic units was based on land use and geotechnical properties, with an emphasis on historic record and, finally, slope, the most influential factor according to the authors. Ahmad & McCalpin (1999) determined the landslide hazard for Kingston, Jamaica, using past landslides, slope angle, aspect and curvature, bedrock type and structure, distance to faults and distance to roads. In a mathematically complex model, Pilotti & Baucchi (1997) mapped the water pathways in a basin at a high spatial resolution and produced two outputs from which a third was derived, providing a fast, accurate topographic input to the RUSLE.

In a study of the geomorphic and environmental controls on flash flood flows, Schmittner & Giresse (1996) used principal components analysis to highlight the empirical relationships between erosion influencing factors and their strength of dependency. Notable relationships included the sandy topsoil which occurred when slope angle increased whilst humus and vegetation decreased. The control that slope had on topsoil characteristics was important for understanding runoff and erosion processes. Niemann & Howes (1991) assumed that shape properties (gradient, curvature and position in the landscape) could be grouped (unsupervised cluster analysis) into morphometric units, and then correlated with the behaviour of specific fluvial processes like landsliding and gully initiation.

Garg & Harrison (1992) used a GIS for monitoring land use change, degradation and erosion risk for the Albudeite catchment in southeast Spain. The distribution patterns of land use classes were computed against the DEM to correlate land use change with elevation. Vegetation cover was less than 10 % where severely eroded land, dry channels and gullies, were restricted to <260 m elevation. The socio-economic relevance of the 260 m contour was not discussed, but grazing and farming practices avoiding the active fluvial areas was inferred. The study also allowed an analysis to be made of land use change/no change maps with the erosion risk factors to see if change encouraged erosion.

Statistical analysis is driven by the inventory of the feature, which has to be carried out in considerable detail and with high levels of precision. This is feasible for features that are discrete, like landslides and severely eroded gullies, although identifying historic features is fraught with questionable scars and deposits (Ahmad & McCalpin, 1999). For activities such as sheetwash, the mapping of sheet and rill erosion at anything above field level scale is too time consuming, inaccurate and difficult for most research. When the feature mapping has good integrity, statistical analysis has important contributions to make to systems and process-based research. However, the disadvantages are that questionable data might be used. The method still assumes that all the influential factors responsible for the spatial pattern of a feature are accounted for, past, present and future. The absence of past or present hazards in a particular area does not mean that the hazard will not occur there in the future (Ahmad & McCalpin, 1999). In a good model, an unfailed area sharing common factors with a failed area will be given a high rank of susceptibility. However, deficiencies in the original inventory will lead to under or over representation of the hazard in the final map.

Process-based modelling

> "The ultimate goal of watershed modelling... [is a] deterministic model in which all cause and effect linkages and feedbacks are known and understood" (Stocking, 1978, p. 130).

This early recognition of things to come predicted that process modelling would still be deterministic. Process-based modelling involves theoretical concepts and computational methods that describe, represent and simulate the functioning of real-world processes. Simulation models, as they are otherwise known, are based on an *a priori* understanding of the forces driving changes in a system. They represent the processes at a certain level of simplification with the most important elements and their interactions. Most traditional geomorphology simulation assumed spatially averaged parameter definitions, but the spatial diversity at catchment scale was simplified or ignored. GIS is well suited to spatial modelling with large and complex databases, although that complexity makes it difficult to transfer to other research areas. Simulations can provide information which is impossible or too expensive to measure, as well as insights which are not amenable or too complicated for analytical theory methods.

Process-based applications are being developed for both event-based and small catchment hydrology. The Limburg Soil Erosion Model (LISEM) is a physically-based hydrological and soil erosion model allowing remotely sensed data to be used (de Roo *et al.*, 1994). The processes incorporated are rainfall, interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow channel flow, detachment by rainfall and throughfall, detachment by overland flow, and transport capacity of the flow. Special attention is given to the influence of tractor tracks, small roads and surface sealing, and the processes changing temporally.

The EUROSEM model is based on the concept of modelling the detachment and transport phases separately (Morgan *et al.*, 1996) and then computing erosion on the basis of the most limiting of these. This model is regarded as a compromise between overly-empirical models (e.g., RUSLE) and models that attempt too fine a level of process description (e.g., WEPP) (Rossiter, 2000). One of the disadvantages is that neglecting raindrop detachment combined with raindrop-induced flow transport leads to underestimation of erosion under certain circumstances (Mitasova & Mitas, 1998).

The Water Erosion Prediction Project (WEPP) is a distributed parameter, continuous simulation, erosion prediction model. The processes include infiltration and runoff, soil detachment, transport and deposition, plant growth, senescence and residue decomposition. For each day of simulation, WEPP calculates the soil water content in multiple layers and plant growth/decomposition whilst including the effects of tillage processes and soil consolidation (Elliot & Hall, 1997).

Although deterministic models are being sidelined in favour of process-based models, the latter are not complete imitations of the real environment. There are causes of inconsistency between models and reality (Mitasova & Mitas, 1998) which enthusiasts for the new paradigm have been slow to admit. Firstly, the process may not be well understood or inadequately treated. Secondly, only limited numbers of interacting processes can be incorporated, as admitted by the authors of EUROSEM (Morgan *et al.*, 1996), regarding combinations of detachment by flow or raindrops, transport by flow and raindrop-induced flow or splash. The level of simplification that a model represents cannot be determined with accuracy since real processes include non-linear behaviour and feedback loops over spatial and temporal scales. Thirdly, errors in input data and the propagation thereof are more likely when very complex models and numerous parameter files are involved. Finally, in common with empirically-based models like USLE and SLEMSA, a model can be incorrectly applied to conditions when its assumptions are not valid. They may have a considerable theoretical element, for example, hypothetical storms of known probability of return (LISEM) and their size means the simulation results cannot be verified. Some authors (Hall, 2000; Renschler & Flanagan, 2002) also believed that process-based models do not have the versatility and applicability of empirical models.

Major limitations of modelling

A number of studies have added a strong empirical dataset to general research, particularly the USLE and SLEMSA. However, the emphasis of much research is still environmentally deterministic, concentrating on cause and effect rather than process. The most obvious limitation of the empirical approach is the applicability of any resulting model outside the area of data collection, but a process-based model does not avoid this problem. The incomplete understanding of the processes involved and the lack of data hampered the development of distributed modelling technology (Lopez, 1991). Spatially variable processes, like runoff and rainfall fields, have been plagued by uncertainty (Lopes, 1996). Most general soil loss models, including the USLE, do not successfully predict the extreme environments (Morgan *et al.*, 1984). In some disciplines there may be inadequate knowledge to support more complex process-based solutions.

The importance of terrain modelling for soil erosion studies has been demonstrated, but it is not without its drawbacks compared to traditional mapping techniques. The raster-based system is based on the assumption that each pixel carries homogeneous data, although they may contain a boundary or two classes. The smaller the resolution, the more likely each pixel is to be homogeneous. Hammer *et al.* (1995) studied the problems of resolution. Slope class maps of 10 m and 30 m resolution DEMs were tested against 10 m grid field measured slope class maps. The level of accuracy for the 10 m DEMs was more than 50 %, but the 30 m DEMs were only 20-30 % accurate. Slope data derived from a DEM tends to overestimate erosion compared to traditional soils survey techniques (Bocco & Valenzuela, 1988; Niemann & Howes, 1991).

Once a number of factors have been integrated in a GIS, there can be considerable variation in results between neighbouring pixels, thus making the final map difficult to interpret. A number of authors have investigated this fragmentation of information (Lopez, 1991; Niemann & Howes, 1991). The polygons have to be reclassified and aggregated for interpretation and evaluation. Casasnovas (1995) used selection, elimination, aggregation and reclassification to reduce the density and complexity of information. A reduced number of erosion TMUs were built on the basis of connectivity and water flow relationships.

It is important to recognise that some temporal and difficult to measure factors cannot be incorporated, even though process-based models do incorporate them. Soil moisture, surface crusting and transport limited runoff may only be modelled accurately at field scale and extrapolating this data to land systems presents the difficulty in testing the homogeneity of land units (Beckett & Webster, 1969). Modelling results cannot be attributed to a reductionist central class concept of soil polygons and a better way of describing spatial variation has to be found, for example, Kriging interpolation (Burrough, 1991). The number of observations necessary to calculate this would be sufficient to allow better soil maps to be produced in the first place. Computers could incorporate the spatial variability of soil attribute data within the original boundaries using resampling methods like bootstrapping (Foussereau *et al.*, 1993). Algorithms for routing flow across land surfaces, up-slope contribution, and non-linear function of catchment area and slope are among some of the new innovations in terrain analysis techniques. Surface depression and, hence, storage is difficult to model at watershed levels although some programmes now incorporate it. Other factors like conduits can be digitised, but only if they are known to be active as accelerators of erosion (Farres, pers. comm.).

Review of GIS assessment techniques

The techniques reviewed offer a wide range of possibilities for soil erosion analysis using GIS. Certainly the 'unique conditions' (Thurston, 1997) and other analysis methods (Lopez, 1991; Claure *et al.*, 1994; Mejia-Navarro *et al.*, 1994) are attractive for the results they produce, but they deal with mappable, discrete events. There are many assumptions in descriptive and predictive research, so error propagation resulting from incomplete models can invalidate quantitative models. In terms of sheetwash erosion, there is an incomplete understanding of soil moisture and permeability where soils are particulary thin, and is one example of introducing inaccuracy in process-based modelling. Model verification would be difficult in a complex environment.

5. The research area

Jamaica is the third largest island of the Caribbean, with an area of 10,982 km^2, and is located 150 km south of Cuba and 650 km from Honduras, the nearest mainland, at 18° N 77° W. A geological history of volcanic activity and marine submersion has created a complex topography and geology. The highest point is Blue Mountain Peak at 2290 m, which forms part of the Blue Mountains. The tropical maritime climate is very variable along the gradient from coastal to mountain position, with temperatures ranging from 13° to 27° and rainfall from 750 mm to 7500 mm.

Background history of land use

The history of Jamaican export cultivation, by eighteenth century white settlers in the hills, was dominated by fairly intensively cropped cocoa, whilst the steepest slopes above 1524 m (the cloud zone) were reserved for Blue Mountain coffee. This coffee mono-culture, that the estates adopted on steep slopes, was damaging the watersheds as early as the 1830s. The concept of cropping the land until it could support no more, before moving on to virgin areas, seems to have been common. The coffee boom, from 1783 to 1838, was short-lived, the end being signalled by increased competition from Brazil, the emancipation of slaves in 1834 and changing social habits in Europe (Higman, 1986). The slaves not only subsisted on the 2000 m^2/slave provision grounds reserved for them, to save the planters having to import food for the workforce, but provided a considerable surplus for free men, too. This surplus was sold, and eventually, for the frugal, the purchase of both public and private land was possible. It was these provision grounds, predominantly in the hills, that formed the basis of the new subsistence activities and land tenure patterns. The small farming practices in Jamaica were less to blame for soil erosion than the export economy of the estates.

Agriculture was given major status as an export earner in the 1950s as the country developed. The adoption of a modernisation policy in agriculture went virtually unchallenged against a background of small farmer condemnation (Hills & Iton, 1983). By the mid-1950s, researchers began to realise that the small scale sector was, and had been, outproducing the estate sector since the 1870s. The economic growth of the 1950s and 1960s funded an injection of public spending into small farm development, credit and subsidies. This intensification of agriculture for national (rather than colonial) profit involved the modification of traditional strategies by shortening or eliminating fallow periods, abandoning crop rotation for monocropping and encouraging quick maximum returns (Spence, 1985). A possible cause of erosion was the removal of important trees on hillslope plots, but a far more harmful factor was the inappropriate insistence on expensive imported inputs that replaced the good farming practices of traditional agroforestry (Hills & Iton, 1983). These reduced the farmer's ability to cope with adversity. This unabated, so-called modernisation involved considerable bribery to adopt the Western materials that went with it. The advice to accept this modernisation came typically from outside the country, and it was being left to the farmers to discover that high input technologies were too expensive in terms of economic and environmental resources.

Selecting the scale of investigation

The spatial scales at which research has been carried out with regard to hillslope erosion range from regional through watershed to small-scale grid cells. Regional land capability mapping has been carried out at 1:250,000, a scale which many believe is at best inappropriate and at worst unusable. At the other end of the scale, field and laboratory studies covering rainsplash and soil aggregate processes are not applicable to the complexities of hillslope forms and processes. Many models, for example the Universal Soil Loss Equation (USLE), are based on plot-based results and then presumed to hold true for higher scales. Several authors have used GIS techniques and modelling for analysing slope erosion, with the advantage that mapping resolutions can be enhanced or aggregated to an appropriate land-use management scale, providing more detailed information is provided for the former or strict homogeneity is not assumed for the latter.

Regional studies – Studies at the regional scale have involved generalising or the aggregation of erosion information, that is, reducing the density of information that has to be processed and analysed. Most geographic information involves simplification of the data to fit the measurement framework, especially at the regional scale. The compromise that researchers make in producing regional maps relate specifically to the concept of homogeneity. Most cause and effect relationships and processes have only been studied at considerably smaller scales, and may not be true at the larger scale, being influenced by factors not included in plot studies. For example, the USLE assumed uniform slopes in the calculation, whereas a watershed calculation would have to assume concave and convex areas. Climatic influences at the microscale become significantly more complex at the macroscale and are not yet fully understood.

Morgan & Nalepa (1982) stated in general terms that area-wide erosion analysis was difficult because sediment comes from extensive source areas, is intermittent in nature, is related to climatic events and is affected by changing land use management. Since field studies were costly and time consuming, they argued, cost-effective methods were popular with planning agencies. Sauchyn (1993) argued that since the conventional approach to the regional assessment of erosion risk was the interpretation of soil maps, the simplifying of the data produced only very approximate models of the soil landscape. This dichotomy between the size of the spatial unit and the actual scale of the processes represented a misuse of process models derived from plot-scale experiments (Sauchyn, 1993). Casasnovas (1995) abstracted hydrographic data at the regional level in order to identify erosion terrain units. However, by first abstracting at the regional level, one presumes a level of information was lost, so that some specific data did not carry through to the post analysis.

Many cartographic techniques are available for reducing the quantity of data to the level of information to be consumed. Some information reduction requires whole entities to be removed to simplify the representation. In order to retain the accuracy of the real data, many agencies have adopted an intermediate scale appropriate to their field. In erosion studies it is commonly the watershed, recognising the important role of fluvial processes in the transport of sediment.

Watershed studies – The assessment of soil erosion at the watershed scale has important implications for conservation programmes as well as geomorphology (Harden, 1990). However, the scale presents problems for homogeneity, since the soil series and other factors mapped at this scale vary considerably within their classification. Pilotti & Baucchi (1997) argued that the processes of erosion suggested research on the scale of catchment. They devised a model that used a high resolution DEM (including complex slopes) and the modified USLE to calculate the soil loss from the catchment, bridging the gap between the hillslope (USLE) and catchment (water path) scales.

The scale of watershed has become increasingly popular due to the development of hydrological process-based models which are now a common focus of research. Suwanwerakamtorn (1994) prepared flood forecasts for a Thai catchment to see if the integration of GIS and a hydrology model could be used to analyse upstream land use changes and downstream flood patterns. The watershed is a useful hydrological unit for planning both on and off-site degradation control. Bishr & Radwan (1995) developed a decision support system for watershed management that used the AGNPS model, Universal Soil Loss Equation (USLE), Nexpert system and GIS (ArcInfo). This method selected an endangered water body to be protected and then ranked the conservation practices which the various components calculated.

The computer model using raster representation can falsely suggest that the model is accurate to pixel level. However, the pixel structure is merely a storage system. A low resolution may be necessary if the input data are not available at the 40 × 40 m plot scale. However, a high resolution is determined by the digitisation of the topographic data, since the contours have to remain recognisable. This scale also gives a better representation of other factor boundaries, but the PED model is not a site specific classifier. Sauchyn (1993) concluded that relative erosion risk for various combinations of climate, topography, soils and land cover was a feasible product of regional based research. Therefore, this model is intended as an indicator of areas in the watershed that have the potential for erosion, if the present vegetation cover is insufficient or removed.

Location of study area

The Buff Bay watershed is located in the parish of Portland in the northeastern part of Jamaica (Fig. 1). The southern boundary of the watershed is the Grand Ridge of the Blue Mountains, the northern boundary is the north coast and the distance between the two measures 18 km.

The Bangor Ridge, topped for a distance of 6 km by a road, forms the eastern ridge. The western ridge comprises two major ranges, the Mount Telegraph Range in the northwest and the Great Ridge in the west. Important rivers rise in the same range as the Buff Bay, the Dry and the Wagwater rivers to the west and the Mammee, Hope and Yallahs rivers to the south.

The coast road connects Buff Bay to other coastal towns. There is one main road down the valley from Hardwar Gap to Buff Bay town (Pl. 1B). South of the Gap the road descends through Newcastle to Kingston. Landslides occasionally close this road, leaving access to the valley via the Junction Road which follows the Wagwater River to the coast and enters the watershed from the main coast road. One other minor road enters the valley from Yallahs, via Silver Hill Gap. The Bangor Ridge is served by the other minor road, from Mahoe Plantation to Tranquility. There are foot tracks linking the valley to the Spanish River to the east. No tracks leave the valley to the west. Of the minor tracks and roads only 20 % can be accessed by regular vehicles and four-by-fours do not give access to many more, several of which have fallen into disrepair and deep gully systems. Part of this neglect has been caused by FIDCO (Forest Industries Development Company) abandoning operations where they had built over 75 km of roads to maintain plantations. CIDCO (Coffee Industries Development Company) has brought some roads back into use, but many roads and tracks fall below the necessary engineering standards for runoff management, with gullying and landsliding the result. Well-used footpaths have the same effect.

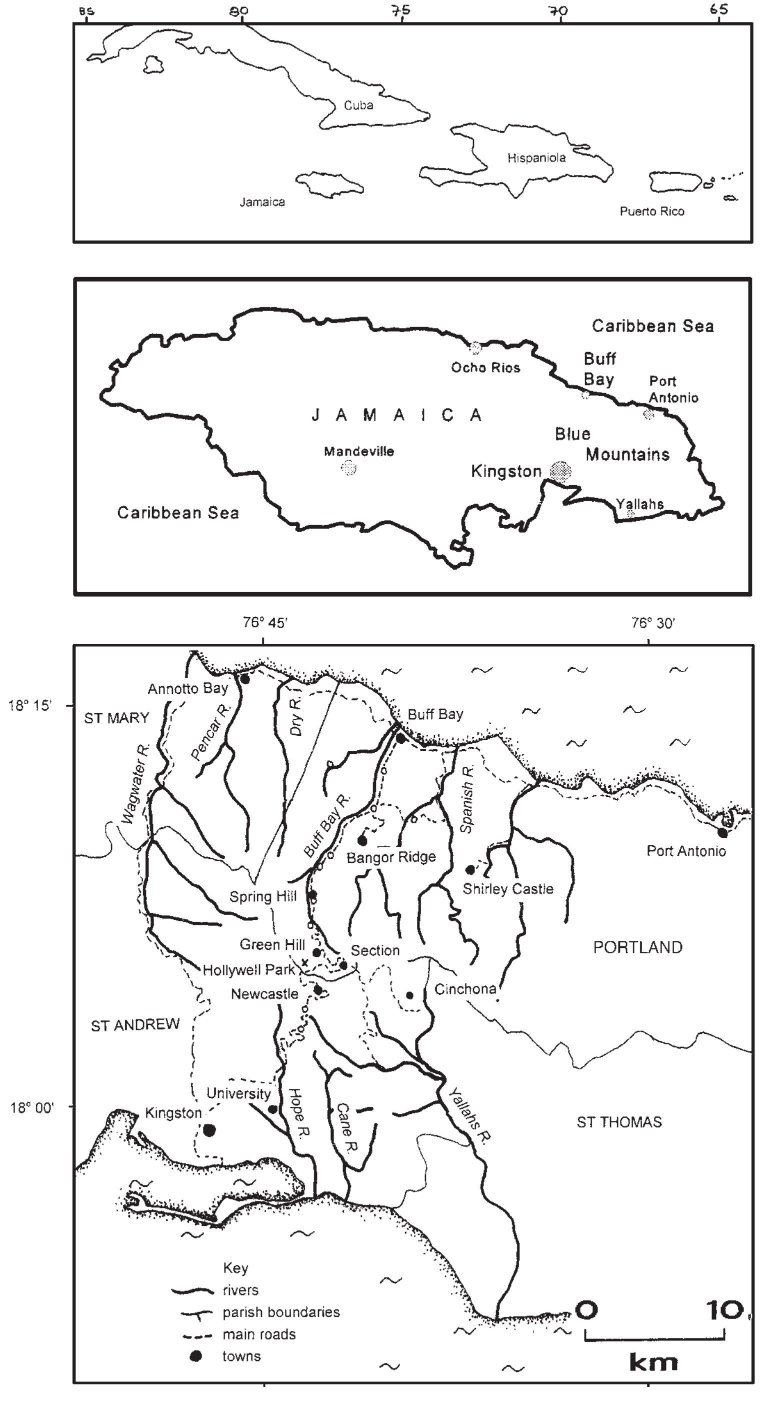

Fig. 1. Location of Jamaica in the Caribbean; the Blue Mountains and Buff Bay in Jamaica; the Buff Bay River, other rivers and towns in west Portland.

The town of Buff Bay is at the mouth of the main water course, the Buff Bay River, which flows roughly northnortheast to the coast (Pl. 1A). There are numerous, small unnamed streams and rivers entering the Buff Bay River, but two tributaries are large enough to be named on the 1:50,000 scale map. The White River (not to be confused with the White River rising near White Hall) flows from Moodies Gap entering the Buff Bay at Wakefield, whilst the Shentamee, the larger of the two, flows from below Westminster Cottage just in the parish of St. Mary. Both of these tributaries are on the western side of the Buff Bay.

The area of the watershed is reported by a number of authors (Gupta, 1975; Nkemdirim & Jones, 1978; CIDA & Forestry and Soil Conservation Department, 1993; Cunningham, 1993), but interpretations of its extent differ. Some authors include rivers that do not flow into the Buff Bay River, but directly into the sea.

Table 11 shows three estimations of the area of the Buff Bay watershed and their references. There is a considerable difference in these figures, but for a comparison with other watersheds the Buff Bay measures an area of 6900 ha. The research area is restricted to the upper part of the watershed, south of Belcarres, an area of 3600 ha.

Table 11. Comparison of watershed area estimations.

References	Reported area	Conversion to hectares
Gupta, 1975	63.17 km^2	6317
Nkemdirim & Jones, 1978	21 $miles^2$	5439
digitised from 1:50,000		6939

Climate

The climate of Jamaica is tropical. This northeastern side of the island is windward, comprising steep slopes, narrow ridges and incised gullies, many of which are dry except in times of heavy rain. The Buff Bay has a consistent flow and floods onto a narrow flood plain in times of heavy rainfall. The Meteorological Office in Jamaica provided the rainfall data for the years 1951 to 1980. The rainfall measurement in the Buff Bay watershed, which is west of the area of highest rainfall, takes place at three stations, Buff Bay, Belcarres and Cedar Valley.

A 30 year annual isohyetal map of Jamaica (CIDA & Forestry and Soil Conservation Department, 1993) shows the concentration of highest rainfall in the country in the parish of Portland. Average rainfall increases from the coast inland and with elevation. The peak of the concentration is located between the John Crowe mountains and the eastern extension of the Blue Mountain range, with the highest rainfall point at Millbank (6517 mm). The pattern of isohyets around the highest point is elliptical, the long axis parallel with the ridge of the Blue Mountain range, but approximately 6 km to the north of it.

The highest 30 year mean, in the Buff Bay watershed, is found at Belcarres (3390 mm), which is only a quarter (400 m) of the way up the watershed (1600 m) in elevation terms (Table 12). In most of the watersheds along this part of the coast, annual rainfall increases with elevation up to an elevation of 700 m. The prevailing rain-bearing winds reach the coast then move inland and upslope, causing more rain as the air cools with altitude. However, at Cedar Valley, higher (600 m) in the watershed, there is a lower 30 year mean of 2512 mm. Above 700 m there is an indirect relationship between annual rainfall and elevation, in which rainfall figures show lower totals for higher elevations. The Pencar/Buff Bay report (CIDA & Forestry and Soil Conservation Department, 1993) puts this anomaly down to a rain shadow effect from the Blue Mountains, suggesting that the prevailing wind is more easterly than hitherto reported. However, analysis by the author (Table 12) has revealed a local rainshadow caused by the Bangor Ridge. Such local anomalies, whatever the cause, need to be assimilated in the hydrological or climatic element of modelling.

Table 12. Relationship between rainfall and elevation.

Place /height (m)	Relation to ridge (height of ridge)	Elevation	30 year rainfall mean
Belcarres	Northwest / 600 m	400 m	3390 mm
Cedar Valley	West (peak to east 1500 m)	600 m	2512 mm
Sportsman Hall	On eastern flank of ridge / 600 m	600 m	3500 mm
Claverty Cottage	East (ridge to west)	700 m	4234 mm

A graph of parish rainfall for Portland based on the 30 year monthly mean shows a seasonal trend of two peaks and two troughs. The highest peak is between October and January, and is caused by upper level troughs and stagnating cold fronts from the southeastern U.S.A. (Nkemdirim & Jones, 1978), with the highest rainfall month invariably in November. Dry spells between June and September are common, but short. Mist clouds commonly cover the peaks at the extreme south of the watershed most days, partially burning off after midday. This cloud zone above 1524 m (McDonald *et al.*, 1996) is responsible for the success of coffee crops. The mists add to the water budget of the hillslopes at higher elevations.

The extreme rainfall events are brought about by tropical depressions. The ‘frequent strike’ classification (one every fifteen years) that is given to Jamaica in respect of hurricanes is born out in the statistics since twenty have hit the island and another 100 have come close in the last hundred years. The heavier than normal rains associated with hurricanes cause landslides in the watershed, but heavy storms with intensities recorded at 50 to 200 mm/hr are also fairly common. Rainfall intensities at Mavis Bank have been recorded as high as 25 mm/hr for nearly three days (McGregor, 1988). Maximum rainfall with high intensities was recorded in the Blue Mountains (Table 13).

Table 13. Rainfall intensity events in the Blue Mountains (1980-1981), Jamaica (McGregor, 1988).

Duration (minutes)	Intensity (mm/h)
5	213
10	90
15	61
30	54

The agroclimatic zones occurring in the upper Buff Bay watershed (Table 14) were determined on the basis of JAMPLES (Batjes, 1994). These give an indication of the rainfall reliability, potential evapotranspiration and, hence, the soil moisture regime.

The extreme upper and lower reaches of the Buff Bay watershed fall within agroclimatic zone three and mean temperatures range from 24° at 300 m to 17° at 1500 m. The middle of the watershed has an agroclimatic zone four classification, whilst on the very eastern boundary of the middle watershed, on the Bangor Ridge, there is agroclimatic zone five.

Table 14. Characteristics of agroclimatic zones found in the Buff Bay watershed (Batjes, 1994).

Pencar/Buff Bay	JAMPLES	annual R75/PET ratio	Dependable growing season	Main dry season
Zone 2	Wet 1	1.00<= R75/PET < 1.25	6-10	1-2
Zone 3	Wet 2	1.25<= R75/PET < 1.50	7-10	1-2
Zone 4	Very wet 1	1.50<= R75/PET < 2.00	8-11	<1
Zone 5	Very wet 2	2.00<= R75/PET < 2.50	12	n.a
Zone 6	Very wet 3	2.00<= R75/PET < 2.50	12	n.a

Seasonality has also been linked to the soil moisture regime (Nkemdirim & Jones, 1978), using probability curves for estimating the return period of floods. The flood seasonality was influenced by the distribution of rain and not its magnitude. The winter rains were found to be persistent, leading to saturated soils and, hence, higher flooding probabilities.

Geology

The Blue Mountain Inlier is composed mostly of sedimentary and igneous rocks, with some minor exposures of metamorphic rocks, all occurring in complex, fault-controlled outcrops (Robinson, 1994). The oldest are the metamorphic schists. Volcanic activity was both subaerial and submarine, leading to interbedded layers of tuffs and lava flows with conglomerates, shales and limestones. The faulting and thrusting which brought all these rocks to their present uplifted position also contributes to the instability of the landscape.

Diverse rock units and recent alluvial deposits are found in the watershed. The Paleogene Wagwater Group outcrops in the upper watershed, comprising the following units.

Richmond Formation – Well bedded, grey to brown weathered, alternating marine sandstones, siltstones and shales, with uncommon thin limestones and massive conglomerates. The bedrock is highly fractured, intensely jointed and faulted, and hence highly weathered.

Wagwater Formation – A sequence of dark red and purple conglomerates, sandstones and siltstones deposited under continental terrestrial conditions ('red beds'). Fluvially reworked pebbles originate from the volcanics and older limestones. The formation is deeply weathered, and characterised by intensive joints and faults. The minerals have been altered by hydrothermal activity.

Newcastle Volcanic Formation – Intermediate volcanics of massive lava flows, with intensive jointing and faulting. The rocks outcrop as crags and cause steep topography.

Chepstow Formation – An impure limestone interbedded with thin shale layers grading into thickly bedded, compact karstic limestone. It outcrops at Spring Hill and Birnamwood.

Gupta (1975) highlighted the susceptibility of the Richmond Formation to slope movements by mapping 107 landslides from air photos. Ahmad (1993) produced a rating scale of six units for the susceptibility of geological materials and terrain types to landsliding. Those applicable to the study area include unit six, the highest susceptibility, where there are outcrops of the Richmond and Newcastle formations on steep slopes; unit five, the mudrocks, siltstones and sandstones of the Richmond Formation and andesitic rocks of the Newcastle Volcanic Formation; and unit three, where there are exposures of the Wagwater Formation in deeply weathered material on slopes greater than 30 %.

Geomorphology and hydrology

Around the watershed boundary are significant peaks, Silver Hill Peak (1600 m), Catherine's Peak (1539 m), Mount Horeb (1440 m) and Mount Telegraph (1274 m). A number of gaps penetrate the Great Ridge, namely Silver Hill, Woodcutters and Hardwar, and these are utilised by major roads and tracks into the watershed. The Grand Ridge continues to rise to the east to more than 2000 m at the High Peak, part of the Spanish River watershed. The river bed is at an elevation of 200 m a.s.l. at Belcarres and the highest elevation of the heads of the mapped tributaries (1:50,000) is 1360 m a.s.l. The watershed has an elongation value of 0.34 (Nkemdirim & Jones, 1978), which reflects short side tributaries.

Estimates of the average slope vary considerably. Nkemdirim & Jones (1978) calculated the average for the whole watershed at 41 % (22°). The average slope of the upper watershed was calculated in Idrisi to be 27°, with 87 % of slopes steeper than 20°, and a maximum slope of 60°. The upper watershed is characterised by steep slopes and highly dissected terrain with sharp ridges and deep gullies. Many of the gullies have boulder beds. The bedrock of clastic materials, sandstones, siltstones and shales, are impermeable. There is percolation of the rainwater that does not immediately contribute to runoff, but it only infiltrates the upper layers of unconsolidated surface soils and underlying weathered rock. With such a low infiltration capacity below the top layers, saturation is rapid and gully formation common. These gullies are dry except during prolonged or intense storms. A number of morphometric studies (Nkemdirim & Jones, 1978; Miller, 1992; McGregor & Barker, 1991) have been carried out on the flanks of the Blue Mountain range, all suggesting that a dense dendritic pattern is common, with fifth order streams sometimes only 600 m from the watershed. Gupta (1975) calculated a stream frequency for the Buff Bay of 10.9 km^{-2}, suggesting a high level of dissection.

The middle of the watershed has a more rounded topography, the ridges are less sharp and there are fewer boulder-strewn gullies. The side slopes are less steep (average 25°), with restricted meandering due to the fault controlled geology through which the main river flows. This is especially noticeable when the river passes through the limestone hills. Alluvium and colluvium have collected at the toes of the slopes, and on the stream and river floors. The alluvial deposits are aquifers from which water is drawn by the local community. The Buff Bay passes through a series of gorges of White Limestone before reaching the sea. The karstic nature of these rocks provides the only real groundwater recharge in the system, since the upper watershed is underlain by clastic material, and the alluvial flood plain of the river is fairly restricted so that it does not have the alluvial aquifer potential of the Pencar and Dry Rivers in the vicinity (CIDA & Forestry and Soil Conservation Department, 1993).

With its origins in the impermeable and shallow soils of the Richmond and Wagwater Formations, there is little groundwater storage capacity and little surface soil water retention, leading to fast flows and flash floods during heavy rainfall as water is channelled directly into gullies and the main river. Hydrology records (1969 to 1992) for Spring Hill show that in 1970, a maximum daily discharge of 1900 cfs was recorded, with an average of 550 cfs. Eight kilometres down river at Tranquillity, after the Shentamee tributary, the highest recorded maximum daily discharge was 9282 cfs in 1988 as a result of Hurricane Gilbert, with an average of 2560 cfs (CIDA & Forestry and Soil Conservation Department, 1993).

Between 1979 and 1993, there were five major flood events in the island, all of which caused damage to houses, farms and roads. The Buff Bay River is prone to landsliding, a fact highlighted by the closure of roads at Hardwar and Silver Hill Gaps. Coffee plantation roads are particularly susceptible, and the tracks that lead off the Bangor Ridge from Mahoe Plantation down to Wakefield are deeply gullied and often closed. Coffee lorries often use tracks that an all-terrain vehicle can barely navigate, such as the Waterfall trail from Hardwar down to Green Hill. The landslide that regularly closes that track is activated by streams that are headcutting up the valley slope. The material that the landslide delivers to the stream causes severe erosion downstream in a heavily vegetated area. There is also documentation regarding the bedload transported during hurricane Flora in 1963 (Gupta, 1975), in which boulders of 1 m diameter, originating from landslides, were transported down stream and broke submarine cables offshore. The effect of all the sediment in the streams is felt down river, since Buff Bay town and other settlements rely on the potability of the river. The benefit of flood water is felt in the banana plantations situated along the very narrow, and hence prone to high water levels, floodplain.

The most comprehensive erosion data for Jamaica come from an experimental station in the far west of the island, but, for the Blue Mountain region, a small number of field and plot experiments were carried out in the 1980s. In the 1990s research focused on the effect of conservation techniques. McDonald *et al.* (1996) compared the erosion under four vegetative cover types for two storm events, whilst others (Table 15) gave a very broad indication of erosion in Jamaica.

The importance of relative over absolute values is highlighted by Table 15. These absolute rates are only accurate when produced as the result of field experiments and used as such. The vast ranges for each land use are the product of extrapolation. McGregor (1995) warned that the statistics had shortcomings, using different methods of measurement, a wide range of locations and many vegetative covers. They could not be used for averages because the wide ranges that were determined would make an average meaningless, whilst extrapolation should not even be attempted. The field scale measurements were representative of that area under the prevailing or seasonal conditions, but tended to be short term. A bare plot experienced less erosion than a cultivated plot that had just been tilled before the rains. Another cultivated plot showed less erosion than the bare plot when it had been dry and the soil needed 'recharging' (McDonald *et al.*, 1996).

Table 15. Comparison of erosion rates from sites in Jamaica (modified from McGregor, 1995; McDonald *et al.*, 1996 [marked *]).

Location	**Method**	**Landuse**	**Erosion (t/ha/annum)**
Mahogany Vale	USLE/guess	Overall	97
Blue Mountains	Traps	Forest	35-225
Yallahs Valley	USLE	Overall	160-280
		Agriculture	24-99
		Gully erosion	54-93
Smithfield	Traps	Agriculture	28-101
		Yam	17-133
Blue Mountains	Traps	Agriculture	22-294
		(Average)	(80)
National	Not stated	Croplands	90
Blue Mountains*	Gerlach troughs	Forest	<1
		Calliandra	4
		Agriculture	7.5
		Bare	11.5
			(tonnes/ha/event)
Blue Mountains*	Gerlach troughs	Forest	0.021
		Bare	1.470
		Agroforestry	1.612
		Agriculture	2.158

Soils

Soil formation in the humid tropics differs from temperate soils since rainfall is heavier and temperatures are higher. Heavy rainfall causes leaching so that, except in immature soils, nutrient levels are lower. However, there are exceptions. On very steep slopes, where there is surface crusting or where there is impeded drainage on flood plains, infiltration rates are low, runoff rates are high and leaching does not occur. This phenomenon can also account for lower levels of weathering. For every 10° rise in temperature, the rate of chemical reactions doubles up to a certain threshold. This causes increased biotic activity, higher weathering rates, and considerable litter production and associated biological activity. However, the presence of a calcareous bedrock or low moisture levels at the bedrock interface delays the development of acidity and, hence, weathering.

In the upper watershed there are four major soil series, some of which have associations, giving a total series of seven (Table 16). The descriptions given here (CIDA & Forestry and Soil Conservation Department, 1993) are based on the surveys carried out by the University of the West Indies of the 1960s, using the U.S. Department of Agriculture textural class names, reflecting particle-size and tillage characteristics. These descriptions have been revised in the Comprehensive Resource and Evaluation System survey (CRIES, 1982). Two problems with the data are immediately apparent. Firstly, the original map was made at a scale of 1:12,500, but published at 1:15,000, with a resultant loss of smaller delineations. Secondly, there was insufficient time to make a complete field check in the later survey, so that only the sample areas have any degree of reliability.

Table 16. Extracts of soil property information (CIDA & Forestry and Soil Conservation Department, 1993).

100	Common Name	Root limit	Internal drainage	Texture	Calc	Remarks
23	Agulta stony sandy loam	None	Rapid	Coarse medium	Yes	Very fertile, stoniness limits fertility
38	Cuffy gully gravelly sandy loam	Varying depths	Rapid	Medium fine	No	Low in N, adequate P & K, erosion steep slopes
46	Hall's Delight clay loam	Shale at 12" - 24"	Rapid	Medium fine	Yes	High in K, low in P & N, very shallow soil
52	Valda gravelly sandy loam	Bedrock	Rapid	Coarse medium	No	High in K, low in N & P, very shallow
301	Hall's Delight Association	Varying depths	Mod. to rapid	Medium fine	Yes	Extremely susceptible to erosion
305 306	Valda-Cuffy Gully Association	Bedrock near surface	Rapid	Medium	No	High in K, low in N & P

Agu(a)lta sandy loam (23) – (Figures in brackets denote series/association number.) This is an alluvial soil occurring in small deposits in river channels. Classed as a cumulic haplodoll with strongly developed A horizon rich in organic matter, it has repeated accumulations (cumulic) from flood depositional events. Erosion hazard is slight (CIDA & Forestry and Soil Conservation Department, 1993).

Cuffy Gully gravelly sandy loam (38) – This soil is very common in the upper watershed. It is a tuff and non-calcareous shale soil underlain by the Wagwater Formation and, in some places, the Chepstow Formation. Classed as a typic dystropept, it is slightly acid, weakly developed B horizon and very rapid internal drainage due to the coarse material in the profile. Erosion hazard is high (CIDA & Forestry and Soil Conservation Department, 1993).

Hall's Delight channery clay loam (46/301) – This is the most common soil of the upper watershed, a calcareous shale soil underlain by the Richmond Formation. Classed as a typic eutropept, it is non-acidic, with a weakly developed B horizon and shale bedrock, only 300 to 600 mm from the surface where not eroded. There is high porosity and rapid internal drainage. As a clay loam it has less than 35 % clay and less than 65 % sand. Erosion hazard is high (CIDA & Forestry and Soil Conservation Department, 1993).

Valda gravelly sandy loam (52) – This soil is very common in the upper watershed, a granodiorite and porphyry soil underlain by the Newcastle Formation. Classed as an ustic dystropept, it also has a poorly developed B horizon, is slightly acid and very porous. As a sandy loam it has less than 18 % clay and less than 82 % sand. Erosion hazard is high (CIDA & Forestry and Soil Conservation Department, 1993).

Valda-Cuffy Gully associations (305/306) – No details are given for these associations.

The soils of the upper watershed are either mollisols or inceptisols. Mollisols are not common in the tropics, only in the continental sub-tropics. These soils occur in the Buff Bay watershed in isolated locations on the river bed as depositional alluvium, with the typical mollic horizon. The cumulic haplodoll has a high base saturation and strong structure which, with the organic layer, renders it a useful agricultural soil.

The very limited occurrence of this soil is of little benefit to the area.

The eutropepts and dystropepts in the upper watershed are inceptisols developing in the mountainous areas, where erosion restricts soil development. The 'classical' description of these soils suggests they are young (Soil Survey Staff, 1960), resulting from the alteration of parent materials, with a cambic (altered) horizon. They tend to be fine textured soils; in USDA terms, the clay loams and clays. This is certainly true of the Hall's Delight, but not the Valda and Cuffy Gully, which have a sandy texture. Inceptisols are typically low in organic material. Generally, there is greater than 3 % weatherable material in the profile and a CEC of clay >16 mug/100g. The Eutropepts have a high base saturation and the dystropepts a low base saturation.

Soil and geology relationships – The Richmond Formation is extensive throughout the Buff Bay watershed. A thick blanket of silt, clay and colluvium deposits develop into very fertile soils, with the high base eutropept, Hall's Delight soil, as evidence of this. Although soil and geology boundaries do not entirely coincide, due to the fractured and complex nature of the geology and the susceptibility to landsliding, the Richmond Formation and Hall's Delight Series have very similar spatial patterns. The Wagwater Formation is also extensive although much more dislocated than the relatively coherent Richmond Formation. Slope deposits comprise significant thicknesses of debris, clay and broken rocks which develop into fertile soils. However, in the upper Buff Bay catchment it is overlain by the Cuffy Gully Series, a typic dystropept. This low base soil is probably a factor of slope, since depositional areas develop the better soils.

The Newcastle Volcanic Formation consist of basalts, andesites and dacites, hydrothermally altered or metasomatised to spilites, keratophyres and quartz keratophyres, respectively (Jackson, 1987). The calcalkaline dacites contain andesine, quartz, hornblende and clinopyroxenes, whereas the quartz keratophyres contain albite, quartz, chlorite and clinopyroxenes (Jackson & Smith, 1978). The high sodic status of the quartz keratophyres suggests susceptibility to erosion, if it can be assumed that this gives a high exchangeable sodium percentage (dispersive and erodible). The soils derived from metamorphic and igneous rocks are highly porous and heavily leached. As such, the Newcastle Volcanic Formation gives rise to fine textured poor soils like the Valda series, another dystropept.

The underlying geology determines the mineralogy of the clays that form during weathering. The albite of the quartz keratophyres weathers to kaolinite and silica. Only the mineralogy of the Newcastle Formation has been found in the literature and there is no other analysis of the types of clays found in the Buff Bay watershed soils. However, alkali feldspars commonly weather to halloysite, whilst increased leaching causes olivine and pyroxene to form montmorillonite. Intermediate clays (smectites) form when water is scarce and as they are highly soluble they are also very erodible (Thomas, 1994). A more thorough investigation of the mineralogy of the underlying geology might highlight another aspect of the erodibility of the soils.

Agricultural activity and demographics

Small-scale farming is very important in Jamaica for a number of reasons. Jamaican settlers were the first to inaugurate a system of provision grounds, an added disincentive for running away (Brierley, 1991). The provision land was not on prime agricultural land, but on the marginal land in the hillslopes behind the plantations. From the beginning, European observers thought the method and organisation of planting backward, with prevalent mixed crop, inter-crop, and an interculture of trees and vegetables. However, a long and valid history of African experimentation had produced the system and skills. Despite substantial growth in mining, industrialisation and tourism, which were all actively pursued by the government in the 1950s and 1960s, small-scale farming still provided an economic base for many hill communities. Since the poor performance of those industries in the 1980s and 1990s, it has become obvious that small scale farming is an important economic basis for up to a third of the population (Brierley, 1991).

There have a been a number of socio-economic surveys of the hill farming communities of Jamaica. Some of the earlier surveys (Interim Agricultural Development Plan, 1983) tried to ascertain the damage that farming the higher slopes was having on the environment or city water supplies. Later studies broached the subject from the viewpoint of the farmer in a less critical manner (McDonald *et al.*, 1993). They recognised that many farmers were engaged in subsistence agriculture, perhaps aware of the erosion problem, certainly unwilling to be moved from owned or even long-term leased land, and quite amenable to relatively new ideas like hedgerow intercropping and advanced forms of agroforestry.

Demographics – Some statistics for the rural hill farms of Jamaica are important for understanding the attitudes of farmers to the present soil erosion situation and attempts to halt the perceived erosion. In 1954, small farms in Jamaica (between 1 and 25 ha) accounted for 38 % of land under farming and 75 % of farm numbers (Edwards, 1995). It is interesting to note that holdings less than half an hectare (regarded by many authors as unsustainable for an average family) accounted for only 1 % of land under farms, but just over 20 % of the number of farms and a considerable number of adults (98,000). The early survey revealed that in the 1950s the majority of small farms were managed by males, over 40, with elementary schooling and using knowledge about the land passed down from the previous generation. Attitudes to farming were fairly conservative.

In 1994, in the Rio Grande, there were more women farmers and half the sampled farmers were under 40 (Meikle, 1998). Many farmers in 1954 had worked abroad to earn money to buy the land, and supplemented income as tradesmen and labourers on the estates (Edwards, 1995). Forty years later, half the farmers sampled had similar employment structures although the activities had broadened (Meikle, 1998). Off-farm work was significant because it complemented farm work and allowed the expansion of farm activities. The farm would not be given up to others to farm since off-farm work was irregular, and there was pride and independence attached to owning and farming the land. Many had tried the pre- and post-participation techniques prescribed, and subsequently abandoned them, citing lack of purpose, lack of labour or lack of financial support.

Thomas-Hope (1993) focussed on the short and long term effects of migration, with some statistics for the parish of Portland. The participation rate in farming at the time of survey was around 80 %, with two thirds of households engaged in growing coffee. Although 80 % of households owned some land in the rural Portland area, only 16 %

were over five acres, "and the great majority were one acre or less". The table gives percentages for 1-5 acres and 'none', and the latter is a very different concept to 'less than one', theoretically unsustainable, but, common as these small patches are (Brierley, 1991), so this last statement cannot be made on the basis of the table. For many households, the production of coffee or other horticultural produce for sale was very small and the activities of the household were supported by remittances from Jamaicans overseas. Thirty-seven per cent of returnees bought the land entirely for agricultural purposes, hence reversing the migrant trend of leaving the land (Thomas-Hope, 1993).

Social inertia and a reluctance to change – Several writers have sought to correct the image of the peasant farmer as ignorant and slow to change. Despite incentives to do so, land owners who become professionals in other non-agricultural fields rarely turn over control of their land to farming families, preferring to let it lie idle awaiting their return on retirement (Hudson, 1981). On the other hand, peasant farmers are increasingly recognised as experts and efficient managers of the land they farm, being aware of the limitations of their often fragmented fields, the best use of limited labour and highly responsive to market forces. Many of the projects that have been developed in Jamaica have fostered a high degree of dependence in the local farmers. As Meikle (1998) discovered, the attitude towards the RGVP was that it should help farmers, explicitly with seed, money and fertiliser. This represented a psychological dependence on government that had been fostered in the boom years of the projects in the 1970s.

Tenancy, land use and conservation – In the Farm Development Scheme of the late 1950s, little soil conservation was carried out on the rented land as opposed to owned land, although occasional accidental barriers (a fallen tree, for example) were appreciated. The farmers stated that unless the tenant could get the benefit of several years of expenditure on conservation, it was not a good investment. It was also found that there was a risk that the owner might take back occupation of the land if the benefits were too advantageous. A better relationship existed between tenant and owner in leased and sharecropped areas because tenancy for several years was expected. Here, the general conclusion was that tenants treated the land as their own. This explained the better take-up of measures in banana fields where trenches were dug to control water, leading to improved banana production. Some farmers gained higher compensation levels from the owner for improving the land (Edwards, 1995).

By 1983 the Integrated Rural Development Project II had shown major inadequacies in the land tenure of the area that thwarted the project's objectives. Short term and insecure tenancy without compensation for improvements did not encourage the occupier to initiate long term capital investment and at least 25 % of the farmers had insecure tenancy. It was found that few in this situation even had the authority, let alone the incentive, to improve the land (Edwards, 1995). Blaikie (1985) supported the contention that land reform was essential where unequal land holdings were disbenefitting the small farmer and causing conservation problems. Private initiatives could be encouraged with secure and long land leases. However, the common incidence of short or tenure conditions meant the tenant was tempted to reap short term rewards from the soil before the source of income was removed. In Blaikie's view, there were few good relationships between the short term tenant and the land owner. Edwards (1998a) stated that two tenancy situations caused extensive and serious soil degradation: squatting illegally on public or private land where there is no security of tenure; and short term rent, as little as three months.

However, not all studies have supported or found such a clear relation between tenancy type, investment and production volumes. Meikle (1998) found that tenure type did not affect the productivity of banana and dasheen crops in a study area of the RGVP. Squatting in the upper catchment of the Rio Grande was not viewed with any stigma. The farmers of the area believed that the land was unlimited and available to all, despite being Crown land, a view imported from nearby Maroon communities. Farmers grew export bananas, and invested and expanded the area of farming, in the same way as they did on their owned land. The illegality of their activities was not a constraint. However, agencies like the coffee industry and extension groups only offered assistance to farmers who could prove legal rights through owner occupancy or Maroon status. Davis-Morrison (1998), working in the same area, commented that the mere presence of cultivable land, despite belonging to the Crown, would ensure a squatter he would not be evicted.

The difference between the communities of Cinchona and those closer to Kingston (McDonald *et al.*, 1993) was interesting because of the relationship between export production and land tenure that some authors have drawn in relation to erosion. The marginalised farms of the upper watershed were smaller on average, about half were leased and hence less secure in tenure, and farmed by younger men who had become disenchanted with the violence and unemployment of Kingston. These farmers in the upper watershed had on average over 3 km to walk to their land and produced mostly for home or very local markets, whilst lower in the catchments farms were less fragmented. It would be interesting to see if these positions manifest in higher erosion as Blaikie (1985) would conclude.

Davis-Morrison (1998) discovered that some land owners would not release the land for cultivation to local farmers, who they distrusted, who would over-exploit the land by crop rotation, not pay their rent on time, deforest the area of valuable trees and might wander on to other areas of the owners property once they had access. Some of these findings would suggest that farm size correlated with erosion statistics is inappropriate and should instead relate to tenure.

Farmers' perceptions of erosion – McDonald *et al.* (1996) found that farmers' perception of erosion was more accurately related to yield levels and, hence, degradation. The structures put in place during the pre-participation projects were largely neglected. Erosion was certainly low on the list of problems encountered by most farmers. Distance to markets and places of alternative employment seem to have had a significant effect of farmers' land use and perception. Attitudes towards farming among respondents in a survey (Interim Agricultural Development Plan, 1983) were negative, with 43 % of Claverty Cottage farmers (Spanish River, parish of Portland) not favourably disposed. The reasons given centred on the hard and unrewarding task of farming, the short term needs of economic return and, hence, cash cropping becoming increasingly necessary. More than three quarters of respondents were ready to work for wages for the new coffee growing projects starting in the watershed.

McDonald *et al.* (1993) investigated the economic situation of farmers in the upper Yallahs River at Cinchona and in watersheds closer to Kingston. The comparison was interesting because it emphasised certain problems of hill farming common to lower and upper watershed farmers, as well as highlighting important differences that might be pertinent to erosion studies. The common aspects included the assessment by farmers that a lack of money was a major problem in developing sustainable farming, whilst poor water supply came second. A small proportion in both communities regarded erosion as a problem, with a recognition by some that fertility had declined a little in the last few years. The term 'erosion' was generally recognised in the upper watershed, although not considered a problem by the majority, whereas nearer Kingston the term was unknown by a large proportion despite 21 % of the farmers receiving assistance with erosion control. However, almost equal proportions in both areas (around 60 %) used some sort of erosion control, mostly log barriers, even if they did not see erosion as a problem or did not understand the concept.

In discussing farm and environmental sustainability, Meikle (1998) highlighted the monocropping of bananas on steep slopes in the northern Blue Mountains of Jamaica. The fields were clean weeded by chemical weedkillers, which eventually found their way into local water courses. Additionally, the need to produce bananas to export quality had led to the use of non-biodegradable bags to protect the bananas on the trees from insect and bird damage. Local farmers were aware of the problems, but only took action to protect their local water supplies from the chemicals and bag dumping. So few were the conservation measures that there was no difference in soil conservation in or outside the project area. It was recognised by some farmers that trees held the soil together, so they were retained, even in monocropping banana fields.

In the 1950s, soil and hillslope damage was already widespread, but economic prosperity afforded the measures prescribed by external agencies. In the 1980s, the only production constraints mentioned by farmers were farm supplies, farm size and fragmentation of land. Steep slopes affected the land suitability classifications, but erosion was not mentioned. In the 1990s, the problem had not gone away, but agriculture was no longer the influential sector it was and the finances of the country were in serious problems, with an increasing reliance on external aid (and debt cancellation) to fund projects, with all the biases and relinquished decision making at local and even national level that it implied. With a soil conservation scheme history of 40 years, the farmers knew what soil erosion was, but either did not think it affected their farming or had more pressing concerns about selling their produce. The incorporation of farmers into national and global markets, or agricultural modernisation, had not taken the perceptions and attitudes of farmers into account (Spence, 1989) and, once monetary incentives were gone, so, too, were the structures.

Present land use in the Buff Bay watershed

It is assumed, given the tropical environment, that natural forests previously covered much of the watershed. In 1982, the Buff Bay watershed was still extensively covered by forest, both deciduous and coniferous (Interim Agricultural Development Plan, 1983). The extent was controlled by climate, soils and elevation. The Lowland Rainforest extends to 800 m on shale and only 400 m on limestone, remaining in remote glades and home to many endemic plant species. From these elevations Lower Montane Rainforest ascends, found in isolated and inaccessible places. Where the mists cover the ridges and some valley heads, the Upper Montane Mist Forests can be found, representing the original vegetation of the Range, and recognisable by the reduced tree height. Between Mount Horeb and Catherines Peak at the southern-most tip of the watershed, is 'Very Wet Ridge Forest', regarded as environmentally sensitive. To the northeast at Silver Hill Peak, very rare trees and associated biota are found, comprising about 40 % endemic species. On the southern and western parts of the ridge, these are mostly public natural forests. This natural forest converges with secondary ruinate forest at altitudes of 650 m to 1300 m.

The High Ruinate (secondary forest) makes up a significant part of the watershed. This secondary vegetation grows after areas are cleared for settlement, agriculture and forest harvesting (timber, fuel and charcoal). Where the area is cleared of natural vegetation, but not maintained, then it is deemed to have been abandoned, leading to the classification of the regrowth as ruinate. There is both high and low ruinate. High ruinate has regenerated a closed canopy, which for the purposes of erosion has the same protective function as closed canopy natural forest. A subcanopy and ground cover exists, although there are fewer species than the original forest. The period of time required for this state to be reached varies according to growing conditions, but some areas were last cleared and then abandoned over 100 years ago. On some soils this high state is never reached, whilst interruptions like landslides and hurricanes reduce the canopy to a state of low ruinate again. Low ruinate comprises grasslands (which may have previously been classified as unimproved pasture) and fernlands. The latter is restricted to higher altitudes (over 600 m) and is the result of a disturbance. Once developed, the density of rooting and leaf cover precludes other species from establishing, even after burning. The abandonment of the low ruinate areas has been relatively recent (20 years) and typically because the soil was not supporting crop production. The ruinate vegetation does well on lower fertility levels (CIDA & Forestry and Soil Conservation Department, 1993).

The climate gives the humid tropics a characteristic tropical rain forest climax vegetation. In Jamaica, the form of this forest is Montane Tropical Rain Forest. Yearly production of organic matter, or litter inputs, has been found at levels of 6 t/ha/yr, but individual areas can produce almost 12 t/ha/yr (McDonald *et al.*, 1996). Hurricanes have been blamed for reducing forests, but research into the impact of Hurricane Gilbert has confirmed the high level of resistance of natural forests at high elevation. Recovery from timber extraction to ground level was considerably longer. The local fuelwood trees have very fast coppice regrowth, although the introduced *Pittosporum* from Australia recovered most quickly in the experiments, evidenced by its very invasive nature.

Forest plantations – FIDCO created some plantations in the 1980s, within public natural forest areas, increasing the amount of land in plantation considerably between 1983 and 1993 (CIDA & Forestry and Soil Conservation Department, 1993). This was not significant in the upper Buff Bay watershed, but significant stands were planted just north of Belcarres. The Caribbean Pine was the most common plantation species, although considerable numbers were destroyed or badly damaged by Hurricane Gilbert in 1988. Although not all existing vegetation was removed during plantation development, pure stands of Caribbean Pine and Blue Mahoe (hardwood) were common, reducing biodiversity. Not all the trees in high ruinate areas were removed before the pines were planted.

Although the report gives no indication of the hectare change of land use, the maps of land use for 1982 and 1993 (Interim Agricultural Development Plan, 1983; CIDA & Forestry and Soil Conservation Department, 1993) make an interesting comparison (Table 17). It must be noted that classification terminology differs between the two. In 1983, the terms used were coniferous and deciduous, and there was no differentiation between natural, ruinate and plantation forest. Table 17 is an attempt at classification comparison, aided by comparable maps of the area provided by the reports.

Table 17. A comparison of land use terminology (Interim Agricultural Development Plan, 1983; CIDA & Forestry and Soil Conservation Department, 1993).

Interim Agricultural Development Plan (1983)	**CIDA & Forestry and Soil Conservation Department (1993)**
Coniferous forest	Natural forest, plantation forest
Deciduous forest	Plantation forest, high ruinate forest
Low ruinate lands	Low ruinate lands
Improved pasture	No record
Unimproved pasture	Unimproved pasture

The west of the Buff Bay watershed is affected by chainsaw and portable sawmill activities, of which the uncontrolled cutting and skidding of trees downhill is the worst problem. The skid trails are thought to damage and remove ground cover plants whilst creating runoff water channels that concentrate the erosive rain. The newly constructed roadways that accompany coffee farming are prone to landslides, particularly to the northeast of Spring Hill and up onto the Bangor Ridge.

Forest depletion – Many forests have a long history of incursion by indigenous peoples, although incursion suggests illegality, whereas perhaps the colonial appropriation of the land ought to be considered as such. A poor remnant of forest now remains in the Buff Bay watershed, reduced by activities such as coffee production, shifting cultivation for food crops, timber cutting and grazing of livestock (CIDA & Forestry and Soil Conservation Department, 1993). The worst affected area of tree clearance for 'Blue Mountain' coffee plantations is between Silver Hill Gap and Hardwar Gap. The high prices being fetched for this commodity have drawn farmers from outside the area to colonise converted pine plantations that had been harvested by the Forest Industry Development Company (FIDCO). Many of the farmers in this area are absentee land owners.

The area is one of the wettest agroclimatic zones, with the most erodible soil of the watershed, Hall's Delight channery clay loam. However, since the majority of slopes are under 27°, the erosion hazard is not as high as the upper Buff Bay watershed above Cedar Valley and Section where coffee is also grown on similar soils, higher angle slopes, but a drier climate, and the farmers are living on the land. On the east facing side of the Buff Bay valley, the geology, soils, slopes and climate should render the area very prone to erosion, but agroforestry trees are interspersed among rows of coffee, providing shade for the coffee, and protection of the slopes from landslide and erosion hazard.

The differing terminology makes an analysis of land use change, and the consequences thereof, almost impossible. Using GIS techniques, it was possible to approximate the land use changes that took place between 1983 and 1993 (Table 18).

An analysis of Table 18 shows a clear relationship between forest depletion (by 50 %) and coffee plantation (increased by 100 %). The calculation is only a rough estimation, based on approximate digitising from poor base maps, but it is an important trend in terms of soil erosion. However, the coffee plantations that have replaced much of the high canopy forest are not singularly responsible for the erosion that is thought to occur in the watershed. The work by Hamilton (1995) found that natural surface erosion also occurred in forests on steep slopes. Coffee production, shifting cultivation, timber cutting and grazing have all cleared large areas of both natural and high ruinate forest, particularly in sensitive areas like the southern ridge.

As with soil loss estimates, the calculation of deforestation has been a contended issue in Jamaica. The results vary widely with estimates of the annual deforestation rate ranging from between 0.1 to 11.3 % (Eyre, 1987). The causes of these differences in the forest cover estimates and the related deforestation rate are issues of definition, the reference area (entire country or region), the reference year (photographs/images/publication year), the precision of the estimates (photographs/satellite imagery/field survey), the information sources (forest inventory/research plots) and the objectives (agriculture, forestry or conservation). When a national deforestation rate of 3.0 %/annum was published by the United Nations, the quasi-government forestry company vigorously rejected the figure as unreliable, since he estimated tree cover had increased by over 100 % (Eyre, 1987). The contention was caused by the definitions of the term clear felling, a rarity in Jamaica according to FIDCO (Eyre, 1987), but which Table 18 clearly suggests. Early estimates that were based on land tax could not be compared with later estimates (high quality air photos). Using comparable surveys from 1954 and 1980, a 59 % rate of forest increase was calculated (2 %/annum), but this was eventually attributed to misinterpretation - where scrub had been detected that regenerated into forest (Eyre, 1987). FIDCO also acquired areas of native hardwood and replaced them with commercial conifer, thus retaining tree cover, but radically altering the biodiversity and nature of the cover and management of the land, that is, access and extraction techniques.

Table 18. Identifying the changes in land use between 1983 and 1993.

Interim Agricultural Development Plan (1983)	**%**	**CIDA & Forestry and Soil Conservation Department (1993)**	**%**	**Change %**
Coniferous forest	2.5	Natural forest	12.0	- 50
Deciduous forest	81.0	Plantation forest	0.1	
		High ruinate forest	27.9	
		Low ruinate lands	15.0	0
Unimproved pasture	16	Unimproved pasture	2.0	
		Coffee plantation	39.0	100
Mixed tree fruit with forest	0.5	Mixed agroforestry/pimento	4.0	

Eyre (1987) was asked to investigate the problem. Using 1 km^2 quadrats of randomly chosen Comprehensive Resource Inventory Evaluation System (CRIES, 1982) designated forest, the nature, species composition, ecological conditions, evidence of clearance, soil erosion, wildlife and logging were all noted. Deforested areas had less than 10 % canopy cover and no tree exceeding 2 m. The rate of deforestation was calculated at 3.6 %/annum. Extra verification was sought in a detailed survey of 24 rural districts, for which a rate of 4.3 %/annum was calculated. Finally, the land above 1000 m was mapped in detail, to reveal a range of rates from 0.6 % on the Grand Ridge of the Blue Mountains through 4.1 % on Mt. Telegraph to 8.6 % in the Mount Rosanna Range. This gave a national average of 3.3 %, a figure that McGregor (pers. comm) regards as questionable. The cause was thought to be agricultural and pastoral activity in the 20 to 25 ha farm size class, driven by a national need to increase export earnings, rather than commercial lumbering.

Deforestation in Jamaica is not due to small farmers, since larger commercial farmers have been responsible for burning mature *Eucalyptus* stands (Eyre, 1992, 1996). In the Cane River basin, 35 % of which had already been deforested, guerilla activity forced the farmers from their land. They had used ecologically sound principles in orchard cultivation and were replaced by indifferent management, in which woodcutting and charcoal burning exceeded sustained yield (Eyre, 1992, 1996). An even more worrying trend was the illegal clearing of pine plantations for crops by Forest Department and FIDCO employees.

Coffee – The land use map of 1982 (CIDA & Forestry and Soil Conservation Department, 1993) had no coffee plantations and no sign of any other land use in the upper watershed except deciduous forest, some coniferous forest on the eastern watershed boundary and considerable areas of unimproved pasture. The unimproved pasture lands were consumed by coffee plantations by the early 1990s, and the forest (from the map, mainly deciduous) had been significantly reduced. A large portion of the land previously owned by small farmers was sold or leased to non-resident part-time farmers for large scale coffee production (CIDA & Forestry and Soil Conservation Department, 1993). A system of Land Utilisation Types (FAO, 1976a) was devised (Interim Agricultural Development Plan, 1983). One of the proposed types, Type V, comprised rainfed coffee cultivation (intercropped in first three years with callaloo and hot pepper) along with carrot by medium land owners with low capital resource and high labour intensity.

The driving force behind this sudden renewed interest in coffee was the potential to earn foreign exchange. In the 1980s there was an 'extremely favourable export market' and the determination to make the Integrated Rural Development Project II (IDRP) work. Although participation in the planning by farmers was minimal and the project fell short of all of its targets, considerable areas of the Buff Bay watershed went over to coffee plantation with the original small farmers offering themselves for regular employment on the now extended plantations.

The areas which were developed for coffee were on the steep slopes of the middle and upper watershed (CIDA & Forestry and Soil Conservation Department, 1993) (Pl. 2A). Bangor ridge coffee production was located on the erodible soils of the Richmond Formation with a 'Very Wet' agroclimatic zone, but 80 % of the slopes were less than 27°. The Wakefield-Silver Hill coffee was grown on the soils of the Richmond and Newcastle formations in a 'Wet' agroclimatic zone with 65 % of slopes greater than 26°.

Spring Hill-Shentamee coffee was grown in similar conditions to the Wakefield-Silver Hill, but agroforestry was interspersed with coffee plant rows, providing soil protection and shade. The push for coffee plantations was resisted by some small farmers who opted to keep their holdings and develop them to include coffee. The plantations typically removed all other trees. The area was close to the Buff Bay River from Tranquility through Belcarres to the Silver Hill district, rather than in ridge areas and higher elevations.

Intensive crops – The higher elevations and steep slopes do not preclude the cropping of intensive food plants. The moderately warm climate of the upper watershed is highly suitable for cacao, coffee and yam. In cooler higher elevations, arabica coffee and vegetables are commonly found, and in temperate areas Irish potato do well. Positions on the ridge near roads to Kingston are flatter and give easier access to an important market. Herbs need clear weeding to become established. Yams (mounded and weeded by hoeing) and coffee (cutlas weeding) showed a soil loss ratio of 4.6:1 since cutlass weeding did not significantly disturb crusted soils (McGregor, 1988). Small plots of coffee were also found on slopes over 40º. The intensity of cultivation requires the removal of protective ground cover and tillage that breaks up the structure of the shallow soils. This clean weeding and removal of trees has encouraged soil erosion, even on terraced slopes (Pl. 2B).

Agroforestry – Agroforestry is becoming increasingly popular with development agencies. In the agroclimatic 'wet' zone in the upper watershed, a range of trees can be grown (banana, cacao, coconut, coffee, yam), but those requiring a marked dry period for pollination or fruit setting (cashew, mango) do not do well. The 'Very Wet' zone favours banana, coconut and dasheen, but also weeds and pests, although less in the higher elevations than low lying areas. Agroforestry has been present in Jamaica in an informal way for many years, particularly among farmers who own their land and on farms over 2 ha. Smaller farms were constrained by the shade that food trees cast on the other crops. Farmers on larger farms realised the benefits of agroforestry in the order of increased incomes (from by-products), windbreaks and soil conservation. Some practices helped to reduce rainsplash. Others, escallion and thyme exposed bare topsoil (CIDA & Forestry and Soil Conservation Department, 1993).

The proposals for land use in the Buff Bay watershed (CIDA & Forestry and Soil Conservation Department, 1993) were based on the principles of ecological zones, watershed protection and agroforestry. This was a change from the emphasis on export crops of a decade earlier. The area classified as ruinate was to be reduced by 9585 ha, whilst other natural and planted forest was to be given more hectarage. The ruinate forest was to be converted to agroforestry/mix and agroforestry/coffee to allow for the total removal of coffee plantations from the watershed, a particular necessity on slopes over 26º. The plan was to plant fast-growing leguminous tree species among existing coffee plants. The reintroduction of planting trees among crops, and along gullies and streams was to be given full support, specifically on slopes above 40º. However, multitiered assemblages of food forests, tall trees (e.g., coconut), medium bushes (e.g., cocoa) and ground level (e.g., herbs, okra) would only be effective in controlling erosion if ground cover was retained (McGregor, 1988).

Calliandra was used in contour hedgerow experiments, in which hedgerows of trees were planted as a barrier along the contours of a slope, with the areas between used for agricultural production. The Calliandra was chosen because of the range of by-products it provided. It was effective in the conservation of soil (erosion reduced by 55 %) and water (2.5 times reduction in runoff), and an enhancement of agricultural productivity in which maize cob and grain weights went up around 50 % (McDonald *et al.*, 1996).

Exacerbating the natural erosion – The agricultural practices in the upper watershed are very mixed. A lack of conservation expertise was evident when drainage channels on plots concentrated the water flow, adding the stress of increased water weight and saturated top soil to the tendency of soil flows to activate (Interim Agricultural Development Plan, 1983). During fieldwork in 1996 there was visual evidence that soil conservation techniques were practiced, particularly small scale terracing.

Of the inevitable erosion that occurs on some slopes, the most commonly reported is that of landslides. Local mapping initiatives (Ahmad & McCalpin, 1999; Maharaj, 1993a) have correlated these with the triggers of proximity to roads and fault lines, whilst noting that lithological type is the most common determinant of an area's vulnerability to landsliding. Poor agricultural practices and activity are often cited in events, but rarely quantified. The perception of the farmers is interesting to note. In a survey (Davis-Morrison, 1998) of local farmers in Jamaica, most understood the concept of soil erosion and thought it was due to heavy rainfall or shale soils. Planting on the steep slopes and removing trees were not considered contributory. The farmers also understood the limitation of the land they worked. The shale soils made terracing unworkable; mulching in dry periods was not practised because the humidity was high, and it encouraged pests and diseases. Meanwhile, they practised minimum tillage, bush fallow and mixed cropping. Their perception of soil erosion was purely biophysical, with no mention of the socio-economic forces which controlled their production levels and limited their development, which they readily recognised as their lack of access to markets.

6. Data collection

Slaymaker (1991) considered the extent of control necessary for a field investigation to be called a field experiment. He noted that in physics, independent factors were changed in a controlled manner to produce an observed effect, which was not possible in Earth sciences. The categorisation and classification of 'natural kinds' requires a degree of objectivity, but social constructionism is inherently subjective and intuitive. Bearing these philosophies in mind, the 'intuitive' approach to the field work presented for this research was influenced both by the nature of the field situation and the parameters within which a student at U.W.I. has to work.

Methodology

The solution for a developing nation, with few field and laboratory resources, is commonly deductive, with a theoretical rather than empirical, inductive reasoning. In the deductive approach, the individual factors hypothesized to influence soil erosion are arrayed in any number of combinations using theoretical assumptions about what makes a soil erodible and rain erosive, whilst vegetative cover and topography are thought to influence extent. In the inductive approach, the manner of priority and combination of factors is based on plot box and runoff plot experiments. Erosion is observed, spatially and temporally, using remote techniques like microphotogrammetry (Merel & Farres, 1998) or spectral reflectance of satellite imagery (Seubert *et al*, 1979) and the factors causing it are induced from the patterns it makes. Inductive reasoning is popular, but it relies on the presence of erosion. The most advanced process-based models cannot accurately reflect the response of the soil to the next rainfall event, vegetation growth or change in tillage practice, that is, its potential erosion risk. An inductive approach would depend on a considerable degree of field measurement, whereas the deductive method has to make assumptions about barely verifiable processes.

This thesis proposes an original deductive and deterministic model incorporating regionally applicable physical and land use factors in an estimation of potential soil erosion in the watershed, under present vegetation cover. The process of hillslope erosion is still incompletely understood, particularly given the complexities of watershed terrain. New modelling techniques using fuzzy mathematics and process-based systems are taking advantage of the potential of GIS analysis, but require enormous data-gathering and analysis facilities, just like the USLE. The USLE is not feasible or applicable to the region, but the choice of factors for the thesis does include a climate, soil, slope and land use element.

The choice of watershed was governed both by accessibility and size. The Buff Bay catchment in the parish of Portland, Jamaica, was described in Chapter 5. Semi- or sub-watershed research has many benefits, like acceptable timescales for digitising, whilst not being too large to groundtruth. Cutting the cost and time spent in the field is not an objective for many researchers, but a necessity of many research programmes. Mitra *et al.* (1998) found a relatively easy way to determine soil erosion potential at a range of scales using only slope angle, slope length, soil erodibility and a land use ratio or land cover. The two-variable model (slope angle and land use) facilitated regional pilot studies with relatively low resolution data, saving the higher resolution research for those areas identified as having a problem. There is a possibility that this system could miss problem areas, but their research showed that lower resolution calculations tended to overestimate the erosion category. Reynolds (1975) showed that, contrary to previous research by the author, only small (<10) sampling sizes were necessary to calculate a reliable mean value for a range of soil properties which could be used for factor input and groundtruthing.

Field preparations

In preparation for the GIS work, Prof. G. Wadge (pers. comm.) suggested the placement of a number of erosion pin sites for verifying the results of the GIS model. Fieldwork was necessary to groundtruth the largely remotely sensed database. Research has illustrated that erosion risk can vary significantly over short distances, making regional mapping an ineffective tool if not based on good field data (Sauchyn, 1993). Verification in the field is essential, strengthening the contention that GIS and field-

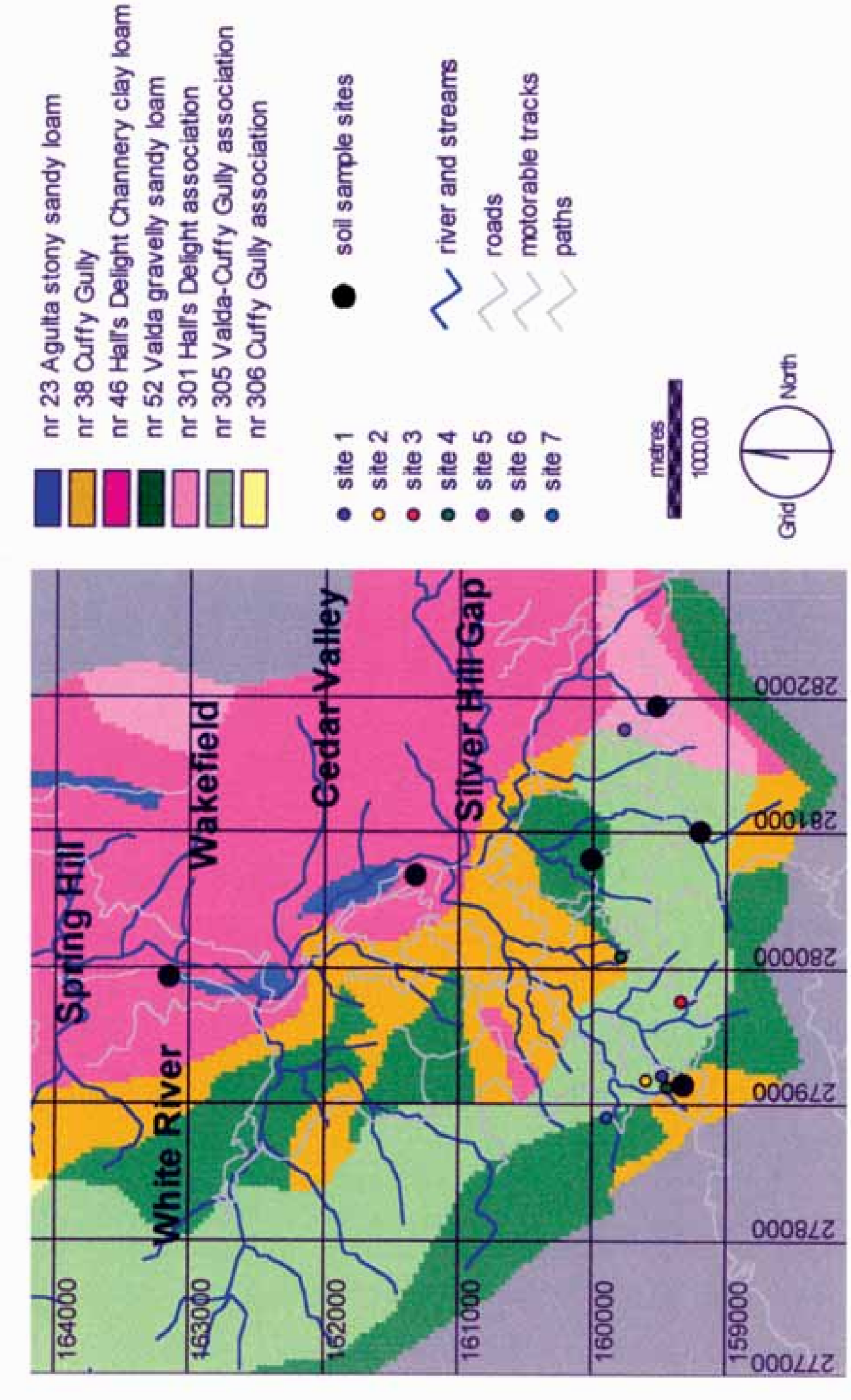

Fig. 2. Location of soil sampling and erosion stake sites in the upper Buff Bay watershed.

work are inseparable (MacGillivray, 2002a). However, in reality, the fieldwork element was constrained to the upper part of the catchment (to facilitate fieldwork in daylight hours) and was below initial proposals. Access to the areas off-road were poor, but a number of observations could be carried out from the roads and tracks, for example, the indicators of surface erosion (Morgan, 1979). The number of erosion stakes was small and not representative, but they were placed to give an indication of erosion trends under the various categories of vegetation cover. Aspect was measured with a compass and slope angle was averaged from a number of clinometer readings taken across the hillslope (a contour line about 20 m long), although significant variations were either given as a range or a minimum.

Vegetation structure assessment

Morgan (1979) suggested that the continuity of canopy, the density of the ground cover and root density were the most important factors controlling soil erosion. The relative canopy height and percentage cover were identifiable from air photos in which the Buff Bay watershed featured. A reconnaissance of both canopy and ground cover (rather than understorey structure) was carried out prior to air photo interpretation during the placement of erosion pins. At each of the seven erosion pin sites, the crowns were inspected from the ground to ascertain the closed (touching) or open nature of the canopy. The percentage vegetation cover was estimated for an area around each pin, either to the nearest boundary (track, fence) or for an area of about 10 m in all directions, whichever was the shorter. A quadrat survey would have given precise information for the specific square metres covered, but a dense sample would have been necessary around the stakes to reflect the complex nature of two sites, 3 and 5. However, at sites 1, 4, 6 and 7, the ground cover was nearly bare or all rough grass, a factor easy to determine. At site 2, the density of the ginger lily stems was such that a quadrat survey would have not been possible.

The land use at each site was identified. There was no natural forest within 2 km of a road or major track, the degree of penetration that is regarded as safe. There was scant evidence of land use boundaries at most of the sites, but it was relatively easy to distinguish ruinate/secondary vegetation from cultivated land. The latter was identifiable from the presence of regularly spaced bushes, recently cut trees to create a clearing, clean weeded soil and, at one site, terrace structures.

Soil series field check

A number of soil series were identified within the upper catchment from the Soil Survey Report (Rural Physical Planning Unit, 1990). The original soil series survey sites of the Rural Physical Planning Unit were no longer known and the CRIES (1982) data have been lost.

At each of the seven erosion stake sites and at seven sites for the distinct soil series occurring in the upper catchment, 0.4 kg of soil was collected from the top 300 mm of the profile (Fig. 2). A local facility was found at which the properties sand, silt and clay percentages, and organic matter content could be analysed. The property $CaCO_3$ could not be analysed at this laboratory and the likely presence of this aggregate binder was inferred from an unpublished geology map. Vandalism and material shortages are recorded in the area (Richardson, 1982). McGregor (1988) referred to the advantages of site protection offered by carrying out research on land owned by U.W.I. McDonald (Bangor University and U.W.I.) found good cooperation (pers. comm.) amongst farmers on soil erosion projects in Cinchona, because they were harvesting a free crop from the plots under study, whilst the adjacent bare plot was rented out to the university. The placement of erosion stakes was, therefore, considered carefully.

Digitising available data sources

Since very few agencies produce topographic or thematic maps at scales greater than 1:10,000, the choice of measurement framework was driven by the availability of resources. The inaccuracies that can be introduced by using regional scale base maps and inferring small scale attributes or processes are well known. In addition to these approaches, the grid cell is becoming a popular scale for research, especially because of the continuous and complete nature of much of the source data and hydrological modelling. The information is held in pixels between a 10 m resolution and a hectare. The base map material needs to be digitised using a common coordinate system. GIS software has projection transformation capabilities to deal with varying source material. The techniques for registration are discussed in Chrisman (1997). It is also possible to change the scale of the digitised material, although this must be done with consideration for the accuracy and lineage of the source material.

The decision to use specific hardware and software combinations for GIS analysis were driven mostly by availability. A DOS version of Idrisi was installed in the Department of Geography and Geology, U.W.I., where this study was initiated, but had not been configured properly or used by any current member of staff. A Summagraphics A3 format digitiser was located in an affiliated department with TOSCA (DOS) software and a Windows Idrisi version. Therefore, a raster representation, Idrisi, was used. The vector files had to undergo rasterisation before Idrisi could calculate certain parameters. There are disadvantages to this. The results are often visually satisfactory, but not for the attributes that the grid cell represents.

Digital Elevation Model (DEM) – The computerised generation of the terrain, or terrain modelling, is a principal component of GIS analysis, providing many important factors for soil erosion models. The steepness, aspect and length of slopes in a watershed are prime elements in many of these models.

Terrain models, or DEMs (Digital Elevation Model or Matrix), are based on the traditional topographic map in a raster representation, where isolines or contours connect points of equal elevation. The isoline generalises the continuous nature of the data by simplifying the distribution into equally spaced discrete intervals. The DEM uses either this framework or spot elevations in a regular rectangle grid or matrix. The control of the spacing is important since the underlying morphology is essentially lost if the contours or grid are too widely spaced. This loss of data is a weakness of DEMs.

A terrain model can be generated in a vector-based system using a Triangulated Irregular Network (TIN), which builds triangular facets to connect point heights. Each triangle in a TIN connects three identifiable adjacent points such as features of peaks, ridges and drainage courses, so that the triangular plane approximates the real situation. The GIS then calculates the slope angle and other elements of the plane and stores them as attributes (Chrisman, 1997).

The modelling of terrain as a DEM or TIN representation assumes a number of limitations, and studies have compared and contrasted the methods used both to acquire and generate elevation data. Accuracy and time savings are important factors that seem to sit at opposite ends of the scale, along which a compromise is usually sought to optimise both. Eklundh & Martensson (1995) noted that substantial gains in time were possible using point sampling instead of contour line digitising. A scheme involving regularly distributed points was used, supplemented by points near break lines in the terrain. This is a recent development combining regular with irregular networks. However, inaccuracies could be introduced to the method because interpolation between estimated points was occurring. Engel (1996) looked at the effects of topographic inputs on hydrological and water quality models, by computing the four DEM interpolation algorithms (neighbourhood, quadratic surface, best fit plane, maximum) and comparing the model outputs. Using the ANSWERS model for four rainfall events in north central Indiana, the maximum algorithm predicted more runoff and much higher sediment yields, but significantly underestimated sedimentation results. The most accurate algorithm was the neighbourhood (Srinivasan & Engel, 1991), which compared modelled results from the DEM algorithms with observed data.

The advantages of using the TIN representation were highlighted by Chrisman (1997). The triangles specify the neighbourhood relationship unambiguously, whilst the measurement at the vertices of one triangle can be used to estimate the vertices for neighbouring triangles. Linear interpolation along the vertices is always assumed. There are also drawbacks to this representation. Significant user input is necessary in choosing the points and, like DEMs, the choice is subjective. TINs are difficult to convert into other representations, since a tracing stage is necessary to create contours, whilst TINs from contours produce a vast array of triangles.

The software programme Idrisi, a raster representation, was used. The vector files had to undergo rasterisation before Idrisi could calculate certain parameters. After manual editing, a resolution of 40 × 40 was chosen, ensuring that the interpolation of elevations at 40 m intervals was calculable from the contour data. A higher resolution would be inappropriate for an estimation of vegetation and land use boundaries from 1:36,000 airphotos and 1:50,000 (GOJ, 1984) maps, and a resolution lower than 40 × 40 (NRCA, 1991) would create interpolation problems for the INTERCON module as some contours would appear to join. The model is designed to facilitate watershed management by identifying patches of land where erosion potential is high, rather than individual plots.

The 1:50,000 map (GOJ, 1984) was used as a base for contours and hydrology, since the 1:12,500 series was incomplete. The contour interval was 20 m up to the 80 m contour and 40 m thereafter. All contours were digitised within the upper catchment to beyond the presumed watershed to allow estimation of the watershed boundary using Idrisi. The contours were digitised using the DOS programme TOSCA, carried out in eight stages, because file size within TOSCA was restricted. Testing the accuracy of the manual operator (C.M.I.M.) was done using a repeat point digitising module, and manually digitising polygons, lines and points in separate files to assemble in Idrisi. The contour, road, water, soil series and vegetation type maps were all digitised using this combination of hardware and software.

The vector file of contours was rasterised before Idrisi was used to calculate the topographical parameters. The elevation of the pixels between the rasterised (LINERAS module) lines was estimated using the INTERCON module (Eastman, 1997, 1999). LINERAS rasterised only those lines that fell in the image area and ignored those that fall outside. The polyline files produced a faceted model and the Idrisi manual strongly recommended the FILTER using the mean filter (low pass) and a 3 × 3 template to remove some of the angularity of the linear interpolation. FILTER created a new image in which each pixel value is based on its value and those of its immediate neighbours. The resulting DEM (Fig. 3) was used as a basis for further topographic derivations.

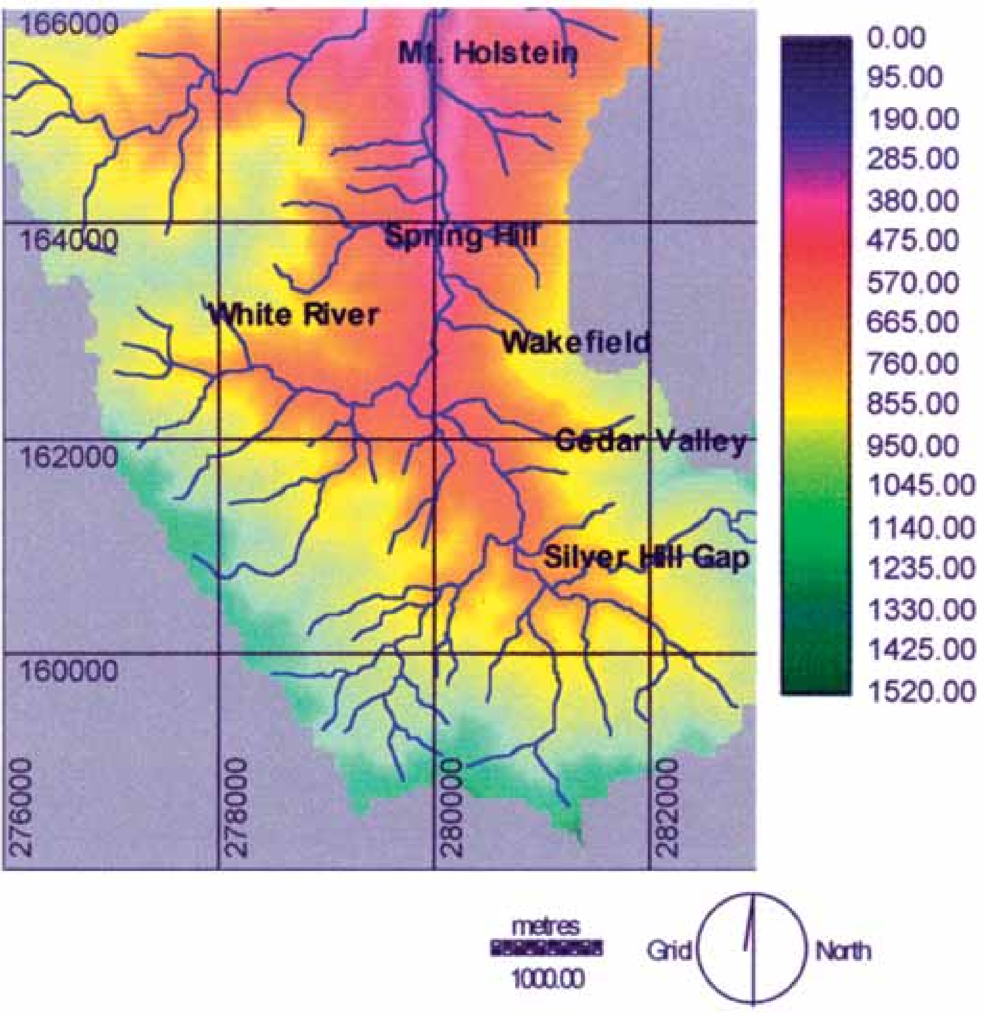

Fig. 3. Digital Elevation Model (DEM) of the upper Buff Bay watershed (height in m).

Slope elements – The slope and aspect elements were derived using the SURFACE module within the TOPOGRAPHIC VARIABLES suite. This required the digital elevation model image. SURFACE automatically calculated the conversion factor to reference units. The calculation of slopes was carried out in degrees. SURFACE determined the slope for a cell based on the cell resolution and the values of the immediate neighbouring cells to the top, bottom, left and right of the cell in question. This is known as a rook's case procedure. The calculation is given in the Idrisi manual (Eastman, 1997, 1999). The slope and aspect algorithms are described in Monmonier (1982).

Within Idrisi, there is no programme for determining the length of a slope from the watershed rim to the first mapped channels. Generating this factor is the most problematic of the erosion model parameters (Hickey, 2000). The best estimates are obtained from field measurements, but this is not practical at the watershed scale. There is a lack of reliable software algorithms and, consequently, regional average slope length values are often used. The method proposed by Hickey (2000) involved identifying local maxima (high points) for the whole watershed and calculating the non-cumulative slope length for each cell (resolution multiplied by 0.5, 1.0, or 1.4142 for high point, cardinal direction or diagonal direction, respectively). However, the low resolution of many DEMs means that microfeatures (conduits and absorbers) which slow or increase runoff (and thus erosion) are not recorded. Hickey did not incorporate slope length interruptions into the model, the local maxima serving as slope head and convergence or deposition serving as the slope toe.

On request, Idrisi devised a DOS programme to produce a distance function using the DEM and the digitised water courses from the 1:50,000 map. This was a highly complex manoeuvre, since both the images had to be divided into smaller images, run through the 'uphill' sequence and stuck together again. The 'uphill' DOS programme to calculate slope length produced an image, but results were marred by the programme's tendency to create watershed rims at the edges of the smaller images; hence, the final image has not been used. The practical aspect of including such a slope length indicator in the analysis can be questioned. One model (Chakela & Stocking, 1988) reduced slope length to a constant (100 m) because the length of slope became progressively less important as it increased. Field reconnaissance of the upper Buff Bay watershed showed that few slopes were simple. Numerous conduits and absorbers, including unmapped gullies, barriers and deflectors (roads, tracks, buildings, depressions and field boundaries), were too numerous and complex to take into account in the model.

Idrisi version I32.05 has a RUNOFF module which calculates the accumulation of rainfall units per pixel as if one unit of rainfall was dropped on every location. Using the RECLASS module, a threshold can be applied to the output to produce drainage networks. This is an inadequate surrogate for slope length because of the complexity of most slopes. However, it provides a useful post-model research theme.

Aspect – The aspect is the direction in which the maximum slope faces. The calculation forms part of the TOPOGRAPHIC VARIABLES suite of modules. Aspects are output in decimal degrees and use standard azimuth designations, 0 - 360°, clockwise from north.

Agroclimatic zones – Agroclimatic zones were presented as part of the JAMPLES project (Batjes, 1994). The base map was poor and presented at a small scale, but this was the best available surrogate for rainfall. The map was photo-enlarged to 1:50,000 and the four moisture availability zones that cover the upper Buff Bay watershed were digitised. The boundaries were probably the least accurately defined of all the factor maps, since they were based on interpolation of a climatic variable between widely spaced stations. At this scale the moisture regime of subcatchments can be reasonably well estimated, but the plot scale (outside the scope of this study) cannot be identified. The coding given to each polygon reflected the degree of wetness specified on the original map.

Soil – The soil series boundaries were digitised directly from the best available photo-enlarged soil series map (CIDA & Forestry and Soil Conservation Department, 1993). The polygons were checked for slivers and edited accordingly. In preliminary analysis, one soil factor layer was used, with the possibility of setting up a database for soil texture (clay:silt ratio), infiltration rates, typical bedrock depth and likely presence of $CaCO_3$.

Vegetative cover – Using hand stereoscopic pairs, the 1:36,000 colour air photos (NRCA, 1991) were arranged to give maximum stereo coverage. Where this was not possible, estimations of vegetation height were made based on colour and shadow comparisons with adjacent stereo sets. The boundaries of vegetation height and cover were traced, and laid over the 1:50,000 topographic map. The process was repeated to ensure accuracy and symbols added to represent the seven vegetative types. Where an entity was deemed too small, it was grouped with its adjacent closest vegetative type. Settlement sizes were minimal, so no separate category was needed, and track, road and river courses were given separate files. A number of modifications were made as a result of a sample of areas that were more vigorously checked in the field, although vegetation cover at the plot scale were not recorded. The model required canopy presence for a ridge or valley side, and this could be identified from ridge viewpoints and open tracks.

Land use – The map of present and proposed ecological areas for the whole watershed (CIDA & Forestry and Soil Conservation Department, 1993) was used to identify which areas of canopy covered ground were managed and which were ruinate. Plantations of coffee and banana were fairly easy to identify. However, the picture was not static. An area of recorded ruinate was being used for illicit coffee and dasheen cultivation at one of the erosion stake sites, so the map could not be used as a verification tool. Seasonality of cropping is known to be important and the one element a single series of photos cannot measure. The map produced was only pertinent to the period of the air photos.

Roads, paths, tracks and water – These were digitised on the basis of the 1:50,000 (GOJ, 1984) topographic map. The view scale for digitising meant that node matching had to be corrected after digitising, but problems with the snap tool meant that gaps were retained. These vector images were only used for presentation and not analysis, but if distance buffers were employed, correction would be carried out first.

Focussing on erosivity and erodibility at watershed level is perhaps the most appropriate activity for researchers, emphasizing relative erosion classes rather than trying to pinpoint absolute classes of erodible and non-erodible soils. However, the merit of an universal indicator of erosion is in comparing the effectiveness of management techniques, which must for scientific completeness, include the method of no interference of traditional techniques. Torri *et al.* (1997) attempted a global comparison of the K-factor, in which it was found that the database of previous research did not use the same soil classification system, let alone the same preparation of the K-factor. Since structural conservation techniques have found disfavour in steep topography (Edwards, 1995) and living contour hedges are more proposed (McDonald *et al*, 1996), identifying areas where potential relative soil loss is highest has its merits.

7. Designing a Potential Erosion Detection (PED) model

There is a difference between assessing the risk of soil erosion and estimating the rate of soil loss. The complexity of the soil erosion system, with interacting factors, has made the task of formulating a conceptual model of the erosion process a difficult one. Most of the models used in soil erosion studies are a grey-box parametric design (Morgan, 1979), in which the most important factors in soil erosion are defined, measured and related to measurements using statistical methods. However, these models do not add to the knowledge of the natural environment and the way it responds to the influencing factors. There has been a shift from parametric towards deterministic and white-box parametric model design to the present concentration of process-based models. Parametric models are based on mathematical equations to describe the processes involved, taking account of the laws of energy and mass conservation. White box models identify statistically significant relationships between defined influential factors, where all the details of the system operation are known (Morgan, 1979). There are a few examples of parametric grey-box models (Fournier, 1960; Wischmeier & Smith, 1978), but few white-box models. Hall (2000) saw the conceptual advantages of process-based modelling, but noted that they were more complicated, required more detailed data and were not sufficiently developed to apply to large areas. However, process-based models would provide a more widely applicable technique for assessing the relative importance of the various factors involved in the soil erosion process.

This research describes a deductive approach in which a specific formulation for a particular problem is developed. This method only develops the images (coverages) necessary for the formulation and assumes the formulation is complete. Some models are specifically designed for field scale, and use considerable empirical data to verify them, like the USLE and SLEMSA models. This study is based on the need to develop a model to identify the potential erosion of large areas of a watershed in Jamaica. However, there is a paucity of empirical evidence in this region. As an example, rainfall data have been collected nationally over a long period, but it is on a very sparse network of gauging stations, making interpolation very unreliable in such complex terrain. Net erosion has been found to be much higher than natural replenishment at the field scale, evident from maps of stripped topsoil and even subsoil in some parts of the Yallahs Valley (McGregor, 1995). Any development recommendations for soil erosion on a catchment-wide basis should focus on non-sustainable activities in areas where erodible soils, the wettest agroclimatic zones and high angle slopes coincide, and then present the findings in terms of relative hazard and sustainable solutions, since the socio-economic factors in the watershed preclude forcible removal of farmers to idle lands or reclaimed bauxite sites.

Choosing the representation

Most issues are pertinent to cartography using any technique, such as the appropriateness of scale and the homogeneity of the mapping entity. However, the issue of vector and raster imagery is peculiar to GIS, having evolved through the use of remote sensing for data capture. The representation of geographic information - spatial, temporal and attribute - is influenced by the measurement framework, in turn dependent on the data model. A data model is a general description of sets of entities and the relationship between the sets. A measurement framework refers to the rules for controlling the measurement of those entities (Chrisman, 1997). These entities are organised into structures which provide the key to technical differences between vector and raster models.

Vector – A spatial data model based on geometric primitives (point, line and area) located by coordinate measurements is referred to as a vector system. A vector model is advantageous when the measurement framework is based on the control of attributes, which is the range of values of a geographic feature. The primitives and their attributes have a 'nested dependency' since areas are described by boundary lines and lines are located by point series, and hence coordinate based. The important characteristic of a vector model, whether isolated or topological, is that point locations and boundary lines can be freely placed in representing categories. However, gaps and overlays are not easily detected.

Raster – The sweeping motion of mechanical engineering tools from whence the term derives is appropriate to the remote sensing devices that characterise the input of this model type. The grid cells or pixels are rectangular blocks which entirely fill the image and are coded with attribute data. A raster model is the appropriate solution where a measurement framework is based on the spatial control of attributes. The raster cells may be referenced to a coordinate system and their size may be independently determined or influenced by remotely sensed data.

In the 1970s, the comparative efficiency and relative merits of raster and vector models were argued on the basis of technology, not application (Chrisman, 1997). The debate should not be exclusive, but tailored to the measurement framework. In recognition of the variation in data sources, some software incorporates both representations. For example, ArcInfo, a vector-based programme, has a raster analysis and input capability. Meanwhile, Idrisi and ERDAS, raster-based programmes, have vector import and digitising capability, but convert them to raster for analysis. It is presumed that these additional capabilities will be developed further, so that full integration of import and analysis of data sources is possible in many software programmes. Karnielli (1991) stated that GIS packages incorporating both raster and vector analysis were necessary, otherwise the rasterisation of each stage in a model became too complicated. The raster format was popular with him because it was simple and inexpensive.

Remotely sensed data from satellite sensors have a raster data storage characteristic. Much cartographic information from thematic (soil, hydrology, geology) and base maps (topography) can be scanned using line-following scanners, which creates a vector data structure, although technician intervention is high (DeMers, 1997). Where this is not available, manual digitising is necessary. There are time and financial savings comparisons for manual and scanned digitising. Scanning is more expensive, in terms of hardware and editing, especially where complex documents and rugged topography are concerned (DeMers, 1997).

However, the fact remains that both vector and raster data sets are needed in the multivariate analysis which make up erosion studies. This point is highlighted in a study by Larsen & Torres-Sanchez (1998) in which landslide susceptibility was measured on the basis of biogeomorphic parameters. This necessitated a point grid being overlain on the attributes map to ascertain the hillslope attribute categories for each point (creating a raster database). This map was then overlain on the landslide map (a polygon map). The incompatibility of the two data sources led to complex solutions in traditional mapping techniques.

In raster representation, the pixel becomes the base object. If two maps have a different resolution, then a common grid reference may be achieved by resampling, prior to overlay. For continuous variables, resampling is similar to interpolation using one of the neighbourhood rules to give the pixel a value representing the previous values in the higher resolution. Again, as long as the scale is not significantly different, a reasonable representation is possible. Each resampling rule makes assumptions about the surface nature of the information. Non-continuous data (like rasterised polygons) are best reimported as a vector file into the new resolution and then rasterised.

The vector solution to overlay is not as simple as raster. The common object of reference has to be created in a geometric phase, in which each new polygon created from intersecting original objects has a unique number and link to the parent attributes. As each original polygon is fragmented, this can lead to large databases and matrices of affiliation. This fragmentation means later reclassifying and evaluating, so soil maps are commonly used as the base map (Lopez, 1991). It is not uncommon for slivers to develop where errors, generalisations or different interpretations of the object boundary (road centre for road verge) cause mismatch. Fuzzy tolerance reduces slivers by redrawing object boundaries to eliminate polygon slivers below a certain width, but these can introduce errors or take out linear objects, as well as removing significant details from the original boundary line. An integrated coverage (introducing base polygons to reduce fragmentation) is thought to be an improvement on geometric operations, but presumes all the data are available with those boundaries (for example, TMUs, HiRUs and HyRUs). Comprehensive overlay is also an option in which each coverage is aggregated into the categories of the query before the overlay is performed. Non-essential boundaries are ignored, and slivers and fuzzy tolerance effects minimised. 'Raster is faster, but vector is correcter,' a folk idiom of the 1980s, is not true, since it ignores the original pixel creation stage. Raster analysis in the overlay is quicker (when image matching has already been carried out), whilst the spatial accuracy of vector is compromised by slivers and fuzzy tolerance.

It is generally accepted that where the spatial control of attributes is needed, a raster model is the appropriate solution. A vector model is advantageous when the range of values of a geographic feature (in a database) is the prime objective. The PED model is adaptable to a vector representation, but the spatial complexity of the DEM and its generatives at this scale make the raster representation the simpler solution. The following section considers the alternative approach for referencing a watershed in a vector system.

Vector-based land unit determination – Sauchyn (1993) used field boundaries to reference polygons. The large number of polygons (due to the high resolution of the map) of soil loss was simplified only after the factors thought to produce the erosion had been combined. A boundary between polygons was removed if it separated two polygons of equal erosion risk class. Alternatively, if the longest boundary between polygons was smaller than 4 ha, it was removed.

Morgan (1978) devised the hillslope response unit (HiRU) for an accurate homogeneous basis for estimating the environmental sensitivity of slopes. Each unit combined local site (lithology, soil, weathering), processes (erosion, deposition, equilibrium) and efficiency of basal material removal to produce profile groupings and site patterns to form land units, such as the valley head. Dietrich *et al.* (1992) also proposed erosion thresholds for land surface elements which were classified as convergent, divergent or planar. A simple steady-state hydrological model predicted zones of saturation and high pore pressure which were related to overland flow, and hence the erosive instability of each element.

Hydrological and water quality models use elements like the hydrological response unit (HyRU; although referred to as HRU in the original texts, the review of another interpretation of this acronym has necessitated a modified form, hence HyRU for hydrological and HiRU for hillslope response units), an irregular area defined by land-use, soil and topography. The GIS has proved to be an important instrument in determining HyRUs, especially the effects of terrain, land-use and soil on simulated erosion, runoff and sedimentation (Engel, 1996). The size of an HyRU will affect the applicability of results obtained from a model, since the conditions within the unit are assumed to be homogeneous. For one watershed in Tarrany County, Texas, Srinivasan & Engel (1991) found that by varying the AGNPS programme grid cell size from 100 to 400 m, predicted sediment delivery increased twofold, whereas average overland erosion and deposition were 14 % and 21 % less, respectively.

The derivation of HyRUs, HiRUs, TMUs and TINs, and the resolution issues of DEMs, assume that the attributes held within those units are homogeneous. The field research required to determine the homogeneity of an area would be enormous, since it is scale and site sensitive. Harden (1990) pointed out that mountain environments and intensively farmed small plots display pronounced spatial variability, especially where land fragmentation is common. This gives a polygon-based model, in which plots and farms are the underlying reference framework, a different emphasis than the PED model proposed here.

Much GIS research using vector-based systems has concentrated on developing homogeneous terrain mapping units (TMU) for simplifying the reference and storage of data. Worosuprojo *et al.* (1992) delineated TMUs based on landform, slope class and land use type differences which were then correlated with USLE values, and analysed on the basis of vegetation density cover. Stephens *et al.* (1985) used aerial photographic interpretation to define erosion TMUs which were homogeneous in terms of soil type, slope length and gradient, crop rotation, and soil conservation practice. Karnielli (1991) used polygonal TMUs based on a topographic base map onto which the factors necessary for the model could be attached, whereas Lopez (1991) used an empirical method which involved assuming the soil map as a base map, and incorporating rock, slope and morphodynamic properties. The cause-effect relationships could only be extrapolated if the geopedological units were sufficiently homogeneous.

Although traditional soil series polygons are reductionist, the fragmentation of polygons or high resolution of pixels in geostatistical approaches is unworkable and has to be reduced by various methods. The difference lies in the stage at which reduction is carried out. If reduced primary information (soil series) is presented, it cannot be interpolated to fit a higher resolution. Reducing the results of a geostatistical model becomes a problem of presenting fragmented data.

Designing a classification system for use with remote techniques

Aerial (air) photography permits the collection of data which are spatially continuous in nature, that is to say they are not discrete like point remote sensing devices (e.g., weather station). Soil scientists have used air photos as base data on which soil maps are placed as well as to assist in perceiving the changes in soil type over large areas (DeMers, 1997). The photograph needs to be converted to digital format for the parameters to be analysed. This can be done by scanning with a microdensitometer, which records and quantifies the reflectance value of each pixel, converting the picture into a stream of numerical data. The other method of conversion presumes a pre-analysis of the data. The photograph may be examined with a stereoscope to identify TMUs, vegetation or soil boundaries before digitising the resulting polygons. The lack of georeferencing data or image references for digital ground control points can make it difficult to accurately place the image. Where there are obvious features like communication masts, it is possible to match successive photos and topographic layers.

A number of instances of remote sensing techniques used for collecting data pertinent to soil erosion have been reviewed in Chapters 3 and 4, including land cover types, USLE values, soil surveys and erosion features. Satellite imagery for the research area was prohibitively expensive, but, in the interests of future data inclusion, satellite imagery was discussed in MacGillivray (2002b, appendix 3).

Air photo interpretation issues – There are a number of techniques involved in air photo interpretation. Different film types have certain benefits when identifying phenomena on the basis of pattern, tone and texture. In a study of soil losses from agricultural areas in South Africa, Garland (1982) compared the use of panchromatic and black and white photographs. He noted that infrared sensitivity aided interpretation where there was vegetal or moisture differences in the terrain, whilst panchromatic photography yielded more data than black and white, due to dry land farming conditions in the study area. Anderson *et al.* (1976) found that varying degrees of sharpness and tone presented various source imagery errors. Black and white copies of Colour Infra Red film, the preferred medium for forested land and forested wetland categories, gave poor results (Loelkes *et al.*, 1977). Colour and colour infra red were better than black and white film for accuracy of interpretation in studies in Costa Rica (Cannon *et al,* 1978), especially for differentiating tree association types, although this was altitude dependent.

The issue of resolution of photography is based on a compromise between cost and coverage. The most common scales for vegetation and soil surveying are 1:20,000 to 1:30,000 (Cooke & Doornkamp, 1990). The scale of 1:20,000 gives a minimum mapping size of 0.01 ha which Schmidt *et al.* (1995) thought could cause some inaccuracies. Larsen & Torres-Sanchez (1998) believed that this scale was the minimum observable and that smaller landslips would not be detected. Sauchyn (1993) found it possible to digitise field boundaries, farmsteads and even windbreaks at this scale, but linear, man-made entities do not have the same constraints of interpretability (P. Collier, pers. comm.). Accurate height data and identification of soil erosion phenomena is possible using air photos at scales of 1:20,000 or greater, although ground control is necessary (Goudie, 1990). Occasionally, landslide scars were better visible in photographs than on the ground (Bergsma, 1978) and Collins (1966) reported a stand of sugar cane in a saline coastal area that was only seen on the air photos and would not have been visible from the ground.

At middle altitudes (1:20,000 to 1:80,000), land cover can be interpreted, but substantial supplemental information is needed (Anderson *et al.*, 1976). Collier & Collins (1980) reported that tenure boundaries were difficult to determine between peasant subsistence area (food crop under canopy of food trees) and agroforestry (commercial food crops under 'natural' woodland). Field verification of a survey in Calabria, Italy (Rao, 1975) at a scale of 1:32,000, identified missed categories like old landslides. Heyligers (1968) found that distinguishing shrub, grassland and mixed herbaceous vegetation in New Guinea was difficult because of the increasing discrepancy between their critical scales and the photo scale of 1:50,000.

A number of studies have identified other problems associated with air photo interpretation. The relationship between the classification proposed and the ability to obtain those classes from the image is a common problem that Becket & Webster (1969) had, for example, when discussing recognisability and reproducibility. Depending on the scale of photography, the film type and the climatic conditions, it may be difficult to identify the detail of vegetation type necessary for existing classification systems. Many features are mapped with hard boundaries whereas in reality they are fuzzy. Indistinct or gradual changes from one category to another involve a degree of membership with both adjoining categories. In identifying them manually, graduation between categories raises the problem of where to draw the line separating them and whether to further divide the area so that the graded area becomes a new category. Interpolation after conversion can be used to create a fuzzy boundary, but the choice of algorithm should match the ground changes, which may not be linear. When a microdensitometer is used to convert analogue photography to raster representation the result is dependent on the 'rules' adopted, as it records the actual reflectance through the graduated area.

Tonal differences are important in interpretation, but present certain problems. Bergsma (1978) found that greytone could not be used to denote erosion because of the density of land cover. Makhanya (1978), on the other hand, found greytone a significant tool for identifying gullies. This illustrates the importance of vegetative cover and climatic environment, since they reached different conclusions about greytone using the same techniques. This suggests the need for appropriate film types for different environments.

Surface erosion – The ITC System of Geomorphological Survey uses photo interpretation to produce qualitative maps on the erosional characteristics from diffuse runoff to lateral river erosion (Rao, 1975). Although Bergsma (1970) recognised that a number of erosional features could be recognised, he suggested that sheetwash could only be inferred. Typically, eroded land showed as a lighter tone, caused by the removal of fine grains, leaving coarser grains behind. Sheetwash was difficult enough to detect in the field, but air photo interpretation could be complicated if darker soil horizons were revealed at the surface when erosion had occurred. Land surface dryness, surface sealing and humus poor horizons would give a lighter tone associated with sheetwash. Vegetation changes had to be used to detect erosion, for example, shorter and less dense grass and shrubs. Makhanya (1978) assumed that where there were no gullies or they were shallow (no stereo), sheet erosion predominated.

Soil redistribution patterns have been assessed providing accurate digital terrain information (x, y, z coordinates) at various time intervals. In recognising the importance of soil surface microrelief in soil erosion, Merel & Farres (1998) used photogrammetry to quantify height changes at the experimental plot scale. Sequential stereoscopic aerial photos were used in Belgium (Vandaele *et al.*, 1996) to produce two digital terrain models that were overlain and the difference in z coordinate calculated.

When air photos are used as the basis for soil loss models, problems of accuracy have been encountered. Morgan & Nalepa (1982) compared CIR photographic interpretation of land cover types and USLE values with traditional mapping, and concluded that it slightly overestimated soil loss. Stephens *et al.* (1985) derived USLE factors P and LS from air photos which correlated very well except in hummocky terrain. However, there was a low correlation for crop rotation and for the upgraded soil series. The greatest error was for soils with a high surface stone content, that is, eroded soils.

Satellite imagery of land cover can be used to identify possible sources of enhanced sediment erosion. Sanchez-Azofeifa & Harris (1994) correlated the occurrence and spatial distribution of specific land use categories as a function of slope for a basin in Costa Rica. The correlation of land-use with measured variations in precipitation intensity and sediment export provided an important assessment of high erosion potential. Seubert *et al.* (1979) used an unsupervised classification to produce a map of ground cover in northern Indiana, U.S.A., carrying out cluster analysis to delineate five bare soil categories, specifically severely eroded cultivated soil. Kaminsky *et al.* (1979) suggested that Landsat MSS data could be used in soil surveys to indicate moderate to severe erosion because it correlated almost 100 % with a particular spectral class.

Cloud cover is a common hindrance to identification and renders large areas of the photo unidentifiable. In mountainous tropical areas, mist not only alters throughout the day, altering the tone of an area of vegetation, but it also drifts. Multiple images may not be an affordable option for developing country agencies. Although essential in land cover and use classifications, vegetation is a problem in other research, where forest canopies and hillside shadows masked a number of landslide features and caused an underestimation of scars (Larsen & Torres-Sanchez, 1998).

Land use and cover – As Anderson *et al.* (1976, p. 4) categorically stated, "There is no one ideal classification of land use and land cover and it is unlikely that one could ever be developed." This pessimistic view of future efforts was based on the premise that the demand for natural resources changes in time and hence land use patterns may vary from classification categories. The derivation of information from land cover requires skilled interpretation, since images do not record activity. Some land use activities are difficult to ascertain on the ground, requiring supplementary information regarding ownership, boundaries and licences. Examples include hunting and fishing, understorey elements of agroforestry and academic research sites. Management cannot be measured as the snapshot in time which air photography provides (Collier & Collins, 1980).

Land cover studies also have interpretation problems. As it is largely controlled by top canopy, physiography, moisture and soil conditions, the nature of the understorey is important for soil studies, but it can only be empirically constructed (Porwal & Roy, 1991). Each of the canopy classes needs to be identified for stratification and density of the understorey using physiographic and floristic analysis which, coupled with canopy-cover type, enabled Porwal & Roy (1991) to depict understorey limits spatially in conjunction with the main vegetation class. In developing a soil moisture model, Karnielli (1991) undertook ground cover estimation using soil survey and ground photograph data. Colwell (1983) also believed that some knowledge of forest communities was essential in order to apply remote sensing techniques to tropical forest. He distinguished photocommunities, the smallest distinct assemblage that was discernable in stereo at a 1:40,000 scale. According to Gils & Wijngaarden (1984), the only part of the vegetative cover that could be clearly identified at the scale of 1:30,000 was the woody component (see also Table 37) and then only a maximum of two vertical layers could be distinguished. They combined higher and lower woody strata dominance with canopy physiognomy to produced twelve structural typification categories (including absence of stratum. Heyligers (1968) noted that the only forest type through which understorey could be identified was open medium height canopies, and that ferns and sedges in grassland were not evident from photos, but only from ground observation, and subsequently reclassified from grassland to mixed herbaceous.

The development of air photo compilation keys has resulted in both country scale (Colwell, 1983; Gils *et al.*, 1991) and regional systems, specifically tested in humid regions where remote sensing has been the only tool available in classification. Before the 1970s, classifications were largely based on listing the elements significant to a given landscape. Harnapp & Knight, (1971) recognised that certain elements had similar signatures, so they incorporated ground corrected data. Different seasons were incorporated in the phase system, although there was no sequential photography which they realised would solve a query regarding continuous or multicropped kitchen gardens. Philipson & Liang (1975) developed interpretive keys for a morphological classification of crop identification by air photo, rather than to infer potential land use, although environmental interpretations might be inferred from crop occurrence. The observable features involved the identification of field, management and crop characterisations (see Table 75). The method for determining density was highly subjective, depending on whether the observer thought the fields were large or small, connected or that cropping occurred beyond defined boundaries. The auxiliary keys referred to the presence of nurseries, and the inference of planting and harvesting techniques, some directly observable and others which would be impossible to infer without interviews or lengthy ground observation (e.g., portion of crop removed). Although the system was devised to be used with panchromatic photos at 1:10,000 to 1:30,000 scale, positive crop identification was only possible with groundtruthing. As they concluded (p. 1080), "Keys - no matter how inclusive - provide no assurance that an observed crop is not some crop or vegetative form which has not been considered by the keys [which] should be resolved by the analyst's familiarity with the study area."

Examples of land use identification (reviewed in Chapters 3 and 4), as opposed to cover, are numerous, despite some authors regarding them as temporary (Anderson *et al.*, 1976) or misleading and inadequate (Collier & Collins, 1980). Schmidt *et al.* (1995) digitised land use boundaries for a number of categories that could be discerned, such as rain-fed agriculture, irrigated agriculture, forest (>10 % crown density), plantation and grassland. Heyligers (1968) was able to distinguish three agri/horticultural and seven natural vegetation classes based on height and tonal inferences, four of which are shown in Table 19.

Table 19. Typical photocharacteristics of vegetation cover (after Heyligers, 1968).

Vegetative cover		**Photo characteristics**
Plantation		Speckled texture
Grassland	Mid-height	Smooth texture, light tones
	Fern and sedge	Rough texture, medium light tones
	Tall	Rough texture, medium dark tones

Cannon *et al.* (1978) could not distinguish coffee and forest land in a study of Costa Rica, using both aerial photos and Landsat, a shortcoming of the scale or technique used, since their management techniques varied considerably. Pasture was extracted from the agricultural category and classified under rangeland, since they were utilised for similar purposes in this area, as well as being difficult to separate due to a similar spectral response.

The problems associated with land cover and use go beyond the issues of interpreting activity. Heyligers (1968) needed to separate native gardens from plantations and regrowth. Only if traces of abandoned gardens could be seen was this easy. Separating natural grassland into height classes was entirely dependent on favourable meteorological conditions since tonal difference was slight. Plantations were identified using pattern, but the speckling that was observed was often more to do with marginal growing conditions than species differences. When the forest stratification was evaluated with field observations, 30 % of height interpretations, and 15 % of crown spacing and size were wrong.

The use of photographs for detecting shifting cultivation in tropical rainforests has also highlighted some of the difficulties of land use interpretation. Smit (1978) found a problem differentiating between secondary forest (after shifting cultivation) and low forest growing on poor ecological sites or landslide scars. An attempt was made to measure the difference in height between the natural and secondary forest using parallax. This highlighted a problem of identifying canopy height categories for erosion studies as well. Finally, Smit used geological information to identify 'pseudo-secondary', in which natural features resulted from a schist formation (individual trees above a low canopy), streams (abrupt change in vegetation type and height) and landslides (straight lines changes in canopy). Another problem was delineating boundaries. Grassland without recent human influence, for example, had a natural gradual transition to higher vegetation or forest, making it more difficult to digitise boundaries on the basis of type. Burning, however, gave a much sharper delineation in height between vegetation types.

Review – Anderson *et al.* (1976) defined the criteria by which a land use classification system for use with remote techniques could be judged. The system had to have a high level of accuracy, which could be maintained between the categories, and be repeatable in terms of different observers and time series analysis. They suggested that seasonal data and larger scale, groundtruthed and multiple use detail have to be used. The system they devised was biased towards a continental setting at smaller scales. At the level at which much land use mapping is carried out, the system became unwieldy in the number of characters used for a code, so, although the authors had recognised that the system would be used at larger scales with new codes developed by the interpreters, the resulting code would be too long.

The interpretive keys of Philipson & Liang (1975) contained subjective elements that would make accuracy and repeatability poor. However, they proposed an interesting array of activity surrogates, and recognised the need to incorporate larger scale and groundtruthed data. Harnapp & Knight (1971) wanted to ensure that all the elements could be distinguished at normal scales, hence improving repeatability. One of the reasons that Collier & Collins (1980) were so dismissive of previous classifications based on remote sensing was that they took no account of farm size, which their research had suggested determined the cultivation techniques and practices. In addition, the normal, as opposed to survey, day usage and multicropping were important.

The cartographic model

A systems approach is a useful tool for integrating the interaction of social and physical activities in the analysis of soil erosion. The chosen factors in GIS analysis involved in soil erosion are arranged in a cartographic model, according to a cause and effect hypothesis. Each factor is isolated to a specific theme, like vegetative cover, with the aim of evaluating whether each coverage is unique (to avoid double counting). As each element is entered into the system, the coverage of that factor is checked against the watershed boundary, so that the results of the model cover the whole watershed area, with no gaps or slivers of missing information for the factors. Some factors are interpolated, others derived by combining two or more elements. Lopez (1991) studied landslide hazards using thematic overlays comprising a generalised soil map (extrapolated from point data), a morphodynamic map (API), a lithological-geomorphic map and slope gradient (DEM). Mean annual rainfall and temperature were generated by GIS using the mathematical transformation of elevation data and point climate data.

By producing individual elements it is also possible to create intermediate combinations of factors as overlays. Slope angle is derived from contour heights, for example, and a soil factor is based on texture, chemical and moisture factors. These intermediate stages can reveal interesting patterns in themselves that may aid a further analysis or suggest new combinations. It is also an important opportunity for correcting errors that might not be visible if the whole model is produced as one stage. Another consideration is the order and nature of reclassification. Each factor has to be in the same spatial measurement level. This research has involved converting the elements from nominal (vegetative cover, soils) and interval (DEM, slope angle and aspect) to ordinal (relative potential erosion).

The multifactorial approach is a particularly appropriate methodology for hillslope erosion studies. The usefulness of GIS is evident from the ease with which the cartographic model and analysis can be modified to reflect new combinations, parameters, criteria and hypotheses. The range of factors available for inclusion in a soil erosion model are considerable. Table 20 is a summary of some of the major models for soil erosion, landsliding, soil fertility and the factors they included (reviewed in Chapters 3 and 4).

From this extensive list and general texts, a number of possible factors were investigated for incorporation in the model. Climate factors are generally restricted to erosivity, in the presence of rain gauges. A textural parameter for soil erodibility is often applied and adopted in the PED model. Visible erosion signs and gully activity are necessary for studies correlating erosion risk with historic record, but the PED model measures potential sheetwash erosion, which is not identifiable from remotely sensed data in subtropical environments. The same is true of drainage density and the various derivatives. The topographical elements in Table 20 include angle and occasionally shape, the latter having been incorporated in PED as a post-model analysis. Aspect is also commonly cited and used in PED, but length is only suitable for plot-based studies. Vegetative cover is used in nearly all the research specifically in a form of canopy cover.

Since hillslope erosion is determined by the presence of overland flow or runoff, the infiltration capacity of the soil is important because poor or slow infiltration will lead to higher runoff and, dependent on soil surface conditions, erosion. This situation may occur during a rainfall event because of high antecedent soil moisture (climatic and aspect factors), high slope angles (topographic factor), minimal interception (vegetative cover factor) or fine texture (soil type/structure factor). At the plot level, Morgan *et al.* (1984) managed to simplify previous modelling techniques for soil moisture and overland flow. However, in order to assess hillslope erosion at the watershed scale, it was necessary to use surrogates (Table 21), allowing for the availability of data sources.

Factor selection

The model comprised 19 potential elements (last column of Table 21), of which six (suffix M in the table) were incorporated into the model (two soil variables, texture and aggregation were combined). Three factors were included for post-model analysis. For each potential factor there was a base map or basis for a derivation. The literature review provided the parameters and thresholds for each factor. Although taken from diverse sources (Table 22), these parameters had a connection either to the environment in which this research took place or the source data. The post-model analysis was also based on sources that provided parameters for analysis (Table 23), but this was more commonly amongst the landslide research literature.

The model is constructed of five phases, erosivity, erodibility, energy, earth and erosion. The factors were added one at a time, thus giving an opportunity to identify errors, but also to determine important intermediate stages in the model. There were

Table 20. Factors used in soil erosion and land degradation research.

Author(s)	Climate	Soil	Topography	Vegetation
Wischmeier & Smith (1958)	USLE R	Erodibility (USLE K)	Angle, length	Cover, conservation
Morgan *et al.* (1984)	Typical intensity	Depth, bulk density, renewal, detachability	Overland flow, slope management	Evapotranspiration, crop management
Meijere *et al.* (1988)	USLE R	USLE K	Angle, length	Type, suitability
Karnielli (1991)	Rain-gauge	Bulk density, texture, hydrologic conductivity		Canopy cover, ground cover
Garg & Harrison (1992)		Gully density	Angle, aspect, drainage	Use
Sauchyn (1993)		Surficial geology capability, productivity	Gradient, length, aspect	Cover type, fields
Claure *et al*. (1994)		Permeability, depth, structure, texture	Angle, drainage	Cover, height, density, root depth
Mejia-Navarro *et al.* (1994)	Isohyet	Clay shrink/swell USLE K	Angle, aspect, stream buffer, landslide history	Biomass, use
Bishr & Radwan (1995)		Texture, erodibility, roughness	Angle, aspect, shape hydrology, gully activity	Cover, use
Casasnovas (1995)		Gully depth, activity	Drainage density, eroded area ratio, crenelation	
Lo (1995)	Iso-erodent	Erodibility	Elevation, shape, angle, hydrology, bank slopes	Cover, use
Pieri *et al*. (1995)		Fertility, erosion rates, visible signs	Rural and downstream, water quality	Cultivation ratios
Schmidt *et al*. (1995)		Carbon, nitrogen, phosphorus	Angle, aspect, elevation	Land use, crown density
McGregor *et al.* (1998)		Texture, consistency, crusting, moisture, depth (A horizon)	Angle, length shortening, evidence of erosion	Canopy cover, bare soil, litter, roots, management

Table 21. The potential factors, their effects on soil erosion and potential model incorporation.

Factor	Parameter	Effect/process	Potential incorporation (M) refers to included
Climate	Erosivity	Impact and runoff	RAINFALL
	Antecedent moisture	Likelihood of runoff, soil moisture availability	ASPECT (M)
	Seasonality	Tendency to runoff, prevailing winds, ambient temps	AGROCLIMATIC ZONES (M)
Soil	Texture	Entrainment/erodibility	SOIL TEXTURE (M)
	Depth to bedrock	Overland flow generation	BEDROCK DEPTH
	Porosity/permeability	Internal drainage	THROUGHFLOW
	Crusting/roughness	Surface flow/particle disturbance	LAND USE PRACTICES (M)
	Minerals, OM	Aggregate binder	SOIL AGGREGATION (M)
Topography	Slope angle	Power of particle entrainment	SLOPE ANGLE (M)
	Slope length	Power of particle entrainment	SLOPE LENGTH
	Shape/ threshold	Pattern erosion or deposition	RUNOFF GENERATOR
		Evidence of reduced slope	TOPOGRAPHIC SHAPE
Vegetation	Evapotranspiration	Reduction of runoff	VEGETATION TYPE
	Ground/canopy cover	Protection from impact	LAND USE CONSERVATION VEGETATION COVER (M)
	Evidence of bare soil	Sediment supply	LANDSLIDE/ CONSTRUCTION
Land use	Crop type	Evidence of bare/loose soil	LAND USE PRACTICES (M)
	Tillage activity	Topsoil disturbance	CULTIVATION RATIOS
Other	Gullies/ravines	Visible signs of erosion	TOPOGRAPHIC VARIABLES
	Stream density/buffer	Sediment removal	BUFFER/DENSITY

Table 22. The source reference for parameters used in the model.

Factor	Parameter	Source
Climate	Agroclimatic zones	Batjes (1994)
Topography	Aspect (points)	Maharaj (1993a)
	Slope angle (degrees)	McGregor *et al.* (1998)
Soil	Texture, drainage, depth, aggregation	FAO (1979), Richter & Negendank (1977), Rural Physical Planning Unit (1990), CIDA & Forestry and Soil Conservation Department (1993)
Vegetation	Cover at two levels	Gils & Wijngaarden (1984)
Land use	Tillage and management	CIDA & Forestry and Soil Conservation Department (1993)

Table 23. Post model factors, their effects and sources.

Factor	Effect/process	Source
Roads/paths/tracks (m)	Increased soil disturbance	Larsen & Parks (1997)
Water channels (m)	Increased erosive power	Ahmad & McCalpin (1999)
Topographical elements	Extent and concentration of runoff	Dietrich *et al.* (1992)
Runoff generation	Extent and concentration of runoff	–

four first level intermediates and two second level intermediates created and analysed. Table 24 identifies the data inputs and the intermediates that were determined.

Table 24. Inputs and intermediate (overlay) phases in the model.

FIRST ORDER FACTORS	**FIRST LEVEL INTERMEDIATE**	**SECOND LEVEL INTERMEDIATE**	**FINAL LEVEL**
AGROCLIMATIC SEASONALITY	EROSIVITY & ANTECEDENT MOISTURE	ENERGY FOR ENTRAINMENT	EROSION
SLOPE ASPECT			
SLOPE ANGLE	ENTRAINMENT POWER		
SOIL TEXTURE	INFILTRATION, SOIL SURFACE & SOIL ERODIBILITY	EARTH (PARTICLE) DETACHMENT OR SUPPLY	
SOIL DEPTH & DRAINAGE			
CROPPING, TILLAGE			
VEGETATIVE COVER	SOIL CONSERVATION		

The determination of the intermediate phases led to the design of the cartographic model which, by GIS tradition, runs left to right for deductive modelling (Fig. 4). Each intermediate phase represents an influential process in hillslope erosion. The model can be run using the Idrisi image calculator, bypassing the intermediate phases. However, it is useful to see the intermediate phases as the relative importance of each factor can be ascertained.

			↙AGROCLIMATIC ZONES
		↙EROSIVITY .... (E1)	
	↙ENERGY (E3)		↖ASPECT
		↖SLOPE ANGLE	
EROSION (E5)			
			↙SOIL TEXTURE
		↙ERODIBILITY .... (E2)	
	↖EARTH (E4)		↖LAND USE/TILLAGE
		↖VEGETATIVE COVER	

Fig. 4. The cartographic model in general detail (see Appendix 4 for file inputs).

Only six factors were digitised or inferred for their significance to erosion. The other factors were not quantifiable when the model was developed, but can be incorporated if they meet the conditions of the model. Addition was used in the overlay since it is the automatic choice for extensive operations, despite McGregor *et al.* (1998) cautioning against the use of simple additive classificatory indices. Although multiplication produces a greater contrast in the resulting overlay, it generates scores that are so high that they, in turn, have to be reclassified. The use of another operator that would support a more refined index would require the sort of empirical plot years spent in determining the USLE. Four other factors were generated as additional interpretive elements to the model, channel, road and track buffers, runoff generator and topographic shape. These were based on digitised elements (see 'Additional factors for post-model interpretation', p. 120, below).

The quantitative data ranges were divided into a number of classes. The first consideration was the number of classes to be used. The main object was to maximize variation, and thus contrast, between classes, and minimize variation, and thus maximize homogeneity, within classes. Usually, the number of classes depends on the total number of values in the data set. However, in this research several different factors with different ranges were being considered and a common number of classes for each factor was necessary. This is true for all factors except where Boolean logic was applied, where there was a lack of information regarding a gradational relationship. The theoretical calculation for discrete data classes requires that the number of classes should not normally exceed five times the logarithm of the number of values in the distribution. However, some of the data were continuous. It was also accepted that no more than eight classes should be used in creating a chloropleth map.

The alternative was to start by identifying obvious class boundaries for each factor, which should reflect the nature of the distribution of the data. The data can suggest class limits if they fall into definable groups and these should be used to maintain the integrity of the data distribution. It is possible to recognise these if the data are frequency based and plotted as a scatter diagram or cumulative frequency graph. If there are no class boundaries or insignificant breaks in the scattergraph, then the range of the data distribution is divided into equal parts by the number of classes suggested by other data. This is appropriate where there is not sufficient information from the literature to determine either the nature of influence some factors have on erosion susceptibility or the mathematical relationship of that factor to erosion. Unless there is proof to the contrary, the class intervals of such continuous data should be fixed, suggesting a linear relationship between the factor and process. However, where there is evidence of a geometric progression (exponential) relationship between the factor and process variable intervals are appropriate. This is also true of skewed data.

The alternative may be to use Boolean or true/false logic. Although runoff concentration declines away from the main channel (from channel to gully to rill to laminar flow), there was no evidence for quantifying the array. Boolean logic was chosen for water channels, roads and tracks, within which the concentration of water flow is significant to erosion and outside of which it is not. There were also factors which did not conform to a singular progressive relationship with the process of erosion such as the soil and vegetation factors. The USLE uses a single variable for vegetation, that of percentage cover. This is appropriate for field sized studies, but not for catchment studies using continuous data. Gils & Wijngaarden (1984) correlated crown density with percentage vegetative cover and combined this with crown height. Their results were reduced (Fig. 9), and allocated a rank system of scoring based on the assumed relationship between these combined variables and erosion susceptibility.

Climate – A particular precipitation event may trigger mass erosion, but the seasonality of precipitation may be more influential for longer term research into hillslope erosion. The seasonality in precipitation is important in determining antecedent soil moisture and, hence, the runoff and erodibility of the soil. Both the seasonal nature of annual rainfall in Jamaica and the distribution of isohyets (see Chapter 5) made it necessary to include rainfall as a heterogenous factor. It was necessary to determine the spatial nature of the rainfall in the upper catchment of the Buff Bay. There were three ways of achieving this, either existing meteorological maps, erosivity indices based on meteorological station data or a surrogate for rainfall.

The isohyetal map of total rainfall was the first option. However, it was presented at a scale of 1:1,000,000 and with no grid references for digitising. The second option was an erosivity index based on the meteorological station data. The most appropriate index of erosivity for this region was rainfall aggressiveness (Fournier, 1967), based on the highest mean monthly (p^2) and mean annual (P) precipitation. The p^2/P index was calculated for 17 stations around the southern boundary of the parish of Portland. A simple correlation of p^2 and P gave a coefficient of correlation of 0.91. This suggested that this index might be a reliable measure of erosivity reflecting the seasonal nature of the climate of the Blue Mountains. The next step involved interpolating this index over the whole of the upper catchment, for which the cause of spatial heterogeneity of the rainfall had to be determined. The isohyetal map had already given an indication of a trend peaking around the eastern end of the Blue Mountain range. However, this was not the highest part of the range and when a simple correlation between rainfall aggressiveness and elevation for the 17 stations was calculated at r=0.14, it was realised that it was not a simple relationship with elevation. When stations outside Portland were removed (for being on the rainshadow side of the mountain range) this was recalculated at r=0.05. Therefore, elevation could not be used to interpolate rainfall aggressivity. There were no other data for estimating erosivity of rainfall without automatic raingauges to calculate the intensity of events. Neither was it possible to validate a relationship between mean monthly rainfall figures and calculations of intensity from neighbouring stations.

The third option, agroclimatic zoning, was based on the use of bioclimatic zones for determining the elevation range and hence moisture zones that are related to a high potential for mass movement (Lopez, 1991). In Jamaica, this zoning (reviewed in 'Defining and measuring erosivity,' p. 15, and 'Classification of land elements and activity,' p. 45, above) was based on the ratio of dependable rainfall and potential evapotranspiration (Batjes, 1994). A R75/PET ratio of less than 1.5 does not suggest saturated soils (Table 25; Fig. 3). However, over a third of the watershed has values greater than 1.5. Therefore, this research assumes that the wetter the soils, the more chance of a relatively rapid onset of runoff especially on thin soils (Table 26).

Table 25. JAMPLES zones and parameters (Batjes, 1994).

Pencar/Buff Bay	JAMPLES	Annual R75/PET ratio	Temperature range (elevation dependent)
Zone 2	Wet 1	1.00<= R75/PET < 1.25	Moderately warm
Zone 3	Wet 2	1.25<= R75/PET < 1.50	Moderately cool - warm
Zone 4	Very wet 1	1.50<= R75/PET < 2.00	Moderately cool - warm
Zone 5	Very wet 2	2.00<= R75/PET < 2.50	Moderately cool - warm

Table 26. Ranks for agroclimatic zones.

Agroclimatic classes	Wet 1	Wet 2	Very Wet 1	Very Wet 2	Very Wet 3
Rank	1	2	3	4	5

Slope angle – The velocity of surface runoff and hence erosion increases as slope angles become steeper (Morgan, 1979). However, most of the studies have been carried out on slopes under 10°. Slope angle is considered proportional to soil loss on steep

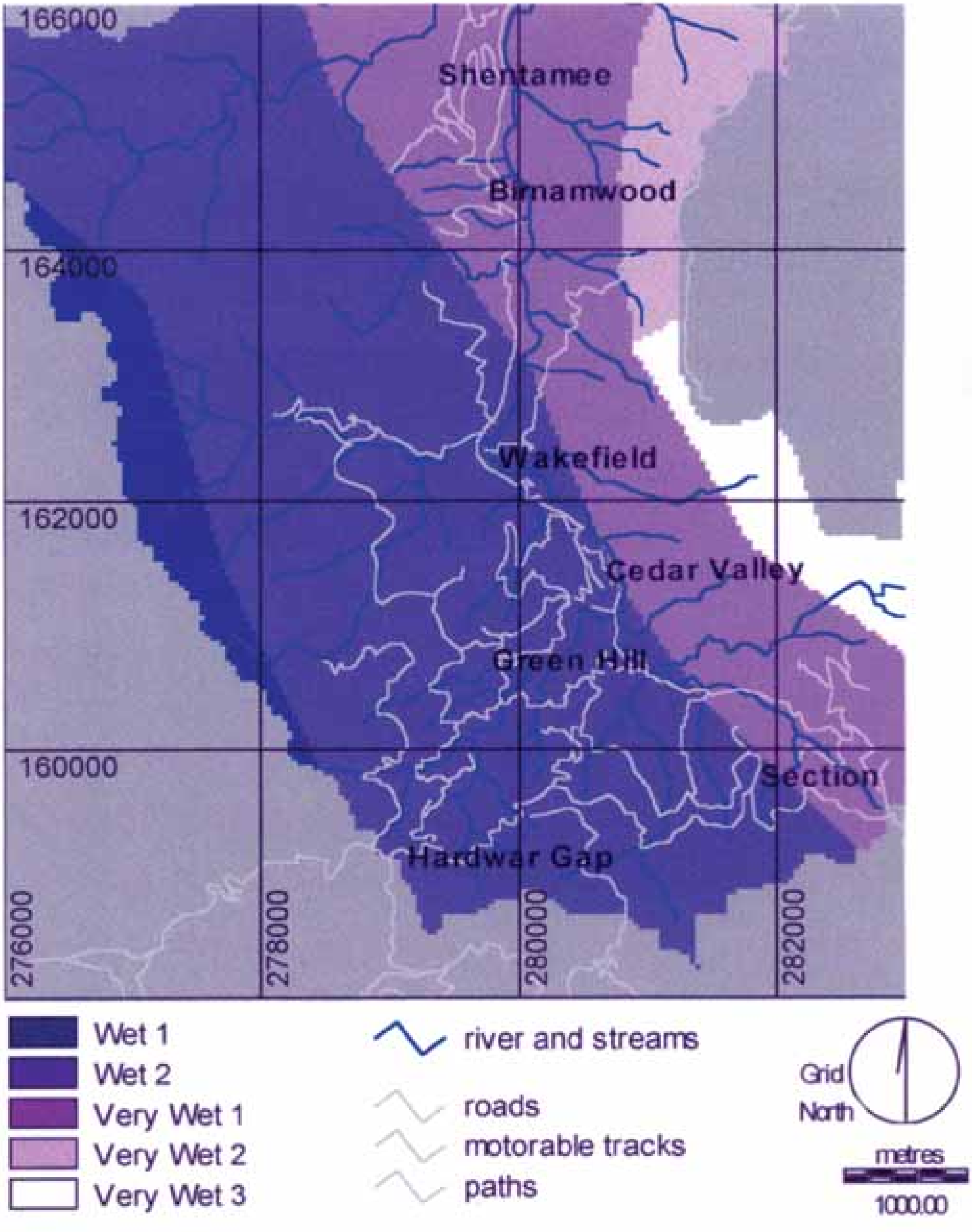

Fig. 5. Agroclimatic zones (after Batjes, 1994).

slopes (Liu *et al.*, 1994; Gachene, 1995), but one study found this not to be true (Ahmad & Breckner, 1974; Odermerho, 1986). On steep slopes, the limiting factor for erosion is soil supply. Since exposure is accounted for in the aspect factor, this research presumed that soil loss and steepness are proportionally related. However, there is no empirical

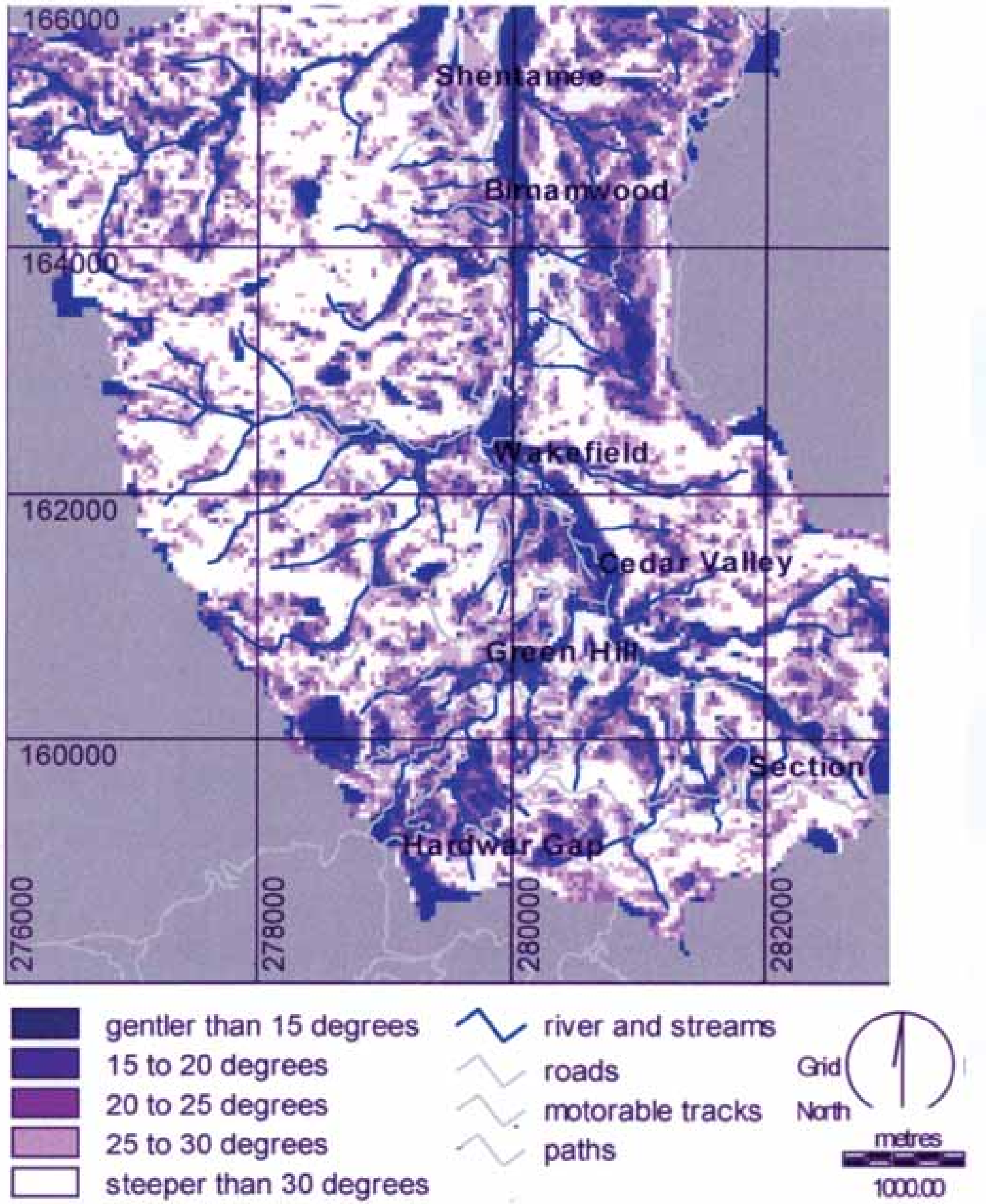

Fig. 6. Slope angle classes (in degrees).

evidence as to the exact relationship. The class divisions of a number of authors researching in Jamaica were studied for suitability (Table 27).

A slope angle of less than 5° is generally regarded as flat ground, whereas above 30° is regarded as very steep. A histogram of all the slope angles in the upper catchment showed a range of 0° to 60°. The mean was just under 25° and the interquartile range approximately 15° to 35°. Thus, a division of categories based on previous studies (Morgan, 1979, in which the maximum was 8°) was inappropriate. The frequency distribution was not sufficiently skewed for a logarithmic operation, since the peak was near the mean. An even distribution into five classes gave ranges in which four of them were above the mean, but Bryan (1968) referred to a threshold of 20° above which slopes are normally erosional, so this was reflected (Table 28; Fig. 6) along with the classification used by McGregor *et al.* (1998).

Table 27. Examples of slope angle classes.

	Slope angle (degrees)	
Sheng (1972)	**CIDA & Forestry and Soil Conservation Department (1993)**	**McGregor *et al.* (1998)**
under 7		0-15
7-15		
15-20		16-20
20-25	Under 26	21-25
25-30	Over 26	26-30
Over 30		Over 30

Table 28. Ranks for slope angle classes.

Slope angle classes	**< 15**	**15-19.9**	**20-24.9**	**25-29.9**	**>30**
Rank	1	2	3	4	5

Aspect – The inclusion of aspect in the model is based on Maharaj (1993a), who concluded that certain slope aspects in the Blue Mountains had a higher frequency of landslides than others. This was partly a function of orographic rainfall, which delivers rain onto eastern (prevailing wind direction) facing slopes in greater quantities than western facing slopes. Eastern facing slopes, despite receiving the first sun of the day, also have lower ambient temperatures (cooler morning air) than western slopes (predominantly warmer evening air). The latter probably experience higher rates of evapotranspiration, making western-facing slopes generally drier. Since the antecedent soil moisture balance is an important factor in both landslide and hillslope (runoff) erosion, it can be concluded that eastern facing slopes (between 80° and 90°) have a higher potential for erosion than other slopes. Maharaj identified two other smaller peaks of landslide frequency (170° to 180° and 220° to 230°) and an analysis of Maharaj's frequency data array identified a total of five clusters of frequencies. Normal statistics could not be used on circular data and preferred direction statistics using (tan) also gave inappropriate results. The frequency of landslides per azimuth class (10° interval) were analysed. First, the proportion of each class value of the total was calculated and this was sorted on the basis of frequency. Secondly, the cumulative percentage of that proportion was used to categorise the data into five classes. The first class was 0 to 20 %, the second 20 to 40 %, *etc*. The highest class, 80 to 100 % were ranked as most susceptible to landslides, the lowest 0 to 20 %, as the least, agreeing with Maharaj's assessment. This information was used as the reclassification system for the upper Buff Bay catchment aspect data (Table 29; Fig. 7).

Soils – The necessary elements for analysing the influence of soil on erosion were discussed in Chapter 2. The list of desired properties included W.S.A., dispersed clay or silt content, bedrock depth, infiltration rates, organic matter content, $CaCO_3$, ESP and presence of iron oxides. Morgan (1979) stated that erodibility could be measured using texture, aggregate stability, shear strength, infiltration capacity, and organic and chemical content. Farres (pers. comm.) suggested that the silt:clay ratio, percentage and type of organic matter, stoniness (>3 mm) and calcium carbonate parameters were necessary, and relatively easy to determine. Each soil unit for the Buff Bay/Pencar area had been described qualitatively (CIDA & Forestry and Soil Conservation Department, 1993) in terms of USDA classification, root limiting layer, internal drainage, texture, calcareousness, pH, and remarks concerning nutrient availability and erosion susceptibility. These descriptions are presumed to have been designated on the basis of identifying potential land use options for the future. The soil series and geological descriptions gave no quantitative textural details.

The original plan for estimating soil erodibility was based on the qualitative assessment using terms such as 'susceptible to erosion' and 'erodes on steeper slopes', which were based on the presence of shale underlying the soil and steep slopes (CIDA & Forestry and Soil Conservation Department, 1993), but took other factors into account (Table 30). Table 31 shows the qualitative indicators for each soil series found in the upper watershed of the Buff Bay. This suggested the order of erodibility, from the highest 38, 46/301, 52/305/306 to the lowest 23. However, one of the parameters used would lead to double counting of slope angle. These results were used as an alternative scenario for the model, but were not sufficiently rigorous for inclusion in it.

Table 29. Ranks for slope aspect classes.

Azimuth	Azimuth	Freq landslide	Sorted %	Cum % freq	5 Class
271	280	3	0.3386	0.34	1
281	290	6	0.6772	1.02	1
351	360	7	0.7901	1.81	1
11	20	9	1.0158	2.82	1
301	310	9	1.0158	3.84	1
1	10	10	1.1287	4.97	1
311	320	10	1.1287	6.09	1
181	190	12	1.3544	7.45	1
291	300	15	1.6930	9.14	1
341	350	15	1.6930	10.84	1
331	340	16	1.8059	12.64	1
321	330	17	1.9187	14.56	1
31	40	18	2.0316	16.59	1
71	80	19	2.1445	18.74	1
21	30	20	2.2573	20.99	2
131	140	23	2.5959	23.59	2
41	50	25	2.8217	26.41	2
51	60	25	2.8217	29.23	2
191	200	26	2.9345	32.17	2
261	270	26	2.9345	35.10	2
91	100	27	3.0474	38.15	2
231	240	27	3.0474	41.20	3
121	130	28	3.1603	44.36	3
151	160	28	3.1603	47.52	3
241	250	28	3.1603	50.68	3
111	120	29	3.2731	53.95	3
201	210	30	3.3860	57.34	3
251	260	33	3.7246	61.06	4
101	110	37	4.1761	65.24	4
141	150	37	4.1761	69.41	4
211	220	37	4.1761	73.59	4
61	70	40	4.5147	78.10	4
161	170	40	4.5147	82.62	5
221	230	44	4.9661	87.58	5
171	180	48	5.4176	93.00	5
81	90	62	6.9977	100.00	5
		886	100.0000		

Table 30. Factors determining the qualitative erodibility of soils (based on CIDA & Forestry and Soil Conservation Department, 1993).

	Parameter	Most erodible value	Explanation
1.	Soil depth	Shallow	Quickly saturated
2.	Drainage	Poor/slow	Rapid overflow generation
3.	Texture	Coarse	Erodible grains

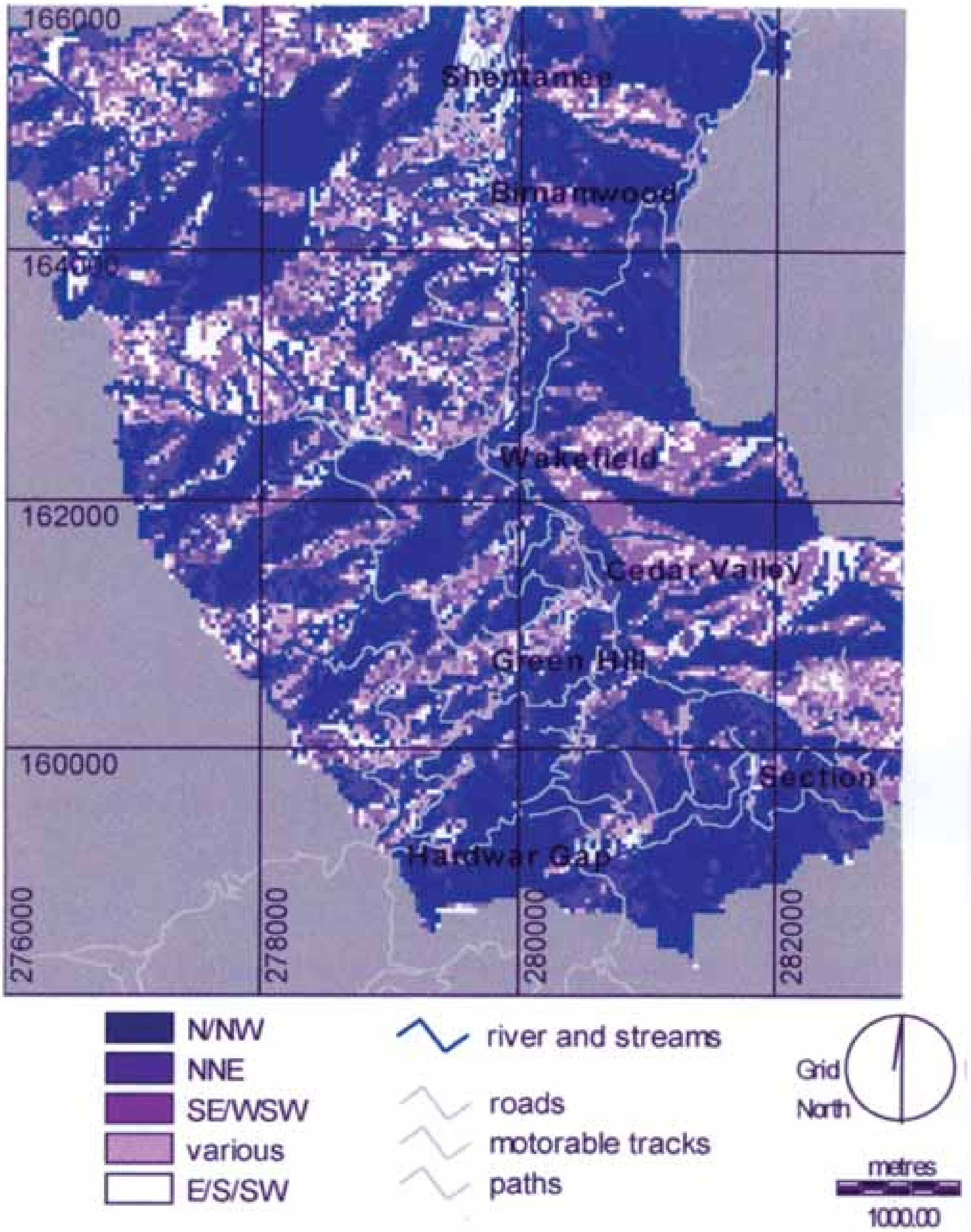

Fig. 7. Aspect classes (cardinal points, with specific degrees in Table 29).

CIDA & Forestry and Soil Conservation Department (1993) classified 90 % of the watershed as environmentally sensitive. Soils overlying the Richmond and Newcastle formations, the Hall's Delight channery clay loam (46/301) and Valda gravelly sandy loam (52) are all highly erodible according to the report.

Table 31. Ranking of soils based on qualitative indicators (based on CIDA & Forestry and Soil Conservation Department, 1993).

Soil series number	**23**	**38**	**46**	**301**	**52**	**305/306**
Fine texture	0	1	1	0	0	0
Shallow, bedrock <24"	0	1	1	1	1	1
Drainage poor or slow	0	0	0	0	0	0
Susceptible to erosion	0	0	0	1	0	0
Erodes on steep slopes	0	1	0	0	0	0
No. Qualitative indicators	0	3	2	2	1	1

Textural considerations – CIDA & Forestry and Soil Conservation Department (1993) stated that coarser textured soils tended to be more loose and easily eroded than finer textured soils, which are more compact. Particles in the finer textured soils bonded together to develop structures and resisted breaking down during rainfall. Both Fournier (1967) and Bryan (1968) found similar results. Richter & Negendank (1977) suggested that silts were more easily entrained than sands and aggregated clays. Claure *et al.* (1994) found that high permeability in coarse-grained deposits carried a high erosion risk because it led to gullying. Low permeability was a lesser risk because it only induced less damaging sheet erosion.

The technical parameters (FAO, 1979) for clay loams (<35 % clay and <65 % sand), like Hall's Delight, and sandy loams (<18 % clay and <82 % sand), like Valda and Cuffy Gully, suggested a medium texture, not the coarse high erodibility class of the Rural Physical Planning Unit (1990). The finest texture soil, Agualta sandy loam (soil series # 23), was reported as having a considerable organic matter content and, thus, aggregation rendered it less erodible.

Farres (pers. comm.) suggested using a clay:silt ratio. The sand-silt-clay fractions of the Buff Bay soils were in a report that the Rural Physical Planning Unit could not make available, so there was no verification of their actual textural status. The properties sand, silt, clay percentages were analysed in the Rural Physical Planning Unit laboratory. Table 32 shows the results of the textural analysis carried out on a small number of samples from the watershed.

The representativeness of the small number of samples is poor, but there is still an indication of loams. Less silt and more clay were found in the Agulta series (23) sample than the Rural Physical Planning Unit classification suggested. The Cuffy Gully series

Table 32. A comparison of textural parameters from field samples and Rural Physical Planning Unit (1990) classification.

Soil series	**23**	**38**	**46**	**301**	**52**	**305/306**
Sand	62	48	44	43	44	52
Silt	18	28	36	34	35	31
Clay	20	24	20	23	21	17
Clay:silt ratio	1.11	0.86	0.56	0.68	0.60	0.55
Sample	Sandy clay loam	Loam	Loam	Loam	Loam	Loam
RPPU	Sandy loam	Sandy loam	Clay loam	Clay loam	Loam	Loam

(38) sample was also finer than the Rural Physical Planning Unit classification. In the Hall's Delight (46/301) samples, more silt and less clay were found than the Rural Physical Planning Unit classification. Only the Valda series (52/305/306) had the same Rural Physical Planning Unit classification as the sample. It must be noted that these are single sample representatives of the series. A more rigorous sampling procedure would be necessary before the model could be used by other agencies. Table 33 shows the ranking based on textural parameters.

Table 33. Ranks for clay:silt ratio classes.

Clay:silt ratio	**37346**	**1-0.8**	**0.8-0.6**	**0.6-0.4**	**<0.4**
Rank	1	2	3	4	5

Aggregation – There was no analysis of the presence of aggregates. The aggregate disperser $CaCO_3$ could not be analysed, so the presence of calcareousness was taken from Rural Physical Planning Unit (1990). Soil loss has correlated well with active calcium carbonate, a function of the instability of large aggregates in its presence, allowing clay particles to become dispersed and transportable, but also causing surface crusting, pore space sealing and lower infiltration rates (Merzoek & Blake, 1991). Since structural stability is a better indicator of erodibility, the organic matter fraction was analysed since it was not reported in the soil series descriptions. Only the mollisol Agulta sandy loam was reported as having a considerable organic matter content rendering it less erodible (Rural Physical Planning Unit, 1990). That the other soils were classed as inceptisols suggested that there was no mollic layer, but McDonald *et al*. (1996) recorded significant litter production in similar soils from forest. The mineral and organic matter values for the soil series are shown in Table 34. Analysis of soil series 46 and 301 suggest an incorporation of litter or recent, but not obvious, fertilizer addition, giving an abnormally high organic matter value.

Table 34. Mineral and organic matter values for the soil series.

	23	**38**	**46**	**301**	**52**	**305/306**
% Organic matter	3.4	1.3	12.4	8.1	0.4	4.3
$CaCO_3$	calc	non	calc	calc	non	non

Internal drainage – Rapid internal drainage (dependent on permeability) was reported for Halls Delight, Valda and Cuffy Gully soils (CIDA & Forestry and Soil Conservation Department, 1993). The Cuffy Gully gravelly sandy loam was regarded by CIDA & Forestry and Soil Conservation Department (1993) as highly erodible because of the coarse-grained materials throughout the profile leading to rapid internal drainage and high surface runoff. However, it is generally accepted that soils with stable aggregates and coarse textures maintain pore spaces, and have higher infiltration capacities. High permeability is usually thought of as reducing runoff and, hence, surface erosion, so the CIDA statement may be referring to a perched water table. Only where an independent factor, shallow bedrock depth, is present is it likely that there is also considerable runoff despite rapid internal drainage. In shallow soils, soil moisture builds up rapidly, but is not stored as it drains or evaporates. Soils described as coarse-grained and with rapid internal drainage would not be generally thought of in terms of high erodibility, but if bedrock is shallow this may be true. Internal drainage was not incorporated in the model since all the soils were shallow and had rapid internal drainage. Not only was there not a consensus about the effect that internal drainage had on runoff, but the soils also shared the same parameter and could not be distinguished on that basis.

Taking these facts into consideration, it is possible that the term erodibility, as mentioned in the soil series descriptions (Rural Physical Planning Unit, 1990; CIDA & Forestry and Soil Conservation Department, 1993), was less concerned with sheet erosion and more with slope instability. In this case the qualitative descriptions of Hall's Delight, Valda and Cuffy Gully soils as highly erodible were not a good basis for the factorial scoring of the model. They were erodible because they occurred on high angle slopes (a factor already included in the model) and they were susceptible to instability (from the reference to soils of the Richmond Formation and Newcastle Porphyry as environmentally sensitive).

This study used sand, silt, clay, organic matter and the presence of calcium carbonate soil parameters, derived from samples that did not exactly agree with the Rural Physical Planning Unit soil series textural classifications. The organic matter content of the sample soils may have been compromised by the laboratory including litter in the analysis. It was not known what degree of $CaCO_3$ dispersed aggregates and if it was evident at the surface (Table 35). Yet the organic and mineral content remained a useful marker in conjunction with a clay:silt ratio, since aggregation is an important erodibility element.

Table 35. Ranks for clay:silt ratio and mineral classes.

	23	**38**	**46**	**301**	**52**	**305/306**
Clay:silt ratio	1	2	4	3	4	4
$CaC0_3$	1	0	1	1	0	0
Ranking	2	2	5	4	4	4

The order of erodibility, from the highest to the lowest, is 46, 52/301/305/306 and 23/38 (Table 36; Fig. 8). This is a different order of potential erodibility from the qualitative analysis. The qualitative analysis was based on coarse grains, whereas the quantitative method placed more importance on the silt (non-aggregated) fraction. An alternative calculation using the USLE (Wischmeier *et al*., 1971) is detailed in Chapter 6.

Table 36. Ranks for soil classes.

Soil series score		**23/38**			**52/301/305/306**	**46**
Rank	1	2	3	4		5

Vegetation cover – The degree of rainfall that becomes runoff is reduced by vegetation, a factor of biomass, season, rooting, and external factors like the humidity and water availability. The percentage of rainfall that becomes runoff is based on field, plot or specific single plant or crop type. It would be difficult to determine a figure for an area of agroforestry or mixed ruinate, for example. The important factors to consider in potential erosion susceptibility are the height and continuity of the vegetation, the density of ground cover, and root density and depth (Morgan, 1979). Morgan specified

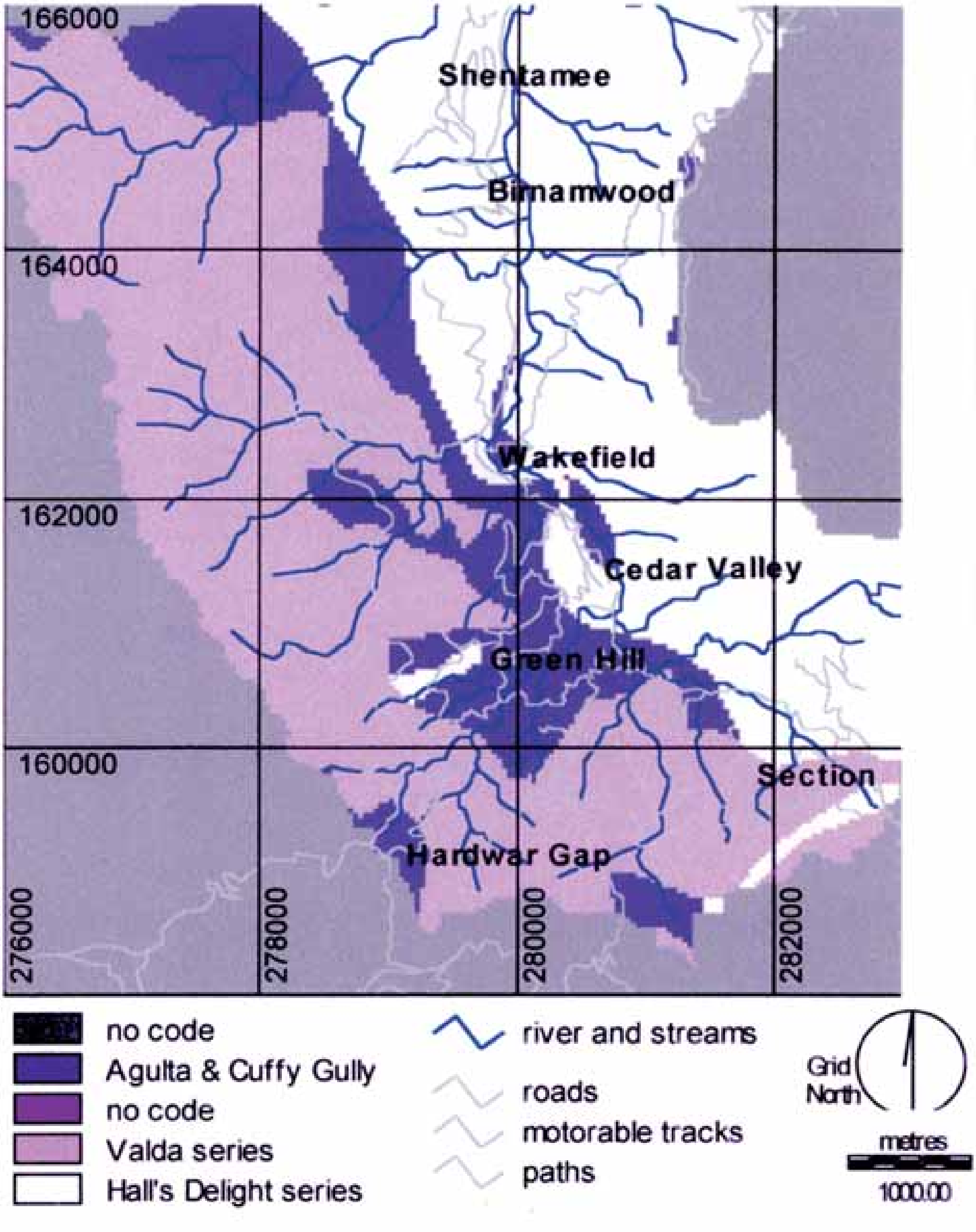

Fig. 8. Soils classes (series names: 23=Agulta; 38/305/306=Cuffy Gully; 46/301=Hall's Delight; 52=Valda).

a canopy height factor of 7 m as the threshold above which raindrops regain their terminal velocity (and hence full erosive capacity on impact with the soil), whilst a cover of at least 70 % is required to completely protect the soil from raindrop impact erosion. Soil loss and runoff do not increase rapidly until total vegetative cover falls below 30 %

(Elwell & Stocking, 1976). Gils & Wijngaarden (1984) developed an alternative approach to percentage cover because they concluded that the cover of the woody component was more accurately discernable in terms of crown distance, not percentage (Table 37). They also stated that the distinction of more than two horizontal layers of vegetation was very difficult from air photos, so they developed a system in which density and the two layers were combined. The vegetative structures in the Buff Bay catchment were grouped into seven categories, which this research reduced to four (Fig. 9).

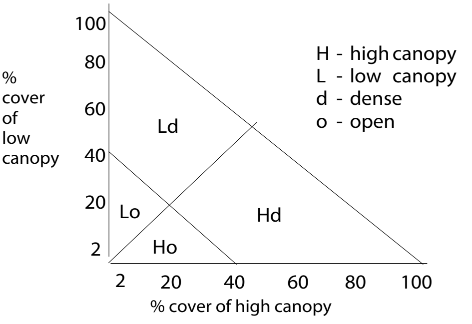

Fig. 9. Canopy height and density parameters (after Gils & Wijngaarden, 1984).

Table 37. Cover and crown parameters for canopy physiognomy classification (after Gils & Wijngaarden, 1984).

% cover equivalent	Crown distance/crown radius	Physiognomy on the ground
100 - 80	0 - crowns interlock	Closed, dense
80 - 40	1	Semi-open, difficult to pass at chest height
40 - 20	2	Opening out
20 - 2	5 - tree densities calculable	Open canopy
2 - 0	10 - very widely spaced trees	Woody component not important

A low open canopy affords a high level of soil protection from rainfall and runoff, especially if grass is evident (Table 38). Grass on low angle slopes affords good protection, but in the Buff Bay catchment some grass slopes showed signs of erosion on slopes above 25°. When the cover is closed, protection of the soil is still high, but light levels preclude ground cover and hence soil protection. Rainsplash involving coalesced drops has a lower impact than under a high canopy. Field evidence showed that grassed areas were sometimes lightly grazed on shallow slopes or provided open ground for tracks to be pushed through to fields or food trees, with evidence of linear erosion.

Table 38. Ranks for land use classes with local examples.

Rank	Structure	Example of Buff Bay vegetation
1	Low and open	Grassland, coffee crop
2	Low and closed	Wild ginger, low ruinate
3	High and very open	Well spaced or intermittent trees, grass or coffee understorey
3	High and open	Canopies at least crown distance/crown radius =>2, high ruinate
4	High and closed	Forest, at least crown distance/crown radius <2
5	Bare ground	Tilled, recent landslide
5	Bare, but regenerating	Bare ground that showed recent crop growth or grass

Interestingly, a high open canopy shows less soil loss (Fournier, 1967; Stocking *et al.*, 1988; Chatterjea, 1989; Nortcliff *et al.*, 1990) than a high closed canopy where there is no ground cover (Bell, 1973; Douglas, 1968; Hamilton, 1995; Hellstrom, 2000). High ruinate has regenerated a closed canopy, which for the purposes of erosion has the same protective function as closed canopy natural forest. A light subcanopy and ground cover exists, although there are fewer species than the original forest (CIDA & Forestry and Soil Conservation Department, 1993). Leaf litter inputs have been measured at 6 t/ha/yr (McDonald *et al.*, 1996), but the amount and effectiveness of soil protection cannot be estimated from air photos.

Some bare slopes were unconsolidated landslide scars and tails showing significant rilling and gullying, but where clear weeding was practiced between coffee bushes, and on terraced fields cleared for dasheen, some erosion was also evident. Regeneration of these slopes was rapid if left untended, except for steeper slopes (over 40°) and the scar and steeper reaches of landslide areas. The image of vegetative cover ranking is shown in Figure 10.

Land use – The first problem of including land use in the model is one of interpreting the CIDA & Forestry and Soil Conservation Department (1993) terms natural, plantation, ruinate, agriculture and agroforestry (with various understorey activity) with the degree of erosion associated with the activity. Garg & Harrison (1992) made a comparison of Mediterranean land uses showing that terraced orchards were more susceptible to erosion than unterraced cereals or orchard. There were no qualitative data in the CIDA & Forestry and Soil Conservation Department (1993) report on how often or to what extent the soil surface was worked, an essential fact in assessing the erosion of any particular agricultural activity. Table 39 is a comparison of different tropical agricultural environments (reviewed in Chapter 2) and their relative erosion ranks (1 is low erosion, 7 is high erosion).

Table 39. Examples of relative land use classes (based on absolute values).

	McDonald *et al*. (1996)	**Wiersum (1984)**	**Stocking (1992)**	**Mitra *et al*. (1998)**	**van Grootveld (1992)**
1	Forest	Multistoried tree garden, fallow shifting cultivation	Grass cover	Deciduous mixed forest	Dense forest
2	Calliandra, agriculture	Forest, mulched tree crops	*Pinus caribaea*, >60 % cover seedling tea	Evergreen forest, good pasture	Mixed garden, degraded forest
3	Bare			Woodland, poor pasture	Well managed tea
4			*Pinus caribaea:* thin layer pine needles	Overgrazed	Coconut small-holding
5		Tree crop clean weeded		Double cropped	Poorly managed tea, shifting cultivation
6		Forest plantation burned/ litter removed	Mixed vegetable/tobacco, <40 % cover seedling tea, gourds on sticks, french beans	Row cropped	Market gardens
7			Clean-weeded strips	Bare soil	

Some general trends can be observed. Natural forest and grass cover give the best protection of the soil, whilst bare, burned ground cover, no litter and clean weeding cause considerable soil erosion. Well managed tea plantations have a low erosion hazard, but poorly managed tea, market gardens and agriculture have a high hazard. Shifting cultivation does not always have high rates of erosion if it is under fallow. In CIDA & Forestry and Soil Conservation Department (1993), secondary forest (high ruinate) represents good slope and watershed protection, as there is a closed forest canopy with sub-canopy layer, shrub layer, and ground layer of herbs and ferns.

The second problem is related to source map and photo interpretation. The Land Use maps (CIDA & Forestry and Soil Conservation Department, 1993) presented the dominant land use types (LUT) of the upper catchment as forest (natural, plantation, ruinate), monoculture agriculture (coffee) and agroforestry (mixed or specifically with coffee or livestock). The more detailed land use categories (LUC) for the watershed distinguished high and low ruinate, and unimproved pasture. The LUC map for 1993 is at significant variance with the LUT map both in terms of natural forest boundaries and the degree of ruinate. The LUT, although less detailed, resembled the air photo interpretation, whereas the LUC had the vegetative physiognomy useful for distinguishing erosion class type. These differences made it difficult to develop the erosion classes, but the LUT was chosen for its relationship to air photo data (see Section 'Errors and uncertainties' in Chapter 8, p. 127, below, for quantification of comparison).

The relative erosion classes determined from the literature (Table 39) were used in the model. The air photos did not reveal the understorey, an important factor under high canopy (Collier & Collins, 1980). The LUT data were coded on the basis of this relative ranking (Fig. 11). Without a considerable fieldwork element, the problems associated with medium scale air photos were impossible to resolve and secondary rather than air photo sources had to suffice in this model (Table 40).

Table 40. Ranks for land use classes with examples of land use activity.

Rank	Type	Example of Buff Bay landuse
1	No disturbance	Natural forest, undisturbed forest, grass
2	Conservation, ruinate	Mulched tree crops, unimproved pasture, high and low ruinate
3	Minimal tillage	Mixed agroforestry
4	Regular tillage, planted	Perennial crops
5	Clean weeded	Extensive coffee, annual crops, yams

Factor absence

If data were unreliable, unpublished or the source not traceable, then it was left out

Table 41. Conditions and rejection of factors not included in the model.

Factor	Significance	Condition not met
Slope length	Increased entrainment	Determination complex
Geological fault zones	Landslide generation	Active faults unknown
Recent landslides	Bare soil	No base map
Vegetation type	Affects evapotranspiration	Not discernable at this scale
Management	Soil conservation activity	Not mapped

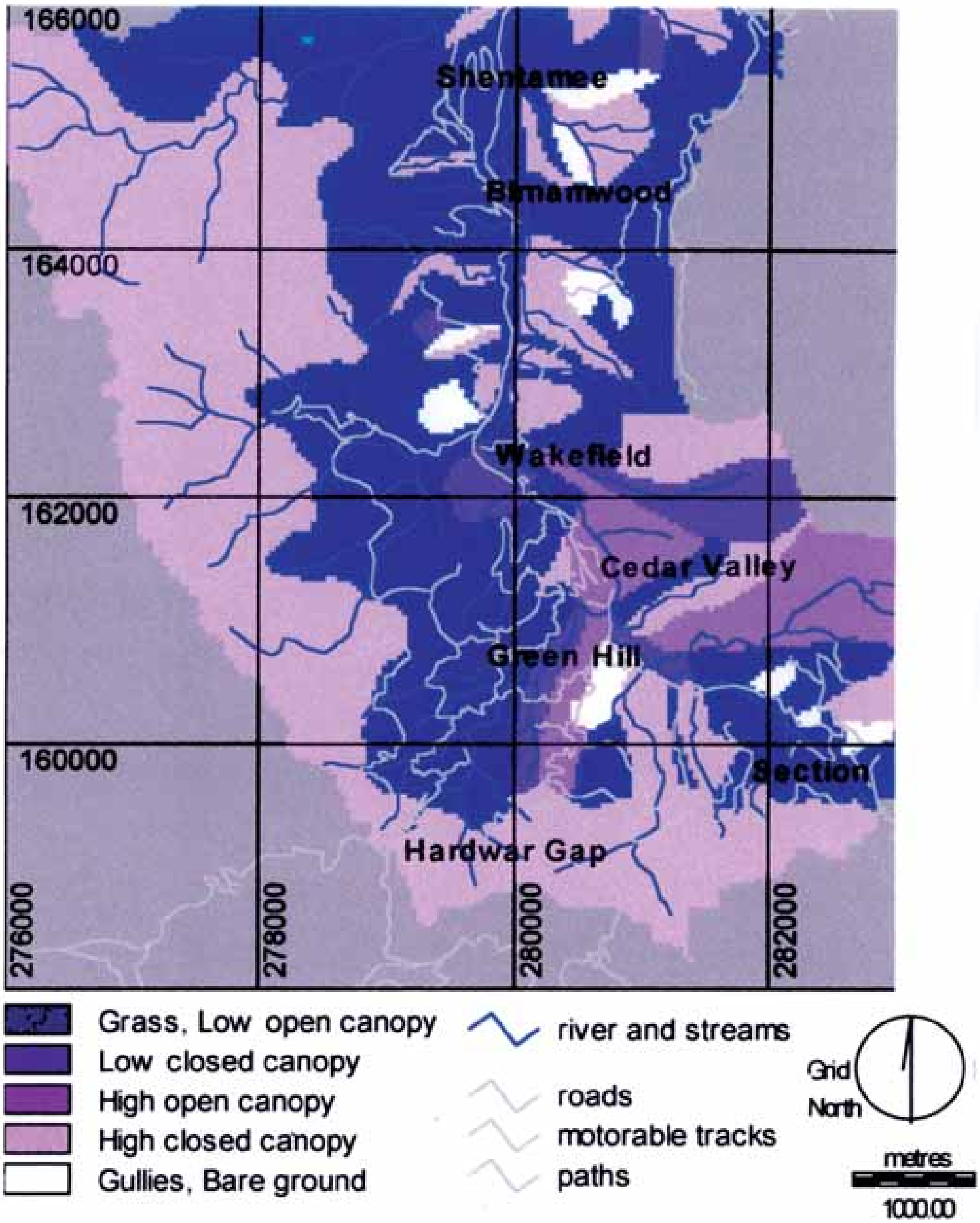

Fig. 10. Vegetation classes.

of the model. The only exception to this rule was the soil data. It was felt that for such an important factor, any indication of influence on erosion was better than non-inclusion. Table 41 gives the significance of factors left out of the model and the conditions that were not met.

Slope length is included in the USLE because it represents the increased entrain-

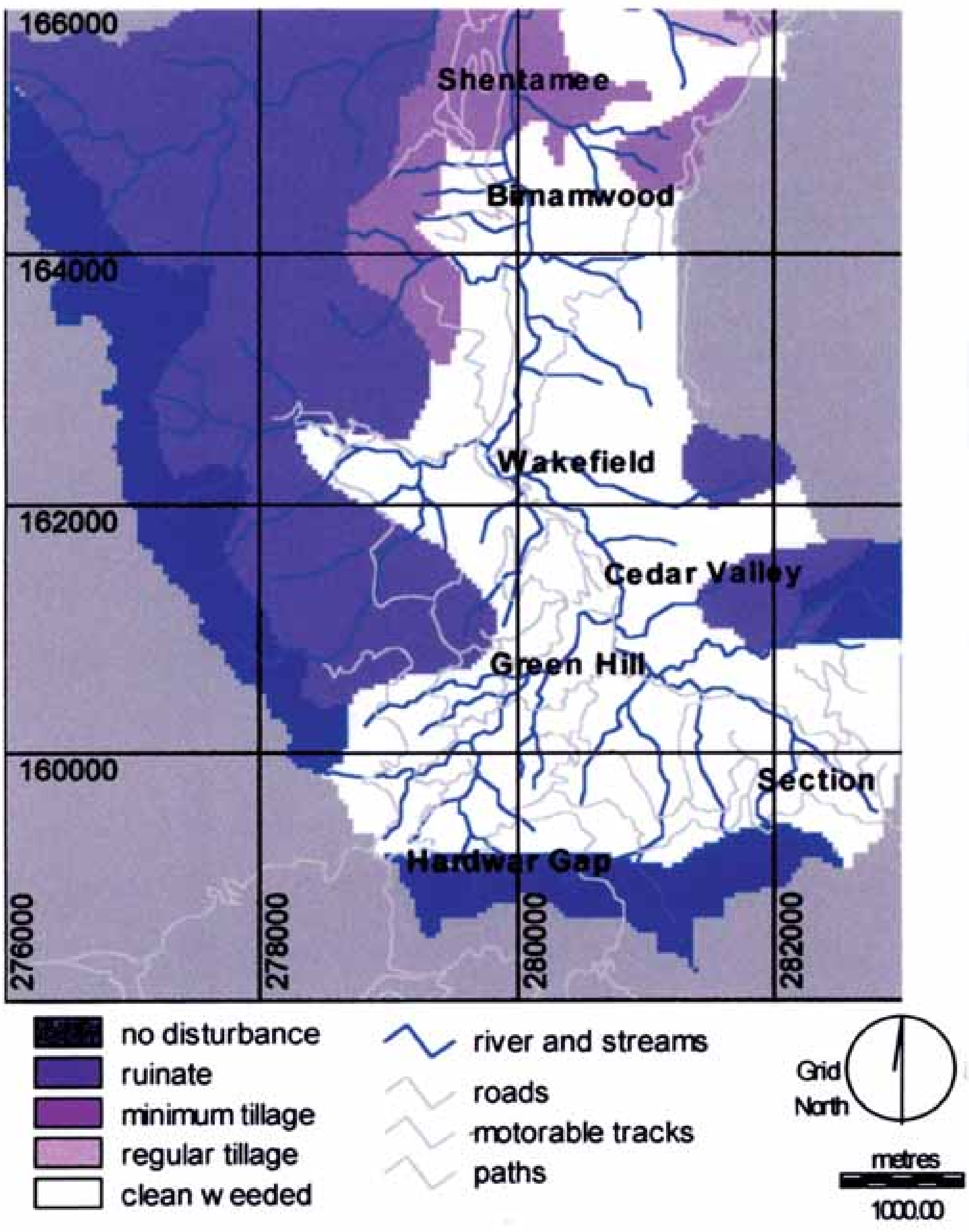

Fig. 11. Land use classes.

ment of sediment. There is scant literature regarding the effect of slope length on run-off and soil transportation in complex watersheds. The USLE assumes a standard slope length of 30 m and SLEMSA is based on 100 m. Runoff velocities over rough terrain are not well understood. The modified SLEMSA model used for large geographical areas reduced slope length to a constant because it was thought to be much less significant as a factor in erosion over larger areas. If new literature reveals that a high correlation between slope length and erosion exists, it can be introduced into the model.

Although studies of landslide activity have been carried out in the Blue Mountains and for the Kingston Metropolitan Area (Ahmad & McCalpin, 1999), no published maps for the Buff Bay watershed have been sourced. An unpublished map of the geology of the area at 1:50,000 has been traced, but it is not known which faults are active and likely to trigger landslides. The model determines potential, not past erosion, so an inventory of past landslides would not be useful.

The degree to which evapotranspiration reduces the quantity of rainfall that becomes runoff is recorded for many plant groups and hence the usefulness of vegetation type as a factor. However, the plant associations could not be distinguished at the scale of 1:36,000.

There was evidence of conservation structures, but they were difficult to map at this scale. Terracing was visible from the air photos if the area was sufficiently large (greater than 50 m across), but if it was overgrown, for example, at one of the soil sample sites, it was no longer obvious. The vegetative cover in such instances is providing protection from erosion just as is the obscured terraced ground beneath. It is visible when the field is being used for clean weeded crops, in which instance it needs to be mapped.

Additional factors for post-model interpretation

In studies carried out in the Blue Mountains, it was found that slope failures were common on artificially cut slopes during and after rainfall. Steep cuts made in the hillsides to build roads were sometimes greater than 45° (Maharaj, 1993b). Given these facts, the network of roads and tracks had to be considered in the list of factors which influenced slope erosion. There has also been research in other tropical areas into the phenomenon of roads becoming channels for water courses due to inadequate drainage facilities. This factor is difficult to quantify in a catchment-based study, but it is clear that roads and tracks affect the slope and local erosion processes. Each road and significant track was digitised and a buffer (the distance perpendicular to a linear target) assigned to the resulting vector image. This image was incorporated in the initial model as an accelerated erosion factor. This factor was taken out of the final model because it was not possible to ascertain which road sections acted as conduits. The final model only used the vector images as overlays for locational presentation. A similar process was proposed for the known stream and river channels, since these are also sites of accelerated erosion. However, the model did not represent channel erosion and so the buffer was excluded.

The Idrisi module RUNOFF (Jenson & Domingue, 1988) calculates the accumulation of rainfall units per pixel as if one unit of rainfall was dropped on every location. DEMs usually contain depressions that hinder flow routing. To reduce the effects of local minima and to ensure that the accumulated rainfall units reached the boundaries of the surface, an adjusted 'depressionless' DEM (least monotonically decreasing path of cells leading to an edge of the image; Eastman, 1997, 1999) was created using the module PIT REMOVAL (Jenson & Domingue, 1988). A path is composed of cells that are adjacent horizontally, vertically or diagonally and that steadily decreases in value. The RUNOFF results identified the theoretical volumes of runoff and the paths it would take. It was overlain with the last three phases of the model to interpret spatial patterns that might give an insight into sediment sources.

The output of the TOPOSHAPE module is a surface shape classification consisting of eleven possible topographic features; peak, ridge, saddle, flat, ravine, pit, convex hillside, saddle hillside, slope hillside, concave hillside and inflection hillside. The algorithm for deriving shape is based on Pellegrini (1995). Surface shape classification is based on polynomial surface fitting of each 3 × 3 pixel area. Eigenvalues are based on a central pixel of a 3 × 3 neighbourhood, and calculate the magnitude of rate of change of a tangent line along the mathematically described curve in both the aspect and orthogonal to aspect direction of the pixel (Eastman, 1997, 1999). Makhanya (1978) suggested that convexity was influential in erosion, so the post-model analysis looked at areas of high susceptibility that occurred on convex slopes.

Stepwise overlay

The process of overlay predates computer information systems, but the principles have remained the same. The overlay operation, vector or raster, provides access to attribute values at a specified location. The rules governing overlay operations can be grouped into three types: dominance, in which only one value from the those available is selected; contributory, in which each attribute contributes through a mathematical function; and interaction, which explores the interaction between factors. Some packages can only combine a maximum of two factors at any stage during overlay, whilst others allow for interaction. Both are referred to as a stepped approach.

One of the significant uses of the technique is for highlighting cause and effect relationships, by investigating how the spatial coverage of one factor is responsible for that of another. This predictive use of overlay is well known for ascertaining environmental sensitivity (McHarg, 1992). This study is also concerned with mapping an intangible, in the sense of potential sensitivity to erosion. However, there are restrictions on the efficiency of overlay depending on the data type. In order to investigate the combined effect of certain factors, the factors need to be merged, synthesised or combined following an algorithm. GIS is particularly suited to this operation, which is referred to as overlay, the combination of different layers of information. However, there are several points to be considered before this is attempted. In manual graphic representation, overlay requires that each layer is registered to the others whilst scale, projection and area of coverage are kept the same for each layer. The use of a computer GIS allows the analysis of factors from divergent sources, although a certain amount of transformation is necessary to prepare the layers for registration.

Overlay has been used by many authors in traditional and GIS analysis. Makhanya (1978) used an overlay approach in a traditional manual mapping of erosion in Lesotho. The maps of slope and convexity were superimposed, and combined with a map of slope lengths and vegetation to produce a map of susceptibility. By combining this with a map of erosion features, an erosion map was produced which, when overlain with cultivation areas, produced a map of risk. Lopez (1991) also combined map pairs in stages to evaluate the degree of severity of mass movement hazard. The first overlay involved soils and morphodynamic processes, and the second litho-geomorphology and slope gradient. The first and second overlays were then combined for hazard. Another application of overlay, soil fertility maps (Schmidt *et al.*, 1995), used forest area data from API-derived land use analysis, and slope and aspect data from DEM sources which, combined with soil type, created a series of overlays for carbon content, phosphorus availability and eventually a composite fertility map.

The cartographic model presented by Meijere *et al.* (1988) ably demonstrated the concept of stepwise overlay for calculating the USLE, although it failed to mention the method of combination or specify the technique. The first map incorporated the KLS-factors, whilst map two comprised the R-factor. These two were combined to make the potential erosion map, which assumed no vegetation, but this was modified to allow for the whole area being under one type of crop. Further maps represented the ecological suitability for a crop allowing for climate and soil, and the suitable areas for that crop. The land available, and accessibility to roads and towns in the forms of buffers (km), were added to give a map showing suitable, available and accessible land for that crop. This logical progression through the factors illustrated intermediate and final applicability of the overlay approach.

Some of the more complex quantitative models have involved significant manipulation, since the layers (TMU, Thiessen polygons, soil polygons, radar pixels) had to be in the same format. The soil series approach to the rainfall-runoff model used by Karnielli (1991) involved extracted relationships for two or more factor layers to produce new data. In the stepwise overlay method, the first step was to compute hydraulic conductivity, using bare soil hydraulic conductivity, % vegetation cover and % ground cover. The same was carried out for capillary potential (soil texture and effective porosity) and soil moisture deficit (saturated and initial water content).

Factorial scoring and weighting

Each attribute value has to have the same unit or unitless system. Hence, the factors used in the USLE have the same value system gathered from charts and graphs. Unless there is a conversion system to follow, factorial scoring has to be considered. This refers to the practice of allocating ascending or descending scores to classifications of each factor. This is a popular solution where an established value system is not being followed. However, the factors being considered may not have equal importance according to the equation or model and will require weighting before being combined. This assumes that there is empirical evidence to rank the importance of these factors, and that a cause and effect relationship has been established in previous research.

Factorial scores and weighting reflect the importance of parameters in the downslope movement of particulates and are used especially in landslide studies. Some scoring systems are relatively simple in which gully density, slope and land use were reclassed into five, and ranked according to susceptibility to erosion (Garg & Harrison, 1992). In a study of a Bolivian watershed (Claure *et al.*, 1994), empirical evidence was used to produce a more complex system of matrices of hazard combining factors with different weights to determine overall hazard. Geology was given a higher weighting than soils, especially where structural controls were evident. Vegetation was regarded as protective and modified the hazard rating down if present in the right density. On the other hand, steep slopes carried a penalty to increase the hazard ranking.

The factorial scoring used by Mejia-Navarro *et al.* (1994) was fairly complex because of the number of variables and the different value systems involved. One of the manipulations required an overlay correlation to identify rock units in which historical events had occurred in order to create the weighting for the geotechnical layer. Land use categories were factorised according to their vulnerability, for example, transport routes (especially roads) tended to truncate slopes, channel runoff and increase bank collapse. The slope map was superimposed on the surficial geology and geomorphic process maps to determine the slope intervals (percentage) with maximum event frequency, allowing the slopes with highest event frequency to carry a 10 weighting.

Table 42 clearly shows the benefits and problems associated with factorial scoring. A mixture of qualitative and quantitative data can be used if there are no available data in the quantitative set. However, there are occurrences of some scores left blank, with no presented logic as to why classes 6 and 8 in the USLE factor are not accounted for. The issues of class boundaries and divisions are not easily resolved, since there may be no empirical data for decision-making.

Table 42. Highest five erosion risk categories and their factorial values (after Mejia-Navarro *et al.*, 1994). Key: @ = vegatation dry weight.

Factor	**6**	**7**	**8**	**9**	**10 (most)**
Slope (%)	4.64-10		10-21.5	21.5-46.4	46.4-100
Aspect (deg)	112-157	157-202	202-247		247-292
Veg @	800-900	700-800	650-700	500-650	0-500
Clay	Moderate				High
USLE K		>0.37		>0.43	>0.53
Land use	Commerce	Public service	Farmland	Residential	Transport/mining
Stream	40-50	20-40	10-20	Streams	River/pond
Record	< 100 yr flood, geol. records	< 100 yr flood, rare debris flows	< 100 yr flood, freq. debris flows	< 100 yr flood, v. freq. debris flows	Floodway
Isohyet (mm)	483		533		610

Increasing weighting complexity was explored for landslide susceptibility by Berry (1994). The Weighted Buffer Extension included a variable buffer width relating to the function of slope. In steep areas the buffer increased in width (low impedance in the distance step function) with slope angle and incorporated the presence of the road network. In the SLEMSA model (Ndyetabula & Stocking, 1991), factorial scoring and combination was carried out by grouping the erosion hazards into eight classes, whilst each of the erosion factor classes (cover, erosivity, erodibility, slope) was categorised into five levels of increasing erosion hazard. The most influential factor was determined by adding up and averaging the scores for all the factors within a grid square and noting the score of any factor exceeding the average. This was then determined to be the most dominant and hence influential factor in the hazard of that square. In hazard class 8 (highest hazard), slope was deemed the most dominant factor, with cover second. In hazard class 7, slope then erodibility dominated, whilst erosivity was the least dominant factor in all the hazard classes. This method was applied to the Buff Bay data (see 'Using the SLEMSA analysis', Chapter 9, p. 142 below).

Modelling coefficients and algorithms

The final consideration, although it will have played a role from the beginning, is the manner in which the factors are to be combined once they have been given values, factors and weightings. The matter of map algebra (Boolean logic, regression, addition or multiplication of factors) is usually implicit in a model or equation, but a simple factorial scoring system has to take the implications of each into account. In Boolean logic, addition represents the OR operation, whereas multiplication represents the AND operation. In factorial scoring, the addition of factors gives a linear scale, and multiplication an exponential scale of results. This is important for interpretation and presentation of visual analysis.

An algorithm is a form of weighting, determining a ranked order of importance for each influencing factor. Mejia-Navarro *et al.* (1994) looked at the multiple controlling factors with GIS-based weighted algorithms. The debris flow susceptibility (Sdf) algorithm was calculated as follows:

*Sdf = slope * (aspect*7 + grain size & liquid limit*4 + surficial geology*9 + vegetative cover*8 + soil runoff:precipitation ratio*5 + clay shrink-swell potential*2 + USLE factor K*7 + land use zone*3 + stream order buffer*8 + historical record*10 + annual isohyet*4) / 67.*

Hence, historical records of debris flow occurrence at any one location was the most influential factor. It is important to note that some factors were combined, for example, soil runoff and precipitation. This weighting by algorithm method is only reliable if there are empirical data to verify it.

Resulting erosion risk classifications

Just as in factorial class boundaries, the end result also has to be divided into relative classes. Lopez (1991) used a qualitative rating of five levels, in which slope, susceptibility and frequency of observed events determined the score (Table 43). However, this assumed that historical event frequency correlated with susceptibility.

Table 43. Class divisions for a qualitative rating (after Lopez, 1991).

Class 1:	None/uncertain	Flat to slightly undulating, materials not susceptible or observed to fail
Class 2:	Very low	Slopes less than 7%, slightly susceptible, no events
Class 3:	Low	Slopes 7% to 25%, slightly susceptible, rarely observed events
Class 4:	Moderate	Slopes 7% to 25%, moderately susceptible, common observed events
Class 5:	High	Slopes 25% to 75%, strongly susceptible (volcanic ash cover), frequently observed events

The five erosion risk classes of Garg & Harrison (1992) had a compounded score ranging. This procedure assumed equal probability of each class and assigned equal weighting, a baseline for further complex combinations and weighting factors.

The final image divisions for the PED model had equal intervals with intrafactorial weighting, but no interfactoral weighting. Overlay used an addition operator, the normal practice for extensive operations, as there was no literature to justify abandoning the simplicity of this method. The cartographic model used relative, qualitative terminology – very low, low, moderate, high and extreme – to describe the classes in each intermediate and final potential erosion image.

Review

The discussion has looked at the factors that can be incorporated in the model and those which have to be left out for the present. The value ranges for each chosen factorial class are summarised in Table 44. The structure of the cartographic model is such that additional factors can be relatively easily incorporated. Social influences on erosion, for example, population pressure on the land in terms of cultivation to fallow ratios, tenure and fragmentation, would be incorporated as a five class scale with equal intervals based on some quantifiable aspect of the factor.

Table 44. Summary of the factors used in the model. Key: [1]Batjes (1994), Lopez (1991); [2]McGregor *et al.* (1998); [3]Maharaj (1993a); [4]Rural Physical Planning Unit (1990); [5]Farres (pers. comm.); [6]Gils & Wijngaarden (1984).

	Low erosion potential			**High erosion potential**	
Factor	**1**	**2**	**3**	**4**	**5**
Agroclimatic zone [1]	W1	W2	VW1	VW2	VW3
Slope angle (degrees)[2]	<15	15-20	20-25	25-30	>30
Slope aspect (points)[3]	N/NW/W	NNE/NE/ E/SE/SSW	ESE/SSE/ SSW/WSW	ENE/ESE/ SSE/SW	E/S/SW
Soil series (qualitative)[4]	23	-	52/305/306	46/301	38
Soil series (structure)[5]	-	23/ 38	-	52/301/305/ 306	46
Vegetation (structure)[6]	Low open	Low closed	High open	High closed	Bare
Land use (tillage)	No disturbance	Ruinate	Minimum tillage	Regular tillage	Clean weeded

A universal index, if one is needed at all, should be simple to measure, reliable in operation and widely applicable. For each local situation where the PED model from this research might be applied, a different set of parameters could be introduced. The model allows for this by producing the results in relative format. This seems to be a more valid use of the term universal than that which is suggested by the USLE where fixed nomographs are applied. A relative classification of soil erosion like that of Sauchyn (1993) is proposed, whilst simple overlay within this reference framework makes weighting unnecessary.

8. Limitations of modelling

Conversion to vector based system

There are certain limitations that modelling imposes on the analysis of geomorphic systems. The discussion of raster and vector-based system (see 'Choosing the representation', Chapter 7, p. 91, above) concluded that the choice of representation should reflect the measurement framework, and the software contain both vector and raster analysis. Although Idrisi coped well with vector inputs, and was the only available software, it would not be everyone's choice for the research (P. Collier, pers. comm.). Therefore, it is important that the model be adaptable to vector representation.

All of the factors in the model were originally generated from digitized information and are therefore readily available for a vector based programme. However, the model produced a score for each pixel and, as results showed (Chapters 9 and 10, below), pixels with the same score were not contiguous in such a complex landscape. For a vector model to be effective in the decision-making process it would have to be able to use a unit area within which slope was homogenous, for example a TIN or HyRU. The attribute is assumed to be uniformly distributed throughout the polygon, just as in pixels. However, the pixel already represents a simplification of the actual ground conditions and a set of larger polygons would simplify the ground conditions even more so. There are studies to support vector-based analyses of continuous data. For example, DeMers (1997) stated that it was not efficient to construct slopes and aspects from contours.

The boundaries of the soil and vegetation maps would need to be matched or slivers would result in the overlay that would have to be resolved. Once new factors with new boundaries were introduced, in a cadastral survey, for example, the boundary matching would have to be resolved again. Fuzzy tolerance could be used to eliminate insignificant slivers, but then boundary details would be compromised. The raster system seems to simplify this overlay procedure in a complex terrain in which slope angle and aspect are important factors. Lopez & Zinck (1991) noted that sequential overlays caused excessive polygon fragmentation, so they followed the empirical approach of using the soil map as the base document that contained all the geopedological factors in its database. DeMers (1997) noted that it was common to overlay all layers into an integrated coverage to construct the database. This made it easier to construct common features and avoid slivers, but the topology of each layer was compromised in the process. Any changes to the attributes, or additional factors, meant creating a new typology. Alternatively, each coverage could be aggregated into categories of query before overlaying, avoiding slivers and fuzzy tolerance problems. However, the PED model regards slope as an influential factor in erosion and even five classes of slope angle does not give contiguous pixels (see Fig. 6).

Another approach is that taken by Morgan (1978) in which hillslope response unit (HiRU) reflected the complexity of hillslope processes and the need for an accurate homogeneous basis. He combined three factors in a hillslope unit; local site (lithology, soil, weathering), processes (erosion, deposition, equilibrium) and efficiency of basal material removal. Using principal components analysis, he produced profile groupings and site patterns to form land units - the valley head, the valley side and the spur end. Each unit had a characteristic form which was a response to its environment. In my view, this method would still not cope with the complexity of the slope map at the watershed scale. Worosuprojo *et al.* (1992) partially solved the slope angle problem by delineating TMUs based on landform, slope class and land use type differences. Landform types were distinguished, such as colluvial foot slopes, which could then be correlated with USLE values and analysed on the basis of vegetation density cover. However, even five slope classes generated from interpolated contours still produce a complex representation at the watershed scale.

Errors and uncertainties

There are errors and uncertainties in all GIS research. Errors were corrected where possible, and involved positional and attribute mistakes during input and analysis. Uncertainties arise from measurement, inherent variability, conceptual ambiguity, over-abstraction or simple ignorance of important model parameters, and are determined and accounted for with probability theories. Two types of uncertainty are commonly distinguished, database and decision rule (Eastman, 1997, 1999). Measurement errors and conceptual errors are common sources of database uncertainty. Decision rule uncertainty arises from the manner in which criteria are combined and evaluated to reach a decision. Inadequate model parameters or inappropriate thresholds are all socially constructed and subjective, whilst a lack of theoretical understanding of a process is a common source of uncertainty. The errors and uncertainties that I have identified are arranged according to the point in the research at which they were found.

Source and evidence – Positional and classification errors were identified during map compilation. The base maps (CIDA & Forestry and Soil Conservation Department, 1993) were enlarged to 1:50,000 scale and then digitised. Paper maps undergo certain distortions with copying, folding and storing, which cannot be easily corrected. These sheets had not only been stored in a relatively humid environment in the tropics, but then had to be enlarged. This was done as accurately as possible.

Inaccuracies due to fuzzy natural boundaries were impossible to avoid. Certain factors had crisp sets on paper, for example, the contours. However, since the 1:50,000 topographic map was produced photogrammetrically, the disclaimers highlighted the potential inaccuracy of contours in areas of high vegetation and the unofficial nature of any boundaries delineated on the map. The land use map was relatively crisp to the extent that it incorporated land ownership boundaries. On the other hand, factors such as the vegetation, agroclimatic zones and soils maps inevitably had fuzzy boundaries, although the conceptual basis of the fuzziness differed. Like the contours, the agroclimatic zone boundaries were based on decision rules, the relevant authority having chosen the point at which the attributes of a continuous dataset belonged to different sets. In digitising these boundaries, the assumption was made that the boundary chosen was an important threshold.

Bocco & Valenzuela (1988) carried out research that compared the accuracy of TM and MSS Landsat data, and found that the factor C (cover) was estimated differently by each. Some research has claimed to identify five different erosion classes for a study area, but, when repeated by others, only one class could be detected (Bocco & Valenzuela, 1988). A common problem in multispectral classification is misclassification. The spectral responses can be very similar for different classes making field verification and experience very important. Baker & Drummond (1984) found that there were shortcomings in digitising and polygon generation of photographs as well as georeferencing satellite images. Based on their observations, it could be said that the use of remote sensed data can be as time and money consuming as the traditional approach to environmental mapping.

The dates of the maps are important, although there are few alternatives for more up to date sources. The topographic map was dated 1984, but the photogrammetric data on which it was based dated from the 1970s and 1980s. The maps (CIDA & Forestry and Soil Conservation Department, 1993) were not dated, but the inventories must have taken place in the late 1980s or early 1990s. The soil surveys on which they were based were not mentioned in the report.

Input and database uncertainty – Causes of errors in inputting include improper use of a digitiser, a fatigued hand, typing errors during attribute input and some registration difficulties (DeMers, 1997). It is possible that more time will be spent correcting small positional and attribute errors than spent preparing maps and inputting them. Positional errors can involve missing, misplaced entities or sliver polygons. Attribute errors, on the other hand, are database typographic mistakes, including codings and misspelling (making retrieval of an entity or its parameter difficult). The error is often not discovered until analysis, which with attributes is traceable, but with positional errors it is difficult to trace.

The act of digitising material is not a perfect reproduction of the source material and, in fact, the opportunity presents itself for manipulating the source material to extract only that information which is required. Errors and inconsistences do arise, whether the digitising is manual or automated, and it is important to take precautions before digitising to minimise these problems. One consideration is the combination of scales. Photoreduction of the 1:24,000 USGS maps to produce the 1:100,000 series is an appropriate exercise whereas the use of a 1:2,500 plan map in combination with a 1:50,000 geological map is not (P. Collier, pers. comm.). Generalisation, or the reduction of information, can be carried out using line reduction algorithms and other similar tools. This can have significant consequences if the reduction is too great, because some objects become unrecognisable or are simply lost. Another risk in combining divergent scales is aggregation. When spatial and attribute data are involved, the production of the map for a lower number of categories introduces new boundaries, which may not have followed certain trajectories or sinuosities if the categories had been reclassified prior to reduction.

The method of converting the paper map to a digital one also contained errors and uncertainty. The contour lines were digitised manually, since no automatic tracing was available. Manual digitising is tedious and introduces the subjectivity of picking points where the contour deviates. Automatic tracing is reliant on the quality of the paper map, since other objects or breaks in the line may distract the line generator.

All the base maps of this research were checked against the GIS outputs for each factor layer. The files were viewed in Idrisi as vector files (to check digitising accuracy) and raster files (to check labelling values). A close comparison with the original map was made and errors corrected. The digitising software was not topological. This meant that boundaries between polygons had to be digitised twice. The view scale at which the original soil and vegetation maps could be digitised meant that boundary matching (sliver reduction) had to be corrected post-digitising. This will have introduced spatial accuracy errors, as one boundary is dragged to match the other. This arbitrary sliver reduction method would have been difficult to avoid given the available software. The actual location of natural boundaries are socially constructed without definitions as to the vegetational threshold at which a boundary is recorded. The real situation is likely to be a fuzzy boundary, hence the problems encountered by other researchers (Naesset, 1998). In the case of land ownership, crisp boundary definition and accuracy is more reliable. The polygon entities had to be broken prior to importing them into Idrisi or the rasterisation process would give all the cells within the boundary a value. This would have created problems in the interpolation sequence. The new polylines were merged with the polylines contours and viewed within Idrisi. Positional errors included three missing polygons in the DEM, resulting in flat topped hills and some open polygons. The errors were digitised, rasterised, then added to the DEM. The track and water vector files contained undershoots and overshoots (dangling nodes) because the fuzzy tolerance limit was not set low enough. During rasterisation, the resolution was such that some of the undershoots were no longer visible. Although these images could be neater, they do not represent an error. Should the images become incorporated in the model, the remaining dangling nodes would need to corrected in the rasterised image using the module UPDATE.

The attribute errors encountered involved the incorrect coding of some contours. These were relatively easy to spot once the DEM had been generated, but some corrections came late in the modelling phase when anomalies were identified. These were all corrected before the final model was run. The DEM was checked against the topographic map for elevational accuracy (Table 45).

Table 45. Comparison of topographic and DEM elevations for certain watershed entities.

Entity	**Grid reference: 13/...**	**Topographic map**	**DEM 10 m**	**DEM 40 m**
Watershed boundary (spot heights)	8.2361782962e+23	1.2911e+15	1.2801e+15	1.2771e+15
Hills within watershed (spot heights)	788631812642	880842	880840	875832
River bed contours	820603807613	800600	800600	802601

The topographic map elevations were routinely underestimated, suggesting that real slopes might be steeper than the DEM estimated. Errors ranged from 5 to 26 m. The contours, as expected, were estimated to within 1-2 m. The errors were accounted for partly by the conversion of the contour image from a 10 m to a 40 m resolution (Table 45) and partly by the activity of smoothing, using the FILTER module. This replaces values with the average of the original height and the neighbouring height, and is commonly performed after interpolation since the linear interpolation creates a slightly faceted surface (Eastman, 1997, 1999). Three spot heights were not estimated correctly in the 10 m resolution image, with errors ranging from 2 to 19 m. The biggest error in both resolutions was St. Catherines Peak, which in the 10 m resolution image was calculated as flat-topped and in the 40 m resolution as a ridge with an elevation below the original last contour. This highlights the problems of using filters to remove faceting, which also reduce spot heights. A further analysis was carried out to compare the GPS calculation of heights (which could only be attained if the GPS handset could receive the signals from at least four satellites), the topographic maps and the DEM from Idrisi (Table 46).

There were no GPS data for three sites, despite moving to a place where there was no canopy. The difference in height read from the topographic maps ranged from 2 to nearly 20 m, but then the nearest contour from the 1:50,000 was accepted rather than manually interpolating between very close contours. The 50 ft map had no heading data, so the reference is unknown, but it is thought to be more accurate than the 1:50,000

Table 46. A comparison of the GPS, topographic map and DEM (40 m and 10 m resolution) elevational data (m). Key: (n) is the number of satellite signals received, but no elevation was given; * converted from feet.

Source	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**
GPS	1092	-3	-4	1123	-3	1185	1185
1:50,000 topo. map	1e+07	1e+07	1e+07	1e+07	1000	1e+07	1e+07
50 ft* topo. map					990		
DEM 40 m 3×3 filter	1e+07	1e+07	1e+07	1e+07	1015	1e+07	1e+07
DEM 40 m 7×7 filter					999		
DEM 10 m 3×3 filter	1155	1200	1166	1032	1025	1205	1180

metric version (D.J. Miller, pers. comm.). There was also a significant difference in the elevations produced by the DEM according to filter types. The two filters produced elevations within 20 m, but the average was only 8 m. The 10 m resolution DEM produced elevations that most closely resembled the 3 × 3 filtered 40 m DEM and least closely followed those of the 50 ft topographic map.

There was a considerable variance between the GPS readings and the 50 ft topographic map of between 34 m and 96 m, and with the 1:50,000 of between 15 m and 108 m. This suggests that either the GPS was not reliable for height evaluations or that the accuracy of the contour estimations in areas of high vegetation was suspect.

Uncertainty in the evidence is usually represented by RMS calculations in the case of quantitative data (Eastman, 1997, 1999). These were carried out for the digitised contours. The root-mean-square (RMS) error was automatically calculated within TOSCA from repeated control points. The RMS error is a measure of the variability of measurements about their true values. The RMS error is estimated by taking a sample of measurements and comparing them to their true values. The differences between the sample and the true values are then squared and summed. The sum is then divided by the number of measurements to achieve a mean square deviation. The square root of the mean square deviation is then taken to produce a characteristic error measure in the same units as the original measurements. The RMS error is directly comparable to the concept of a standard deviation. The allowable RMS error may be calculated for any accuracy standard. The accuracy standard may already be specified for the project, the use to which the data will be put may suggest a logical accuracy objective. The allowable RMS can be calculated from the map scale. The procedure refers specifically to United States National Map Accuracy Standards, but the technique applies to any standard based on map scales.

According to the 1947 revision of the U.S. National Map Accuracy Standards, maps shall have no more than 10 % of tested points in error by more than 1/30 inch for 1:20,000 scale maps or smaller and no more than 1/50 inch for maps greater than 1:20,000. Conversion of accuracy standards into statistical analysis of the allowable RMS requires that 90 % of accidental errors shall not be larger than 1.64 times the RMS (i.e., 1.64 standard deviations, assuming a normal distribution of errors). Therefore:

Allowable RMS = (Acceptable error on the ground / z score probability of occurrence)
= (Acceptable error on the ground / 1.64)

Therefore, the acceptable RMS for the map of contours, the DEM for the Buff Bay project, based on the 1:50,000 series was as follows:

Acceptable error on the ground = Error on the map * scale conversion * units conversion
= 1/30 inch * 50,000 * 0.0254 m/inch
= 42.3 m

Allowable RMS = (Acceptable error on the ground / z score probability of occurrence)
= (42.3 m /1.64)
= 25.8 m

Since the RMS of contour image was 3.0 m and of the soils 9.2 m, the error was deemed to be acceptable. The latter only refers to the accuracy of the boundary digitising. The other aspect that has to be assessed is the error in qualitative datasets. The assessment of measurement error is normally carried out by groundtruthing, comparing the new measurements to those in the data layer. Idrisi supplies two modules for this purpose, SAMPLE and ERRMAT. The former defines sample points for groundtruthing and the RMS (quantitative data) is calculated for those points. The latter is used for qualitative data, in which an error matrix is used to assess the relationship between the mapped categories and the true values.

An analysis of agreement between the land use data provided in a very general form by CIDA & Forestry and Soil Conservation Department (1993) and the vegetative cover (air photo interpretation) was carried out using ERRMAT. This module (typically used in accuracy assessments of supervised and unsupervised classification) identifies categories for which the difference between the ground and derived image is greater than desired. Errors of commission involve those pixels mistakenly included in a particular category, that is, land use category 1 that was really vegetative covers 2 and 3. They give an indication of how the accuracy of the map needs to be improved. Errors of omission are those pixels that are mistakenly excluded from the category, that is, vegetative cover 1 pixels that have been classified as other land use and should have been land use category 1. They are an indication of the adequacy of the land use mapping. Although this matrix is normally used with sample points, it has been used here to compare the whole image.

Firstly, the land use map was reclassed into three categories to reflect the vegetation types present in the upper watershed. Secondly, the vegetative cover was reclassed to reflect the level of potential tillage activity. This made the two images comparable on a physiographic basis rather than an erosion rating basis. The Kappa Index of Agreement (KIA) was also calculated as part of the module, representing a proportional accuracy figure adjusted for chance agreement (Table 47).

In perfectly matched images, the diagonal (grey shaded) contains the values and the other cells contain zero, whilst KIA is 1. In Table 47 there are high values between class V1 and class L1. This would be expected in ruinate, natural and even plantation areas. The exceptions would be agroforestry and kitchen gardens with shade and cropping trees, where high values between V1 and L3 would be seen. There are reasonably

Table 47. ERRMAT comparison of land use and vegetative cover images.

	Class V1: high open and closed canopy	**Class V2: low closed**	**Class V3: grass and bare**	**Errors of commission**	**KIA**
Class L1: no disturbance and ruinate	**7415**	102	2888	0.29	0.43
Class L2: minimum tillage	215	**32**	1500	0.98	-0.02
Class L3: regular tillage and clean weeding	3366	873	**5962**	0.42	0.22
Errors of omission	0.33	0.97	0.43	0.4	
KIA	0.38	-0.05	0.22		

high values between these two, but this is due to coffee plantations having been planted on previously forest and ruinate areas, a time lag factor between the two data sources. Given the very general land use map, it is also encouraging to see there is a reasonably high KIA and low errors values for classes V1 and L1.

There is clearly no agreement at all between classes V2 and L2, and the division into three categories must have been too contrived. The ERRMAT module was rerun with two categories. When low closed canopy was reclassed as canopy and minimum tillage as ruinate, the average of errors was 0.39 and the overall KIA was 0.22. However, when low closed canopy was reclassed as grassland and minimum tillage as regular tillage, the average of errors was 0.30 and the overall KIA was 0.41. The two images have reasonable agreement for two categories in which high canopy is identified in the photos. This is particularly important as mixed agroforestry is treated like coffee plantation in terms of tillage activity and this might actually be the case if annual crops are being harvested under the tree crops.

Analysis and decision rule uncertainty – Database uncertainty, in terms of measurements errors, is recognised in deriving parameters from DEMs. The slopes are interpolated from contours and error propagation is inevitable. This is important when thresholds are applied to the parameters. This has two consequences, the first of which is dealt with as a database uncertainty. In this case, we cannot be sure if a slope that was measured as 20° really is that value, as there is a finite probability that it is higher, depending on the accuracy of the topographic map and the RMS of the digitising process.

The concept of a steep slope belongs to the category of decision rule uncertainty. The statement is made in reports that erosion occurs on steep slopes, quantified as 26° (CIDA & Forestry and Soil Conservation Department, 1993). However, in GIS analysis, if this threshold is introduced, then a slope of 25.9° is not steep. Since no such boundary has empirical value, the concept of fuzzy sets is introduced. The concept of gradual physical boundary changes has already been discussed in this chapter. All continuous factors in modelling are fuzzy set membership functions, whilst Boolean constraints are crisp set membership functions.

Decision rule uncertainty in a multicriteria model is sometimes termed model specification error (Eastman, 1997, 1999). Two issues can be discerned in this research, whether the criteria are adequate to define the potential erosion areas and whether the evidence from the criteria has been properly aggregated. The research needs to address whether the aggregated value predicts the degree to which the classification belongs to the decision set (the single outcome of the incorporated criteria). A considerable sampling density would have been necessary to validate the model in such complex terrain. Therefore, it has to be assumed that each factor has a degree of influence on hillslope erosion and, when aggregated with the other factors, that relative erosion potential can be determined. The logic behind the decision set may be wrong, a concept that is described as decision risk (Eastman, 1997, 1999).

A relatively new development is the soft decision concept, the likelihood that the decision set is correct and that a threshold of acceptability can be set. This would be based on probability and might be couched in terms of the likelihood that an area has a problem with soil erosion, rather than a hard judgement of whether or not it does. This might result in a research team being sent to investigate areas of potential erosion where the likelihood of a soil erosion problem exceeds a certain threshold percentage. This research represents a much simpler form of the same concept, having introduced relative potential erosion areas, the upper two classes of which could be investigated further by field teams.

9. Results from the PED Model run

The results of the model run are described below in six sections, and include the individual factors, the intermediate stages, the final potential erosion detection image and a detailing of the patches in that image, as well as alternative scenarios and a collection of post-model analyses. The method for identifying factorial dominance for any location was also calculated (Ndyetabula & Stocking, 1991).

Individual factor statistics

Agroclimatic zones – Two thirds of the research area fell primarily in the Wet 2 zone (verified by a class mean of 2.42) (Table 48), which represents a dependable growing period (DGP) of 7 to 10 months, with 1 to 2 dry months. The Very Wet 1 zone also covered a significant part of the watershed, with a DGP of 8 to 10 months, with 1 to 2 dry months. Over a third of the watershed, located primarily in the east, has a R75/PET ratio over 1.50 and no discernable dry season, which may suggest high soil moisture values.

Table 48. The percentage of the research area in each agroclimatic class.

Agroclimatic classes	**1:Wet 1**	**2:Wet 2**	**3:Very Wet 1**	**4:Very Wet 2**	**5:Very Wet 3**
% of research area	5	59	27	5	4

Slope angle – Idrisi uses an algorithm to calculate slope angle that is based on four cardinal directions, called the rook's case procedure. It calculated maximum slope from a 3x3 pixel neighbourhood. This gave overall higher slope angles than an average or maximum downhill slope angle and hence higher erosion estimates (Hickey, 2000) (Table 49).

Table 49. The percentage of the research area in each slope angle class.

Slope angle classes (degrees)	1:< 15	2:15-19.9	3:20-24.9	4:25-29.9	5:>30
% of research area	10	12	18	20	40

A histogram of slopes derived from the DEM showed 78 % of the pixels with a slope angle steeper than 20°, the threshold slope angle at which erosion was said to take place (Morgan, 1986). The class mean was 3.7, but it is more representative to look at raw data statistics since the class boundaries were artificially skewed.

Although the image class divisions are important for both process and land management purposes, a histogram of equal intervals of the data gave a better indication of the nature of the slopes (Table 50). The actual mean of 27.8° indicated that slopes were generally steep and that almost half the slopes were between 24° to 36°. The image class divisions showed over a third of the slopes steeper than 30°. A more detailed examination revealed 98 % of slopes gentler than 44°. The maximum slope calculated by the DEM was 60°.

Table 50. The percentage of the research area in each slope class (equal interval).

Degrees	Percentage
0 to 12	6.17
12 to 24	28.78
24 to 36	47.23
36 to 48	16.35
48 to 60	1.47

The steepest topography occurs in the western and southern parts of the watershed. The image of slope angle was reclassed to isolate slopes over 45° and these pixels seemed to show a pattern. In order to ascertain if this pattern was elevation related, the pixels over 45° were used as a MASK for the DEM and a database QUERY initiated. A histogram of this data highlighted seven peaks (a peak accounting for around 5 % of the total) of frequency, the details of which are given in Table 51. There may be a geological control for this phenomenon, but certainly the two peaks at 695 m to 795 m and 845 m to 946 m are notable elements of this landscape.

Table 51. Elevation classes in natural clusters and the frequency of extremely steep slopes.

Elevation (m)	Frequency of slopes >45°	Percentage of slopes >45°
425 to 475	37	4.95
695 to 795	122	16.33
805 to 835	38	5.09
845 to 945	126	16.87
965 to 995	42	5.62
1005 to 1035	40	5.35
1085 to 1145	72	9.64

Slope aspect – The headwaters originate in the east-west running ridge of the Blue Mountains. The majority (68 %) of the valley sides of the numerous ravines and tributaries face northwest, north and northnortheast (Table 52). This was not the most susceptible aspect for landslides due to higher pore pressure (Maharaj, 1993a). Therefore,

Table 52. The percentage of the research area in each slope aspect class. Key: * = class 4 slope aspects are detailed in Table 29.

Slope aspect classes	1:N/NW	2:NNE	3:SE/WSW	4:Various*	5:E/S/SW
% of research area	47	21	11	12	9

it is probable that aspect is not very influential in the erosion processes in the Buff Bay watershed.

Soils – Over 80 % of the research area had soils with an erodible combination of clay: silt ratio and calcium carbonate (Table 53), the significance of which was also evident from the class mean of 4.1. CIDA & Forestry and Soil Conservation Department (1993) stated that soils of the watershed were highly erodible and these statistics revealed the extent of that erodibility.

Table 53. The percentage of the research area in each soils class. Key: * = soil series names are found in 'Soils' (Chapter 5).

Soil series score	**1:none**	**2:23/38***	**3:none**	**4:52/301/305/306***	**5:46**
% of research area	0	16	0	44	40

Vegetation – Very little bare ground was identified from the colour air photos (Table 54). This was not unexpected in a humid tropical environment where vegetation regeneration is rapid. It should be stated that bare ground is a temporary phenomenon in this environment, but the coding has to take it into account. Bare ground occurred at landslide sites (which regenerate some cover, but typically remain unstable) and recently cleared land (the regeneration time of which is faster if planting or sowing is involved). Roughly half of the watershed was covered in vegetation that protected the soil, whilst the other half was covered in vegetation under which there was little understorey and low litter levels. The class mean of 2.6 was considered to be fairly meaningless in this context.

Table 54. The percentage of the research area in each vegetation class.

Vegetation classes	**1:low open**	**2:low closed**	**3:high open**	**4:high closed**	**5:bare**
% of research area	44	4	6	43	3

Land use – The dominance of one crop type with a particular tillage regime, coffee, ensured that just under half of the research area had soils that were regularly disturbed if based on this one factor alone (Table 55). However, the other half of the research area was barely or not tilled. The land use map of CIDA & Forestry and Soil Conservation Department (1993) presented a large area of coffee plantation, and showed no evidence of smaller areas of high canopy, grass and low closed canopy identified from air photos of 1991. Using the maximum function of the EXTRACT module in Idrisi, the slope angles at which the various land use categories were recorded were analysed (Table 56).

The coffee plantation land was the largest land use in the upper watershed. The

Table 55. The percentage of the research area in each land use class.

Land use classes	**1:no disturbance**	**2:ruinate**	**3:minimal tillage**	**4:regular tillage**	**5:clean weeded**
% research area	15	32	8	0	45

land uses previous to the ruinate area were not known, but they would have been carried out on the steepest slopes in the upper watershed on which coffee was now being cropped. The minimum slopes for all the above land uses was flat land, but the averages give some indication of the skew of the data. Unimproved pasture occurred on the least steep slopes, which may be a function of the degree of slope that cattle will tolerate. Goats and donkeys are found tethered on very steep slopes.

Table 56. Slope statistics and area for each land use category.

Land use category	Total area (ha)	Maximum slope (degrees)	Average slope (degrees)
Natural forest	527.68	59	28
High ruinate	1137.44	61	30
Mixed agroforestry	148.96	56	25
Low ruinate	130.56	52	28
Unimproved pasture	16.48	40	22
Coffee plantation	1618.08	60	26

Intermediate stages in the cartographic model (E1 to E5)

The scores of the intermediate phases are constantly divided into five classes - very low, low, moderate, high and extreme. These terms are used in describing the percentage of the research area falling in a specific class.

E1 Erosivity – The very few high and extreme scores (Table 57) that resulted from overlaying agroclimatic zones and aspect were found within the Very Wet 3 zone in the extreme east of the research area (Fig. 12). Two contiguous areas were obvious on the image. The first was a southwest facing valley head (13/818624) where a stream rises that drains towards Cedar Valley, but turns just north of west, joining the Buff Bay River at Wakefield. The second area (13/824615) was just south of the first, a south-facing valley side, at the top of which is a peak (1291 m) and at the foot of which flows a stream that forms part of the headwaters of the Buff Bay River. It is not known if the streams are ephemeral, since there is a marked seasonality and lithology varies. Around Mt. Holstein and the Bangor Ridge there were discrete pixels with very high scores. About two thirds of the research area had low erosivity scores relative to the rest of the upper catchment.

Table 57. The percentage of the research area in each erosivity class.

Erosivity scores	1-2	3-4	5-6	7-8	9-10
% of research area	3	59	28	9	1

E2 Erodibility – Over 90 % of the research area was erodible in terms of soil structure and tillage practices, with over a third of the area at extreme risk from tilled or clean weeded, silty soils (Table 58). The highest score was found where coffee plantations were situated on the Hall's Delight channery clay loam,

Table 58. The percentage of the research area in each erodibility class.

Erodibility scores	1-2	3-4	5-6	7-8	9-10
% of research area	0	7	35	20	38

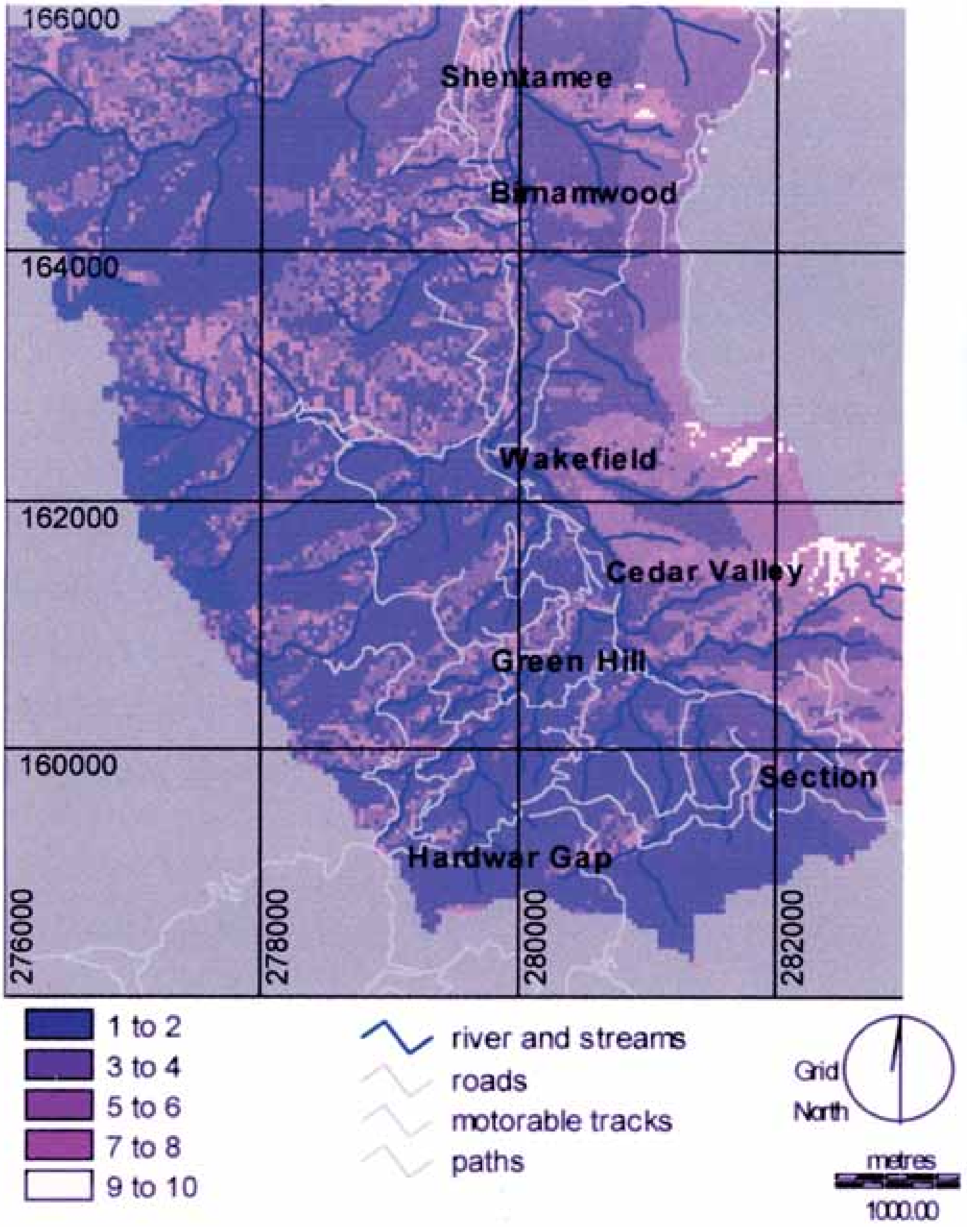

Fig. 12. Erosion scores for E1 Erosivity

which was also a thin soil. Coffee was also grown on the Cuffy Gully and Valda gravelly sandy loams, and this still gave a very high susceptibility to erodibility. The main areas of high erodibility were in the eastern and southern watershed, with a lobe of erodibility up into the Shentamee River valley, where coffee is grown (Fig. 13).

E3 Energy – The addition of the slope factor to agroclimatic zones and aspect increased the potential entrainment in terms of the energy and availability of runoff (Table 59). There are very few areas centred around the high scoring areas described in E1 that score the maximum in all three factors. A new area of disconnected patches also shows high scores around southern-facing slopes of the Shentamee River, Mount Holstein and the village of Birnamwood (Fig. 14). A very large part of the research area (75 %) has moderate and high scores, reiterating the predominance of high angle slopes (>20°).

Table 59. The percentage of the research area in each energy class.

Energy scores	**1-3**	**4-6**	**7-9**	**10-12**	**13-15**
% of research area	0	23	56	19	2

E4 Earth – The influence of the vegetative cover was to reduce the proportion of the research area that was extremely erodible by half (see Table 58; class scores 9 and 10). The percentage of the area that was highly erodible increased to 40 % (Table 60). The area that was moderately erodible (35 %) was not influenced by the addition of vegetative cover. Gullies and bare earth influenced the location of the high scoring patches. Wherever there was coffee indicated, the score was further increased by patches of high canopy, when coffee was grown under shade. The erosion classification of coffee as a land use was high due to soil disturbance during seedling planting and weeding. However, the erosion classification was low for coffee as a vegetative cover, since the low open canopy that coffee provided was not potentially damaging, but rather the frequency and manner in which the soil is managed. Further fieldwork, focusing on the coffee industry, would be necessary to finely tune the model, since McGregor (1988) noted that cutlass weeding (common for coffee plantations) did not necessarily break up the surface and cause higher erosion (the presence or absence of shade trees was not mentioned).

Table 60. The percentage of the research area in each earth class.

Earth scores	**1-3**	**4-6**	**7-9**	**10-12**	**13-15**
% of research area	0	6	35	43	15

E5 Erosion – The scores for the pixels in the final erosion image ranged from 9 to 28. To be classified in the highest class, at least one of the factors must have a maximum score of five, whilst at least three factors must score maximum before the remaining three drop their maximum to stay in this class. Table 61 gives an indication of the distribution of pixels for which erosion was estimated. Using the six factors in the model, the indication would seem to be that approximately 30 % of the upper watershed has the potential for moderate to extreme erosion. Areas of high potential erosion were concentrated on the eastern side of the main valley, from Mt. Holstein to Section. The headwaters of the Buff Bay River also showed high potential erosion, not at the stream

Table 61. The percentage of the research area in each erosion class.

Erosion scores	**1-9**	**10-14**	**15-19**	**20-24**	**25-30**
% of research area	0	13	58	27	2
hectares	5.76	470.88	2069.12	984.64	67.68

heads, where undisturbed natural forest provided soil protection, but at lower elevations where a number of tourist trails began from the Newcastle road. This was a high scoring function of erodible soils and coffee plantations. However, the patterns that the patches (contiguous pixels) formed were elongate along some of the headwater valleys. One example followed the Green Hill Trail, and another was enclosed by the Section road and the Wallengford trail. In the example of the Green Hill Trail, no one factor accounted for the pattern, since trails were not included in the model. Lower down the trail there were moderate to high scores of E3 Energy, whilst at the head of the trail, it was the E4 Earth scores that extended the pattern, influenced mainly by coffee plantation on Cuffy Gully Association soil. The patch also had a high closed canopy from the 1991 air photos. Obviously, the two land uses cannot coexist unless considerable numbers of shade trees have been left to protect the coffee crop, but the transition from forest to coffee would be an extremely hazardous activity for the soil, both in logging the tree cover and preparing the ground for seedling coffee.

The relative importance of factorial classes – Further analysis was carried out on the areas which scored extremely high. Six areas were identified where there were patches of contiguous pixels (see 'Patches of the extreme erosion class', this chapter, p. 144, below). Table 62 identifies the classes within which the extreme scoring pixels occurred. As expected, the classes in each factor with the highest rank feature strongly in this list. Some factors displayed a class presence in the extreme erosion image that was expected. The increasing influence of aspect on erosion was related to aspect class, with half the extreme erosion class occurring in the aspect areas of class 3 and 4, and the other half in class 5. The three categories were present in the research area in approximately the same proportions (Table 62). The relationship between slope angle and extreme erosion class also followed an expected trend, with the highest class of slope angle (which occurs in 40 % of the research area) accounting for 88 % of the extreme erosion area. Only one soil category, Hall's Delight, was found in the extreme erosion area,

Table 62. Classes per factor in which extreme erosion was predicted, pixel frequency and percentage of extreme area.

Factor	Category	Pixel frequency	Percentage
Agroclimatic zone	2: Wet 2	43	10.62%
	3: Very Wet 1	277	68.40%
	5: Very Wet 3	85	20.99%
Aspect	3: SE/WSW	98	24.20%
	4: Various	114	28.15%
	5: E/S/SW	193	47.65%
Slope	4: 25 to 30 deg	50	12.35%
	5: > 30 deg	355	87.65%
Soil	5: 46 (Hall's Delight)	411	100.00%
Vegetation	3: High open	65	15.74%
	4: High closed	239	57.87%
	5: Bare	109	26.39%
Land use	2: High ruinate	65	16.25%
	5: Coffee plantation	335	83.75%

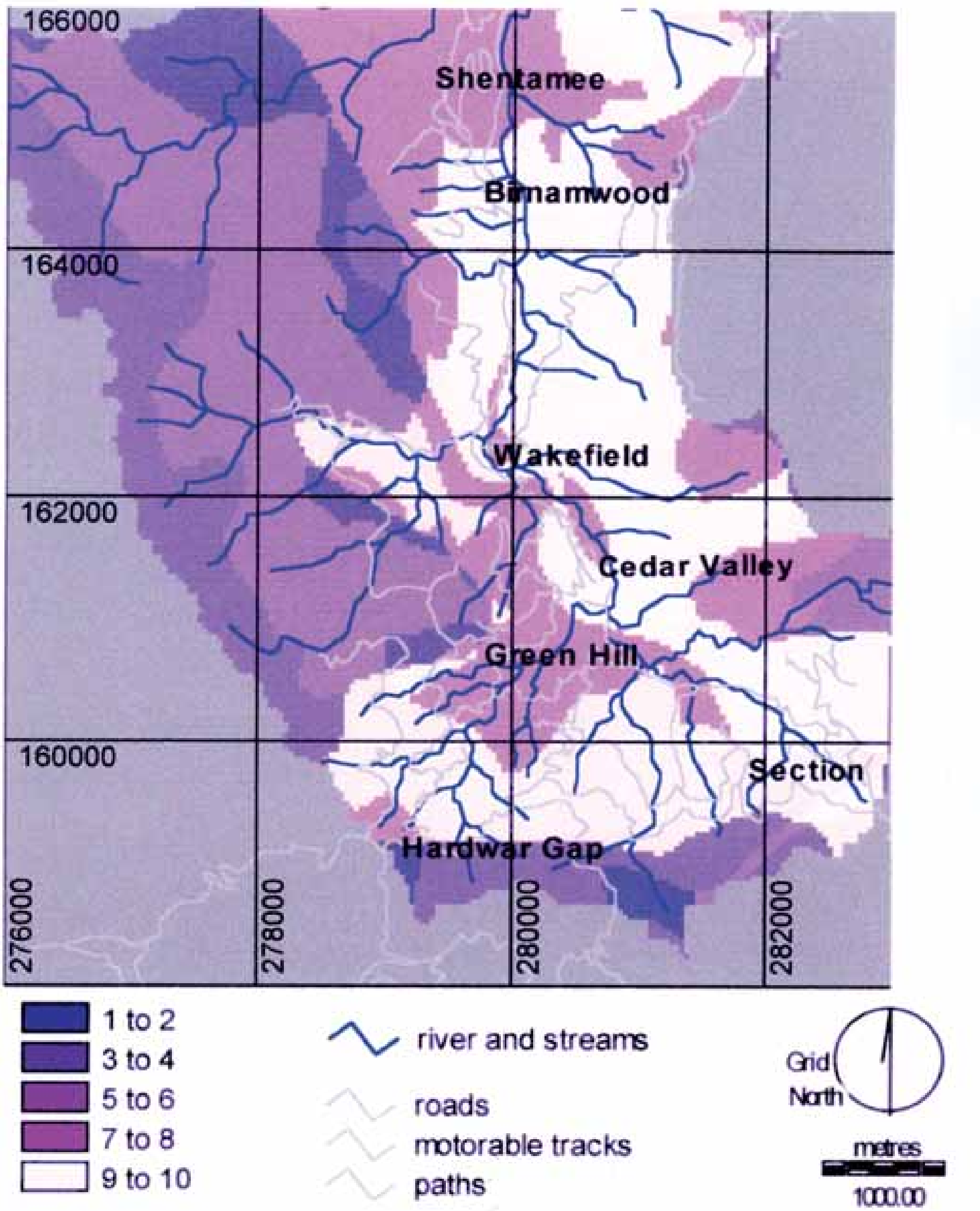

Fig. 13. Erosion scores for E2 Erodibility.

highlighting the important influence of this factor, despite this category only being present in 40 % of the research area. The vegetation factor was the last of the factors that followed an expected pattern in determining extreme erosion. The top three ratings were represented in the extreme erosion class, with over half of that area covered in a high closed canopy. Considering that the area of bare ground identified from air

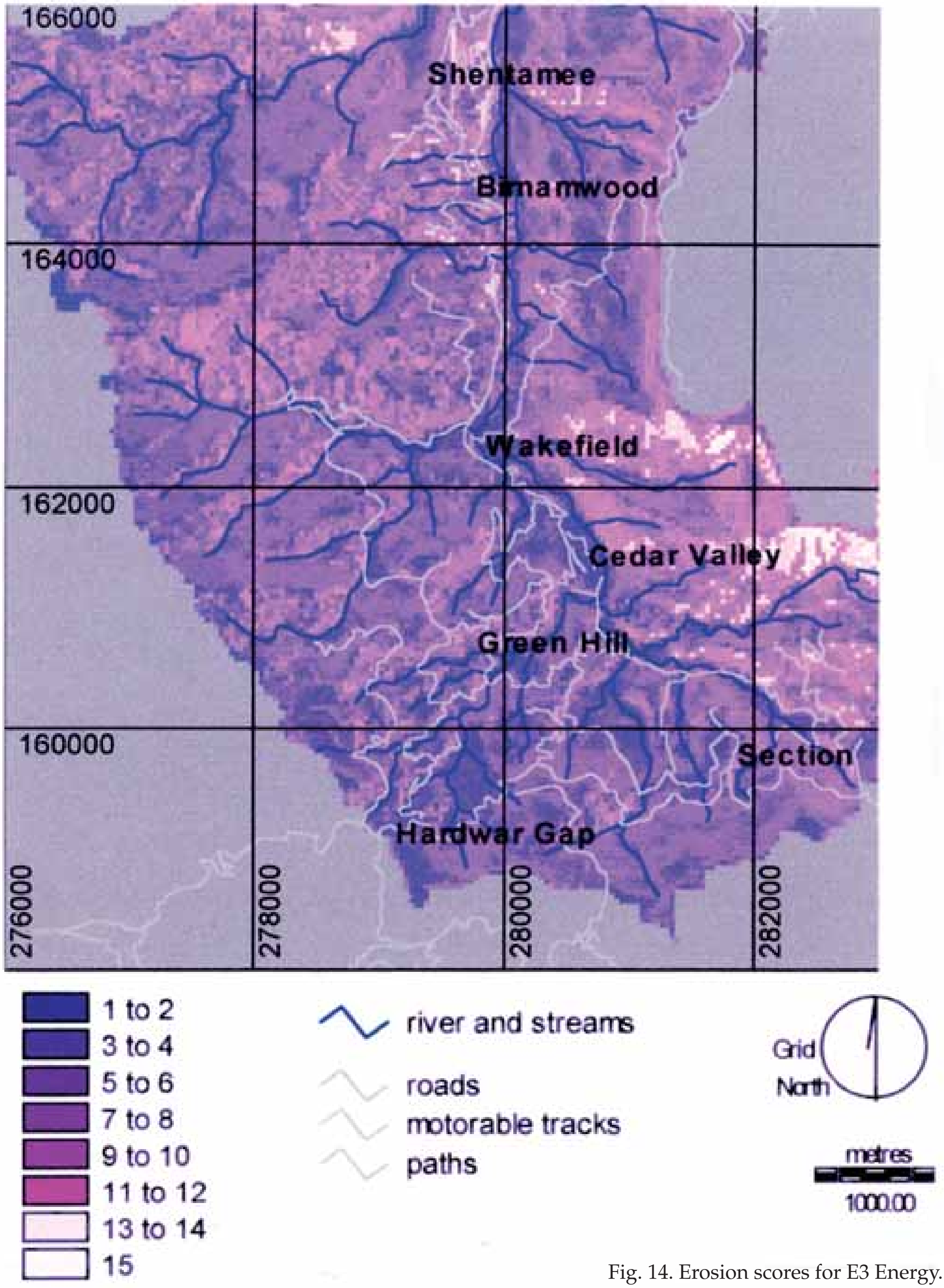

Fig. 14. Erosion scores for E3 Energy.

photos was only 3 % of the research area, the influence on the erosion statistics was considerable, with 26 % of extreme erosion accounted for by the bare areas. However, this figure must be treated carefully since bare ground is a very temporary feature of humid tropical environments except where landslide scars remain active.

Two other factors need a more detailed analysis of the nature of their representation in the extreme erosion area. Firstly, the Very Wet 1 zone accounted for 27 % of the research area, but 68 % of the extreme erosion area. The Very Wet 3 zone accounted for 4 % of the research area, 1 % less than the Very Wet 2 zone, and 21 % of the extreme area, in which the Very Wet 2 zone does not feature. The Very Wet 2 zone was restricted to the northeastern edge of the watershed where aspects were typically to the north and northwest, slopes were gentler (just off the top of Bangor Ridge), and there was grassland and low open canopy, although it was an area of coffee plantation on Hall's Delight soils. On the other hand, the Very Wet 1 zone ran the length of the research area through areas with easterly aspect, steep slopes and patches of high closed canopy, although some of it was ruinate.

Secondly, although 84 % of extreme erosion potential was found in coffee plantation areas, as defined by CIDA & Forestry and Soil Conservation Department (1993), the other 16 % was accounted for by ruinate, which had an erosion classification of 2. Two areas of high ruinate were responsible for this, the centres of which are found at grid references 13/817624 and 13/824616, between Cedar Valley and Silver Hill Peak. These areas that accounted for 16 % of extreme erosion were both within Very Wet 3 zone on steep slopes (average 40°) with a southerly aspect. In fact, 40 m to the southwest, the DEM calculated slope angles of 53°, which did not appear as a potentially extreme erosion area due to a change in aspect and canopy height (high to low closed canopy). In the extreme erosion patches, the climate, aspect, slope angle and soils scored the maximum, whilst vegetation and land use had moderate scores. The total score for the pixels in the southernmost of the two high ruinate areas was 25, which is the lowest boundary of the extreme class. In the northernmost of the two high ruinate areas, the vegetation was high closed canopy and the score 26.

Using the SLEMSA analysis

In an adaptation of SLEMSA for presenting an Erosion Hazard Assessment, Ndyetabula & Stocking (1991) developed a system for identifying the most influential (dominant) erosion factors within the Erosion Hazard Units. The author is unaware of any previous adaptation of this technique to GIS and what may be a first utilization is presented here (Table 63), although it must be understood that dominance in the statistical and not the process sense is presumed.

Using the Idrisi image calculator, the factor scores used to present the erosion potential map were totalled and averaged for each pixel in the watershed image. The image calculator logical function was used to compare each individual factor with the average and a boolean image created for the pixels where the average was exceeded. The scores of the factors that exceeded the average were noted. The boolean image for each factor was multiplied by the erosion potential image so that a histogram could be analysed to show the dominant factor for each erosion category.

The factor that dominated PED class 5 (extreme erosion) was soil erodibility, which, with an area of 66 ha, represented 95 % of the total area under this class. The influence of slope steepness featured second and covered over 80 % of the area under class 5. Land use featured third, but still with a relatively high coverage of just under 80 %. The extreme erosion potential of the area was observed as patches (discussed in 'Patches of

Table 63. SLEMSA style analysis of dominant factors for erosion potential classes (after the methodology devised by Ndyetabula & Stocking, 1991).

PED class	**Area (ha) and% of research area**	**Area (ha) occupied by dominant factors and percentage (in brackets) of the area under respective erosion class**					
		agroclimatic zone	**aspect**	**land use**	**slope**	**soil**	**vegetation**
1	5.76	5.12	4.00	4.00	0.64	4.00	0.00
	0.16	(89)	(69)	(69)	(11)	(69)	(0)
2	470.88	79.01	62.85	152.26	231.74	226.46	126.99
	13.08	(17)	(13)	(32)	(49)	(48)	(27)
3	2069.12	482.36	405.91	854.52	1432.51	1789.80	976.39
	57.48	(23)	(20)	(41)	(69)	(87)	(47)
4	984.64	272.05	312.51	701.46	744.65	948.08	455.01
	27.35	(28)	(32)	(71)	(76)	(96)	(46)
5	67.68	18.71	30.87	53.58	56.78	65.73	18.07
	1.92	(27)	(45)	(78)	(82)	(95)	(26)
Total	3598.00	857.24	816.14	1765.81	2466.32	3034.08	1576.45
	100.00	(24)	(23)	(49)	(69)	(84)	(44)

extreme erosion class,' this chapter, p. 144, below) in which coffee was cultivated on slopes up to 60° on soils of the Hall's Delight series.

The analysis of PED class 4 (high erosion) was similar to that of class 5. Again, the dominant factor was soil erodibility, representing 96 % of the area with 948 ha. The second and third most dominant factors were slope and land use, respectively, both representing over 70 % of the class area. Almost 50 % of the class area was represented by vegetation. Class 4 was most obvious on the eastern side of the watershed, where the Hall's Delight soil series dominated and the agroclimatic zones became increasingly wetter. Two other areas were located west of the Buff Bay River, one on the southeasterly facing closed canopy covered slope of the White River tributary, on the Valda soil series; the other on the east-facing steeper slopes of the headwaters, where coffee plantations dominated.

Class 3, moderate erosion potential, was the largest area of all the classes. Soil erodibility still dominated, representing 1790 ha (87 % of the total area under this class). Slope (69) and vegetation (47) were the second and third most dominant factors, respectively, but land use was still significant at 41 % of the class area.

The area represented by class 2 (low erosion) was 470 ha and dominated by slope, although there was only a one percent difference with soil erodibility. These two factors accounted equally for the low erosion potential. Patches of this class were found along the western watershed boundary. There were more significant patches at Warminster and the northeast facing slopes south of Birnamwood. Here there was undisturbed ruinate (including grass and low open canopies) on the Cuffy Gully soil series in a relatively dry part of the watershed. Around the Middleton Mountain and Waterfall trails down to Cedar Valley, the dominant factors determining the pattern were the presence of the Cuffy Gully soil series and some shallow slopes, since the whole surrounding area was low canopy ruinate.

Class 1 pixels were not contiguous, with no patches larger than 3 pixels. Although the dominant factor was agroclimatic zone, aspect, land use and soil were all significant. One very small area on the Shentamee River, part of the flat river valley bottom facing north, had low open ruinate vegetation on Cuffy Gully soil. Other pixels had almost identical factorial environments. Importantly, the very low erosion pixels did not occur near category boundaries. Had this been the case, there would have been the possibility that the absolute boundaries of vegetation, land use and soils were inappropriate, and that fuzzy algorithms should have been employed. Since this phenomenon was not evident, the conclusion must be that very low erosion potential was a rare event.

Patches of extreme erosion class

Approximately 68 hectares of the watershed scored extremely high on the erosion image. There were 423 individual pixel occurrences throughout the image, but six patches of more or less contiguous pixels were identified, totalling 325 pixels (77 % of the total of extremely high scores). Table 64 gives the areal statistics. All the patches occurred on the eastern side of the watershed, except White River. The image E2 Erodibility (soils and land use) determined the extent of the highest scores into the western side of the watershed. The highest scores were also only found on Hall's Delight channery clay loam. A qualitative description of the patches follows.

Table 64. Statistics for the patches of extreme erosion.

Patches	Pixels	Percentage	Hectares
White River	29	7	4.64
Mt Holstein	35	8	5.6
Spring Hill	32	8	5.12
Wakefield	111	26	17.76
Cedar Valley	39	9	6.24
Silver Hill Gap	79	19	12.64
Total patches	325	77	52
Remaining pixels	98	23	15.68
Total extreme erosion	423		67.68

White River (grid ref: 13/795626) – This five hectare patch was located on the south-facing hillslope of the White River, at the foot of which runs the road leading to the Middleton Trail. This was an area of Hall's Delight channery clay loam, with bare, but regenerating, vegetation, slopes steeper than 30° and eastsoutheast aspect. This was actually two patches, one on the southern flank of the spur that has the White River at its base, the other on another spur 0.5 km further north. The coffee plantation was the dominant land use, although the agroclimatic zone was Wet 2, with one to two dry months a year.

Interestingly, there is both a road and major tributary (White River) running along the bottom of the hill. Including accelerated erosion in the image would have masked the occurrence of potentially high erosion on the slope, hence the use of the factors in post-model analysis, but it does present the phenomenon of transporting sediment downstream from the base of the highly eroded slope.

Mount Holstein (grid ref: 13/802653 to 13/810650) – There were six small patches (totalling 5.5 ha) within a restricted area, all with bare or regenerating ground on Hall's Delight channery clay loam. Slopes were steeper than 25° and aspects ranged from west-facing through south- to east-facing. This area, on the eastern side of the Buff Bay River, was one of wetter agroclimatic zones (Very Wet 1 and 2). One of the small patches was on a northnortheast facing slope of 20 to 25°, but the combination of Hall's Delight channery clay loam, a Very Wet 2 zone and bare ground in preparation for coffee planting placed it in the extremely erodible class.

Spring Hill (grid ref: 13/802636 to 13/805633) – This patch was located very close to the Buff Bay River at the base of a south-facing slope where the Bangor Ridge track draws parallel to the river as it approaches Wakefield. There were some gullies and bare soils in the area, where a small high canopy wood had been cleared. This wood reached down to the Buff Bay River and seemed to determine the pattern of highest erosion potential.

Wakefield (grid ref: 13/808626 to 13/812621; 13/816623) – This was the most notable cluster of patches, measuring nearly 18 ha in total, and including a patch of 52 contiguous pixels. This was the wettest of all the areas which, combined with a southwest aspect, produced the best opportunity for overland flow. This was also an area of very steep slopes (>50°) just below the watershed boundary, providing the necessary energy to entrain the erodible Hall's Delight soils. The eastern boundary of the patch was restricted by high ruinate vegetation, a high closed canopy with an undisturbed soil and unknown litter layer.

Cedar Valley (grid ref: 13/820614 to 13/826616) – There was no general assumption of extreme potential erosion occurring on very steep slopes, since the highest category was for all slopes steeper than 30°. Cedar Valley village is confined to the western side of the Buff Bay River on a very shallow spur between two major tributaries. On the eastern side, the valley side rises up very steeply (averaging 50°), yet this area only registered high potential erosion, not extreme. The soil near the river was the Agulta sandy loam and an area of moderate erosivity. Erodibility increased away from the river, but not to the degree of extreme.

The patch of extreme potential erosion was relatively small (6 ha) compared to Wakefield, but in a very similar climatic and topographical environment. Erosivity and Energy scores were at the maximum and covered an area of 13 ha, but the vegetation of the area was high open canopy and ruinate land use, which reduced the area of extreme potential erosion.

Silver Hill Gap (grid ref: 13/819605 to 13/821605; 13/827600 to 13/829606) – There were two significant patches within 0.5 km of each other, on the southwest facing slope above the Wallengford trail. Together they formed the second largest patch of extreme potential erosion. The climate was marginally drier in the Very Wet 1 zone, although the score was high at 8 (out of 10). The erodibility was at a maximum with coffee plantation on Hall's Delight soils, and there was evidence from air photos that considerable patches of bare soil existed (perhaps even landslide scars). Bare soil and high closed canopy vegetation determined the pattern of the patches.

Alternative scenarios

The model is user-friendly and sufficiently flexible to allow new factors to be incorporated. It is possible that the factor parameters will need to be modified in applying

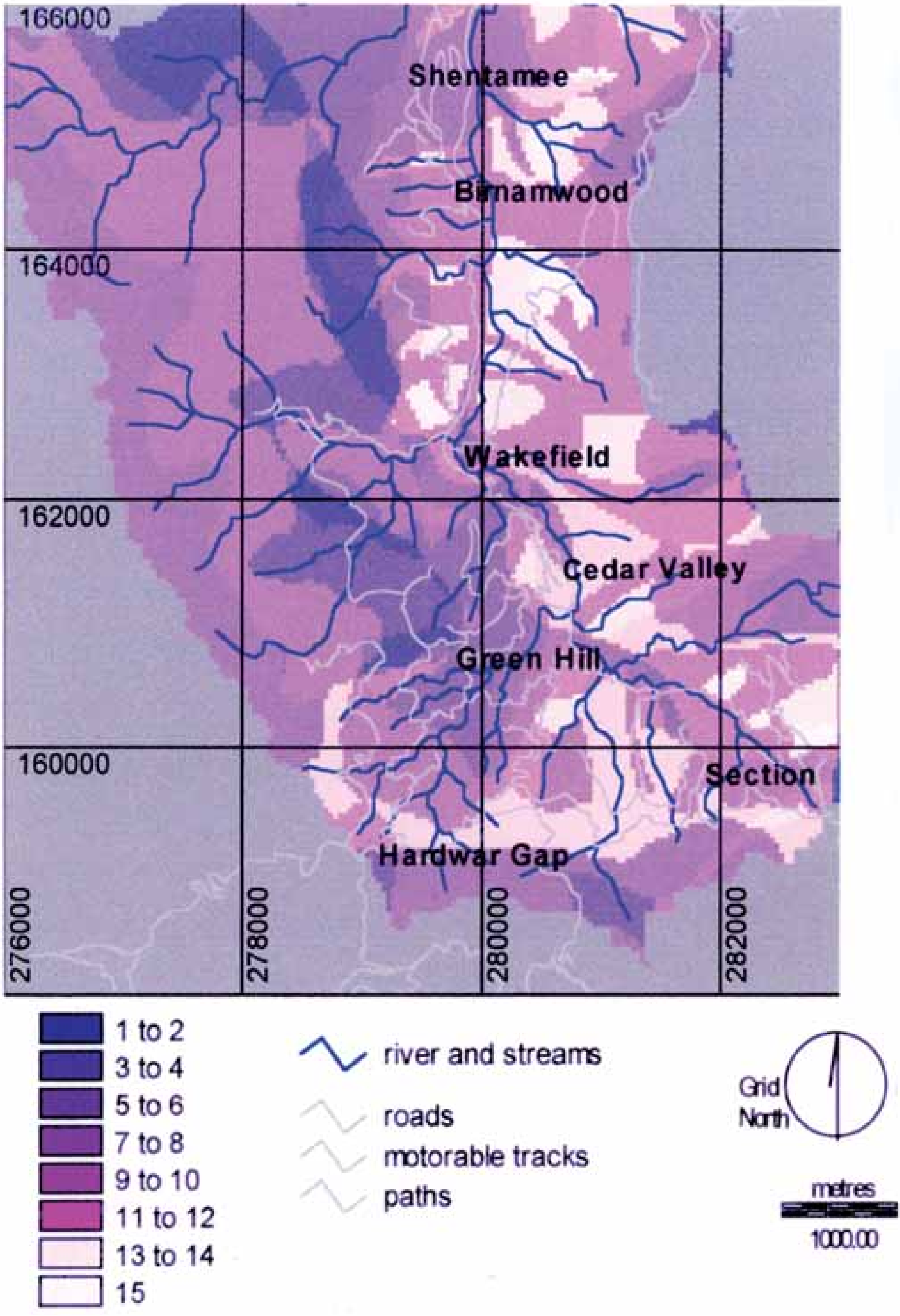

Fig. 15. Erosion scores for E4 Earth.

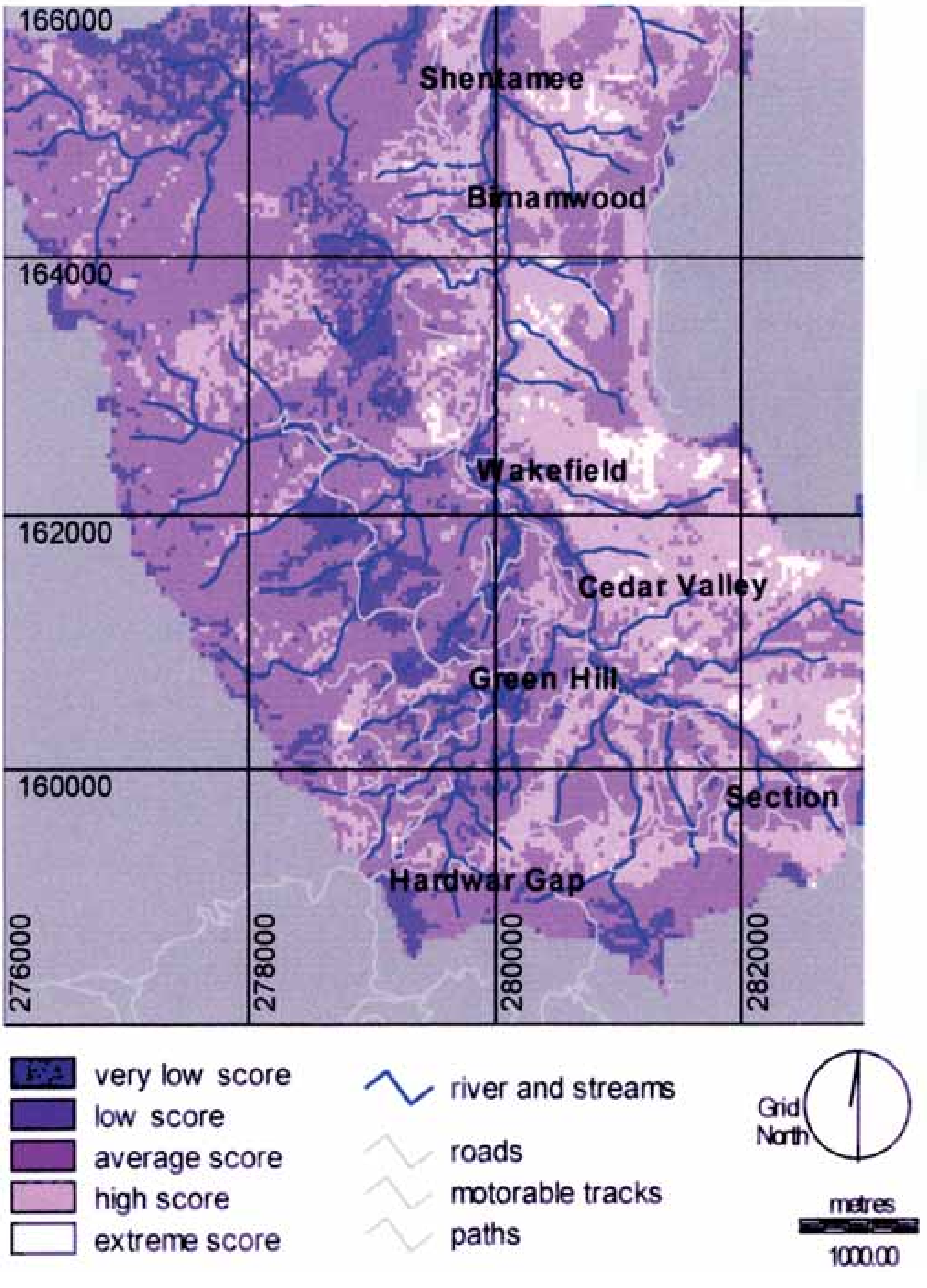

Fig. 16. Erosion classes for E5 Erosion (reclassified into 5 classes from the E5 erosion scores).

the model to other watersheds. For example, the plant associations or plantation species in another watershed may require the recoding of the vegetation cover factor taking vegetative litter into account. The model in the present form represents the best factor parameterisation for the Buff Bay watershed. However, the utility of the alternative scenarios allows agency officers to speculate how the model would work in their area and the influence of modifications on the output.

The first alternative considered a soils classification based on the frequency of erodible indicators (Table 65), since qualitative data may be the only available information in a research area (see Chapters 6-8). This highlights the problems of only having qualitative data and the difference in results when better data (as used in the PED model) are available. This ranking differed from the PED model in placing the Cuffy Gully series highest on the erodibility scale instead of Hall's Delight. This altered the pattern of erodibility in the watershed, with the most susceptible soils west of the Buff Bay River (Fig. 17).

Table 65. Qualitative indicators of soil erodibility used as an alternative ranking system for soils.

Soils series	**23**	**38**	**46**	**301**	**52**	**305/306**
No. qualitative indicators	0	3	2	2	1	1
Ranking	1	5	4	4	3	3
PED model rank	2	2	5	4	4	4

The second alternative was based on the calculation of the USLE K-factor. During contact with the Natural Resource Conservation Authority in Jamaica, it became clear that the USLE was regarded as the only reliable measure of erosion rates, despite evidence to the contrary (McGregor, 1995). Soil erodibility (K) is estimated from nomographs in which silt, sand, organic matter, soil structure and permeability are provided by the user. The sand-silt-clay and organic matter data for one sample taken from each soil series were analysed (Table 66).

Table 66. USLE nomograph (Wischmeier *et al.*, 1971) and equation (Loch & Pocknee, 1995) used as an alternative ranking system for soils. Key: ** = organic matter (OM) read from the 4% OM maximum.

	23	**38**	**46**	**301**	**52**	**305/306**
Sand	62	48	44	43	44	52
Silt	18	28	36	34	35	31
Clay	20	24	20	23	21	17
Organic matter	3.4	1.3	12.4	8.1	0.4	4.3
Structure	coarse medium	medium fine	medium fine	medium fine	coarse medium	medium
Permeability	rapid	rapid	rapid	moderate	rapid	rapid
USLE K (chart) (equation)	0.05 (0.06)	0.13 (0.13)	0.10** (0.13)	0.08** (0.12)	0.21 (0.18)	0.09 (0.10)
Ranking	1	4	3	2	5	2

There were some problems calculating this factor. The values shown in the table were taken from the nomograph (Wischmeier *et al.*, 1971). Loch & Pocknee (1995) gave an equation for calculating K, but it produced very low values (<0.01). When

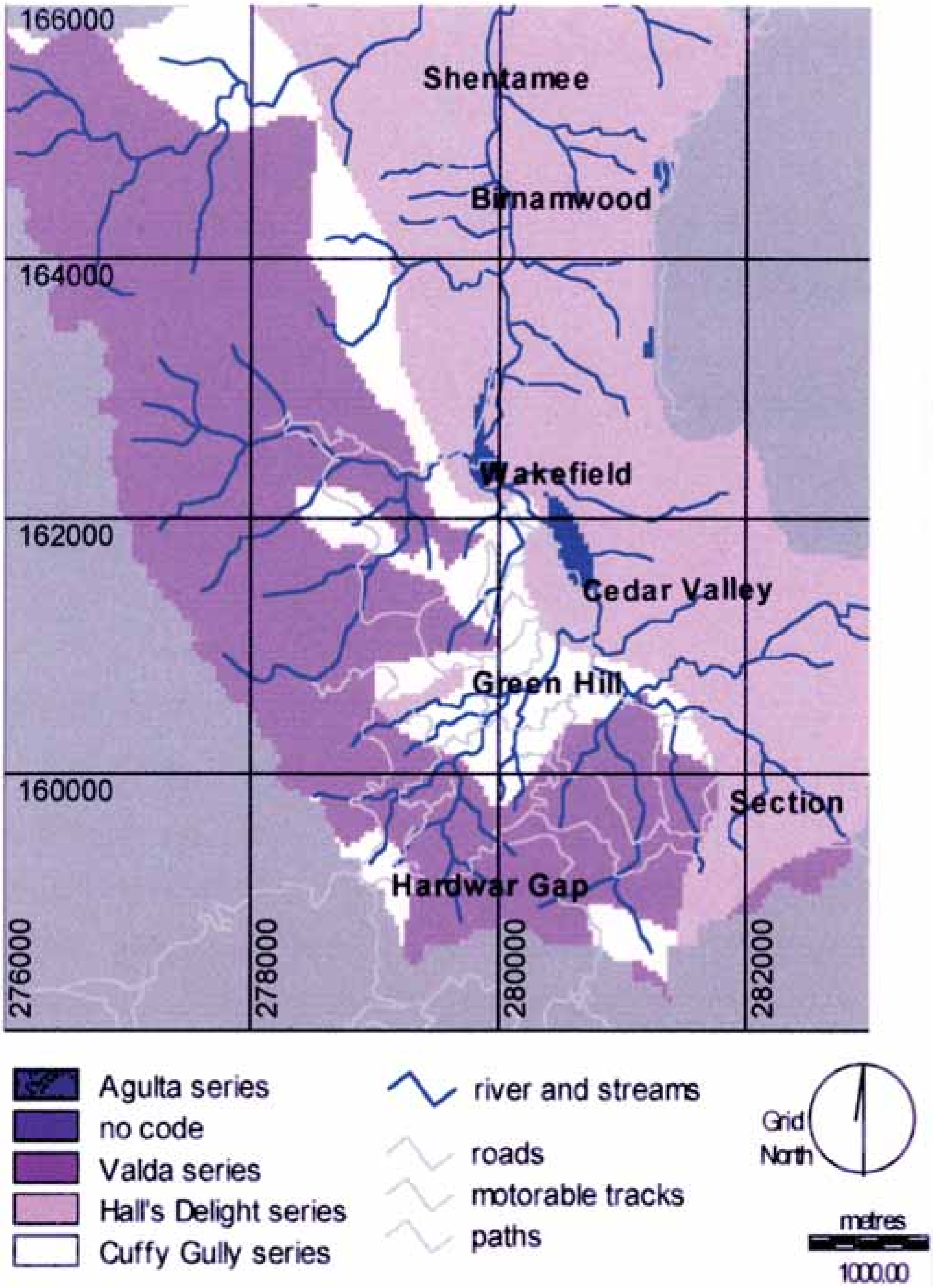

Fig. 17. An alternative qualitative soil parameter scoring system (after CIDA & Forestry and Soil Conservation Department, 1993).

this author rewrote the equation in which the silt factor, M, was calculated using 10^{-4} instead of 10^{-7}, the equation was:

$$K=2.77\ M^{1.14} \times 10^{-4} \times (12\text{-}OM) + 4.28\ (10^{-3}) \times (SS\text{-}2) + 3.29\ (10^{-3}) \times (PP\text{-}3)$$

where M is silt, OM is organic matter, SS is structure and PP is permeability. The values were the same magnitude as those from the nomograph (for full table of calculation, see MacGillivray, 2002b, appendix 5). However, as Table 66 shows, there was up to 0.04 of a difference, which did not alter the relative ranking, but did not accurately reflect the values estimated from the nomograph. The results suggested that the soils were not particularly erodible, but the relative nature of the model showed a pattern of erodibility in which the most susceptible soils were to the west of the Buff Bay River, and on the southern and western watershed boundaries (Fig. 18).

The third alternative scenario highlighted the soil protection offered by vegetative cover when the canopy produces a significant litter, not a situation that occurs in the Buff Bay watershed. The PED coding presumed that a closed canopy would reduce sunlight and hence understorey. Plantations are of *Pinus caribaea,* an evergreen. Litter was also known not to collect on steep slopes (Chatterjea, 1989). The alternative coding showed the results of allowing for a significant litter layer generated by a closed deciduous canopy that gave some soil protection (Richardson, 1982; McDonald *et al.*, 1996; Thomas, 1994). The ranks of the closed canopy categories were reduced by one (Table 67). This resulted in an image in which the previously high scoring western and southern watershed areas became less significant for erosion (Fig. 19). The area of the research area in each of the relative erosion classes, for both the PED and the alternative scenarios, is given in Table 68.

Table 67. Alternative ranking of vegetation cover taking account of litter as a protective layer.

Rank	**Structure**	**Example of Buff Bay River vegetation**
1	Low, open and closed	Coffee, grassland, wild ginger, low ruinate, litter protecting soil
3	High, open and closed	Forest, high ruinate, litter layer introduced
5	Bare regenerating ground	Tilled, recent landslide, recent crop growth or thin grass

Table 68. Model results for alternative soil and vegetation scenarios (in ha).

Erosion scores	**1-9**	**10-14**	**15-19**	**20-24**	**25-30**
W5E5 original	0	13.09	57.51	27.37	1.88
W5E5 CIDA	0.05	12.56	65.07	21.54	0.77
W5E5 USLE	0.15	18.53	64.59	16.42	0.31
W5E5 veglitter	0.16	16.31	59.04	23.38	1.11

Both the alternative soil rankings of CIDA and USLE placed less land in the high and extreme erosion classes, compared with the PED model run. The explanation for this lies partly with the proportion of land that was coded with the most erodible soil. In the original model, the Hall's Delight soil was most erodible and accounted for 40 % of the research area. The CIDA based soil ranking gave Cuffy Gully soils the highest score, accounting for 15 % of the research area, whilst the USLE ranking placed the

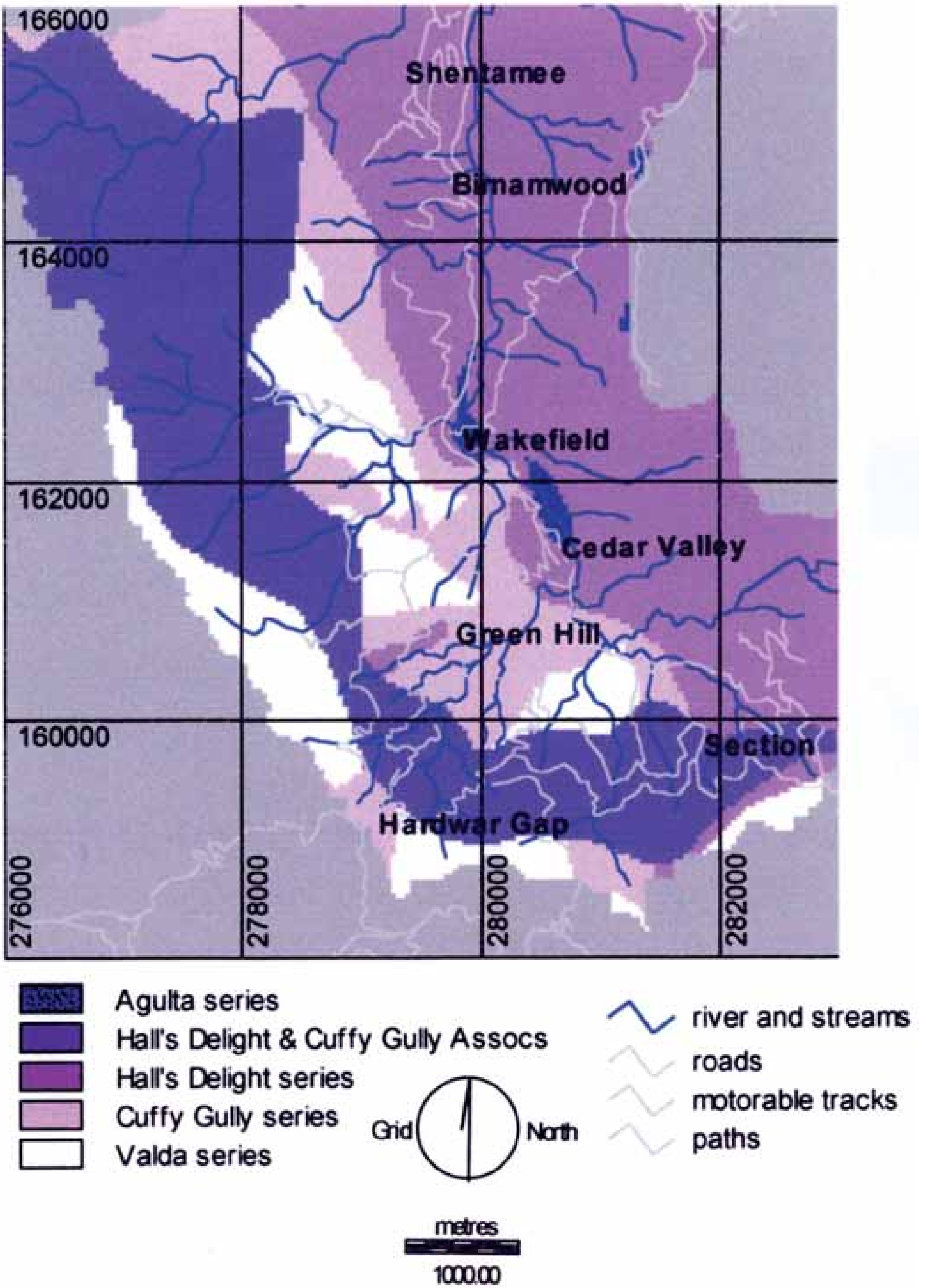

Fig. 18. Alternative soil scoring system using USLE parameters (after Loch & Pocknee, 1995).

Valda soils top of erodibility, just 14 % of the research area. The Valda soils were also restricted to the west of the Buff Bay River and southern watershed boundary, where it was drier and the land use was forest and ruinate.

The impact of the alternative vegetative cover ranking on the original model results was minimal. There was a slight reduction in the area of the watershed in the high and extreme potential erosion classes. The reduction of one rank class for high closed canopies affected the western and southernmost parts of the watershed, and individual valleys in the eastern part. As a more detailed analysis of the extreme potential erosion patches shows, it was the eastern part that was most generally susceptible to erosion (Fig. 16).

The alternative CIDA soils analysis (Fig. 20) showed a 50 % reduction in the total contiguous patches (Table 69). The White River, Mount Holstein, Wakefield and Silver Hill Gap patches were all reduced by half, whilst Spring Hill and Cedar Valley virtually disappeared as contiguous patches. A new patch of 2 ha was created at Green Hills which, although outside the wettest agroclimatic zones, was an area of bare soil on the most erodible Cuffy Gully soil series (CIDA & Forestry and Soil Conservation Department, 1993).

Table 69. Extent of the extreme erosion patches under the alternative scenarios.

Patches (ha)	Alternative soils (CIDA)	Alternative soils (USLE)	Alternative vegetation	Original
White River	2.88	1.12	4.64	4.64
Mt Holstein	2.56	0.32	4.64	5.60
Spring Hill	0.96	0.32	1.76	5.12
Wakefield	7.84	3.84	8.00	17.76
Cedar Valley	1.28	0	5.44	6.24
Silver Hill Gap	5.92	1.76	8.32	12.62
Green Hill	2.24	2.72	0	0
Hollywell Park	0.32	0.80	0	0.64
Total patches	24.00	10.88	32.80	52.64
Discrete pixels	3.84	0.32	7.20	15.04
Total extreme erosion	27.84	11.20	40.00	67.68

The USLE soils analysis not only significantly reduced most of the patches in extent, it led to the complete disappearance of the Cedar Valley patch (Fig. 21). A patch was again created at Green Hill, a little larger than under the CIDA analysis, but the extreme erosion class was reduced to just over 11 ha.

The resulting image for the alternative vegetation scenario (Fig. 22) gave a reduction in the extreme erosion class area from 68 to 40 ha. Although large swathes of the western and southern watershed boundary were reduced by one rank level, these were not previously areas of extreme erosion potential. The alternative coding reduced significant areas to the moderate erosion category. Unlike the alternative soils scenario, there was no major change in the ranking, only a small reduction for three categories. All but one of the patches were reduced and no new patches were created. The patches that were least affected were in areas of bare or regenerating ground. At Silver Hill Gap, three smaller patches were reduced to two with the reduced coding of some high closed canopy forest. At Wakefield, the patch that coincided with low closed canopy disappeared

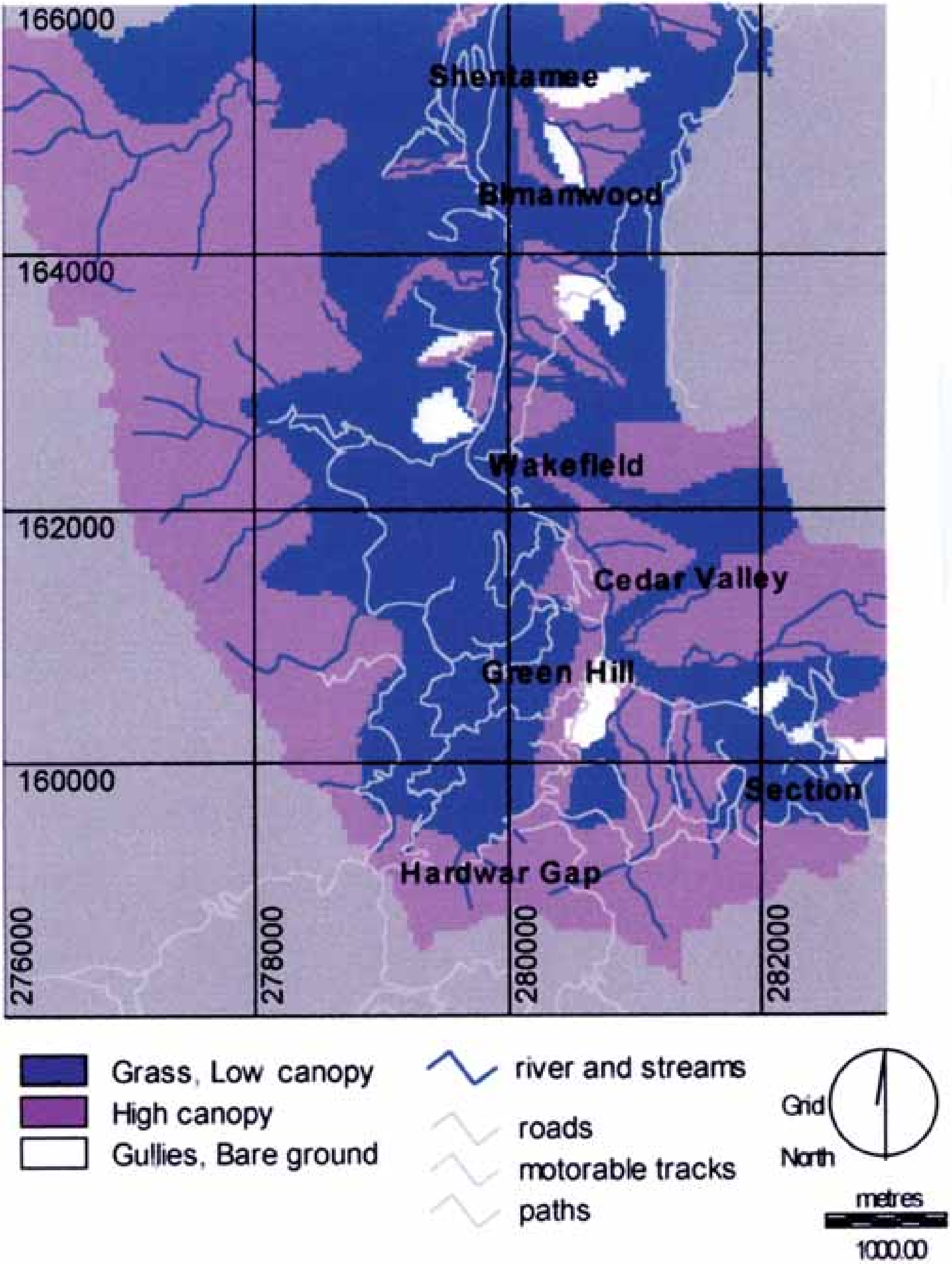

Fig. 19. Alternative scoring system for vegetation taking litter on the soil surface into account.

from the extreme into the high potential erosion category. The patch containing high closed canopy reduced in area a little. However, at Spring Hill, the reduction of the rank of high closed canopy caused the extreme potential erosion to practically disappear.

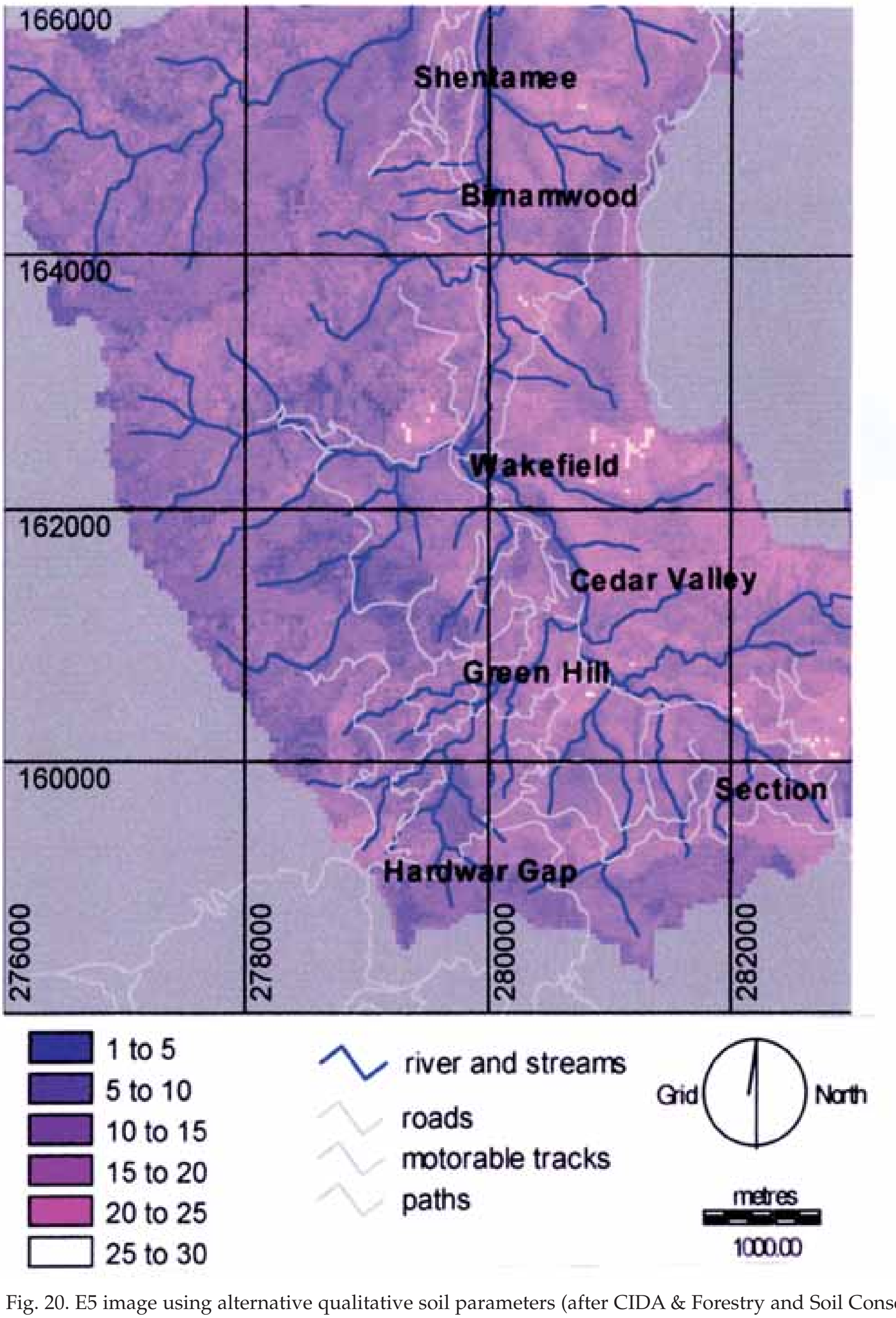

Fig. 20. E5 image using alternative qualitative soil parameters (after CIDA & Forestry and Soil Conservation Department, 1993).

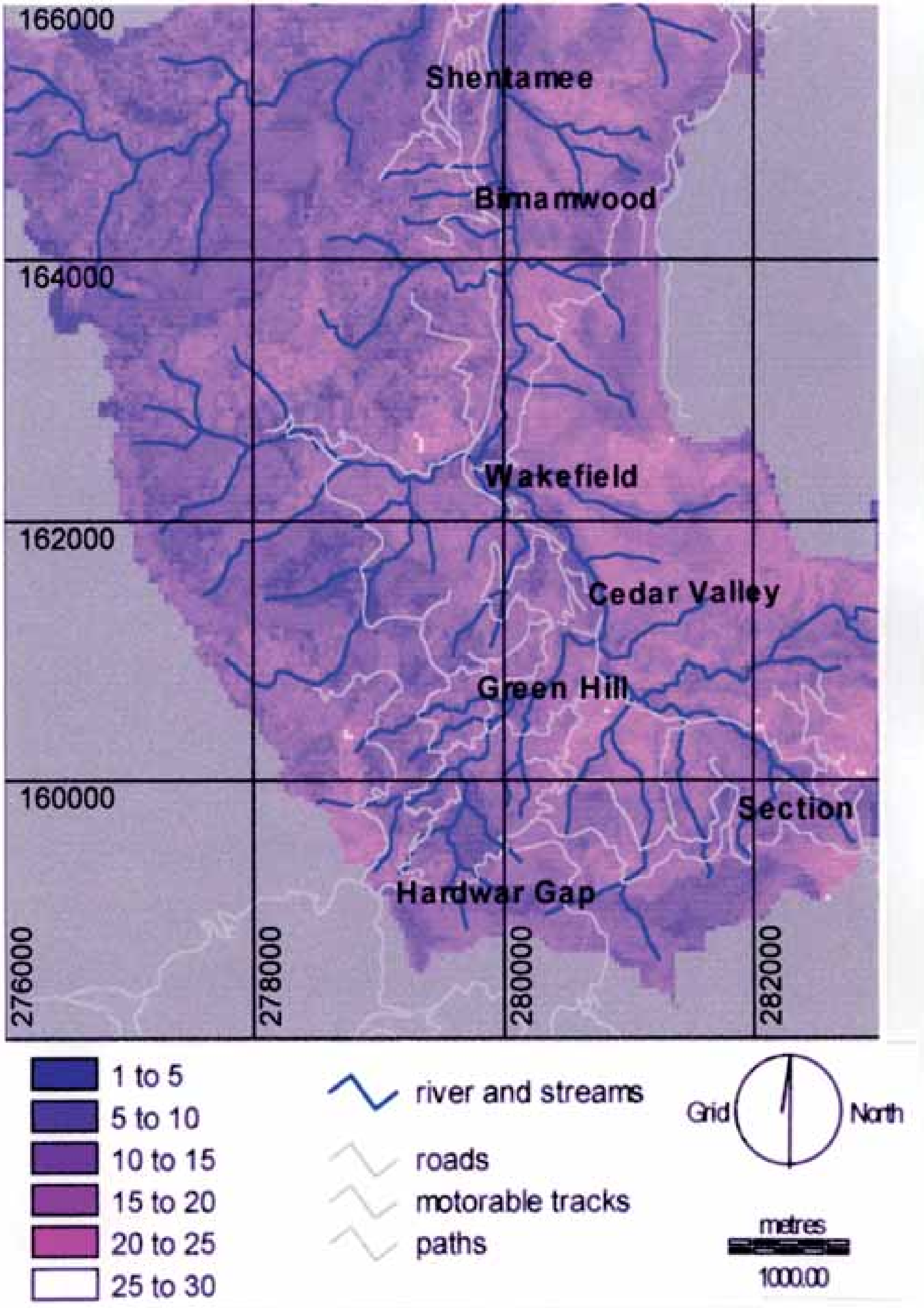

Fig. 21. E5 image using alternative USLE soil parameters (after Loch & Pocknee, 1995).

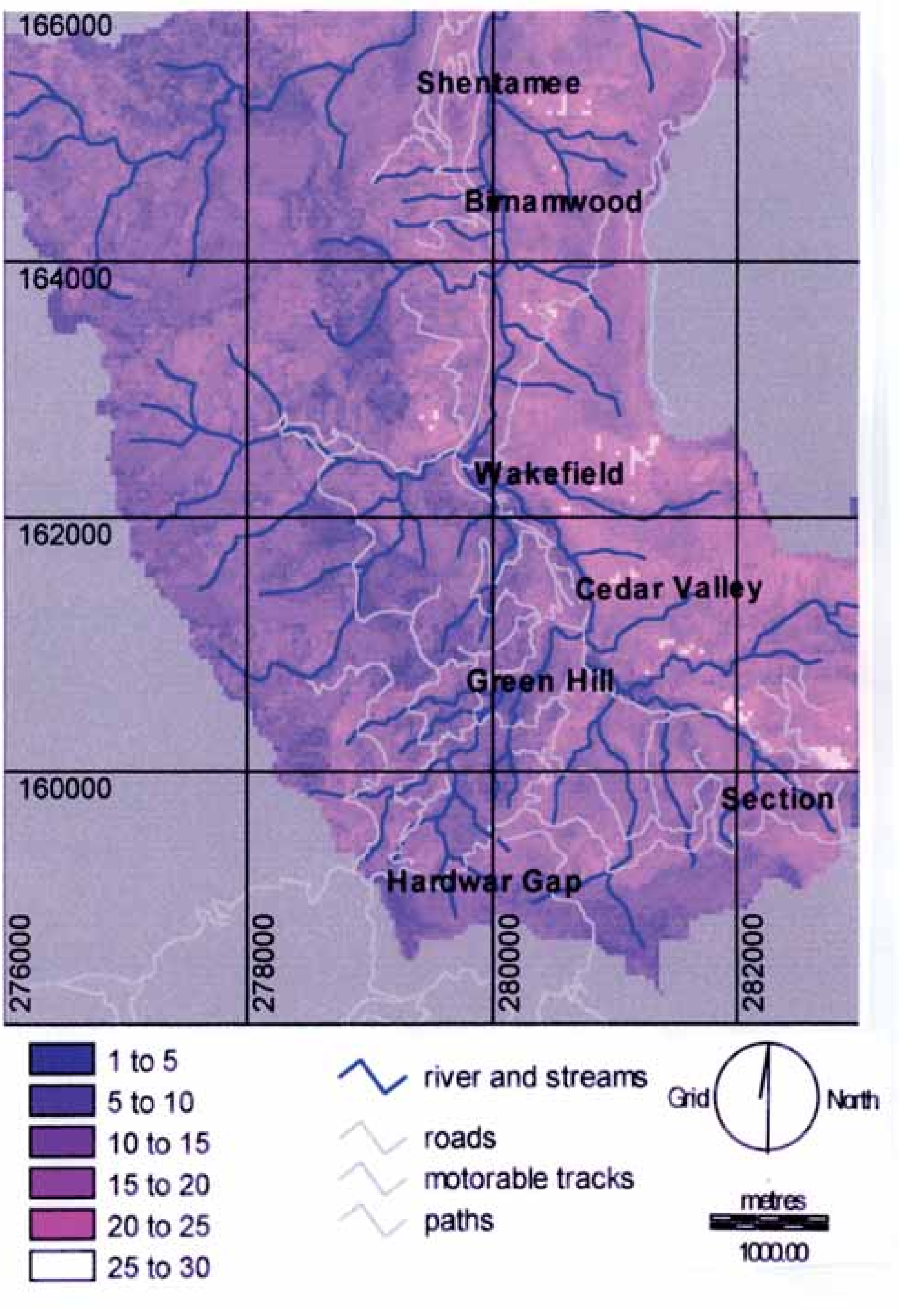

Fig. 22. E5 image using alternative vegetation parameters taking litter into account.

This analysis is useful for assessing the flexibility of the model and the effect of reranking the factors. Since the category boundaries, both for factorial layers and potential erosion maps, are arbitrary, it is important to talk of reduced potential erosion in relative terms, rather than presuming that some areas are no longer at risk from erosion.

Post-model analysis – water and track buffers

Localised erosion would be expected at the toes of cut slopes, and at river banks and heads. These have been seen in the field to regenerate ground cover very quickly (due to increased light levels at the roadside) and commonly be stabilised using walls (especially where riverbanks have been reinforced to protect the roads). Both Larsen & Parks (1997) and Ahmad & McCalpin (1999) defined buffer widths for increased erosion and landslide frequency either side of roads (60 m) and fault zones (90 m), respectively. Since the model is ostensibly about hillslope erosion, rather than removal of sediment from the watershed, the definition of linearity buffers is a possibility, but of limited use to an extension agency.

Runoff generator – During the cartographic modelling, the factor slope length was investigated for inclusion (discussed in Chapters 6-8), but could not be incorporated and would have been of limited use in such a complex terrain. The RUNOFF module produced a surrogate river network, once the PIT REMOVAL module had been run. It produced the anomaly of parallel channels at its exit from the upper watershed. Tributaries should have joined the main river, but flowed parallel to it for a distance, as if ridges had been established between the tributary and the main river, when there was no elevation data to support it. Although unreliable in one or two places, the resulting network was overlain with the intermediate (E3, E4) and final erosion potential (E5) images (Figs. 23-25). The RUNOFF module highlighted the pattern of erosion and how the surrogate water channels could remove sediment from the upper watershed. It gave an indication of where sediment delivery ratios for subcatchments would be expected to be highest, which could prove a useful tools for verification.

Toposhape results – The Idrisi module TOPOSHAPE identifies twelve topographic entities and classifies the DEM accordingly. It does occasionally produce inaccuracies, with one or two streams digitised from the 1:50,000 map apparently adjacent or running through a ridge. This was partly an issue of resolution (although a 10 m resolution did not entirely solve the problem), partly a problem associated with digitising the water channels and perhaps even an original problem of contour accuracy in areas of high vegetation. However, in general, the entities identified were in the appropriate place. The DEM was passed through a 7×7 fil-

Table 70. Total area and higher erosion class statistics for TOPOSHAPE elements.

Toposhape	**% of total area**	**% high and extreme erosion class**
Ridge	14	20
Ravine	21	16
Convex slope	14	14
Saddle slope	34	35
Concave slope	16	15
Inflection	1	1

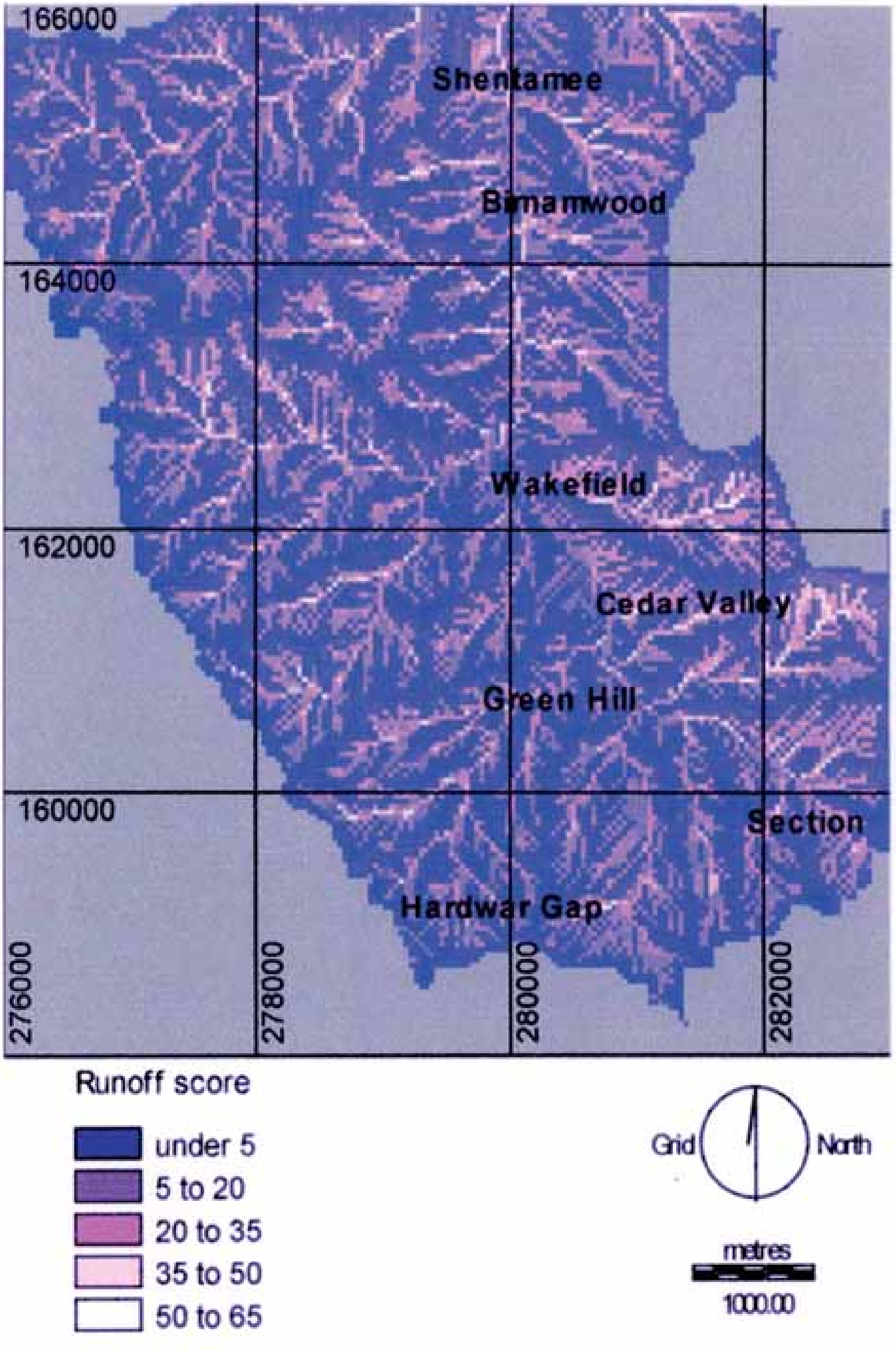

Fig. 23. Overlay of E3 and RUNOFF to show sediment generating areas.

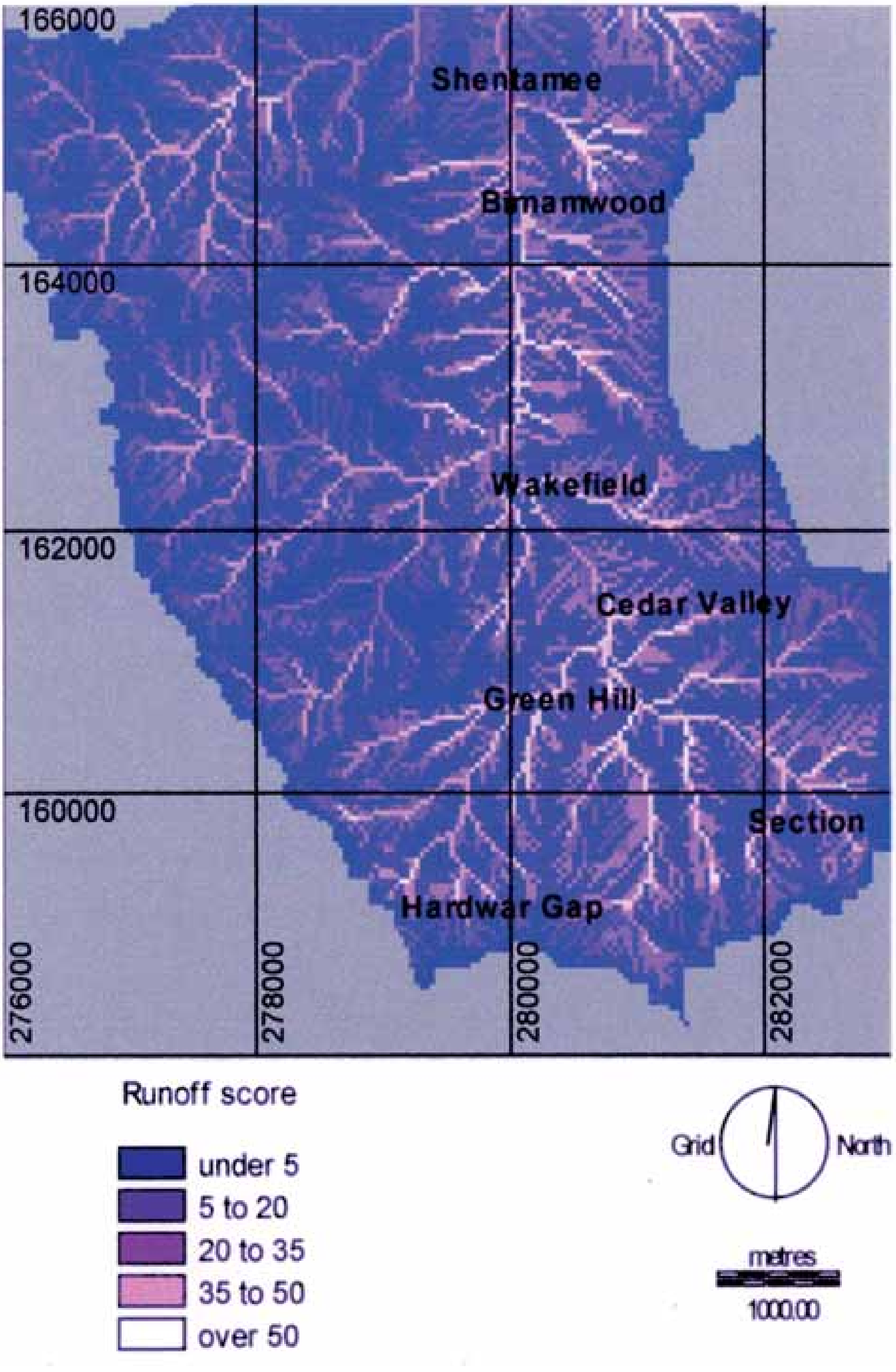

Fig. 24. Overlay of E4 and RUNOFF to show sediment generating areas.

ter to remove pits. For reasons of clarity, the most dominant entities (greater than 1 % of area) that were identified in the watershed were described in terms of their areal extent and erosion class statistics (Table 70).

The definition for saddle slopes varies according to author. The definition that belongs to the TOPOSHAPE was no longer traceable, but a comparison of saddle slope location (Fig. 26) with the topographic map showed it to be the same as a very broad spur or interfluve, projecting downwards from mountain crests separating two rivers flowing into the same watershed (Whittow, 1984). A saddle point is the intersection of ridge and valley. A saddle hillside has a positive curvature in one direction and a negative curvature in the other, orthogonal direction (Herrington & Pellegrini, 2000), in other words, a low ridge joining two peaks (P. Collier, pers. comm.), which is also termed a gap in the Caribbean. Saddle slopes made up over a third of the watershed area. The interfluves were not continuous from the crest to the point where the tributaries met and were not easy to identify as such. Of the total area of the top two erosion classes, 35 % occurred on saddle slopes, but this was more a function of their ubiquitous nature than a particular factor of the slopes.

A ravine is a deep, narrow river valley, bigger than a gully. In the Buff Bay watershed, many ravines are ephemeral and, except for landslide areas, well vegetated. About 20 % of the watershed was identified as ravines, and these were concentrated on the western side of the watershed (Fig. 26), along the Shentamee, White River, and headwaters arising at Hardwar Gap and Woodcutters Gap. Only 16 % of the highest erosion area was calculated as falling within the confines of a ravine. Due to the dense vegetative cover observed in ravines, the potential for erosion is lower than for ridges and saddle slopes (which Horton, 1945, described as areas of zero erosion), and the same as concave and convex slopes. The ravines that occur above 900 m are cloaked in mixed closed canopy (high erodibility), but undisturbed (low erodibility) vegetation. At lower altitudes on the Shentamee and White River, there is a low open canopy (low erodibility), some of which is low ruinate (low erodibility), but much of which is coffee plantation (high erodibility). The ravines of Hardwar Gap are covered in coffee (high erodibility) and the vegetation at Woodcutters Gap varies from undisturbed high closed canopy through coffee plantation to low open canopy.

The ridges of the watershed, described as contiguous lines of cells higher than the cells either side (Herrington & Pellegrini, 2000), are confined to the eastern side of the watershed (Fig. 26), which is also the wettest, hence the higher percentage of the highest erosion class area (20 %) represented here. The difference between ridges and saddle slopes is not obvious from the topographic map, but Idrisi identifies a slightly sharper crest. Ridges are not identified as areas of erosion according to Horton's overland flow model, there being an insufficient volume of water at the top of a slope to entrain particles. Ridges are not so enthusiastically cultivated as saddle slopes because they are steeper, nor are they as densely covered by forest. However, the addition of the mists to the water budget at higher elevations (especially on this wetter east side) may mean that the ridges are better protected by vegetation here than elsewhere. Certainly, the air photos did not reveal much bare soil.

There was a clear pattern to the distribution of convex slopes (in which gradient becomes progressively steeper), which formed interfluves between the headwaters and tributaries (Fig. 26). The concave slopes, on the other hand, were found at the bottom of the hillslopes along the channels (Fig. 27). Each shape accounted for about 15 % of the total area and about the same proportion of the high erosion class area. Both positions on the hillslope are cultivable, although steepening slopes (convex) are more erodible.

There is some evidence in the literature that slope form is influential in erosion. Gachene (1995) found that steep convex slopes over 30° were most susceptible to erosion. Horton (1945) found no evidence of overland flow, and hence erosion, on ridges and the tops of slopes, but his quasi-mathematical model contained assumptions about overland flow initiation that was not supported and did not explain headward erosion (P. Collier, pers. comm.). Dietrich *et al.* (1992) found that convergent elements showed saturation overland flow most commonly and exceeded thresholds predictably when surface resistance changed, that is, vegetative cover. The method divided the landscape into areas prone to channel instability because of runoff (convergent zones) and stable areas (divergent zones). These topographic factors could form part of the model if enough evidence could be found to support inclusion. However, they also form an important part of the post-model analysis.

10. Assessing the reliability of the model

The reliability of the model can be measured in terms of other methodologies and soil loss measured in the area. Firstly, the results were compared with locally determined empirical relationships between erosion and other influential factors. Secondly, the results of the model were analysed with a parametric equation, the Universal Soil Loss Equation (Wischmeier & Smith, 1978). Thirdly, a comparison was made with the map of erosion produced as part of a reforestation project (CIDA & Forestry and Soil Conservation Department, 1993). Finally, erosion stake measurements were compared with model based estimates.

Analogous area index concept

It is possible to validate a model for soil loss predictions using predicted and measured rates of runoff and erosion from other sites with similar environmental conditions. Table 71 is a summary of regional research in which an indication of factorial influence on measured soil loss is suggested.

The interesting points in Table 71 occur where the soil loss results do not confirm the assumptions on which the PED model was based. The first study (Ahmad & Breckner, 1974) suggested that the higher the slope angle, the lower the soil erosion. The authors attributed this to exposure (aspect) in relation to prevailing (rain bearing) winds and effective length of the plot. Not only was one high angle slope in a lee position, but the effective length of the plot on high angle slopes received 1.14 times less vertical rainfall.

The *Pinus* plantation results (Richardson, 1982) suggested that a plantation is more effective in soil protection than a fully developed rainforest. The rainforest had a dense low canopy (1.5 to 5 m) and some trees above this height, with a canopy cover of 90 %, but no herbaceous layer. The plantation, on the other hand, had a dense Guinea Grass layer and considerable pine needle litter, although canopy cover was only 60 %. The

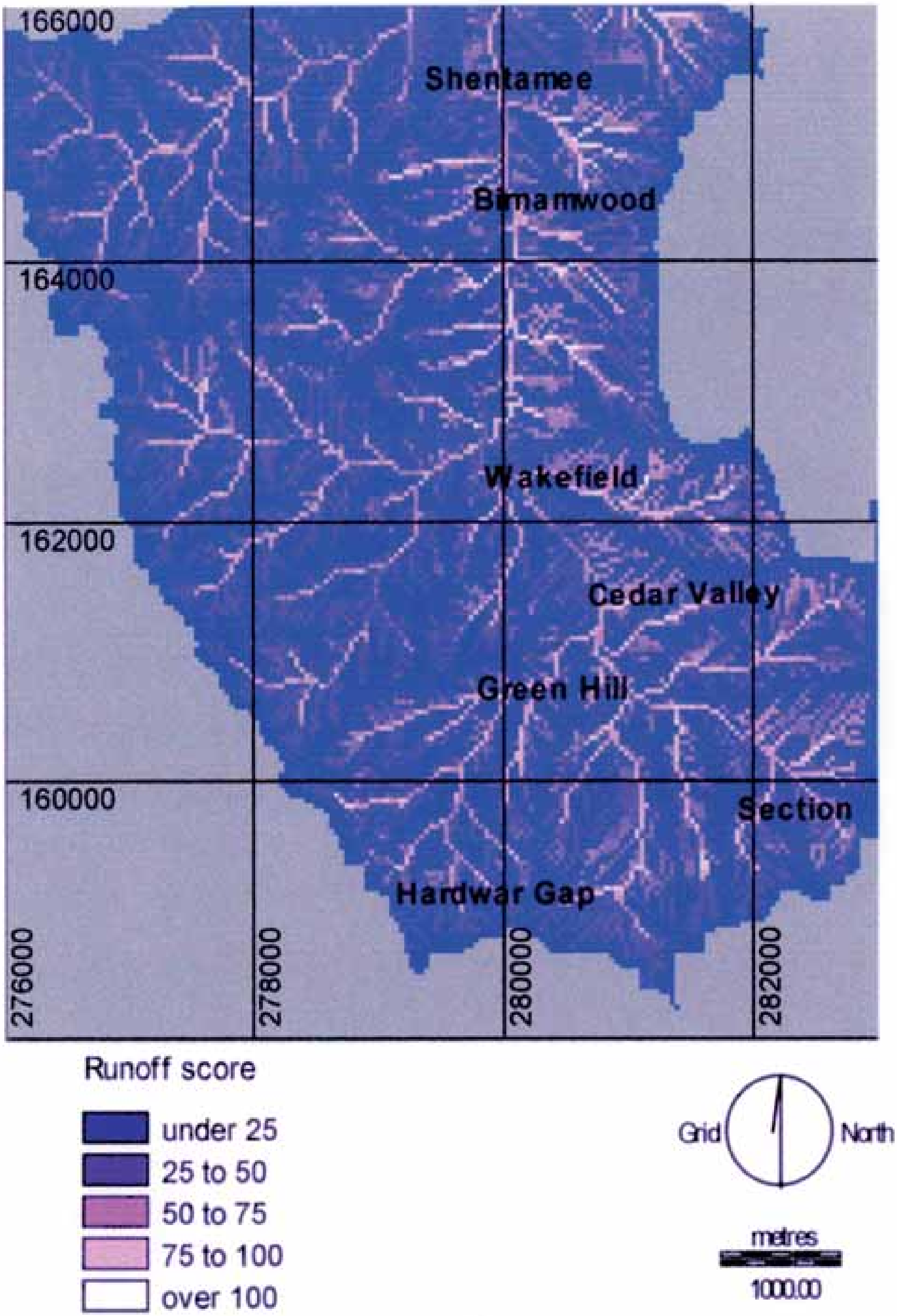

Fig. 25. Overlay of E5 and RUNOFF to show sediment generating areas.

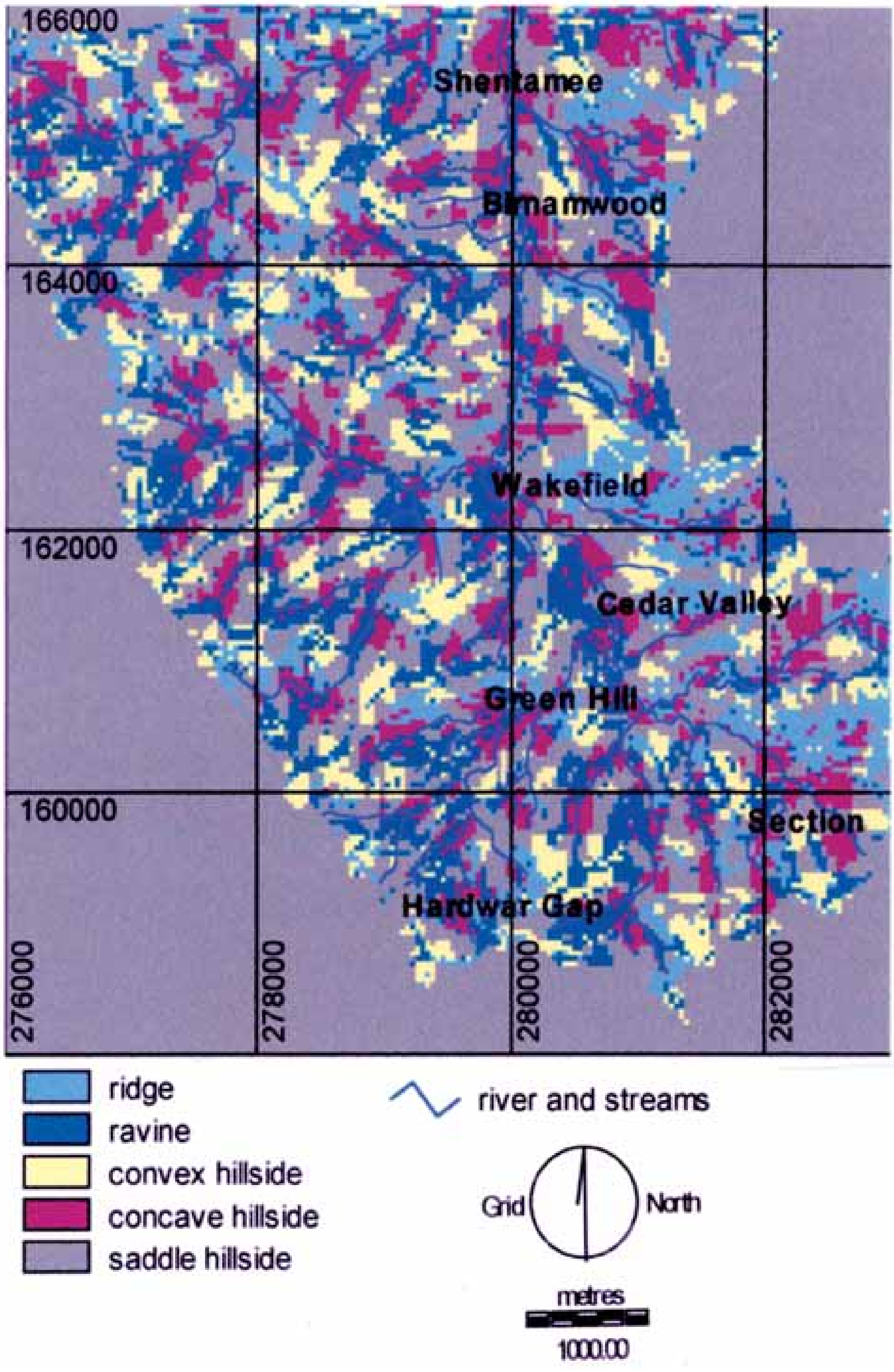

Fig. 26. Selection of topographic elements generated by the TOPOSHAPE module.

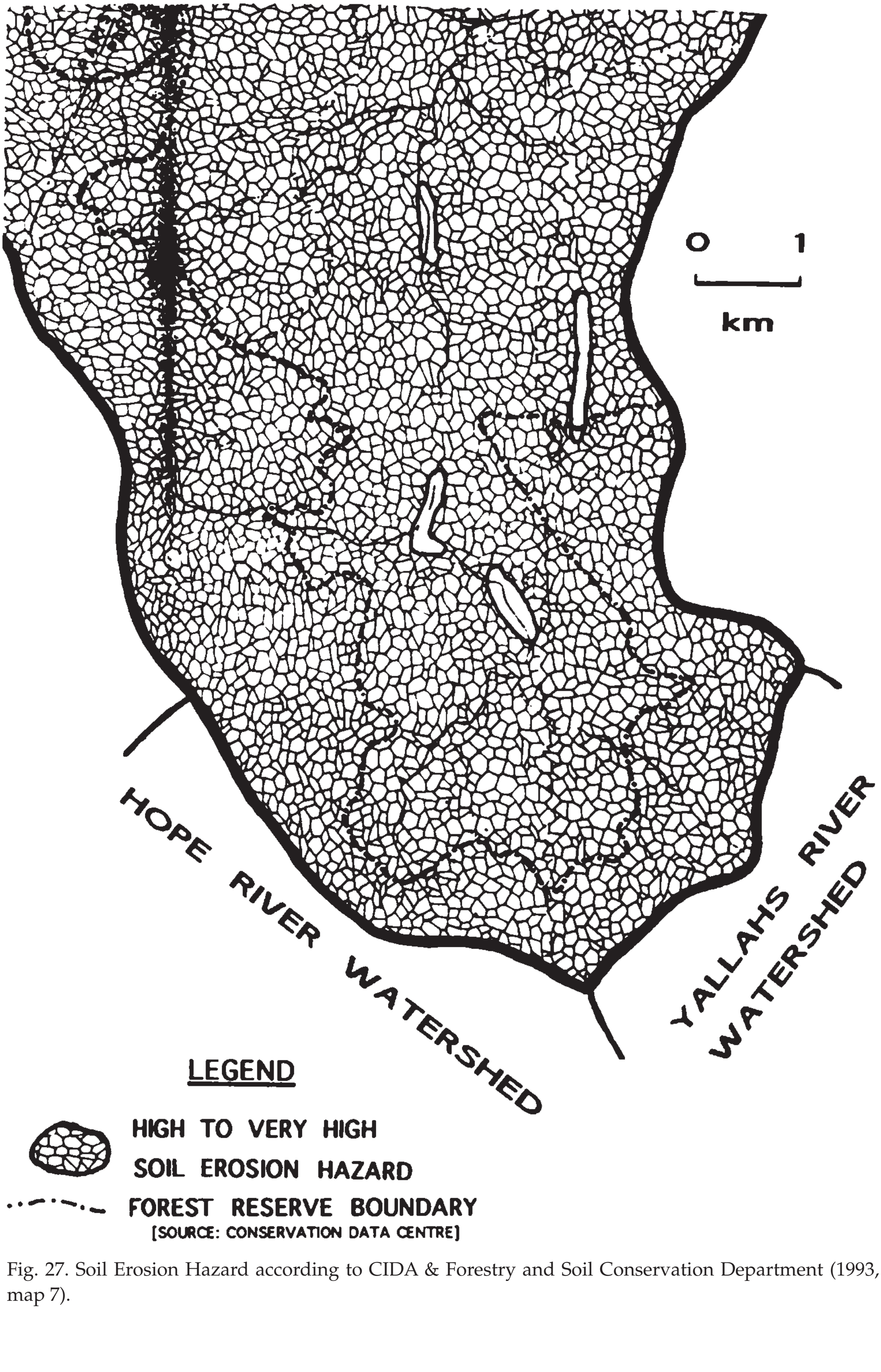

Fig. 27. Soil Erosion Hazard according to CIDA & Forestry and Soil Conservation Department (1993, map 7).

Table 71. Comparison of erosion factors and soil loss for several studies from the region.

Factor	**Erosion**	**Reference**
10 degree slope	122 and 212 t/ha	Relationship between soil and slope properties and erosion in Tobago soils (based on Ahmad & Breckner, 1974)
30 degree slope	15 and 180 t/ha	
4% OM, 71% agg. stability < 2 mm, dispersion ratio 22, suspension 11%	average 184 t/ha	
5% OM, 85% agg. (< 2mm) stability, dispersion ratio 10, suspension 7%	average 102 t/ha	
Rainforest	2.3 $cm^3/cm/yr$	Surface wash erosion in the Mt. Airy district of Jamaica (Richardson, 1982)
Pinus caribaea	0.43 $cm^3/cm/yr$	
Cocoyam (tilled with hoe)	460-1150 grms	Erosion from cultivated field with average 30° to 35° slopes, Fall river, Jamaica (based on McGregor, 1988)
Mature coffee (cutlass weeded)	87-177 grms	
Ruinate land and grass, coffee and bananas	235-244	Degradation index values and ranges for several sites in the Fall River basin, Jamaica (McGregor *et al.*, 1998)
Steep slope coffee, yam and bananas, abandoned terrace	202-226	
Pinus caribaea plantation	181	
Mixed agriculture/terraced, coffee and bananas	102-110	
Eucalyptus plantation	92-115	
Market gardening, food forest (+ ground storey crops)	63-85	

PED model assumed the situation that Richardson (1982) found in natural forests, a virtually bare surface. The alternative scenario in which litter was accounted for more closely resembled the situation under a *Pinus* plantation. McDonald *et al.* (1996) identified 9 t/ha/yr litter accumulation in secondary forest and the PED model also assumed that ruinate would give significant soil protection.

The land use aspect of the PED model is based on the level of tillage activity, but not the method. However, local knowledge of crop maintenance techniques are important for the correct coding of the model (McGregor, 1988), where hoeing loosened the soil and cutlass weeding did not. However, the maps on which PED land use was based gave insufficient detail of the complexity of horticulture in the research area. McGregor *et al.* (1998) failed to explain the unexpected high degradation found under ruinate land and grass, an area of low soil disturbance and high vegetative cover, giving idle land and scrub a land use weighting lower in value only to bare land and more erodible than rough grazing (based on FAO, 1979). The reasoning behind the ranking of ruinate susceptibility to erosion was not identified, but explained as the result of soil exhaustion under the land use previous to, and leading to, ruinate growth (D.F.M. McGregor, pers. comm.).

McGregor *et al.* (1998) recorded a reasonably high degradation index value for *Pinus caribaea* that contradicts the protective nature that Richardson (1982) had identified. Market gardens, considered elsewhere to be susceptible to erosion (van Grootveld, 1992), had low DI values, but this was due to low angle slopes, making it difficult to isolate the susceptibility of a particular land use activity. It is these differences that make modelling so difficult.

An unpublished report into the status of the Jamaican watersheds highlighted the suspected causes of degradation (Cunningham, 1993). The parameters mentioned in the report can be used as a comparison of the PED model results, even though it means comparing the upper with the whole watershed. Cunningham referred to the Buff Bay as a class one degraded watershed with a high drainage density, very steep slopes, narrow ridges and deep gullies, although without quantification. TOPOSHAPE indicated significant areas of saddle, convex and concave slopes in the upper watershed, suggesting a less sharp relief. Cunningham saw tree planting as a major conservation requirement to improve the percentage tree cover for the watershed, dependent on a DGP of 10 to 11 months. In fact, over 50 % of the upper watershed has a DGP of 7 to 10 months, a drier regime than Cunningham suggested. The permanent tree cover of the watershed was calculated by Cunningham as 40 %. In the upper watershed the percentage of the area which is closed canopy is 43 %, in addition to which there are smaller areas of high open canopy. The lower watershed has not been analysed and, in the absence of tree cover, this would significantly reduce the watershed protection. Cunningham regarded the low canopy of coffee bushes as a poor interceptor of precipitation compared to high canopy. However, a high canopy may temporarily intercept more rainfall than a smaller coffee bush, but raindrop coalescence and regained terminal velocity may lead to higher soil particle detachment under the higher canopy.

Universal Soil Loss Equation (USLE)

The use of GIS, remote sensing and the USLE to develop erosion maps is becoming more common, despite the non-universal nature of the index. The overall accuracy of one study in Malaysia was 74 % (Kamaruzaman & Baban, 1999), which the authors attributed to the difference in pixel resolution between the maps and the mixed class pixels being given a dominant cover classification based on visual interpretation. The USLE is still regarded by many as applicable to Jamaica and any research undertaken in the region would be expected to include at least an estimation of erosion rates (see 'Alternative scenarios,' Chapter 9, above). In a complex watershed such as that of the Buff Bay River, the calculation of the USLE is impossible, as the following analysis shows.

In the thesis research area, the USLE rainfall parameter (R, intensity) was not recorded as there were no automatic rain gauges, but there was supporting literature for other regions (Chakela & Stocking, 1988; Renard & Freimund, 1994) for a calculation of R from mean annual or monthly precipitation. The only map of annual rainfall that could be located was island-wide and of poor quality, the digitising of which would be very inaccurate. There were insufficient meteorological stations in the catchment to support interpolation for the monthly data, especially given known local climatic anomalies.

The values from the nomograph (Table 66) gave a different soil ranking than that used in the PED model (Table 53). A discussion of the USLE K-factor as a soil factor layer (see 'Alternative scenarios,' Chapter 9, above) concluded that the soils of the Buff Bay watershed were not very erodible. The USLE is very sensitive to OM, and the samples for soil series 46 and 301 were thought to have incorporated surface litter or fertilizer, introducing a significant flaw in the analysis.

Slope steepness (S) was available as a factor for each pixel in the research area. Slope length was difficult to generate accurately from an interpolated DEM. There was no regional constant that could be applied in order to calculate the LS factor. The crop factor (C) is dependent on crop growth stages. Land use and canopy height/density were digitized for the area, but there was no seasonality in this analysis. Other workers have analysed this factor for crops other than those used in the American USLE trials (Morgan *et al.*, 1984; Hall, 2000), but the PED model does not use crop associations at plot scale level. Conservation (P) would have to be assumed at 1, since there are no available maps of recent measures and it is not obvious from air photos. This also would give the worst case scenario of erosion whereas PED indicates the conservation value of vegetative cover.

An approximation of the USLE soil loss equation cannot be attempted for the stated reasons. Wischmeier (1976) stated that it was not appropriate to use the equation in complex watersheds, for specific rainfall events or where accurate evaluation of the parameters was not possible. Since the standard slope for the USLE trials was 9 % (5°), and the mean slope for the Buff Bay watershed is 26° (49 %), any calculation of the USLE will contain potentially significant errors and this should be reiterated to any agency that insists that the USLE should form part of the watershed degradation ranking.

Erosion map of Portland

The Canadian International Development Agency (CIDA) studied the Pencar/Buff Bay watershed management unit as part of the 'Trees for Tomorrow' project (CIDA & Forestry and Soil Conservation Department, 1993). This addressed the sustainable development of the tropical forest environment, with the objective of increasing the capacity of the Forestry and Soil Conservation departments to develop and implement soil conservation measures. One third of the watershed had slopes in excess of 26° and that the removal of vegetation contributed to 'accelerated' erosion, magnifying the effects of 'geological' erosion with contributing factors limited to parent material, slope, soil texture and structure. The explanation for soil erosion was: "Because most of the rocks in the watershed are located on steep and very steep slopes, the tendency is for the soils to obey the laws of gravity and move downslope as they are produced. It is in these circumstances that soils are classified as "erodible or 'highly erodible'"" (CIDA & Forestry and Soil Conservation Department, 1993, p. 33).

The actual derivation of the map was not explained in the text, neither the difference between high and very high classes. The erosion coverage seemed to have been based on the OR function (slopes over 26° OR soils with loose, coarse textures and weak structures) and took no account of present land cover or use. The resulting map covered the whole watershed except for six small outcrops of the Agulta series (representing 1.12 % of the research area), thus giving the impression that over 95 % of the watershed had a high hazard of soil erosion. In one sense it represented the empirical experience of soil erosion on bare slopes on certain soils, but without sufficient information regarding the experience of erodible soils, it cannot be rigorously tested.

Map 7 of the CIDA report, "shows soils with high erosion hazards," "soil degradation and erosion," "steep to very steep slopes" and "accelerated erosion... deforestation... vegetation disturbance...agricultural practices...road construction" (CIDA & Forestry and Soil Conservation Department, 1993, pp. 63, 25, 33 and 7, respectively). Figure 27 identifies a Boolean situation regarding erosion.

Erosion stake sites

Vegetation cover is a principal determinant of specific erosion rates under intense tropical rainfall (Stocking, 1987). It was decided to concentrate research sites under each vegetation type based on Gils & Wijngaarden (1984): low and open (e.g., extensive coffee crop, weeded annual crops); low and closed (e.g., wild ginger, intensive coffee); high and open (e.g., well spaced forest or ruinate/secondary vegetation canopies); high and closed (e.g., dense forest or ruinate); bare ground (e.g., tilled or freshly sown or cropped); and bare, but regenerating ground (e.g., recent landslide).

Wooden erosion stakes were used in the 1950s to gauge the degree of slopewash which, compared to more recent, thinner metal stakes, had the disadvantage of greater local surface disturbance (in placement and to surface water flow) (Goudie, 1990). The pin favoured by Haigh (1977) had a diameter of only 2 mm, and was made of non-corrodible metal. A metal washer around the pin was supposed to aid the reading of a depth gauge, but since this would inhibit erosion under it, Goudie (1990) noted that it could be a disadvantage in studies where deposition and not only erosion was measured. He mentioned that an alternative method in which the washer was placed over the pin at observation time was more appropriate. Other considerations included inserting the pin deeply to minimise disturbance, but the head should remain 20 mm above the surface. In tropical experiments, 20 mm would be insufficient for depositional environments. Clusters or contour-parallel lines of pins were suggested to calculate an average, since slopewash rates vary considerably over short distances. Goudie reviewed a number of alternative measuring designs involving steel stakes and depth-gauging rods in an erosion frame, the advantages of which were the minimal soil disturbance from the placement of the equipment and the free movement of the surface water flow at the measuring point. None of the equipment mentioned was available for this research and the use of wooden stakes was also less obtrusive in areas where measurement was taking place covertly. Analogous studies in the natural sciences in Jamaica also suggest that a 'low' technology solution would be less likely to be stolen (S.K. Donovan, pers. comm.).

Although some authors have suggested that erosion pin results are often flawed (Goudie, 1990; Haigh, 1977), the use of such equipment should be appropriate to the study. An extensive network of pins can give a significant range of results so that the average is compromised by a high standard deviation. On the other hand, a small number of pins may measure the sheetwash erosion in an interill area. Slopewash may become concentrated into rills above the sample area, so that only interrill erosion is measured. The pins might generate the rilling of the slope so causing bias in the observations. Aldrich (1992) worked in the vicinity of the Blue Mountains in Jamaica and used very basic erosion stakes equipment. He found that the net change of the first erosion pin reading under all the cover types was cumulative, suggesting deposition or perhaps an unforeseen redistribution of the soil when placing erosion pins. However, the forest plots continued to show this process through the period of six months, beyond the three months settling period for pins. There was a net loss in soil under non-forest in the latter part of the period, but it did not exceed the original accumulation. Since the slope angles were typically around 35°, this raises interesting questions regarding plot experiments with pins, and also the inverse relationship between soil loss and slope angle found by other authors in terrain over 30° (Ahmad & Breckner, 1974). Since relative rather than absolute erosion was important in this study, it was decided that the advantages provided by the wooden stakes, which were relatively easy to obtain, read and place in the field, whilst remaining inconspicuous, outweighed the disadvantages.

Sites for soil loss analysis using erosion stakes were selected on the basis of representability (vegetation and soil series) and accessibility (Fig. 28). As much of the catchment was inaccessible, appropriate tracks and roadsides were targeted. Twenty sites were visited and seven sites chosen. The position of a site on the slope was located a minimum of 10 m from a road or track, typically halfway down the slope length, from the top boundary, avoiding uphill obstacles like trees and rocks where possible. The nature of the slopes was complex, with variable depths of leaf litter or roots at the surface. The stakes were placed at points where leaf litter was minimal and roots (particularly ginger lily) absent, but the positions were determined to be susceptible to erosion and/or deposition. Few of the assumptions of a field experiment could be controlled, with one site in use for coffee under forest canopy, by squatters, who had no knowledge of the research. At each site, three numbered 4 × 4 cm stakes were hammered into the ground about 30 cm apart along the contour, with 7 cm above ground and a corner of the stake facing uphill to minimise the runoff flow disturbance.

Natural vegetation

Site 1 Hollywell Park, Hardwar Gap trail: unimproved pasture on downslope side of a track (Pl. 3A).

Site 2 Hollywell Park, Hardwar Gap trail: unmanaged wild ginger (2 m high), some leaf litter, bordered by a stream at the bottom of the slope (Pl. 3B).

Site 5 Section: ruinate vegetation mixed open canopy, ferns and ginger, upslope road verge (Pl. 5A).

Site 7 Hollywell National Park: recent landslide toe on upslope coffee factory track (Pl. 6).

Partly managed

Site 3 Section road: squatter site of clear weeded coffee crop and annuals under tall (>10 m), closed forest canopy, upslope above retaining wall (Pl. 4A).

Managed

Site 4 Yacca Farm: intensive coffee crop (3 m spacing) on tree cleared land, downslope verge of road. The stakes disappeared entirely during the one month settling period, presumed removed by weeding activities. They were replaced and allowed to resettle before measurement (Pl. 4B).

Site 6 Section road: considerable terraced structures, with earth riser, signs of clear weeded dasheen crop, recently fallow or abandoned, grass cover (Pl. 5B).

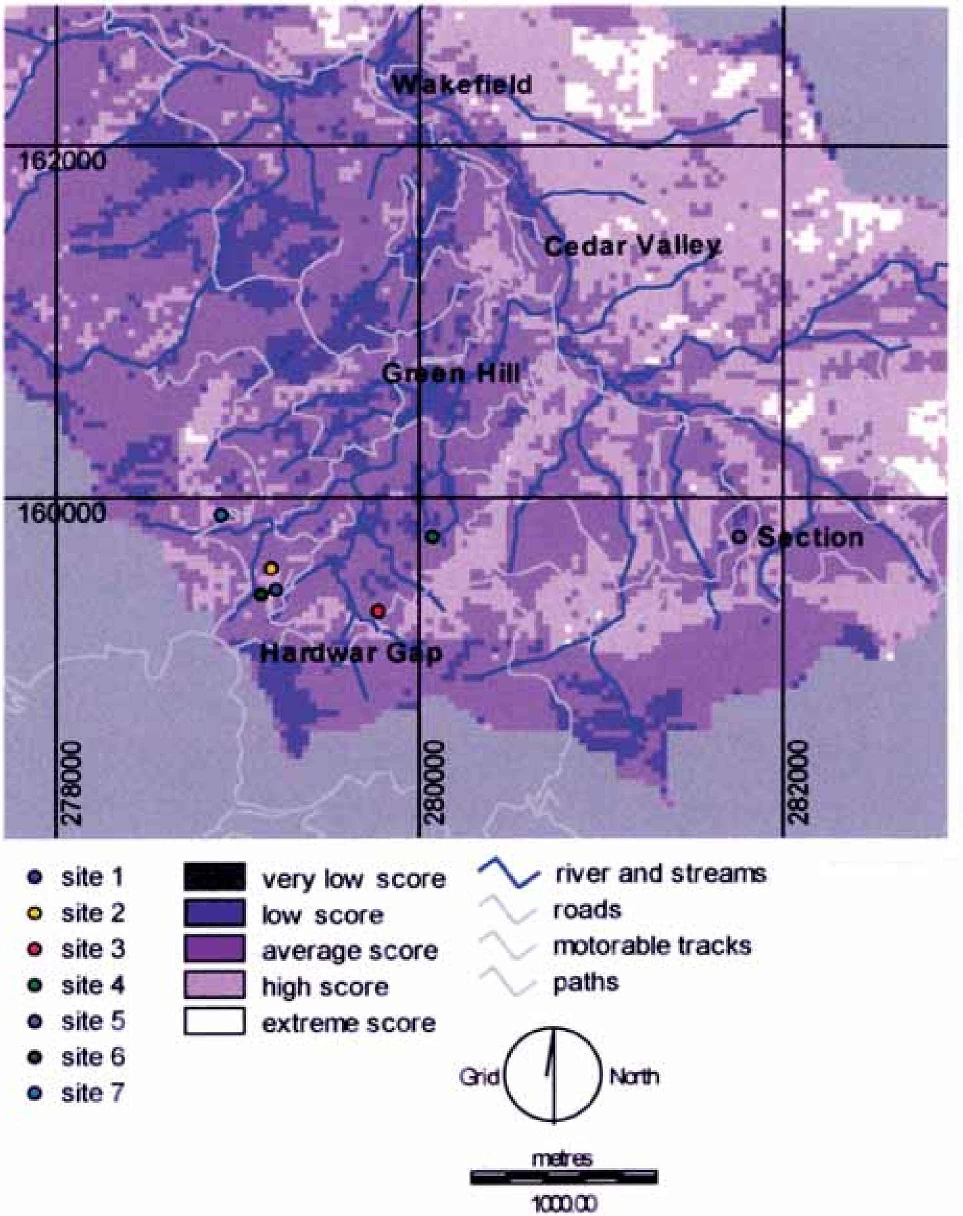

Fig. 28. Location of erosion stake sites with model result (E5) as background.

The sites were set up in May of 1997, the preliminary soil level was marked and the distance, typically around 40 to 100 mm, to the top of the stake noted. The sites were photographed both to aid future observation and as a record of the vegetative cover state at the time of erosion pin placement. Erosion measurements were not taken from the sites until a settling period of one month had passed.

Soil loss results – The data recording dates were June, July and August, 1997; and February and June 1998 (see MacGillivray, 2002b, appendix 6). At these times, the level of the soil from the top of each stake was measured, allowing both deposition and erosion to be quantified. The top of the stakes did not disappear during the measurement period, although at Site 4 the stakes could not be relocated. They may have been buried, but the photograph showing nearby tree bases showed that the soil levels had not accumulated to the degree of 7 cm, the known distance to the top of each stake. They were removed either as a result of verge maintenance or clean weeding. New stakes were placed marginally downslope to the same level and these survived to the end of the fieldwork.

Figure 29 shows that over the period of a year, all sites, except Site 7, lost soil. At Sites 1, 5, 6 and 7, there was soil deposition at the stake between August 28 and February 4, which is the rainy season. At Sites 2 and 3 there were small deposits at other times. Sites 1, 3 and 6 showed the most significant losses, but this data are not usefully presented in terms of identifying a relationship with site conditions or the model.

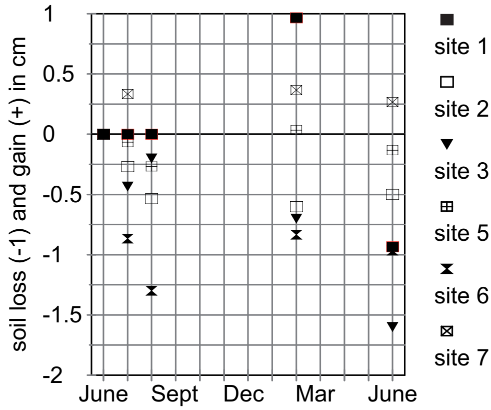

Fig. 29. Soil loss and gain from the seven erosion stake sites (site 4 omitted).

Cumulative erosion potential – This author devised a concept in which the incremental measurements at each site, whether erosional or depositional, were regarded as representing an erosive event somewhere on the slope (see MacGillivray, 2002b, appendix 6), called cumulative erosion potential (CEP) (Fig. 30). Only the position of the stakes on the slope determines whether the soil loss that is measured is eroded from that contour or upslope (and depositing at the stake site). Although there is no empirical evidence to support this measure of total erosion, it gives a relative indication of erosion activity on the slope.

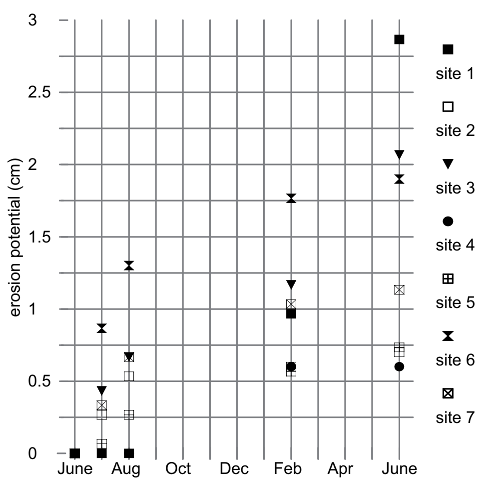

Fig. 30. Cumulative erosion potential (CEP) for six of the seven erosion stake sites.

Site 1 shows a CEP of nearly 3 cm, Sites 3 and 6 a CEP of around 2 cm, Site 7 a CEP of just over 1 cm and the other sites gave CEPs of just under 0.75 cm. It is interesting to note that erosion is highest where there is an undisturbed grass cover at Site 1. It is possible that this grass area was regenerating from being bare (hence the disadvantage of not knowing the recent history of land use) or that the slope was so steep (48°) that no protection was sufficient to stop significant soil loss. On the other hand, the landslide area at Site 7, showed only moderate erosion compared to the other sites, even utilising the CEP concept, whereas more was proposed by both field and model inputs, and the resulting erosion class (4).

Comparing field and model results – The field observations and measurements are given in Table 72 for each of the seven sites. The results from the field and laboratory research were compared with those from the model in two different analyses. The first analysis (Table 73) concerned the factor inputs into the model and how closely the model topographic factors resembled those observed in the field. The second analysis (Table 74) compared the predictions of potential soil loss calculated by the model with those of the erosion stakes.

Table 72. Field observations and laboratory results for the erosion stake sites. Key: # site locations were confirmed using a GPS.

Site	**1**	**2**	**3**	**4**
Location#	76:43:44 18:05:14	76:43:46 18:05:21	76:43:12 18:05:08	76:42:95 18:05:31
Soil series	305	38	305	52
Slope angle°	48	>35	24	44
Aspect	80	0	334	266
Vegetation cover %	low open >70	low closed 40 - 60	high open <20	high open >70
Land use	undisturbed grass	ginger/ruinate	cleared	weeded coffee
Surface	compact	crumbly	loose	crust
Sand %	40	32	21	42
Silt %	36	45	64	29
Clay %	24	23	15	29
O.M. %	2.8	7.3	19.5	7.6

Site	**5**	**6**	**7**
Location#	76:42:00 18:05:30	76:43:48 18:05:12	76:43:61 18:05:37
Soil series	301	305	52
Slope angle°	29	26 to 35	42
Aspect	330	96	170-180
Vegetation cover %	high closed 60 - 70	low open <20	bare <20
Land use	undisturbed forest+litter	annuals	ruinate
Surface	compact	crumbly	loose
Sand %	38	16	55
Silt %	41	48	29
Clay %	21	36	16
O.M. %	8.9	9.7	0.5

Despite considerable variation in the land use classification, the model and the field observations have very similar scores and erosion classes. The land use map source was known to be very general, especially the classification of a large proportion of the watershed as coffee plantation, whilst a much more complex land use was observed on the ground.

Table 73. Values and scores of factors from the field and PED model. Key: (xx) refers to the table in which the scores are given for factor values; PED based on 1991 air photos and 1993 report. Fieldwork took place in 1997; * neither acz or soil series were observable in the field, so both scores include the model-based values.

Factors	**Site 1**		**Site 2**		**Site 3**		**Site 4**	
	PED	Field	PED	Field	PED	Field	PED	Field
Aspect (29)	94	80	337	0	280	334	326	266
Land use	5	1	5	2	5	4	5	5
Slope (28)	40	48	16	>35	20	24	49	44
Vegetation (38)	HC	LO	LO	LC	LO	HO	HC	HO
Acz+soil*	6	6	6	6	6	6	6	6
Score	21	18	15	16	16	17	21	20

Factors	**Site 5**		**Site 6**		**Site 7**	
	PED	Field	PED	Field	PED	Field
Aspect (29)	294	330	91	96	122	175
Land use	5	1	5	5	5	2
Slope (28)	30	29	14	26	31	42
Vegetation (38)	LO	HC	HC	LO	LO	bare
Acz+soil*	6	6	4	4	6	6
Score	16	16	16	16	20	23

Table 74. Soil loss compared to the results from the PED model for the erosion stake sites. Key: * 12 months equivalent (6 months ×2.7, where 2.7 is the factor of change from 6 to 12 months for all sites averaged).

Indicators of soil loss	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**
Clay:silt	0.673	0.515	0.237	1.001	0.515	0.752	0.554
order	3	5	7	1	5	2	4
Ave. soil loss (cm)	0.934	0.53	1.66	1.62*	0.132	0.975	-0.271
order	4	3	7	6	2	5	1
CEP (cm)	2.93	0.71	2.12	1.62*	0.71	1.92	1.12
class	7	3	6	4	3	5	1
Model calculations							
PED USLE	3	2	3	3	3	3	4
PED W5E5	4	3	3	4	3	3	4
PED field	3	3	3	4	3	3	4

The vegetation classifications do not generally agree in terms of height of canopy, except at Sites 2 and 4. At Site 1, it is possible the site was cleared and is now grassed. The Section road forms the boundary between high and low canopy, and both Sites 3 and 5 are on that road. The interpretation of low canopy does not agree with the high canopy found in the field at both sites. At Site 4, the formerly high closed canopy had been thinned out to allow coffee planting. The clearance and terracing of Site 6 observed in 1997 may well postdate the air photos (NRCA, 1991). The landslide and gullying at Site 7 was recent. It was also sufficiently small not to have been seen on the air photos if it had been active in 1991.

The aspect values generated by the DEM were within approximately 20^o of those measured by compass at Sites 1, 2 and 6. At Site 5, the values were within 35° of each other, which can be accounted for by variations in the local topography that the contours at 1:50,000 do not imitate. However, at Sites 3, 4 and 7 the anomaly is significant (between 50° and 60°) which can be accounted for either by inaccurate digitising of contours or inaccurate contours in areas of high vegetation. A difference of 1° can change the value of a score, so that at Site 1 an aspect measurement of one degree less would have reduced the score by four and the erosion class by one. In fact, it is the land use and vegetation score differences that have led to different PED classes for field and model at Site 1.

The erosion stake data are a point source, whereas the Idrisi data represents an area of 40 m, so the two are not directly comparable. Soil traps across the bottom of a 40 m plot would be more directly comparable, but this would be difficult and expensive to carry out for more than one or two plots. Some researchers have set up experimental field plots in the Blue Mountains under the cover of extension aid using local farmer protection (McDonald *et al.*, 1996), yet still suffered equipment damage or interference. The original plan involved sites for each of the soil series on bare plots, but this proved impossible as bare sites were few or temporary and attracted the unwanted attention of local inhabitants.

Several observations can be made about Table 74. Firstly, the erodibility order of the clay:silt ratio and the CEP or average soil loss values are not correlated. The reasons for this might be that the clay:silt ratio is not a good indicator of soil loss, the observed soil loss at the sample sites was not rigorously enough measured (the potential error in using a small number of stakes) or other factors influenced the soil erosion apart from its inherent erodibility. Secondly, the CEP values are not significantly related to any of the PED model outputs or scores, but this would be difficult given the limited differentiation (with classes 3 and 4 almost exclusively present) in model classes.

Thirdly, the alternative scenario PED USLE erosion classes are almost identical to those produced by field observations, except for Sites 4 and 2, whereas the PED (W5E5) model run is almost identical to the field observed classes except at Site 1. This is a reasonable test of the robustness of the model. In both these cases there is only a difference of one erosion class and, in the latter, the actual scores differ by one. However, the range of PED classes analysed is too small to form any conclusions about the verification of the model by both erosion stake and PED field results.

In a provisional model run calculated during the fieldwork year in Jamaica, one area of potential extreme erosion was visited in the field at Wakefield and showed evidence of erosion (Pl. 7). The slope looked to be covered in rough grass (classification of rough pasture), but there was significant rilling and deposition at the foot of the slope, which the river was removing. This same area was identified in the latest version of the PED model as an area of potential extreme erosion, the White River patch. The bare ground was not the result of tillage operations, but would have become eroded after low ruinate had been removed in preparation for agriculture. This illustrates the use of the model in determining the erosion potential of the watershed once the protective vegetation cover has been removed. There was no financial support to return to the fieldwork area by the time the other patches had been identified in the latest model version, so there are no observational data concerning the other patches.

11. Discussion

Defining erosion and degradation

As the review of definitions has shown ('Relevance of relative soil loss model,' Chapter 1, p. 3, above; MacGillivray, 2002b, appendix 1), the distinction between erosion and degradation is not always clear. This research regards soil erosion as involving the removal of soil particles downslope over (surface runoff) and through (groundwater or seepage runoff) the top of the soil profile, leading to a decrease in soil depth (FAO, 1979), and concentrates specifically on sheetwash, that is, erosion caused by surface runoff.

The perception of erosion as a problem

In many SIDS, the 'colonial' model, one of surplus extraction, has evolved into a post-independence model of survival and avoidance of debt. Government agencies have traditionally blamed the small farmer for inappropriate cultivation techniques, and a refusal to maintain capital and labour intensive conservation structures. However, the same agencies have little or no awareness of actual erosion in the watershed, whilst there is no evidence of soil loss studies in eastern Jamaica except those carried out by academics (Richardson, 1982; McGregor, 1988; McGregor & Barker, 1991; Aldrich, 1992; McDonald *et al.*, 1996; Ahmad & McCalpin, 1999). McGregor (1988) suggested plot-based soil losses of about 120 t/ha/year from agricultural land, which compared to soil formation rates estimated at 10 t/ha/year (McGregor, 1995), explains government agency concerns about reservoir siltation and watershed degradation (CIDA & Forestry and Soil Conservation Department, 1993).

McDonald *et al.* (1993, 1996) found a reasonable awareness of the term erosion amongst farmers, but a general lack of priority concerning its occurrence and prevention. However, degradation, in terms of reduced yields, was recognised as a problem. Academics seem to have a better understanding of farmer's perceptions than local agencies. Blaikie (1985) and Edwards (1995) both agreed that sustainability, and hence soil conservation, were not primary requirements for most marginalised farmers, whilst Hudson (1981, p. 47) was clear in his assertion that "soil conservation has never won a vote, nor is it likely to."

The consequences of erosion awareness

The awareness of soil erosion and initiatives presented to combat it (Chapter 1; MacGillivray, 2002b, appendix 2) have not evolved much from the colonialism of the Yallahs Valley Land Authority to the neo-colonialism of the Rio Grande Valley Project, forty years later. The current Natural Resources Conservation Authority initiative (NRCA, 2001) employs modern terminology to disguise old concepts, "strategies ... ensure ... sustainable use and development, proper land use ... [for] watershed conservation," whilst accepting that "studying farmers' and other land users' acceptance of conservation treatments and identifying incentive needs and effectiveness" are necessary. The need for a simple predictor for potential erosion was evident from the NRCA website, highlighted in Chapter 1. However, the emphasis of much research has moved from erodibility indices to degradation indices. Since agricultural development is inevitable, due to population pressure, the degree of acceptable tolerable erosion is an important issue that nobody has quantified or extrapolated at a scale pertinent to the development in question.

The very term soil erosion is loaded with negative emotions as if the denudation of the landscape is inherently wasteful. Even in social terms, one man's erosion might be another's gain. Therefore, it is important in designing a model to appreciate the consequences of social constructs. It is essential to find a responsible way of presenting the results so that the end user can make an objective assessment of the situation.

The processes of soil erosion

The processes involved in surface or sheetwash erosion, in which particles are detached by raindrops and transported by surface runoff, were reviewed in Chapter 2. There is disagreement about the conditions necessary to generate surface runoff, the best indicator and threshold for erosivity, and the soil parameters that need to be included in a measure of soil erodibility. Despite this it is possible to conclude that rainfall intensity is important not only in detaching soil particles, but also in generating surface runoff when infiltration rates are exceeded. However, there is a difference in the interpretation of the Jamaican climatic situation. Whereas Nkemdirim & Jones (1978) referred to a climatic regime in which soils were persistently saturated in the winter leading to rapid overland flow and flooding, CIDA & Forestry and Soil Conservation Department (1993) suggested that saturation rarely occurred since steep slopes and shallow soils ensured that water retention was minimal as it rapidly entered the gullies. It is an important distinction in terms of estimating erosion. The measurement of rainfall intensity requires automatic raingauges outside plot-based experiments and, as this is not measured in the Buff Bay watershed, surrogates like the R75/PET ratio (Batjes, 1994) were examined (e.g., 'Defining and measuring erosivity,' Chapter 2, p. 15). There are numerous indicators of soil erodibility (Table 4), but the main issue appears to be the water stability of aggregates in soils with significant clay and silt content. The factors involved in aggregation involve clay type, organic matter and the presence or absence of certain minerals.

Essential factors in determining the spatial nature of soil erosion

The factors that influence the processes of soil erosion were reviewed in 'Identifying cause and effect relationships' in Chapter 2 (p. 28). In the Buff Bay watershed, rainfall distribution was found to be highly correlated with the seasonality of flooding (Nkemdirim & Jones, 1978). It was concluded that slope angle and vegetation were more important than rainfall, in terms of erosion in the headwaters, where rainfall totals were lower. The extent of entrainment is determined by the slope steepness, with soil erosion increasing with slope angle. However, detachment may be limited by reduced runoff depth on very steep slopes and soil loss is not always related positively to slope angle (Odemerho, 1986). Aspect was studied by many authors and found to be an important factor (Ahmad & Breckner, 1974; Maharaj, 1993a; Larsen & Torres-Sanchez, 1998). The detachment of particles is determined by rainsplash impact and, hence, the type of vegetative cover. Many important thresholds were determined (Hudson & Jackson, 1959; Fournier, 1967; Elwell & Stocking, 1976; Stocking *et al.*, 1988) during early research. However, conclusions regarding canopy protection need to take the presence or absence of a herbaceous layer into account.

Crop and land management are more important than slope, soil or rainfall in determining the rate of soil erosion in Jamaican watersheds (Collier & Collins, 1980). Other reports (Cunningham, 1993; CIDA & Forestry and Soil Conservation Department, 1993) have referred to food crops (intensive tillage) and the intensification of coffee cultivation with the loss of permanent trees, as the principal causes of soil erosion. Tillage activity and timing was a major feature in the rainfall event-based high levels of soil loss (McDonald *et al.*, 1996). However, erosion and runoff do not necessarily accumulate downslope and may not even be correlated (McGregor, 1988). Natural levels of erosion are not easy to identify and the extent of man's influence is contested, whether as an important control variable (Stocking, 1978) or principal cause of erosion.

Assessing (measuring and predicting) the extent of erosion

It is important to understand classification philosophy in order to produce a robust classification system for land evaluation. Since landform classification is said to be socially constructed, land evaluation, with its political and economic frame of reference, can never be objective. Only by understanding the history of classification philosophies can the researcher understand the presumptions and frameworks within which all aspects relating to soil have been classified. Classification of land elements has moved from a rigorous homogeneity of facets towards measures of potential economic viability ('Classification of land elements and activity', Chapter 3, p. 45). The same issues of class boundary identification and class homogeneity have faced researchers in all the classifications.

The negativity associated with many of the reports of soil erosion is partly linked to an ignorance of the speed of natural processes and partly to prejudices regarding traditional (non-European) cultivation methods. Stocking (1978) could find no link between population pressure and gully growth, whilst McGregor (1988) showed that cutlass weeding did not significantly disturb crusted soils.

Descriptive and predictive research have produced considerable bodies of empirical data, whilst the factorial deterministic approach of prescriptive research has produced many useful indices, particularly estimations of soil loss using relative qualifiers (Chapter 3). However, predictive research cannot be used outside the test area and prescriptive research may not include all the necessary causal factors. Parametric indices have their critics (Rossiter, 2000), but rates of soil formation and erosion are also contested. This is mainly because rates of erosion are determined by factors which are difficult to measure, like antecedent soil moisture, soil surface condition and rainfall variability.

Environmental determinism (prescriptive research) has become old fashioned, just as some authors believe field work is old fashioned (MacGillivray, 2002a). An early definition of determinism was "... a relation between some inorganic element of the earth ... acting as a control, and some element ... of the earth's organic inhabitants, serving as a response" (Davis, 1906, p. 8), but the concept of this causal relationship was not popular as a methodological principle (Stoddart, 1986). Cause and effect analysis was most popular in the 19th century, in which the search for factors that governed distributions dominated much research. From the literature at the present time, this sort of analysis is still popular, if in a more restrained application. Landslide (Lopez, 1991; Larsen & Torres-Sanchez, 1998; Ahmad & McCalpin, 1999) and multivariate soil erosion analyses (Kamarauzaman & Baban, 1999; Hall, 2000; Hellstrom, 2000) are still commonly published. Geographical Information System modelling has reflected the conventional assessments of erosion, but added the dimension of process-based analysis. Whereas qualitative models were simplified due to inadequate data (Claure *et al.*, 1994), the WEPP model, for example, was criticised for involving too much detail (Rossiter, 2000). Models with a statistical or historical element (Lopez, 1991; Niemann & Howes, 1991; Mejia-Navarro *et al.*, 1994; Thurston, 1997; Ahmad & McCalpin, 1999) have relied heavily on the feature inventory. However, the identification of spatially discrete entities like landslides is sometimes doubtful, particularly if they were prehistoric events. A statistical model does not guarantee that the predicted feature will have the same process as the historical event.

Critique of the PED model design

The raster model is justified on the basis of the ease of computing some of the factors from DEM and the availability of the software at the start of the research. A Boolean methodology as a basic concept is fairly restricted in GIS analysis, hence the only Boolean image in the model being the watershed boundary. The PED model goes one step further than extreme risk aversion (Boolean) to suggest a susceptibility continuum. This could be taken to the extreme of byte-range 0-255, but since the positioning of thresholds along that line would be just as arbitrary as the subjective justification for 5 categories, the latter was chosen as more appropriate for a simple model. The factors being considered may not have equal influence in the process and could be weighted based on empirical evidence to rank the importance of these factors. However, McGregor *et al.* (1998) abandoned the weighting based on FAO (1979) guidelines because it obscured subtle internal differences between and within classes.

Weaknesses – The model assumes that soil moisture and runoff are determined by agroclimatic zones and that such zones can be used as a surrogate. The only example of this was related to landsliding (Lopez, 1991), research into which also provided aspect data. The landslide data on which the aspect classification was based caused inconsistencies in the analysis. A 2° difference in aspect measurement could mean a difference of four erosion classes. However, there is no basis on which to modify the ranking based on Maharaj (1993a).

Land use, which both McDonald *et al.* (1996) and Collier & Collins (1980) regarded as the most important factor in assessing erosion, was taken from a secondary source that had been produced with very general categories, losing much of the detail that the 1982 land use map had shown. For example, there was little observational data to support the extent of the coffee plantation suggested (CIDA & Forestry and Soil Conservation Department, 1993). A better land use map could be derived from air photo keys

(Philipson & Liang, 1975; Collier & Collins, 1980) if local knowledge identified the tillage techniques, ground preparation, harvesting techniques and seasonality for each crop. However, as an example of the features used to identify coffee plantations (Table 75) shows, this is not a simple task.

Table 75 highlights the difficulties in identifying one crop, coffee, using air photos at the intermediate scale. Only the circular nature of the actual crop and the regular spacing of the bushes are fairly easy to recognise. Permanent shade makes identification more difficult, especially if plantations/fields are small. As mentioned ('Designing a classification system for use with remote techniques,' Chapter 7, p. 94), understorey identification of crops would be difficult from air photos, where permanent shade trees or agroforestry areas were significant. These areas would have to be iden-

Table 75. Air photo keys for coffee (Philipson & Liang, 1975). Key: * = useful for identifying crop.

	Feature	Coffee
IA1	Field: density	Low to medium
IA2	Size	Small to large or undefined
IA3	Shape	Variable or undefined
IA4	Assemblage	Variable or undefined fields appear to have same crop
IA5	Appearance	
IB1	Relief	Moderately to steeply sloping
IB2	Subunits	Subunits rarely occur
IB3	**Permanent shade**	*** Common**
IB4	Irrigation/drainage	Never
IB5	Special structures	Drying areas, process plant, workers' houses
IC1a	Intercropping when young	Common, not always
b	Intercropping when mature	Mixed likelihood
IC2a	Distinctiveness of individuals	Variable; fairly distinct if unshaded
b	Distinctiveness of pattern	Variable; fairly distinct if unshaded
c	Pattern	Single or parallel rows and/or grid
IC3	Tone of individuals or population	Intermediate to dark
IC4a	Form of mature individuals: height	Height 2-4 m; depends on pruning and variety
b	**Outline**	*** Circular 3 m; 4 m depends on pruning and variety**
c	Compactness	Dense; possibly relatively open
IC5	Texture of population of individuals	Usually undefined; coarse in close spacing
IC6	Special features	Varieties differ substantially
IIA1a	Nursery occurrence	Nearly always
b	Nursery aspects	Shaded
IIA2a	Planting pattern	Spaced rows or open grid
IIA3a	Harvesting method	By hand
b	Portion of crop removed	Fruit only
IIA4a	Seasonal rotation	Rarely or never
b	Annual/long term rotation	Rarely or never
IIB1a	Duration of plant life	Long, over 12 months
IIB2	Common altitude range	Generally intermediate (300-1000 m) to high (>1000 m)
IIB3	Common latitude/climate	Wet-dry tropics
IIB4	Common landforms	Variable
IIB5a	Sensitivity to drought	Fairly high
b	Sensitivity to waterlogging	High
III	Confusing vegetative forms	Cacao, citrus, forest

tified as 'confused vegetative types' and visited, since "knowledge of the region is invaluable for crop identification and subsequent interpretation" (Philipson & Liang, 1975, p. 1080).

The results of ERRMAT ('Errors and uncertainties,' Chapter 8, p. 127) were not used to correct the land use category map, merely to see if the land use map could be included as a factor in the model, and hence the comparison with vegetative cover. It was broadly representative of cover in the upper watershed and, therefore, certain activities at the time of mapping were assumed. The most serious problem with the map, however, was the unknown tillage or weeding activities associated with coffee. Reports (CIDA & Forestry and Soil Conservation Department, 1993) have suggested that maintaining the crop causes severe soil degradation, whilst McGregor *et al.* (1998) found that the weeding technique did not significantly disturb compacted soils.

Each of the ranking scenarios for the soils gave a different 'most erodible' soil. A more robust method of determining the erodibility of the soils is needed, even though all the soils, with the exception of the Agulta series, were regarded as very erodible by the local agencies (Rural Physical Planning Unit, 1990; NRCA, 2001). The boundaries presented between potentially low or high erosion are not a reality, neither are they internally homogenous, any more than a 40 m^2 pixel has a homogenous slope or vegetation cover. The concept of erosion remains socially constructed.

Strengths – Morgan (1979) could see that the model of, for example, Stocking & Elwell (1973), in which erosivity, erodibility, slope, ground cover and human occupation were added and arbitrarily divided into three erosion hazard classes, has the indisputable advantage of simplicity. The obvious simplicity of such a model has many advantages from which the PED also benefits. The problems of giving each factor equal weight and not accounting for interaction between factors are more important in absolute systems. The PED model uses six factors to produce a relative potential erosion result. Such a qualitative model is easier to produce in an area where there are data insufficiencies, but it makes validation a problem. The GPS points were taken where the canopy was clear enough to receive three satellite signals, which could vary with the erosion stake position by up to 30 m (equivalent to one pixel). In such a complex terrain, both slope angle and aspect were not always accurately calculated by the DEM (Table 73), but the model is meant to be applied to a sub-watershed scale and not field scale.

The factors were categorised on the basis of regional information (Table 44) which accounted for local agroclimatic zones, aspects, soils, slope classes and land use types. Only the classification of vegetation used a system devised outside the region. The resulting images can only be used as a guide to potential erosion areas and the model used to highlight the relative influence of those factors. There is the facility to add other influences, like socio-economic factors, when they can be mapped according to the conditions of the model.

There is a need to determine the spatial heterogeneity and erosional influence of socio-economic factors, such as land tenure, market access, farm size, subsistence or commercial production (surplus extraction) and fragmentation. The government department responsible for the cadastral inventory is engaged in computerising the national data. If those data were made publicly available, they could be combined with socio-economic factors for a degradation index instead of an erosion index. The watershed 'attractiveness' approach ('Descriptive research,' Chapter 4, p. 54) of Meijere *et al.* (1988) combined socio-economic factors, like land accessibility and development pressure, in a typical GIS suitability analysis. However, there is no consensus about certain social elements, like land tenure type, and whether they have positive or negative effect on soil erosion and degradation.

The reliability of the final images, after the conversions from ground data into non-stable paper maps and subsequent digitisation, has been investigated. The GPS site data have been compared with the DEM (Table 73) and the topographic maps (Table 46). The GPS and topographic maps varied considerably, but the 40 m resolution DEM was a reasonably accurate version of the original 10 m resolution image that was derived from the 1:50,000 map, justifying the use of the smaller filter and lower resolution for the purposes of this research.

Although identifying the highest scoring pixels was an interesting exercise, there was a risk that they were located on the image near factor category boundaries. Not only were these boundary areas potentially inaccurate due to the aforementioned mapping processes, but also socially constructed and thus prey to subjective interpretation by field workers, air photo analysts and the arbitrary nominal scaling of the factors. Therefore, the maps can only be used as a guide to potential erosion areas and the model used to highlight the relative influence of those factors, with the proviso that other influences can be added when they can be mapped according to the conditions of the model. Despite these reservations and limitations the model has considerable use in watershed management where a relative indicator of erosion potential is a necessary planning and conservation tool. However, it is difficult to calibrate, verify and validate the usefulness of the model with sufficient groundtruthing.

Interdependency

The model proposed by this research identifies individual factors, recognises that factors might be related (Table 76), but makes no claims as to their independence. In particular, the influence of slope angle and tillage activities on soil texture acts independently of surface runoff so that a water erosion model would under-

Table 76. The interdependency of factors used in the PED model.

Factors	**ACZ**	**Aspect**	**Land use**	**Slope angle**	**Soil**	**Vegetation**
ACZ		x	DGP	Runoff	Formation rates	DGP
Aspect	Moisture budget		Sunlight for crop growth	Soil moisture	Landslide frequency	Sunlight for biomass
Land use	x	x		Terracing, conservation	Tillage activities & structure	Planting controls % cover
Slope angle	x	x	Restriction on cultivation		Particle movement	Reduced soil depth, treefalls
Soil	x	x	Type, density planting	Erodibility		Nutrient and water availability
Vegetation	Micro-climate	x	Deforestation and reclaimed ruinate nutrient levels	Understorey protection, rooting strength	Depletion of nutrients, humus provision	

estimate the downslope movement of particles. Conversely, vegetative cover may reduce slope angle and, hence, erosion by the activity of natural terracette creation, which is exactly the process the conservation work of McDonald *et al.* (1996) was trying to effect in using contour hedgerows. A runoff based model cannot predict this effect. Since degree of slope controls between 25 and 30 % of topsoil characteristics (Schmittner & Giresse, 1996), it is important to understand these interdependencies in runoff and erosion processes.

In a rigorous model there is a need to separate the factors as if they were each independent. As Wischmeier (1976, p. 372) said, "The relation of a particular parameter to soil loss is often appreciably influenced by the levels at which other parameters are present. To the extent that these interaction effects could be evaluated from existing data, they are reflected in the equation through the established procedures for computing local factor values." Wischmeier gives some other examples where interaction is partly accounted for, but the basic assumption is that each factor is an independent variable. However, without the considerable empirical database that was gathered for the USLE, it would be impossible to quantify these interdependencies, although recognising them (Table 76) is an important first step.

Generalisations and predictions

Generalisation and the ability to predict are important aspects of modern geomorphology. Much research is concerned with the development and testing of theories and models of general validity that explain and predict spatial patterns. As such, uniqueness and anomalies are seen as problems rather than the extremes of a continuum. The PED model is a prescriptive analysis of the factors thought to influence the spatial pattern of erosion. It enabled generalisations to be made about sheetwash erosion in the Buff Bay watershed. However, anomalies, contradictions and unique conditions ('Analogous area index concept,' Chapter 10, p. 161; Table 71) impinged on the ability of the model to predict. The generalisations can be summarised in three different analyses.

[A] The intermediate stages of the overlay process and the spatial extent of the factors highlighted the following:

1. Three patches of high potential erosion scores in E1 were seen in the final E5 image.
2. A score of 8 or more on the E2 Erodibility (soils and land use) image marked the limit outside of which extreme scores on E5 were not found.
3. The addition of slope angle to create E3, did not create more extreme areas in E5.
4. Vegetative cover significantly reduced the number of high scoring pixels. The extent of bare ground and mapped gullies was the main influence that the soil, land use and vegetative cover images contributed to the extreme patch patterns of E5.

[B] The most common combinations or frequencies of factorial scores were determined. Using the Collection Editor in Idrisi it was possible to investigate the factorial properties of each extreme scoring pixel. These were transferred to a spreadsheet and the frequency of each factorial combination analysed. Table 77 is a summary of the results.

Nowhere in the E5 Erosion image did all the factors have a maximum score. The most common combinations had three factors that scored 5, and they were land use, slope and soil. Slope and soil always scored 5 in the most common combinations, whilst land use scored mostly 5. Vegetation scored mostly 4, rarely 5 or 3. Aspect and agroclimatic zone occasionally scored 5, but whereas agroclimatic zone scored mostly 3, aspect varied from 3 to 4. The influence of each factor on the final image of the extreme scores was also analysed in 'Using the SLEMSA analysis' (Chapter 9, p. 142), using an adaptation of SLEMSA. The factorial influence showed similar results to Table 77 with a decreasing order of importance of slope, soil, land use, aspect and vegetation.

[C] There were expected relationships between factorial class rank and extreme erosion for most of the factors. The exceptions were protective vegetation and northerly aspects that downgraded the influence of the Very Wet 2 zone, and areas of ruinate for which all the other factors were at or near the maximum.

The determination of soil erodibility was one of the more challenging factors. The textural parameters suggested moderately erodible soils, but combined with other parameters, one or two soils took on highly erodible properties. However, a calculation of the USLE value of the research area soils concluded that none of the soils were as erodible as local agencies (such as CIDA & Forestry and Soil Conservation Department, 1993) suggested. When this was incorporated in an alternative model run, the proportion of research area with an extreme erosion classification was considerably reduced (Table 68). Other alternative class rankings showed how sensitive or otherwise the model is to changes, particularly in the reduction or creation of contiguous patches of the highest level of potential soil erosion.

The achievements of the research in terms of the original objectives

This research has emphasized the need for a relatively simple predictive tool. Both Cunningham (1993) and CIDA & Forestry and Soil Conservation Department (1993) recommended the classification of the Buff Bay watershed as

Table 77. The most combinations of factorial scores in the extreme erosion class. Key: acz=agroclimatic zone.

	Score 5	Score 4	Score 3	Score 2
Most common combination	Land use, slope, soil	Aspect, vegetation	Acz	
2nd most common combination	Land use, slope, soil	Vegetation	Acz, aspect	
3rd most common combination	Acz, aspect, slope, soil		Vegetation	Land use
4th most common combination	Acz, aspect, slope, soil	Vegetation		Land use
Joint 5th most common combination	Aspect, land use, slope, soil	Vegetation	Acz	
Joint 5th most common combination	Land use, slope, soil, vegetation		Acz, aspect	

a class one degraded watershed, using qualitative and extreme risk aversion (Boolean) parameters. The model has produced an image of the watershed in which five classes (a simplification of a susceptibility continuum) of potential erosion were presented and areas of relatively high potential soil erosion were identified. Two of the objectives (‘Constraints,’ Chapter 1, p. 5) were met, but the verification of the model was inconclusive.

1. The agroclimatic zones, aspect, slope angle, soil erodibility, vegetative cover and land use factors influence and determine hillslope susceptibility to erosion, at the scale of the watershed. The degree of influence of each factor has been analysed for the erosion classes using both the SLEMSA dominant factor approach (Ndyetabula & Stocking, 1991) and the most common combination approach (extreme erosion class).
2. The factors were reclassed and overlain to provide an image showing the extent and relative susceptibility of the watershed to erosion. Contiguous patches were identified for the extreme erosion class, the extent and factorial class nature of which were further analysed. Alternative scenarios for soil and vegetative litter were considered, although fieldwork would be needed to verify new parameters.
3. A simple field monitoring programme measured actual hillslope erosion, but was inconclusive in verifying the model results (Table 74), despite introducing the concept of CEP, but also taking the limited range in model results classes into consideration. Regional data confirmed some of the model parameters, but refuted others. Steeper slope angles had a shorter effective length and hence lower erosion rates (Ahmad & Breckner, 1974), plantation offered more soil protection than natural forest due to higher levels of understorey (Richardson, 1982) and cutlass weeding did not disturb compacted soil surfaces under coffee (McGregor, 1988).

The vagaries inherent in the approach are less significant than the purpose of the research, which is to provide a much needed, simple, decision-making tool that is not dependent on an historical (erosion signs) database or equipment densities (raingauges, soil testing) beyond the budget of the government. There are no complex algorithms or indefensible weighting mechanisms, just factors known to influence erosion combined to represent potential susceptibilities to surface erosion.

Geographical Information Systems can be critically evaluated for this kind of research as a tool, but it is only as good as the information it contains. Inherent inadequacies in the unpublished geological and published topographical maps are to be expected, as well as the boundaries of the thematic maps. The accuracy of data was compromised to a degree before the issues of natural kind classification and pixel resolution were contemplated. The model produced six patches of contiguous pixels carrying a score of over 25, indicating extreme potential erosion. One of these areas was easily located on the ground using the Idrisi coordinates, despite the accepted inaccuracies. It proved to be an area where erosion signs were already well advanced. Fieldwork to locate the areas where erosion signs were already evident and check them against the model would give a measure of existing erosion. However, the purpose of the model is to identify areas, given current vegetative cover and land use information, that are potentially erodible, which may not yet show signs of erosion.

Consequences of the research

It is essential to consider the consequences of producing the results for a non-academic audience. The author intends this publication of the method and findings as a potential tool for local agencies. The cartographic model and data collection system is system independent and its application in Idrisi should be seen as an example of how the concept can be used in GIS. Mitchell (1991) suggested that parametric and physiographic classifications could be complementary. A parametric system, like the USLE, is objective, but the results are no more 'responsible' than relative physiographic results, since both have to be interpreted in terms of concepts like 'tolerable' soil loss, 'acceptable' cultivatable slope angles and 'sustainable' management techniques. It is the author's assertion that the most appropriate activity for research is to focus on erosivity and erodibility at watershed level, emphasizing relative erosion classes rather than trying to pinpoint absolute classes of erodible and non-erodible soils. No model can ever be truly universal; even process-based models need site-specific correction parameters. Ideally, each country or region should design its own prediction models to match its own conditions and to suit its database. This research does not attempt to provide an universal index, but one easily adapted to the inclusion of other physical factors.

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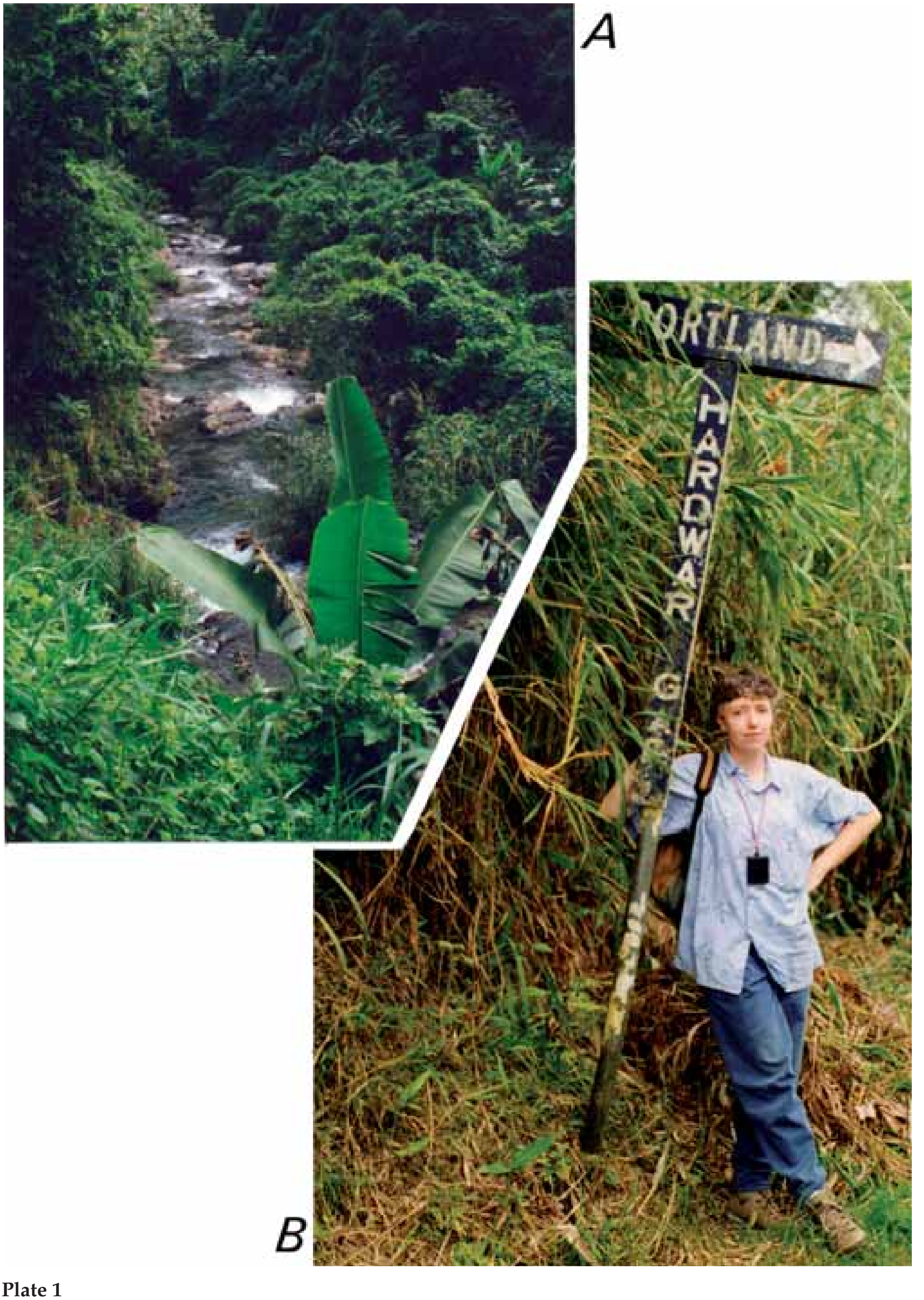

Plate 1
Fig. A. The Buff Bay River at Spring Hill.
Fig. B. The author on the watershed at Hardwar Gap.

Plate 2
Fig. A. Coffee plantation on a spur near Green Hills.
Fig. B. Freshly created terracing at Hartley Hill.

A

B

Plate 3

Fig. A. Site 1 is a grassy slope that falls away from Dr Miller’s feet (p.169).

Fig. B. Site 2 is in this wild ginger near a gully (p. 169).

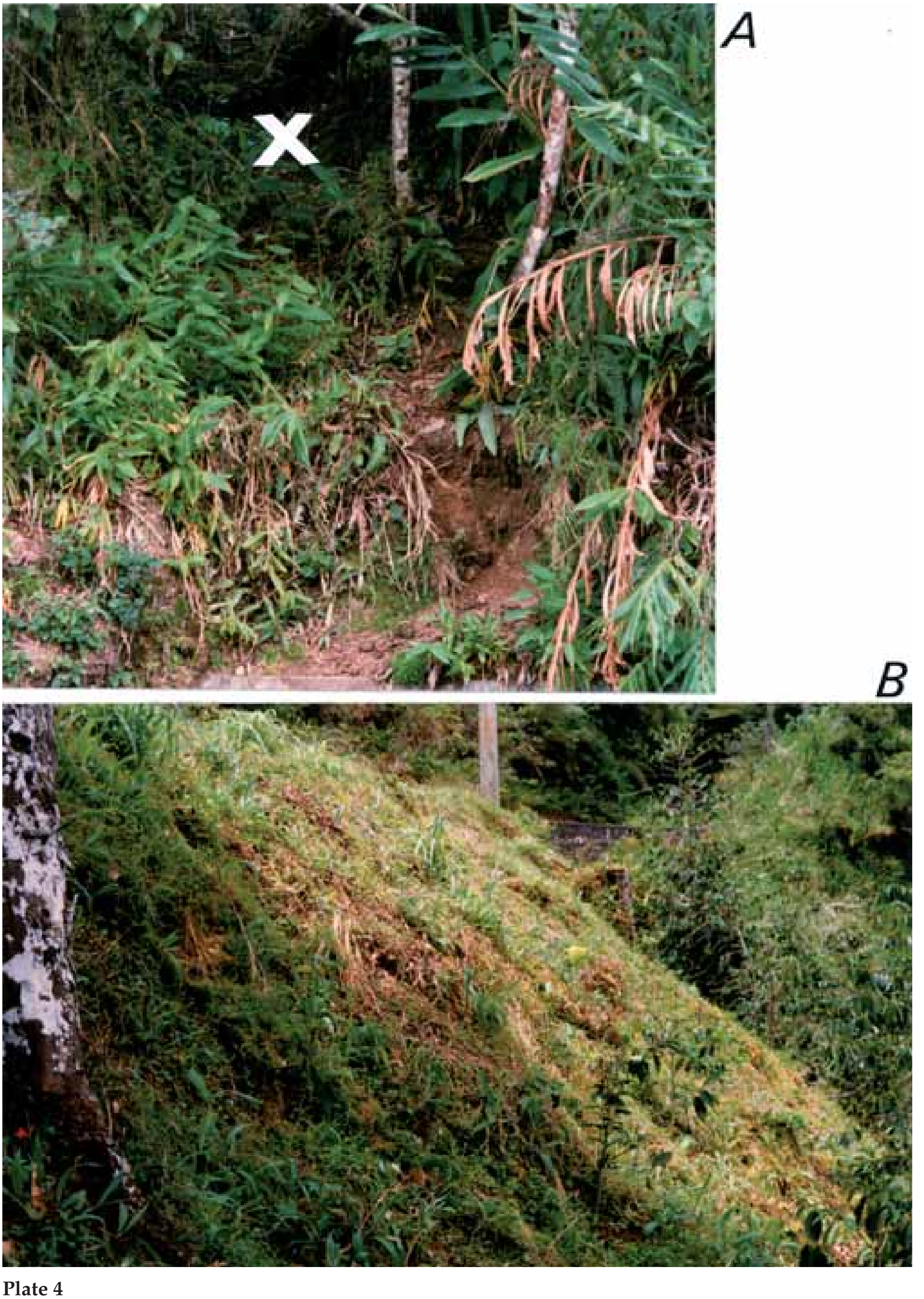

Plate 4

Fig. A. Site 3 is under canopy beyond the trees in the foreground (p. 169).

Fig. B. Site 4 is a coffee plantation (coffee seedlings) with intermittent trees and rough grass that is regularly weeded (p. 169).

Plate 5

Fig. A. Site 5 is a mixed open canopy of natural vegetation (p. 169).

Fig. B. Site 6 is an abandoned terrace (p. 169).

Plate 6
Site 7 is a bare slope near an active landslide scar (p. 169).

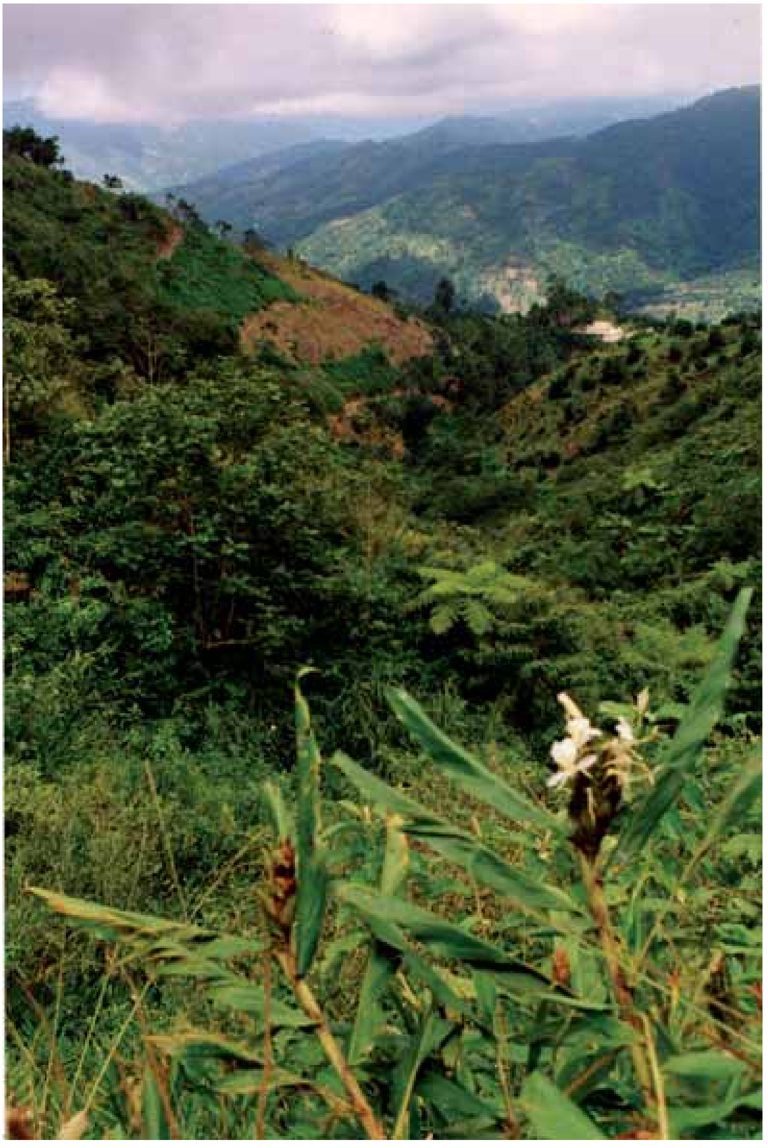

Plate 7
The bare slope in the middle distance of the photo, confirmed an area of extreme erosion in the PED model.