A DEM BASED INVESTIGATION OF MASS MOVEMENT SEDIMENT DELIVERY

A thesis presented in partial fulfilment of the requirements for the
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ABSTRACT

Environmental legislation in New Zealand has required local and regional government to place a greater emphasis upon the external effects of land use. For New Zealand hill country this means a quantitative understanding of accelerated soil erosion in terms of its effects upon downstream sedimentation and subsequent flood events. This study was an investigation into the spatial distribution of soil slip erosion (NZLRI) for the Waipaoa River Catchment (~2204km^2), East Cape, New Zealand. A combined Remote Sensing and GIS approach using orthorectified aerial photographs and digital elevation models was employed to investigate the topographic attributes influencing the spatial pattern of erosion, utilising a series of classified erosion maps. Of the variables examined, slope, aspect, elevation, and the soil moisture index (SMI) were quantitatively reaffirmed as controlling influences upon mass movement. The erosion maps in conjunction with hydrological flow accumulation images were also found to objectively determine thresholds for identifying stream channel networks from the DEM. The erosion maps when combined with historical data were used to construct sediment delivery ratios and sediment budgets for each landsystem investigated. The most significant influences upon landsliding were combined in a data driven model to assign a probability of landsliding for each pixel, which can later be used to create landslide susceptibility maps and assist in the allocation of soil conservation resources.

Keywords:

ORTHORECTIFIED AERIAL PHOTOGRAPHS, DEMs, SOIL SLIP EROSION, SEDIMENT DELIVERY RATIOS, SEDIMENT BUDGETS

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CHAPTER ONE.

INTRODUCTION.

Since the Resource Management Act (1991) was passed in New Zealand, the onus of environmental responsibility has been placed upon regional and district councils, in what has been a decentralisation of government's role in environmental monitoring. The Gisborne District Council (GDC) is now responsible for the monitoring (Section 35) of land use within its administrative region, and quantifying the effects of land use activities in terms of environmental values and sustainability.

More importantly, the GDC and other local authorities are now required to play a more active role in the mitigation of adverse environmental effects. In the context of this project, this refers to the monitoring of hill country erosion and quantifying the effects in terms of sediment delivered to the Waipaoa River, and the downstream flooding caused by aggradation of the river bed. As many more people become affected by flooding such as in the Cyclone Bola (1988) storm event, the GDC recognises that erosion in the headwaters and tributaries of the Waipaoa River is a concern of all its ratepayers, not merely residents in those locations. In accepting its role as environmental monitor the GDC hopes to influence land use through its regional policy.

The off site effects of hill country erosion are a recognised issue in landuse, and are known to have a direct effect upon the agricultural productivity and the economic viability of the wider Gisborne region. Trotter *et al.* (1990), estimated the 'cost' of Cyclone Bola storm damage to be in excess of $NZ120m to the entire North Island. Trustrum *et al.* (1984) first alluded to the deleterious effects of soil slip erosion on hill country pastoral productivity, calculating that erosion caused an 18% loss in pastoral productivity. They identified the need to quantitatively assess the effects of erosion to promote effective land management policy, and to prevent both the long term biotic and economic losses.

Trotter *et al.* (1990) claimed that pastoral productivity recovers within 1 to 3 years for surfaces covered by the debris material from erosion scars initiated by high intensity rainstorms, but by comparison the rate of soil development for the exposed scar surface itself, and its ability to sustain a productive pasture sward, is markedly slower. Lambert *et al.* (1984) had earlier found that productivity recovers rapidly over twenty years but only to 70-80% of that before landsliding.

Scientists at Landcare Research have developed a computer simulation model of shallow regolith landslides for the Waipaoa River catchment (Dymond *et al.*, in prep.). The model is aimed at running a series of land use scenarios and observing what effect these have upon the incidence of erosion and subsequent siltation of the Waipaoa River. However, at present the topographic attributes such as slope, aspect, and elevation etc. are only notionally represented in the model, and may not accurately represent the actual influence or control that each attribute has upon the spatial distribution of landslide incidence. The outcomes of this study are designed to facilitate the quantification of input parameters for the simulation model.

The essence of this project was to take a combined Remote Sensing and GIS approach to 'catchment wide' erosion mapping and modelling, for the Waipaoa River Catchment. Our aim was to investigate what level of information relating to mass movement erosion existed within the series of historical aerial photographs that were captured three weeks after the Cyclone Bola (March 1988) storm event and to relate it to topographic attributes derived from a digital elevation model (DEM). Although airphoto interpretation has become a standard technique within most landslide projects and is considered to be the most important remote sensing tool (Mantovani *et al.*, 1996), land use studies utilising aerial photography by Landcare Research staff since the early 1980's, and more recent studies (e.g. Hendriksen 1996), have identified the need for more spatially explicit imagery because of the inherent distortion that airphotos contain. This need has required the use of orthorectified stereoscopic aerial photographs as part of this project in an attempt to provide more precise locational information.

If the aim of the GDC and other similar organisations that influence land use policy is to monitor the effects of land use and mitigate their potential effects, we need to identify the areas within the Waipaoa River catchment that are deemed to have a high susceptibility to landsliding. Landcare Research have previously divided the entire Waipaoa river catchment (2204km^2, Anon. 1994) into landsystems and have ranked them according to their capacity to supply the Waipaoa River with sediment. Within each of these sixteen defined landsystems it is necessary to identify the controlling influences or combinations of controlling influences on landsliding, so that these can be used to target the potential sediment source areas. This conceptually allows areas to be targeted for soil conservation plantings and remediation techniques, promoting the most appropriate distribution of soil conservation funds for the amount of protection received.

Siltation of the Waipaoa River bed is the most significant consequence of hill country soil erosion within the Waipaoa River catchment, because of its influence on downstream overbank flooding there is a direct need to quantify the actual volume of displaced sediment that reaches the river channel. It is possible to determine this firstly by identifying the areal coverage of landslide scars in our study areas, and then combining this with depth measurements taken by Landcare Research staff following the Cyclone Bola storm event to calculate a grand total for the sediment volume produced.

Determining a volumetric measure for erosion scars addresses the question of how much sediment was displaced during the storm event. However, not all of that sediment reaches the steam channel. Therefore it is necessary to ascertain a sediment delivery ratio (SDR) to quantify the proportion of sediment produced that is actually delivered to a stream channel. Multiplying the sediment volume for each landsystem by the SDR factor will provide an indication of sediment volumes actually delivered to the Waipaoa River. The volumetric figures can then be used by hydrological and sedimentological modellers to determine subsequent bed aggradation characteristics and the resulting likelihood of flood peak locations and occurrences.

Other authors (e.g. Crozier *et al.* 1980, Eyles 1971, Fransen 1996, Gao 1993, Gokceoglu and Aksoy 1996, Shu-Quaing and Unwin 1992, have identified some of the topographic attributes shown to be significant upon the spatial distribution of landsliding in both a New Zealand and an international context. The impetus for this project is to identify to what extent these are significant within the Waipaoa River Catchment. Specifically we need to have a more quantitative understanding of these variables and how they vary across the different landsystems of the catchment.

OBJECTIVES.

1. **To identify from a DEM the key topographic attributes that influence shallow regolith landsliding within North Island Tertiary hill country.**
2. **To identify sediment delivery systems and quantify the volume of displaced material supplied to the hydrological network.**
3. **To calculate sediment delivery ratios for landsystems of the Waipaoa River catchment susceptible to landsliding.**
4. **To produce a model for prediction of the spatial distribution of soil slip erosion for landsystems of the Waipaoa River catchment susceptible to landsliding**

CHAPTER TWO

AN OVERVIEW OF DIGITAL ELEVATION MODELS (DEM'S) AND GIS APPLICATIONS OF LANDSLIDE ANALYSIS

2.1 Digital Elevation Models.

Digital Elevation Models, or altitude matrices as they have been referred to by some authors (Pike, 1988; Shu-Quiang and Unwin, 1992), have been used to such an extent in geomorphological applications that Dikau (1989) considers DEMs a necessity for quantitative analysis in geomorphology. Hydrologists for decades have been investigating their uses in calculating topographical attributes (e.g. Heerdegen and Beran, 1982) and determining their influences on overland hydrological flow characteristics.

In certain instances they are being employed as a cost effective tool to understand environmental processes in areas of limited land resource information (Gessler *et al.*, 1994). In New Zealand DEM's are becoming increasingly available (all NZ now having entire 20m digital contour coverage) giving the ability to acquire land resource information at district and farm scales (1:10,000- 1:25,000) (Dymond and Harmsworth, 1994).

Digital Elevation Models may generally take one of three forms: 1. Square grid network, 2. Triangulated Irregular Network (TIN), 3. Contour based network (Moore *et al.*, 1993). Figure 2.1 illustrates the major structural differences between common DEM formats. Grid based DEMs generally provide the most efficient structures for estimating terrain attributes (Moore *et al.*, 1993). For the remainder of this document the term DEM shall refer to a regular grid based DEM.

Moore *et al.* (1991) recommended the use of grid based DEMs for topographic attribute analysis for three specific reasons:

1. *grid based DEMs are the most commonly available form of digital elevation data,*
2. *the methods of analysis are computationally efficient and simple,*
3. *the structure is compatible with remotely sensed techniques and geographic information systems.*

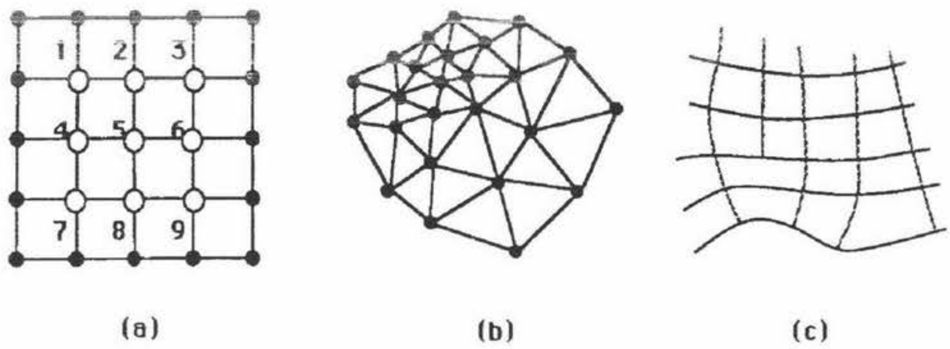

Figure 1 Methods of structuring an elevation data network: (a) square-grid network showing a moving 3 × 3 submatrix centred on node 5; (b) triangular irregular network TIN; and (c) contour-based network

Figure 2.1 DEM structure formats. From Moore *et al.* 1991.

Tribe (1991), supported the use of DEMs in geomorphology for three reasons:

1. *Digital elevation data are becoming increasingly available,*
2. *It is easier to integrate landform information represented digitally with other data than using manually/visually derived landforms,*
3. *DEM's allow automated landform recognition (DEM's being less error prone than humans and objective to questions like when is a bump a ridge?).*

Pike (1988) investigated the use of DEMs to identify landslide prone topography by its *'geometric signature'* (which he defined as 'a set of measurements that describes topographic form well enough to distinguish geomorphically disparate landscapes') faster and more economically than field mapping and airphoto interpretation techniques. Landform characterisation by DEM based analysis was believed to have the potential to reveal much about the underlying geology and its effect on geomorphic processes. Such 'topographic finger-printing' was considered to be of importance to landform analysis if it could be linked to actual geomorphic materials and processes (Pike, 1988).

Harmsworth and Dymond (1994) investigated this prediction in their study of automated land resource data acquisition utilising DEM derived techniques. They applied this concept of a 'geometric signature' to landform wide polygonisation using manual interpretation of DEM shade maps to detect lithologic changes, and tectonically influenced landforms. The authors discussed the advantages of manual interpretation on DEM shade maps that facilitated the simultaneous processing of large areas to detect subtle changes where this proved difficult with collections of individual aerial photographs.

Carrara *et al.* (1991) used a DEM to facilitate the geomorphological analysis in their evaluation of landslide hazard investigation. The DEM was considered necessary to automate the handling and manipulation of the data. Gao and Lo (1995) considered DEM's to be the best method for modelling terrain susceptibility to landsliding, and concluded that they (DEMs) provide a realistic model where geology, soil, and rainfall remained relatively constant. Gao's earlier paper (1993) considered DEMs facilitated the acquisition of land resource data by:

1. *Enabling the detection of terrain morphometry,*
2. *Making measurement of terrain variables consistent across space,*
3. *Determining the topgraphic features in areas not affected by landsliding.*

Where Geographic Information Systems (GIS) are being integrated with surface based physical models there is tremendous scope for DEM based terrain analysis. Moore *et al.* (1993) state that surface process models require topographic based data describing terrain characteristics and configuration. Using the AGNPS[1] water quality model as an example, they stated that DEM derived data (topographic attributes) can in some cases provide one third of the required input.

However, this is not to suggest that DEMs are viewed as a universal panacea for topographic analysis or surface/subsurface modelling objectives. Tribe (1991), investigated the appropriateness of DEM's, citing Mark's (1979) conclusion that DEM's do not represent an appropriate data structure for elevation data compared to TIN's (Triangulated Irregular Networks), which tend to be more information rich. Tribe (1991) identified a data inefficiency characteristic of DEMs whereby they tend to oversample areas of low relief and undersample areas of complex relief. Moore *et al.* (1991) referred to this as data redundancy. However, the regular grid structure of the DEM facilitates surface analysis by the ease of connectivity between pixels.

Mitasova *et al.* (1996) argued that although topographic investigation was a common part of GIS analysis, the methods used to construct the DEM and algorithms employed to calculate the topographic parameters did not always contain the integrity needed by physically based modelling. They specifically identified depressions and limited flow path directions (multiples of 45° = 8) for tracing overland flow as two such inadequacies. Moore *et al.* (1991), identified four weaknesses in grid based DEMs:

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[1] Agricultural Non Point Source model, U.S. Department of Agriculture.

1. *they cannot easily handle abrupt changes in elevation,*
2. *the size of grid mesh affects the results obtained and the computational efficiency,*
3. *the computed upslope flow paths in hydrologic analysis tend to zig-zag,*
4. *precision is lacking in the definition of specific catchment areas.*

DEM resolution is a subject that has received much attention in the literature. Pike (1988) originally identified *'topographic grain'* as an objective measure for optimal DEM resolution. Wood and Snell (1960) define topographic grain as *'the size of a sample area beyond which altitude range ceases to increase with area size'*. Dikau (1989) discovered that 40 and 50m resolution grids offered no adequate results in the modelling of micro-relief, features such as gullies, dunes and terraces. As a premiss for geomorphological analysis using a DEM, Dikau (1989) idealised that the smallest object under investigation should be at least twice that of the grid resolution. Wadge *et al.* (1993) gave a more quantitative indication, stating that DEM's are appropriate at medium (1:50,000 - 1:25,000) to large (1:10,000 - 1:5,000) scales for modelling because they can adequately represent the topography. Gessler *et al.* (1996) probed the DEM resolution argument issuing the caveat that topographic attributes are scale dependent.

Repetto and Wilson (1996), used five DEM datasets to calculate the slope length factor for the RUSLE[2] model and discovered that the spatial pattern varied strongly when comparing different resolution DEMs. Panuska *et al.* (1991) had earlier examined the effects of DEM resolution on topographic attribute sensitivity. Upslope contributing area or 'flow accumulation' was observed to vary greatly with cell size. Zhang and Montgomery (1994) observed a similar response for the topographic index $(ln(A_s/tan\beta))$ when investigating DEM grid size on landscape representation.

Of all the topographic attributes calculated from different resolution DEM's, slope has been found to have a remarkably stable value regardless of grid size (Panuska *et al.*, 1991). This may well have been a function of the grain size. Dymond and Harmsworth (1994), when correlating the calculated slope values for a 2m and a 12.5m DEM, noted a strong dependency upon grid size. However, Zhang and Montgomery (1994) concluded that sub 10 metre (2m, 4m) DEMs only marginally improved topographic representation. They considered that a 10m resolution DEM would be sufficient for many geomorphic and hydrologic modelling applications.

[2] Revised Universal Soil Loss Equation, U.S. Department of Agriculture.

The adequacy of DEM resolution is considered to depend upon the characteristics of the terrain under observation, with dissected topography requiring a smaller cell size than moderate relief (Panuska *et al.*, 1991). For any catchment study then, the DEM grid size must relate to the size of the features of interest, with high resolution DEM's necessary if small drainage features are important (Garbrecht and Martz, 1994). Mitasova *et al.* (1996) concluded that 2m -20m resolution DEM's are appropriate for models using upslope contributing areas in regions with complex terrain.

2.2 GIS and landslide analysis.

Many environmental models require spatially distributed inputs because solutions to accelerated soil erosion, non point source pollution and other pervasive environmental problems involve changes in land use and management at the hillslope and catchment scales (Moore *et al.*, 1993). GIS have long been associated with landslide susceptibility and hazard modelling. Van-Western and Terlien (1996) judged the spatial capabilities of a GIS to surmount the previous impediments to large area hazard zonation. Several soil erosion and non point source pollution models have been modified and combined with GIS software to take advantage of these new capabilities and provide regional soil erosion and non point water quality assessments during the past decade (Wilson, 1996).

Wadge *et al.*, (1993) considered GIS technology to have a noteworthy contribution to hazard assessment by way of three main virtues:

1. *Spatial modelling and map creation can be done on the same computer.*
2. *A variety of models can be created and displayed to reflect different hazard scenarios and in forms other than the traditional map.*
3. *The implications of hazard in terms of risk and planning can be made understandable to planners.*

Vector based systems have been used to investigate soil conservation planning at the farm scale using resource information (Priyono, 1993), or for combined geological and topographical analysis of landslides at the hillslope scale. However, the most common GIS format by far is the raster (grid) based structure which is ubiquitous in erosion and water quality models. The raster format has been shown to be more agreeable than a vector format for the calculation of factor weighted indices, although some of the resulting images have been considered to be rather pixellated (Shu-Quiang and Unwin, 1992), although the authors overcame this by applying filter techniques. Gao (1993) enthusiastically supported the raster based GIS approach to landslide analysis because of the total hillslope-wide analysis that it offered. He lamented that traditionally landslide investigations had only examined topographic attributes at the point of failure. Whereas, the grid based GIS is able to analyse all terrain influences including those at non-landslide affected locations, offering a non-biased approach (Gao, 1993).

Shu-Quiang and Unwin (1992) used a GIS to model landslide on the Chinese loess plateau using three methods: 1.Sieve mapping, 2. Factor weighting, 3. Log-linear regression. They considered the vector based approach of sieve-mapping or polygon overlays to be a particularly crude approach. The same authors viewed sieve-mapping as somewhat 'binary' in its classification and found that it tended to produce spatial discontinuities not consistent with the continuous terrain and landslide controlling factors. The choice of inputs (topographic attributes) to the sieve mapping method are viewed as being partly arbitrary. Mantovani *et al.* (1996) referred to this subjective choice of inputs as qualitative map combination. Wadge *et al.* (1993) recommended that such choice of topographic attributes requires expert judgement based upon factor relevance to the study.

To a certain extent this opens another debate regarding the subjective/objective biases of the modeller. Mantovani *et al.* (1996) used the terms *objective* and *subjective* to describe whether the methods employed in a landslide hazard model can be easily reproduced and validated by other researchers, or whether they depend upon the personal knowledge of the researcher. Hence, guidelines or strict objectives need to be identified when specifying topographic attributes for investigation.

Beven (1989) considered there to be two main aims of simulation models: *1. To explore the implications of making certain assumptions about the nature of real world systems, 2. To predict the behaviour of the real world system under a set of naturally occurring circumstances*. Wadge *et al.* (1993), categorised GIS models into either an empirical (inductive) or deterministic (deductive) approach. Figure 2.2 outlines the typical order of events associated with each approach:

Empirical/Inductive	Deterministic/Deductive
1. Expert choice of coverages that might be significant in the hazard process.	1. Generate coverages for each independent variable in the equation
2. Determine weightings of coverage variables at hazard sites.	2. Global mapping of hazard process using map algebra
3. Global mapping of hazard potential based on aggregation of weightings.	3. Retrospective validation of mapping from previous events.

Figure 2.2 Spatial modelling approaches (Wadge *et al.*, 1993).

Deterministic models assume adequate knowledge of the physical hazard to allow formation of the governing equations. The models also assume that the variables in the equations will be readily obtained from the GIS database (Wadge *et al.*, 1993). By comparison the empirical approach uses the spatial and/or temporal characteristics from past events to infer about future conditions. Here, the spatial locations of the independent variables are identified (e.g. erosion scar surface), and then analysed with the environmental attributes deemed appropriate or considered to be controlling influences (Wadge *et al.*, 1993).

Carrara *et al.* (1991) provide an example of an empirical approach to the evaluation and modelling of landslide hazard, identifying 243 historic landslide events where they investigated the geological and topographical data relevant to each site. Utilising a raster based approach they recognised the fact that in the majority of investigations into landslide occurrence the spatial analysis is centred around the single cell. The authors attempted to deviate from this pixel approach by identifying what they termed *'morphologically-meaningful slope-units'*. Thus they abandoned the discrete pixel approach and opted to analyse surficial processes at the hillslope level.

Fransen (1996) applied an empirical raster based GIS approach to the modelling of soil slip susceptibility for production forest planning purposes. Employing geological and topographic attributes risk classes were assigned to each layer according to their perceived importance upon the influence of landsliding. The study identified the flaw in ordinal summation models whereby the independent variables are not completely independent. Similarly, Gao (1993) investigated the topographical influences on landsliding following a high intensity rainstorm using a factor weighted empirical model. He found regional significance in slope instability, but local significance in topography.

Some authors regard GIS as under exploited. Wilson (1996) in his review of surface/subsurface models stated that the recent development of GIS software and databases has not significantly improved existing land surface/subsurface models or stimulated the production of new models. He concluded that the GIS was a convenient way to organise model inputs and display model predictions. Other authors have been more caustic regarding the (any) unbridled enthusiasm for GIS incorporation into surface based process modelling. Moore *et al.* (1991) referred to the rushed development of GIS using *'half-digested secondary data of different scales, with no consideration of scale effects'*

CHAPTER THREE

WAIPAOA RIVER CATCHMENT

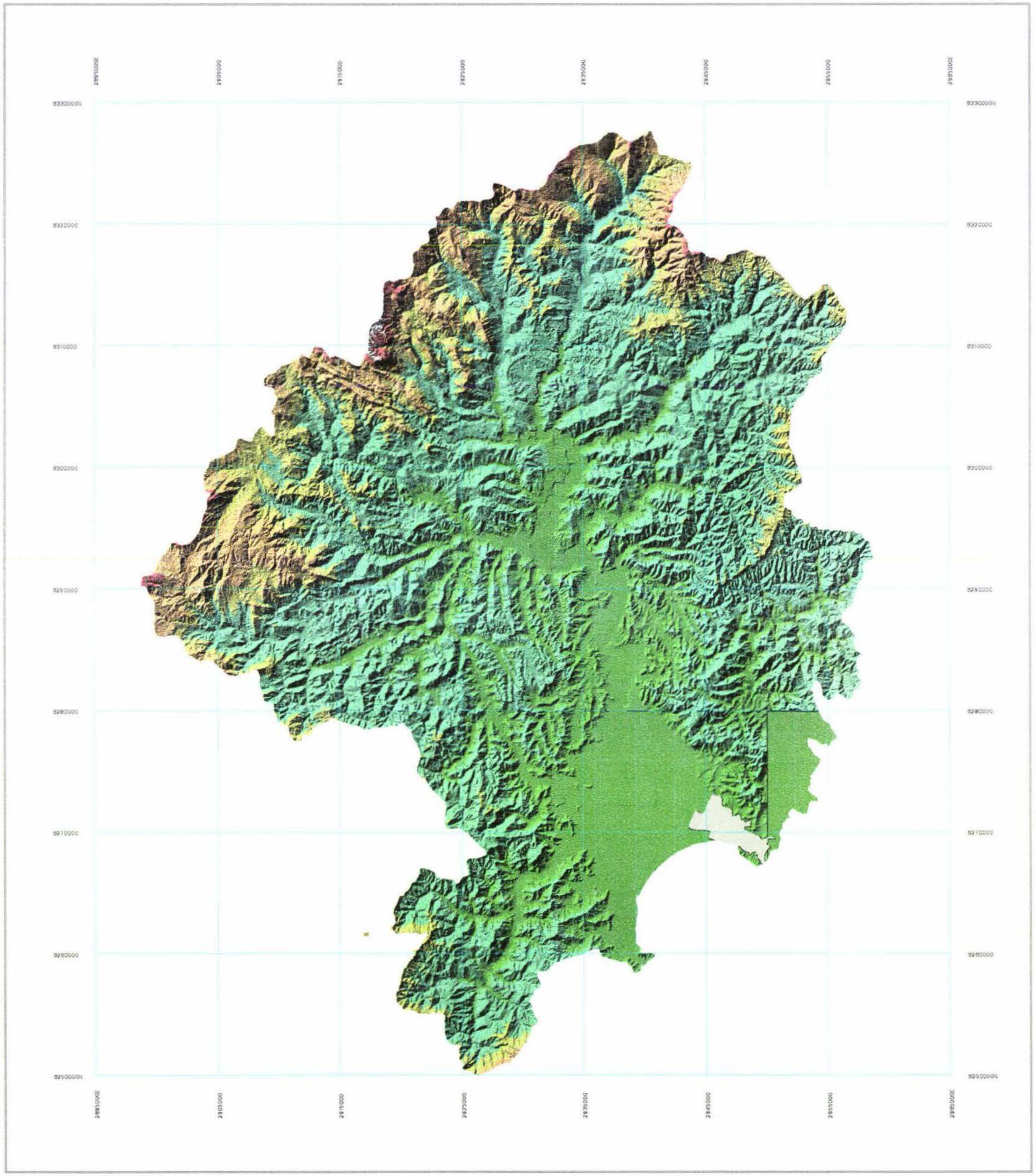
3.1 Geology and geomorphology.

The Waipaoa River comprises a 2204km^2 catchment area draining part of the Raukumara Range watershed, with its outlet to the south of the Gisborne township. Catchment geology, structure and tectonics are considered to predispose the landscape to high rates of geomorphic activity with mudstones and argillites being inherently susceptible to crushing and shearing (Anon,1994).

The Waipaoa River catchment is located on the East Coast Allocthon and the Motu Block components of what was previously termed the 'Eastern Structural Belt' of the East Cape region. The Motu block consists of Cretaceous greywacke (sandstone and mudstone) overlain by a younger Cretaceous 'cover' of alternating sandstone and mudstone, siltstone and siliceous shale. The East Coast Allocthon is a series of sheets each separated by a high to low angle thrust fault or bentonitic melange zone. The internal structure is very complex, and the rocks are tightly folded, fractured, and intensely sheared in places (Moore and Mazengarb, 1992).

With the renewed Pleistocene tectonic activity of the Hikurangi subduction zone, the former Eastern basin and the units that comprise the Raukumara peninsula have been elevated above sea level, in places creating a complex ridge and basin topography (Lewis and Pettinga, 1993). Anon (1994) provides figures of 50-60mm/yr for the subduction of the Pacific plate by the Indo-Australian plate in the vicinity of the Raukumara Peninsula. Uplift rates for the Waipaoa river catchment have been calculated at 3mm/yr, with exception to the Poverty Bay plains of the lower catchment which has zero or low (<1mm/yr) uplift (Pillans, 1986 cited in Anon, 1994).

The process of uplifting and the resulting fluvial incision (Crozier, 1983) create the relief needed to fuel the mass movement denudation of the East Coast hill country. Figure 3.1 provides an illustration of the relief for the entire catchment. The influence of tectonic activity on mass movement erosion for the East Coast region has long been identified. Bishop (1968) had earlier described the influence that rapid down cutting and over



Scale 1: 400 000

10 0 10 20 30 40 50 km

Waipaoa River Catchment

Coloured Shaded Relief

Scale 1:400 000

LEGEND

Elevation in metres

0 - 150	451 - 600	901 - 1050
151 - 300	601 - 750	1050 - 1200
301 - 450	750 - 900	Gisborne City

LOCALITY MAP

Figure 3.1

This map is drawn on the New Zealand Map Grid projection.
Coordinates are in metres at an interval of 10 000 metres.

Reliability : Topographic reference information is derived from mapping at 1:250 000 scale and should not be relied upon for measurement at scales greater than this

Plot Prepared : December 1997

Data from : Landcare Research New Zealand Limited
Digital Data Archive

Land Information New Zealand Limited (LINZ)
Digital Topographic Database
Digital Licence Number TD201200/90

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steepened slopes have on fuelling erosional processes. Gage and Black (1979) also recognised the tectonic influence on landform development and the creation of relief necessary for mass movement denudation, when working in the Mangatu Forest area of the Upper Waipaoa River catchment.

Landform expression is characteristically associated with underlying geology. Downcutting in mudstone sediments tends to produce a rounded, hilly topography, whereas alternating sequences and thick sandstones generally form asymmetric topographic features. Deep seated slumps are more common in mudstone and on the down dip side of asymmetric hills underlain by alternating beds (Moore and Mazengarb, 1992). Gage and Black (1979) also alluded to the predisposition of the long dip slopes to large scale slump features, even at very low slope angles. Surficial slides confined to the regolith zone tend to occur on steeper slopes cut across the bedding (Moore and Mazengarb, 1992). Physiographic features for each landsystem analysed in this study are listed in Table 3.1 .

Landsystem	Physiography
Makomako	Moderately steep to very steep landslide-prone hills. Slopes are moderately long with closely spaced streams and narrow ridge crests. Slopes are generally planar in profile, leading directly into streams.
Te Arai	Moderately steep to steep landslide prone hills consisting of a complex of ridges and spurs and colluvial basins and footslopes. The hills are of variable shape which is enhanced by the broken irregular surfaces formed by soil slips, narrow shallow earthflows and occasional linear gullies. Streams are narrow and often incising.
Waihora	Steep to very steep landslide prone hills. Slopes are long with closely spaced steams and narrow ridge crests. Slopes are planar in profile and lead directly into streams.
Wharerata	Long steep to very steep hills, scarps and bluffs. The hills form a system of alternating ridges and valleys with narrow ridge crests. The scarps are components of cuestas and plateaux.

Table 3.1 Landsystem Physiography. Reproduced from Anon (1994).

3.2 Land management practices.

Since the arrival of the European and their subsequent settlement (~1830 on), the Waipaoa River catchment has undergone a major change in vegetative cover from its former predominantly forest cover. A heavy bush association of podocarp-broadleaf forest existed in the valleys of the Te Arai, Mangatu, Waipaoa, Waingaromia, and Waihora rivers below the Raukumara range watershed (Hamilton and Kelman, 1952). Vegetation of the plains were dominated by kahikatea with pukatea on poorly drained soils. Tawa, titoki, puriri, matai, and totara occupied the more well drained ground (Clarkson and Clarkson, 1991).

Vegetation clearance of the hill country commenced after the 'easier' plains had been converted to pastoral landuse. Hamilton and Kelman (1952) dated the peak activity of the bush clearance at 1890-1910. Clearance generally took the form of felling trees less than 1 metre in trunk diameter followed by a subsequent burning (Gage and Black, 1979). Soon after clearing, much of the land displayed elevated grass growth (Howard, 1976). However, the productivity post clearing soon began to decline rapidly. Apparently stock numbers were maintained regardless, and only lowered under conditions of extreme stock ill thrift (Hamilton and Kelman, 1952). Shortly after clearance the initial signs of erosion became apparent. The land use practices continued and the first effects of the accelerated erosion became evident around 1910. The potential dangers of such erosion were enunciated as early as 1920 (Howard, 1976).

The continued soil erosion over the next few decades and marginal pastoral productivity of the region led the Soil Conservation and Rivers Control Council to commission a report into these issues for the Poverty Bay-East Cape district. The resultant report (SCRCC,1967) provided six cumulative reasons for the poor agricultural performance:

1. *depletion of initial fertility and soil cover,*
2. *general problems of soil stability,*
3. *land tenure and size of holdings,*
4. *isolation and a conservative attitude towards new ideas,*
5. *lack of continuous investment in farming,*
6. *farm labour difficulties.*

The dominance of current day pastoral land use within the Waipaoa River catchment can be seen in Table 3.2 which illustrates the types and extent of current land cover.

Vegetative Cover	**Waipaoa Catchment**	
	area (ha)	area (as %)
Pasture	16905	77.0
Crops	5815	2.5
Exotic forest	28667	13
Primary forest	5358	2.5
Secondary forest	3797	1.5
Kanuka/manuka	548	2.5
Fern	447	0.05
Bare-ground	986	0.5
TOTAL	**220499**	**100**

Table 3.2 Current vegetative cover of the Waipaoa River Catchment (Anon, 1994).

3.3 Catchment Analysis.

A landsystem approach of landscape subdivision has been applied to the Waipaoa River catchment to aid general catchment analysis and sediment budgeting (Anon, 1994). Christian and Stewart (1953, cited in Lynn and Basher, 1994) first proposed the concept of a landsystem and defined it as *"areas, or groups of areas, throughout which there is a recurring pattern of topography, soils, and vegetation with a relatively uniform climate"*.

Management units based upon a physiographic definition have for some time been identified within the Waipaoa River catchment (Harmsworth and Dymond, 1994), which formed preliminary landscape subdivisions. These management units have been further defined and aggregated into 16 landsystems based principally on lithology, which influences landform, erosion process, drainage density, and channel morphology (Anon, 1994). Table 3.3 details the range of geological, biological, and climatological characteristics for the four landsystems analysed in this study. Figure 3.2 provides an illustration of the spatial distribution of these four landsystems within the catchment.

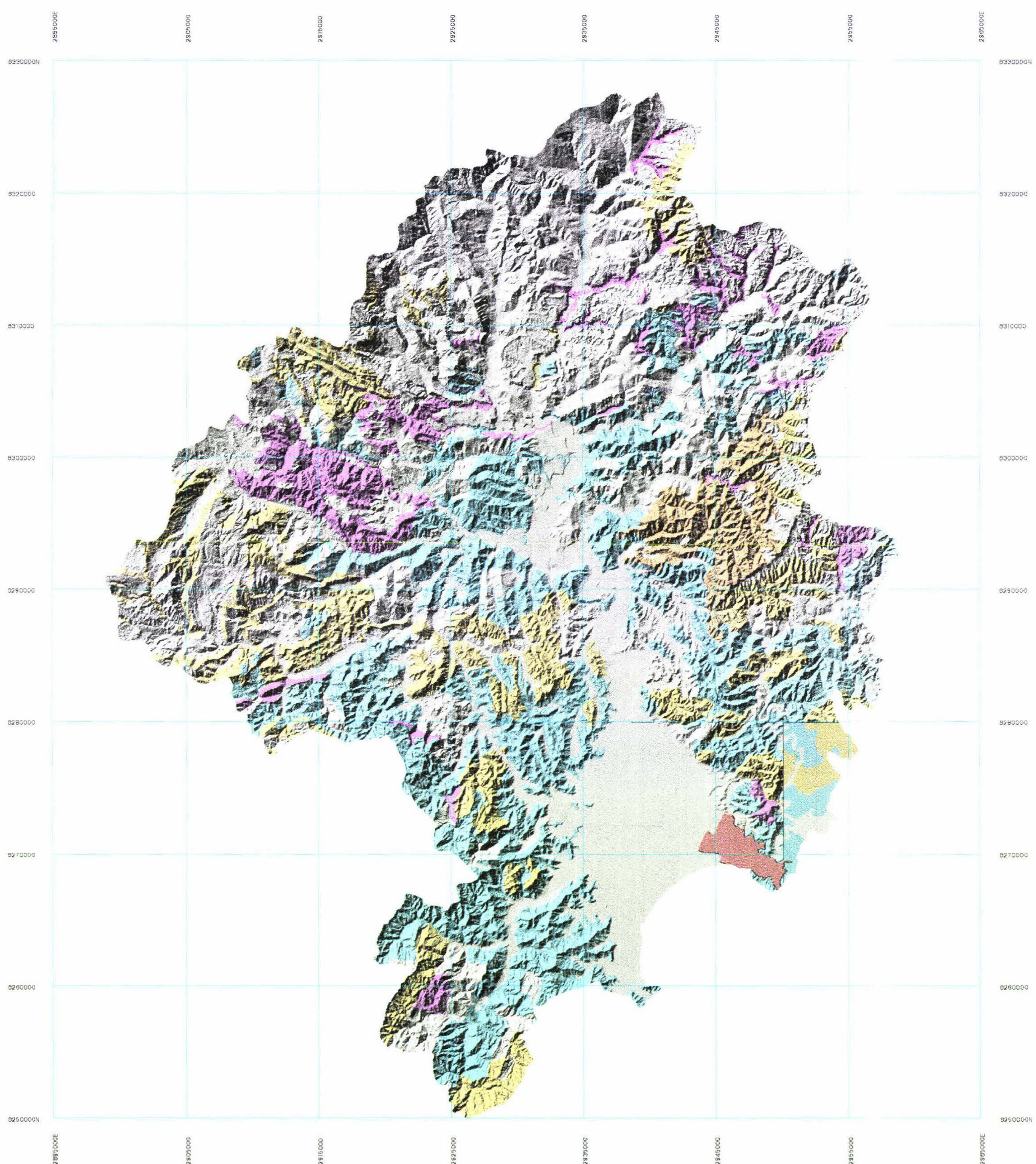
Landsystem	Lithology	Vegetation	Rainfall (mm)	Elevation (m)
Makomako	Banded mudstone	Pasture, kanuka/manuka, exotic forest	1200-2000	0-700
Te Arai	Close jointed mudstone	Pasture, manuka/kanuka, exotic forest	1000-2000	0-800
Waihora	Siltstone (massive or poorly bedded)	Pasture, manuka, mixed indigenous scrub	1200-1600	100-500
Wharerata	Sandstone (massive or bedded)	Pasture, kanuka/manuka, mixed indigenous scrub, exotic forest	1200-2400	20-1000

Table 3.3 Landsystem biogeographical data. Anon (1994).

3.4 Accelerated Erosion.

This project looks at the *'soil slip'* type of erosion process as classified by the New Zealand Land Resource Inventory (NZLRI) (NWASCO, 1979). Eyles (1983) later defined soil slip erosion as *"rapid sliding (or flowing) movements of soil and subsoil exposing a slip surface which is approximately parallel to and usually less than one metre below, the original surface"*. Table 3.4 details the erosion severity for the four studied landsystems as well as their areal proportion of the Waipaoa Catchment as a whole.

Studied Landsystems
Waipaoa River Catchment
Scale 1:400 000



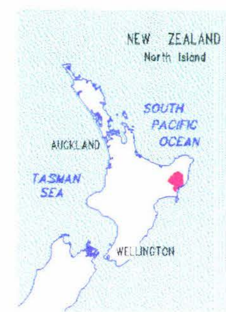
Scale 1: 400 000

10 0 10 20 30 40 50 km

LEGEND

- Landsystems not studied
- Makomako
- Te Arai
- Waihora
- Wharerata
- Gisborne City

LOCALITY MAP



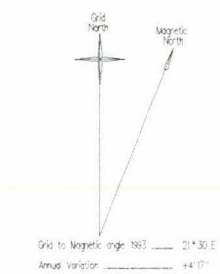


Figure 3.2

This map is drawn on the New Zealand Map Grid projection.
Coordinates are in metres at an interval of 10 000 metres.

Reliability :	Topographic reference information is derived from mapping at 1:250 000 scale and should not be relied upon for measurement at scales greater than this
Plot Prepared :	December 1997
Data from :	Landcare Research New Zealand Limited Digital Data Archive Land Information New Zealand Limited (LINZ) Digital Topographic Database Digital Licence Number TD201200/90
Prepared for :	Sediment Delivery Project (Masterate Thesis)
Supervisors :	Mr. M.P.Tuohy — Massey University Mr. J.R.Dymond Mr. M.J.Page — Landcare Research
Prepared by :	L.R. Lovell Department of Soil Science Massey University Private Bag 11 222 Palmerston North New Zealand

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Landsystem	Lithology	Erosion severity	Sediment Supply	Waipaoa Catchment area (ha)	area (%)
Makomako	Banded mudstone	Moderate to V severe	Severe	13767	6.0
Te Arai	Close jointed mudstone	Moderate to severe	Severe	51319	23.0
Waihora	Siltstone	Moderate	Moderate	7755	3.5
Wharerata	Sandstone	Slight to moderate	Moderate	27767	12.5
TOTAL				**100608**	**45**

Table 3.4 Landsystem erosion data (Anon, 1994).

The terminology applied to discrete mass movement events is a contentious issue. Crozier (1996), in his work on similar hillslope failure types in Tertiary Mudstone sediments further south on the East Coast, North Island, New Zealand, used the term *'shallow rapid earthflows'*, which is consistent with Varnes (1979) landslide classification nomenclature. From field observation of the Mangatoetoe study site in the Te Arai landsystem, where the failures occur on interbedded sandstone/mudstone sequences, they tend to be more translational in nature. In the Varnesian terminology these would be shallow debris slides, with the evacuated material being mobilised as debris flows.

Part of the problem with the lack of universal agreement over the nomenclature of mass movement events is the behaviour of the displaced materials. Pierson and Costa (1987) state that the flow of a liquefied sediment may be identified by a confusing number of terms. Coussot and Meunier (1996), in their classification of debris flows, allude to the difficulty in distinguishing flow processes as being distinct from each other. Temple and Rapp (1972) had earlier written about the difficulty of nomenclature when dealing with landslides on soil mantled slopes because of the transitional nature between one another. Varnes (1979) states that there is a complete gradation from debris slides to debris flows depending upon the water content, mobility and character of the movement. In the same paper Varnes also refers to the triggering effect of intense rainfall, stating that debris flows commonly result from unusually heavy precipitation.

Hereafter the term soil slip will be employed because of the organisational support of this project, however, the contention amongst geomorphologists regarding the nomenclature of hillslope failure is acknowledged.

CHAPTER FOUR

MATERIALS AND METHOD

4.1 Data.

Five data sets were generated for the spatial analysis component of the project from four different landsystems. The Te Arai landsystem had two data sets, with the extra acting as a benchmark for data processing and a calibration tool for algorithm construction. Primarily each data set was chosen as a representative of its landsystem. The landsystems were chosen on the basis of their susceptibility to soil slip erosion and contribution towards the total sediment loading of the Waipaoa River, which is also dependent upon their extent within the catchment. Although sixteen landsystems have been defined for the entire catchment only those four (Te Arai, Waihora, Wharerata, and Makomako) that are significantly affected by 'soil slip' were investigated.

Landcare Research archives contain a series of medium scale (1:25,000) panchromatic aerial photographs (SN11485, NZAM[1]) flown three weeks after the Cyclone Bola (1988) storm event. These airphotos provided the analogue reference to which any questions were directed during the soft copy photogrammetric classification. The stereo interpretation of the hard copy aerial photographs provided an important assistance in the erosion classification because of the ability to expedite the morphometric influences on debris tail behaviour. For the purpose of this study we focused upon *'soil slip'* erosion. The stereoscopic imagery became relevant when other mass movement processes operating in the study sites needed to be identified and edited out, e.g. gully processes.

The soft copy photogrammetric interpretation revolved around digitally orthorectified copies of the airphotos (digital orthophotos). These digital orthophotos had been produced from each of these analogue images as part of a concurrent catchment processes study objective by Landcare Research staff. The images were converted to digital form using a Hewlett Packard flatbed scanner employing a scanning density of 400 d.p.i. to provide a cell resolution equivalent to 2.5 ground metres (Betts, in prep.). An exception to this was airphoto SN11485F H20 which was orthorectified as part of an earlier study, with a cell

[1] New Zealand Aerial Mapping, Hastings.

resolution of 3.0 ground metres. The differential rectification of the aerial photographs used a 12.5m DEM to remove the planimetric distortions induced by relief displacement (Dymond, 1986), and enabled a more precise locational attribute to be identified for each hillslope failure pixel prior to the spatial analysis of the project.

Fundamental to this project was the use of digital elevation data for selected areas of the Waipaoa River Catchment, which originated as 20m contour vector format data from the DoSLI[2] NZMS260 series. The NZMS260 mapping standard ensures a 0.26mm r.m.s. error or 13 ground metres at 1:50,000 (Dymond, 1986). Prior to this study these data were threaded into a raster structure, grown using the algorithm described by Letts and Rochon (1980), which maintains the fidelity of topographic breaklines, and subsequently filtered (Dymond and Harmsworth, 1994) to produce the 12.5m resolution DEM.

4.2 Equipment.

The project was based upon the soft copy photogrammetric interpretation and analysis of the hard copy aerial photographs and their orthophoto derivatives. The ERDAS/ IMAGINE[3] image processing software was used to orthorectify the imagery, to perform the general preprocessing requirements of the data during the data capture phase, and to map the erosion during the classification process. All subsequent classified images were exported to the ARC/INFO[4] Geographic Information System. The GRID module and ARC Macro Language (AML) were employed for the spatial analysis of the datasets.

4.3 Study site selection.

The study sites were chosen in consultation with a geomorphologist well experienced in land resource interpretation and especially conversant with the hillslope transportation processes of the Waipaoa River catchment. The process of soliciting geomorphological advice was also favoured to help eliminate any potential operator bias during the study site selection process (Mantovani *et al.* 1996). Similarly, throughout the classification process, the results of the erosion mapping were verified in consultation with the same geomorphologist to ensure agreement between interpreters and to avoid any subjective or *a*

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[2] Now Terralink, and Land Information New Zealand Ltd.
[3] ERDAS Inc. Atlanta, Georgia
[4] Environmental Systems Research Institute, Redlands, California

priori knowledge assisting decision making. Table 4.1 illustrates the corresponding air photo from which study sites were chosen for each landsystem examined, and the areal extent of each study site. Boundaries defining the study sites were terminated at the hillslope-floodplain interface because the study was primarily concerned with hillslope transportation processes.

Landsystem	**Airphoto** Run / Scene no.	**Study site** Location	**NZLRI** (LUC unit)	**Area** (ha)	**Bola Rainfall** (mm)
Makomako	SN11485F / J13	Tauwhareparae	VIIe2a	105.92	~800
Te Arai (lrl)	SN11485E / J7	Ngatapa	VIe6a, VIIe5hb	395.27	~500
Te Arai (mrj)	SN11485E / J13	Waimata	VIIe1a, VIe3	346.25	~600
Waihora	SN11485F / H19+20	Ahioteatua	VIIe2b, IVe3	286.86	~650
Wharerata	SN11485E / J8	Ngatapa	VIIe5hb	95.30	~500

Table 4.1 Airphoto/study site data. Rainfall data courtesy of Page *et al.*, (in prep.).

Study sites were required to be typical of the landsystem. For Te Arai this is seriously eroded unconsolidated Tertiary Mudstone hill country. Geomorphologically, the site had to be representative of slope morphology, slope angle, the range thereof, and had to be indicative of characteristic drainage basin shape (Jessen pers comm., 1997). For the three remaining landsystems under investigation the resource data contained within the 1997 revision of the Gisborne/East Cape region of the New Zealand Land Resource Inventory (NZLRI) (Landcare Research, 1997) was consulted to provide the uniform geomorphic characteristics central to the selection of potential study sites. The rationale behind employing the NZLRI data was that for each landsystem there existed characteristic LRI units that essentially defined the 'topographic finger-print' which Harmsworth *et al.* (1994) had earlier specified as being indicators of a landsystem. Consulting the NZLRI made study site selection more accurate when defining boundaries from the airphotos and orthophotos. Table 4.1 lists the characteristic LRI units for each landsystem study site investigated.

Common to many projects relying upon photogrammetric interpretation is the practice of 'clipping' out the central region around the principal point of the aerial photograph, using only what is termed the *'effective photo coverage area'* (Lillesand and Kiefer, 1994), to minimise the effects of relief displacement (Gao, 1993). Using orthorectified imagery for all spatial analysis effectively surmounted any constraints caused by having to select study sites within close proximity to the principal point of any image. This proved to be extremely beneficial in the course of this project, as all study sites tended to be distant from the principal points. Figure 4.1 illustrates the off nadir location of the Ngatapa study site for the Te Arai (lrl) landsystem, relative to the extent of the aerial photograph as well as the severity of the erosion.

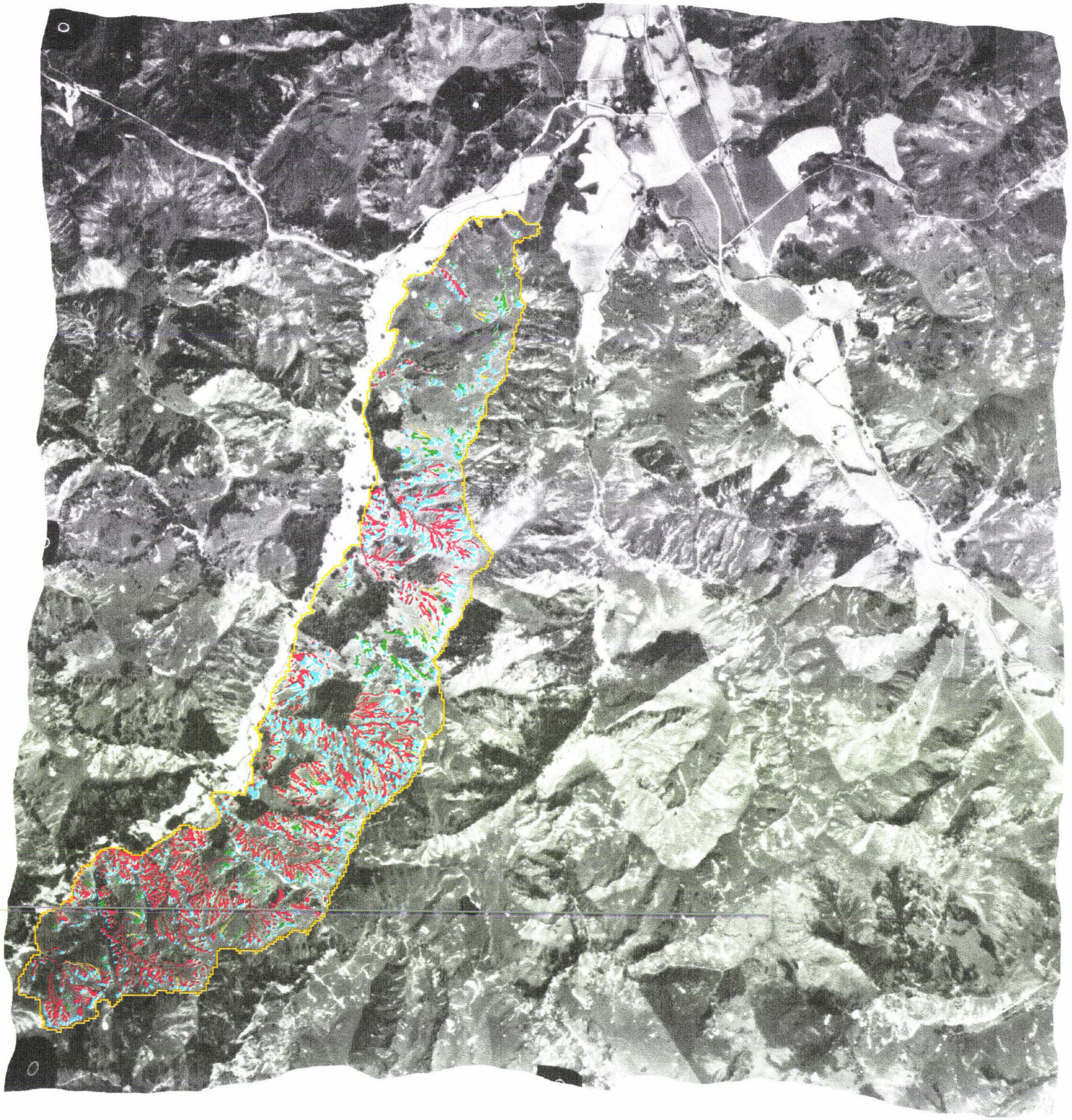
It was decided to discretise the areas of interest (AOIs), for each study site on the basis of aspect, in a form of terrain segmentation. A relatively broad aspect grouping of 90 degree intervals (N 315-45°, E 45-135°, S 135-225°, W 225-315°) was chosen. Each aspect class was clipped from the parent orthoimage for separate post erosion classification before mosaicing to produce a daughter image for each landsystem. That way a more equal representation of land area and storm induced erosion could be identified for each landsystem, as opposed to selecting one large AOI with a potentially disparate range of possible aspect values.

The AML processing conducted for the spatial analysis of bare-ground was designed to counter any imbalances in the areal proportion and frequency of the independent variables. However, it was considered better to have approximately equal representation of each independent variable prior to any spatial analysis being performed. Essentially the project was an investigation into fast, large area erosion mapping. As such the process of terrain segmentation or discretisation greatly increased the rate of data capture and minimised the amount of subsequent manual editing that was required.

4.4 Classification.

It was envisaged that a semi automated procedure be taken towards the mapping of soil slip events. This was largely necessitated by the large areal extent of the AOIs and the high spatial density of hillslope failures. There was also the need to establish a fast and reliable method of data capture. A method for classification had previously been investigated to examine the feasibility of such an approach (Jessen pers comm, 1997).

A two step approach was adopted. Firstly, a supervised classification algorithm was applied to each image based upon training signatures identified for scar and debris features. This broadly detected the majority of both the exposed erosion scar surface and the displaced regolith material based upon the bandwidth of their brightness values and their



Scale 1: 25 000

0 1 2 3 4 5 km

Erosion Classification

Te Arai Landsystem

Ngatapa study site

Scale 1:25 000

LEGEND

- Debris tails reaching channel
- Debris tails not reaching channel
- Erosion scar surface
- Debris tails for field study

LOCALITY MAP

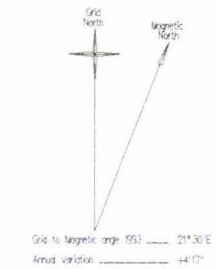


Figure 4.1

This map is drawn on the New Zealand Map Grid projection.
Classified erosion is displayed over SN11485E/J7 digital orthophoto.

Reliability :	Topographic reference information is derived from stereo air-photo interpretation at 1:25 000 scale and should not be relied upon for measurement at scales greater than this
Plot Prepared :	December 1997
Data from :	Landcare Research New Zealand Limited Digital Data Archive Aerial Surveys Ltd. P.O.Box 2031 Stoke, Nelson
Prepared for :	Sediment Delivery Project (Masterate Thesis)
Supervisors :	Mr. M.P.Tuohy — Massey University Mr. J.R.Dymond Mr. M.J.Page — Landcare Research
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tonal contrast with surrounding pasture or other vegetation. Secondly, a manual editing procedure was applied to the classified image to more accurately delineate the area and path of each landslide failure and to differentiate the scar surface from the extent of the mobilised debris and its path. The process also ensured the adequate representation of the spatial coupling of debris tails. The editing process also differentiated between sediment delivery systems (i.e. those landslides and landslide complexes which possessed hydraulic connectivity with a stream channel) and sediment non-delivery systems (i.e. those which exhausted the transported/mobilised debris supplies prior to connection with a stream channel).

Trotter *et al.* (1990) had earlier found that scar and debris complexes could not be distinguished on the basis of their radiance levels, using SPOT[5] panchromatic satellite imagery. Similarly, the exposure characteristics of the original aerial photographs (and AOI footprints in relation to the photo coverage) precluded a truly automated classification of scar separate from debris components, hence the need for the manual editing procedure based on stereo airphoto interpretation.

The resultant thematic images were given a four level definition in accordance with that previously defined by Jessen (pers comm, 1997), with the addition of a fifth class employed to represent materials for field examination. The classified differentiation of scar surface and displaced regolith material was defined as:

1. scar/debris complex not discernible separately
2. debris tail not reaching stream
3. debris tail reaching stream
4. erosion scar surface
5. debris tail not reaching stream, and selected for field observation.

4.5 Analysis.

The spatial analysis performed upon the datasets for each landsystem investigated the percentage bare ground (PBG) of erosion scars versus one of a number of independent topographic attributes derived from the DEM. Moore *et al.* (1991) divided topographic attributes into primary and secondary attributes. Primary attributes are derived directly from the raw elevation data in the (usually) 3x3 matrix. Examples are slope, aspect, and

[5] Systeme Pour l'Observation de la Terre.

elevation. Secondary attributes are combinations of primary attributes forming indices such as the soil moisture index (SMI) or water power index (WPI).

An AML was written to investigate firstly, the geomorphic surface or topographic attributes that could be derived from the DEM such as aspect, elevation and slope. All of the preprocessing and data processing is outlined in geomorphia.aml (Appendix I). It is not my intention to saturate this document with GIS operational details, instead they are documented within each of the appropriate AMLs. However, pertinent GIS and remote sensing issues shall be discussed readily.

Slope values were calculated from the DEM using the ERDAS/IMAGINE supplied algorithm based on a non centre-weighted 3x3 kernel. Pike (1988) viewed slope as the first derivative of elevation and considered it to be the most important parameter of topographic form. It was decided to examine the percentage bare ground versus slope values initially on a continuous value basis. Subsequently the slope values were level sliced into two, three, four, and five degree class intervals to observe what effect this would have on the spread of the data in terms of reducing any noise, yet still providing an indication of the relationship between percentage bare ground and slope.

Elevation was another terrain attribute to be investigated. The rationale behind choosing elevation was to determine whether or not it acted as a controlling influence upon the location of the hillslope failures. We wanted to know if the landslides occurred only at selected elevations or if they were distributed widely across the hillslopes and thus completely independent of elevation. However, the often wide range of elevation values within the datasets tended to create very noisy images when plotted on a one metre interval. As described above for slope, these values were level sliced into 10 and 25 metre wide intervals. Similarly all processing techniques are detailed in geomorphia.aml (Appendix I).

Aspect was the third primary attribute to be examined, and is defined as the slope azimuth or slope orientation (Moore et al., 1991) in degrees clockwise from North. Similar to the elevation data the wide range of values (360 using a 1 degree interval) created a noisy plot of percentage bare ground. Thus aspects were sliced into groupings of varying width into

4,8, and 16 classes, (90°, 45°, 22.5° respectively) to determine the most appropriate measure of data aggregation.

One aim of the project was to investigate the relationship between catchment area, defined as the number of upslope contributing pixels for any given pixel, and the average percent bare ground. This objective was designed to determine whether hillslope failures were greater in pixels with large catchments and therefore having greater water discharge during a storm event.

Following the derivation of the flow accumulation images (i.e. catchment area images) these data were used to construct secondary topographic attributes or indices such as the Soil Moisture Index (SMI), and the Water Power Index (WPI). Moore et al. (1991), define the Soil Moisture Index as:

$$SMI = \ell n\left(\frac{A_S}{\tan\beta}\right)$$

Where

SMI	=	Soil Moisture index
A_S	=	Specific catchment area
β	=	Hillslope angle

The same authors define the Water Power Index as:

$$WPI = \left(A_S \tan\beta\right)$$

A benefit of DEM derived topographic attributes is that they can act as surrogates for topographic features. Flow path length was another hydrologically derived topographic attribute to be examined for its relationship with percentage bare ground. It was included for use as a surrogate for hillslope length, to give an indication of distance from ridge or other local topographic maxima to the point of hillslope. Hydrologia.aml (Appendix I) details all of the data processing steps required to conduct the analysis in relation to bare ground.

Previous authors (e.g. Gao, 1993) have shown a relationship between hillslope failure and slope configuration. Hugett (1975) defined the nine possible elements of slope configuration according to overland flow paths, and their combined convergence or divergence of travel. Slopeform.aml (Appendix I) was written to identify units of consistent slope configuration from the DEM. This required identification of two hillslope curvatures, one for the profile curvature, and one for the planform curvature. The outputs of each were combined to represent one of nine possible slope form configurations.

4.6 Sediment Delivery Ratios and Sediment Budgets.

The second and third objectives of the study were to determine the relative proportion of sediment delivered to the Waipaoa River from each of the landsystems The classified images provided the quantitative details for the spatial distribution characteristics of the displaced sediment. These when combined with 100 debris tail measurements were used to calculate a sediment delivery ratio for each landsystem. Standard error of the mean figures were derived for the sampled debris tails and used to construct upper and lower limits of confidence for the resulting sediment delivery ratios. The sediment delivery ratios derived for each landsystem were then used to quantify the volumetric flux of sediment that reached the stream channel.

The sediment delivery ratio was defined conceptually as:

$$SDR = \left(\frac{\textit{sediment delivered to stream}}{\textit{total sediment produced}} \right)$$

$$= \left(\frac{\textit{total sediment produced - sediment on hillslope}}{\textit{total sediment produced}} \right)$$

$$= 1 - \left(\frac{\textit{sediment on hillslope}}{\textit{scar area}} \right) x \left(\frac{\textit{scar area}}{\textit{total sediment produced}} \right)$$

$$\approx 1 - \left(\frac{\textit{area of hillslope debris}}{\textit{scar area}} \right) x \left(\frac{\textit{scar area}}{\textit{total debris area}} \right)$$

$$\left[\text{Assuming that } \left(\frac{\text{sediment on hillslope}}{\text{total sediment}} \right) \approx \left(\frac{\text{area of hillside debris}}{\text{total area of debris}} \right) \right]$$

$$= 1 - \frac{R'}{R}$$

Where $R' = \left(\frac{\text{measured area of hillside debris}}{\text{scar area}}\right)$

and $R = \left[\left(\frac{\text{total debris area}}{\text{scar area}}\right) \approx \left(\frac{\text{average scar depth}}{\text{average debris depth}}\right)\right]$

4.7 Landslide probability.

The last objective of the project was to produce a model, specific to each landsystem that would help predict the spatial distribution of landsliding. Residual mean square (r.m.s.) figures or the standard error around the mean were used to calculate a probability of landsliding for each given pixel. The value of the r.m.s. was used to help assign a weighting coefficient to each independent variable or topographic attribute when combining with others in the model.

CHAPTER 5

RESULTS.

5.1 Bare ground classification.

The ability to select study sites across entire orthophoto scenes introduced difficulties during the classification process, because the image suffered an increasing degree of exposure falloff outwards radially from the principal point of the image. The single study site 'block' of the Te Arai landsystem straddled a wide range of exposure characteristics of the original image and thus a wide range of digital number (DN) values. Table 5.1 details the variation in brightness values of the combined scar/debris material for each landsystem according to aspect. From this table the highly variable parallelepiped limits can be seen, and some indication gained for the over-classification. A DN value of 255 was in many cases higher than the observed figures for the reflectance values of the scar surfaces. However, it was chosen as the upper limit for the parallelepiped limits because it avoided the need to arbitrarily assign an upper limit for scar features, and because such high features could only be attributed to scar surfaces in the image.

Landsystem	Aspect	DN value	Average BG (%)
Makomako	North	130 - 255	21.4
	East	140 - 255	12.6
	South	100 - 255	7.3
	West	110 - 255	17.7
Te Arai (mrj)	North	115-255	29.6
	East	75-255	33.8
	South	95-255	17.2
	West	110-255	24.7
Te Arai (lrl)	Zone 1	110 - 255	10.5
	Zone 2	130 - 255	18.0
	Zone 3	105 - 255	26.8
	Zone 4	70 - 255	28.5
Waihora	North (fh19)	110 - 255	21.7
	North (fh20)	160 - 255	17.0
	East (fh19)	115 - 255	14.0
	East (fh20)	130 - 255	25.0
	South	100 - 255	22.0
	West	70 - 255	16.7
Wharerata	North	150- 255	11.5
	East	100 - 255	7.6
	South	60 - 255	10.7
	West	110 - 255	6.9

Table 5.1 DN values of bare ground for study site.

Applying the supervised classification algorithm using parallelepiped limits to encompass values at both ends of the DN histogram led to a scene-wide gross over-classification of scar/debris material. Other incidental factors such as slope aspect, antecedent moisture conditions, pasture vigour, and variations in lithology also helped to exacerbate the over-classification, although, to a lesser extent than the inherent exposure characteristics of the airphoto. To overcome the effects of exposure falloff it was decided to divide the study site into four zones based upon similar exposure characteristics to enable a tighter cluster of scene brightness values for the DN histogram in the classification process. The other landsystems investigated were discretised on the basis of aspect (thus defining similar ranges of exposure values) prior to any classification being performed, helping to avoid the potential for over-classification due to the application of inappropriate parallelepiped limits.

Once a suitable range of parallelepiped limits had been identified to adequately represent the combined scar and debris material, it was possible to proceed to the phase of differentiating individual scar surfaces and debris tails from the initial classification of bare ground material. This step of refining the classified images relied upon the manual editing of the image. It was found during the classification process that the 2.5m resolution images produced a more accurate representation of the bare ground material. For the single 3m resolution image there was a tendency for the classified subjects to become slightly pixellated. Although this did not produce unacceptably 'blocky' results it was slightly less precise than the classification results obtained from the 2.5m resolution images.

5.2 Topographic variables as controls upon landsliding.

5.2.1 Slope.

Geomorphia.aml (Appendix I) was executed using a 2 degree interval for the level slicing operation on the original continuous value slope image. The slicing of the original image essentially smoothed the original data with an averaging method. The 2° chosen interval provided a clear indication of the overall data trend and variability, whilst removing excessive noise. Slope classes were assigned from 0 degrees (a valid data value), giving classes of 0-1°, 2-3°, 4-5° and so forth. The 2° interval also partly straddled DEM slope values for the scar surface failure plane without being an excessively wide (e.g. 5°) category.

Figure 5.1 is a composite plot of the percentage bare ground of erosion scars versus slope for each of the five data sets. As previous authors, Eyles (1971), Fransen (1996), Shu-Quiang and Unwin (1992), have noted, slope is a very important factor in the occurrence of landsliding. All datasets with the exception of the Waihora show high positive correlation figures (R^2), and landsystems with moderately long to long planar hillslopes such as the Makomako, Waihora, and Wharerata show positive linear correlation for percentage bare ground versus slope, whilst the more broken, irregular topography of the two Te Arai datasets displays a more curvilinear pattern. The fitted polynomial curves for the Te Arai data closely resemble that published by Gao (1993).

The Makomako landsystem displays the strongest linear trend for percentage bare ground versus the slope angle topographic attribute amongst all of the datasets. This strong positive correlation has an R^2 value of .856. Interestingly, percentage bare ground increases at steeper slope angles regardless of the regolith budget limitation that is generally assumed to occur on steeper slopes. The two Te Arai landsystem datasets tend to be more bimodal in their distribution, with a noticeable decline in bare ground at higher slope values. The Waihora landsystem shows a less significant linear trend for percentage bare ground versus slope angle (yet, still positive), returning an R^2 value of .462. The Wharerata landsystem shows another strong positive correlation between percentage bare ground and slope angle, with an R^2 value = .701.

The Te Arai (lrl) dataset was not sited entirely on a uniform mudstone lithology. Part of the study site contained an interbedded sandstone/mudstone sequence. This naturally affected the slope morphometry within the site, whereby the usually more rounded topography adopted a noticeably planar hillslope profile which tended to be of greater length, and produce steeper slope angles by comparison with the mudstone topography. At 29° there is a slight discontinuity in the percentage bare ground figure which appears be the upper limit of the mudstone lithology, when compared to the Te Arai (mrj) data. The increase in PBG above this point might well be a function of the change in lithology from mudstone to the inter-bedded sandstone/mudstone sequence. If so this would also explain the forcing of the curve (Figure 5.1) out to the right into the domain of greater slope angles, over and above that of the pure mudstone derived data. Any decision making shall thus rely on the greater specificity of the Te Arai (mrj) dataset.

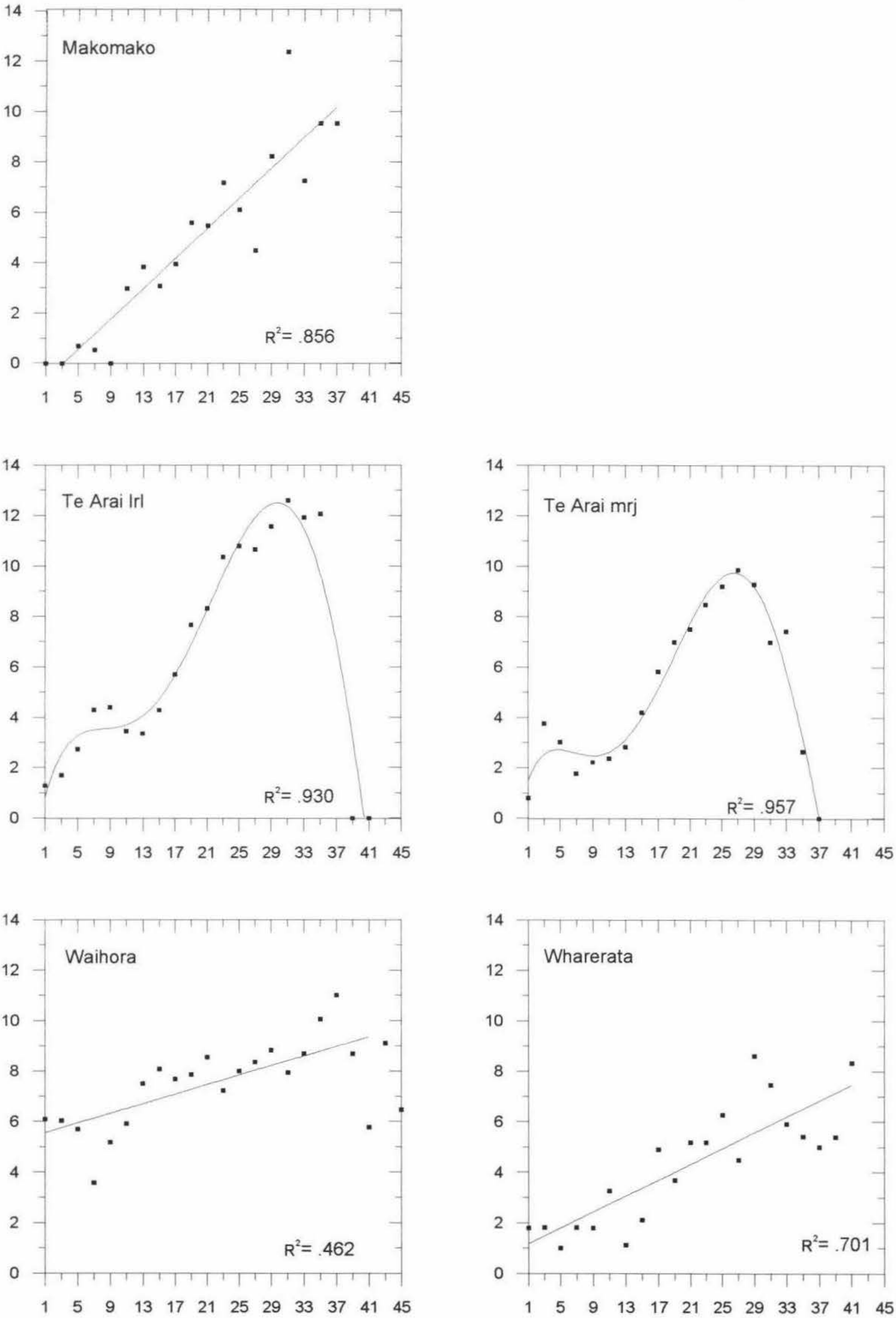

Figure 5.1 Percentage Bare Ground of Erosion Scars vs. Slope angle (X axis = slope angle in degrees, Y axis = PBG).

The slope angle frequency distributions (Figure 5.2) also illustrate the difference between the Te Arai (lrl) and Te Arai (mrj) datasets. The falling limb of the Te Arai(mrj) data is concave with pixel counts falling in the region of 26/27° onwards. However, looking at the falling limb of the Te Arai (lrl) data its shape appears to be more convex, displaying a greater number of pixels with a higher slope angle. These partly explain the greater slope angles achieved by the more stable interbedded sequence, and thus the anomaly between the two Te Arai datasets.

Noticeable from the plots in Figure 5.1 is the maximum slope angles affected by erosion which vary from 37 degrees for the Te Arai landsystem to 45 degrees for the Waihora landsystem. This suggests that the more competent and interbedded lithologies are able to reach steeper slope angles. However the plots are from study sites only and cannot be considered as absolute indications of maximum slope angles for entire landsystems.

Spread or variability in percentage bare ground around the fitted curves and regression lines does differ between landsystems. For instance, both of the Te Arai datasets are tightly clustered around the fifth order polynomial curves, whilst the Makomako dataset contains some spread around the fitted linear regression line. The Waihora and Wharerata datasets have more spread again than Makomako.

In all of the datasets, there are relatively constant percentage bare ground values at low slope angles, especially in the Makomako, Waihora, and Wharerata datasets, and slightly less so in the Te Arai datasets. At a slope angle of around 17° a noticeable increase occurs in the percentage bare ground, defining what is essentially a range of slope angles more susceptible to erosion processes for each of the different lithologies. For comparison purposes the range of percentage bare ground and affected slope angles for each landsystem are detailed in Table 5.2. Figure 5.3 illustrates the cumulative frequency distributions of slope angles for each study site allowing us to quantify the extent of the more erosion susceptible slope angles within each site

Landsystem	Slope angle ranges (°)	PBG range (%)	Susceptible slope range (°)	Corrected susceptible slope range (°)
Makomako	1-39	0-12	18/19 - 38/39	24/25 - 44/45
Te Arai (lrl)	1-41	1-12	16/17 - 36/37	22/23 - 42/43
Te Arai (mrj)	1-37	1-10	16/17 - 32/33	22/23 - 38/39
Waihora	1-45	4-12	12/13 - 42/43	18/19 - 48/49
Wharerata	1-43	1-9	16/17 - 40/41	22/23 - 46/47

Table 5.2 PBG data for the slope variable.

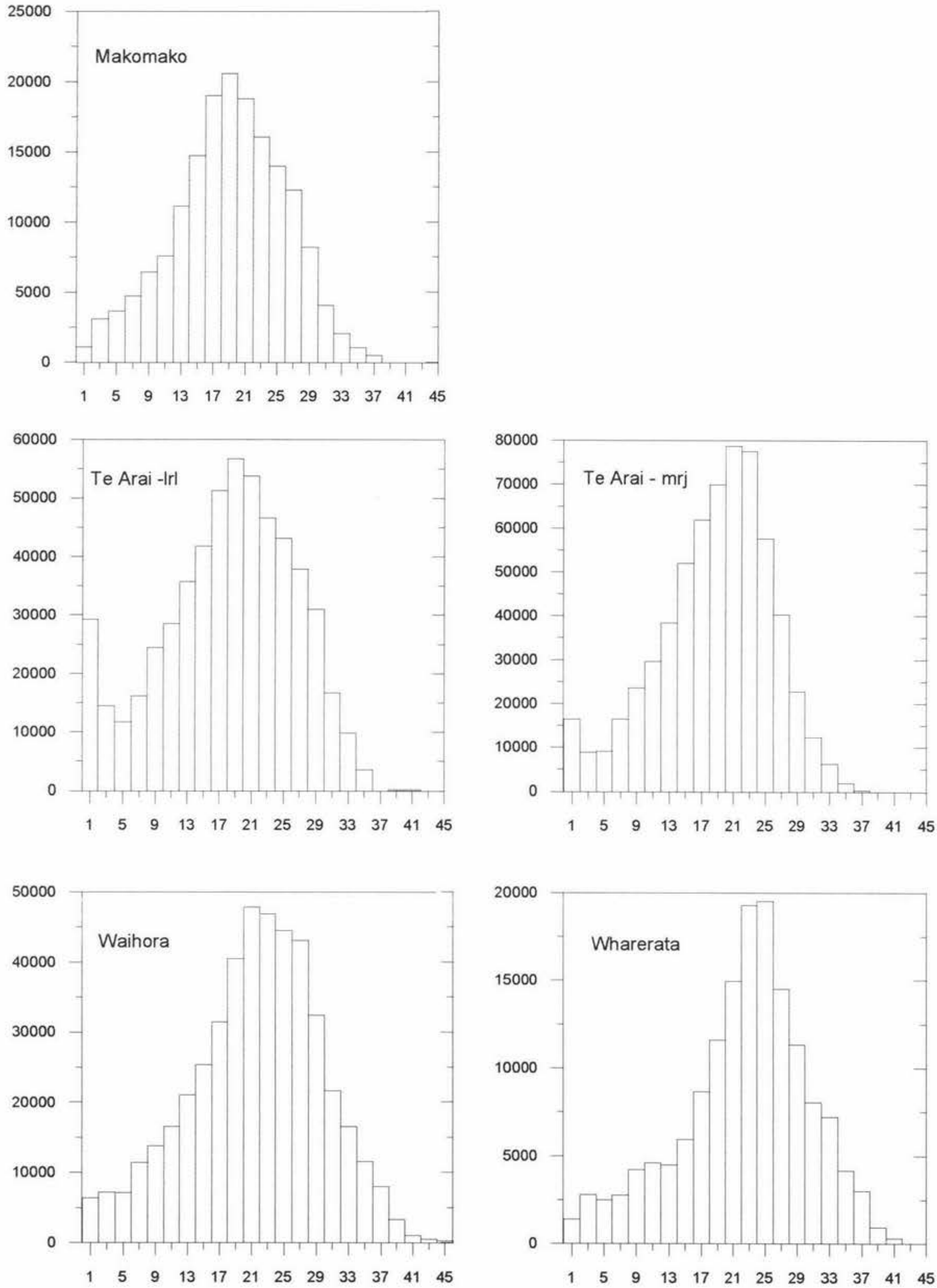

Figure 5.2 Slope Angle Frequency Distribution
(X axis = slope angle in degrees, Y axis = pixel count).

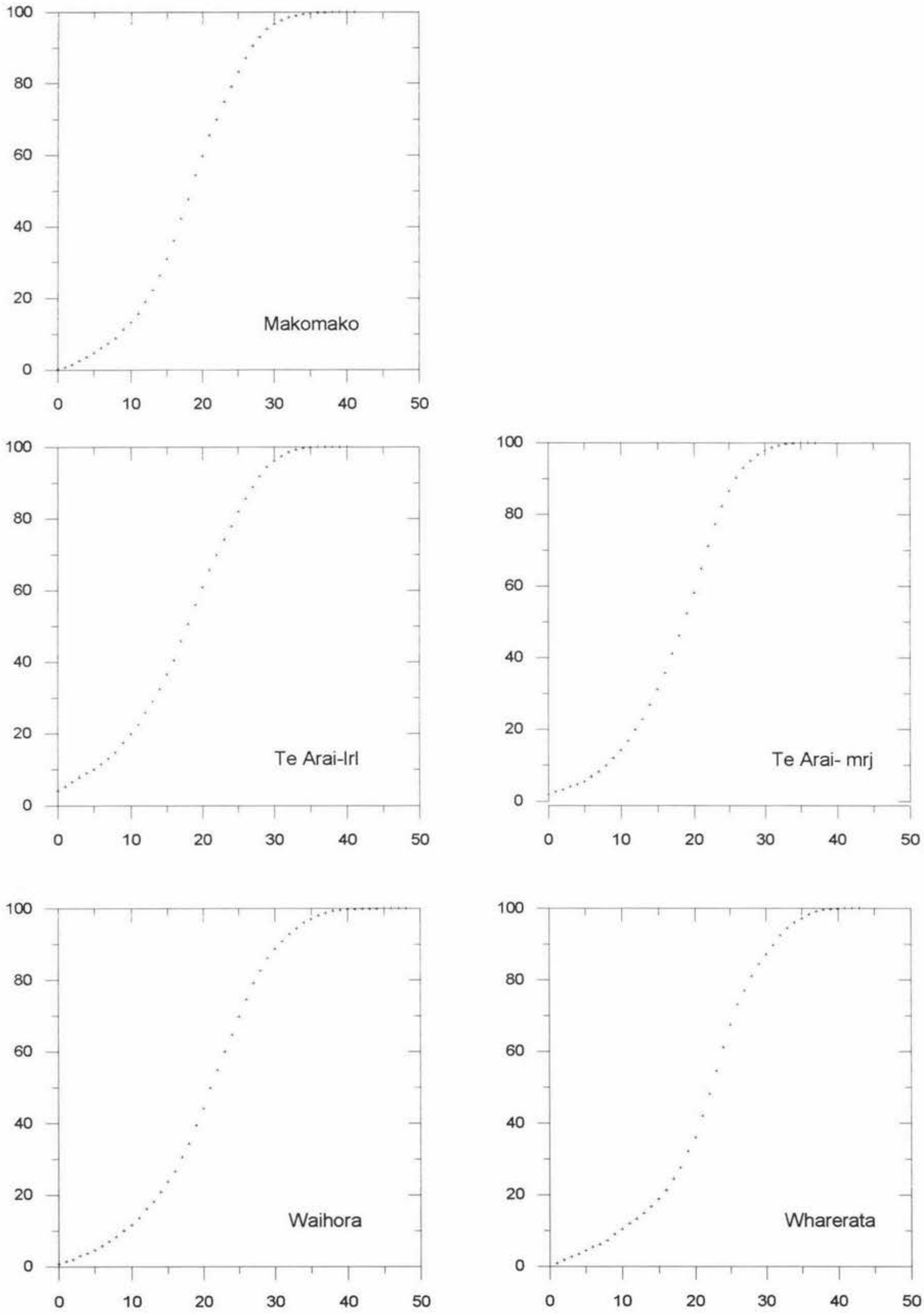

Figure 5.3 Slope Angle Cumulative Frequency Distributions (X axis = slope angle in degrees, Y axis = cumulative frequency

Dymond and Harmsworth (1994) found that DEM derived slopes underestimated field slope values by 6 degrees on average for slopes over 10 degrees, using DEMs of the same heritage as this project. Adding these known errors to the observed trends created the corrected susceptible slope range column in Table 5.2.

The Waihora landsystem shows that a lower slope angle is required for the initiation of accelerated erosion. It is suggested that this is because many of the upper portions of the hillslopes and ridge tops tend to support shallow slope angles (as observed from stereo airphotos). Although the erosion still occurs high on the hillslope in what are relatively small catchment areas the slopes tend to be lower.

The upper extent of the proportion bare ground figures, where the average is 10.5% across all landsystems, raises the point of limiting thresholds or natural equilibria capping the erosion processes. The ranges of percentage bare ground referred to above as corrected critical slope ranges display similar values to those quoted by authors overseas e.g. 24-40° (Ellen and Fleming,1987); 25-40° (Wieczorek,1987); 24-40° (Temple and Rapp,1972); 28-36° (Corominas *et al.*, 1991).

5.2.2 Aspect.

Aspect was the next terrain attribute to be examined (see Geomorphia.aml Appendix I), because of its importance in hillslope failures as suggested by previous New Zealand authors (Eyles, 1971; Crozier *et al.*, 1980; Fransen, 1996), and overseas authors (Gao,1993; Gokceoglu and Aksoy,1996). Sixteen aspect classes, or 22.5 degree intervals, were determined to be the most appropriate interval size for the calculation of percentage bare ground. Eight aspect classes (45°) gave a tighter aggregation of data values to the fitted fourth and fifth order polynomial curves. Yet intuitively, they seemed to under represent the spread of the dataset. Sixteen classes (22.5°) gave a much better indication of trends in variability or deviation from the fitted curves, whilst providing good data aggregation.

All plots of percentage bare ground in Figure 5.4 display a modal distribution (if we picture aspect as a circular variable) with a notable decrease in bare ground around the southern compass orientations. Likewise, a strong correlation exists for bare ground with

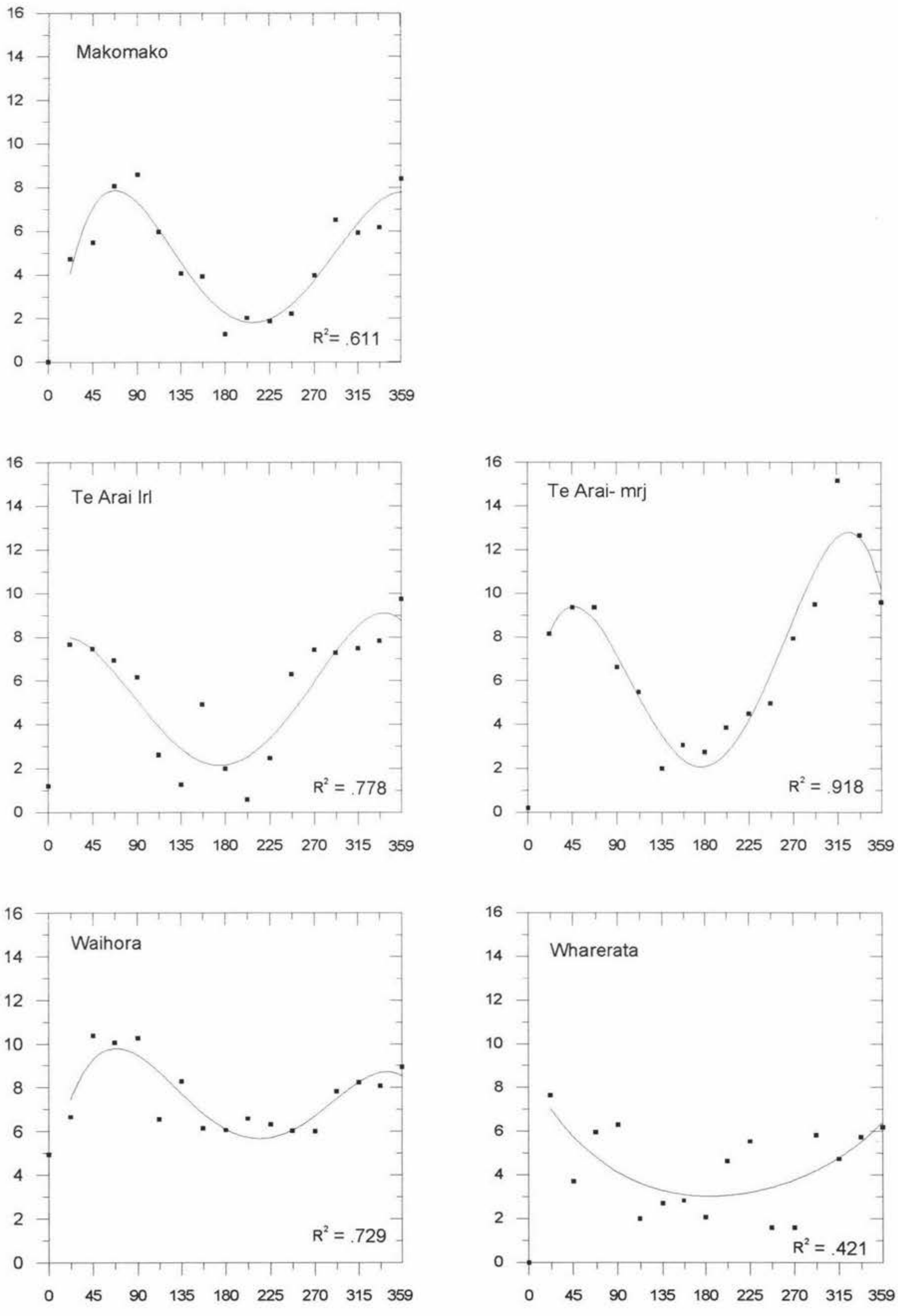

Figure 5.4 Percentage Bare Ground of Erosion vs Aspect.
(X axis = aspect class (n=16) (North= 0) , Y axis = PBG)

the more northerly facing aspect. All sites with the exception of the Wharerata data return high positive correlation values between percentage bare ground and slope orientation. Table 5.3 details the bare ground extrema as determined by aspect for each study site.

Landsystem	Min PBG (°)	Max PBG (°)	Min PBG (%)	Max PBG (%)
Makomako	180-247	270-157	1-2	4-9
Te Arai (lrl)	112-225	247-90	1-3	6-10
Te Arai (mrj)	135-247	270-112	2-5	5-15
Waihora	157-270	292-135	6	8-11
Wharerata	112-270	292-90	2-3	4-8

Table 5.3 PBG data for the aspect variable.

Overall the data conforms reasonably well to the fitted curves although minor outliers exist in the datasets. The variability of the plots tends to resemble that of the slope data whereby the Makomako and both Te Arai datasets display a fairly tight spread of data points conforming reasonably well to the fitted curves, and the Waihora and Wharerata data having a slightly greater spread.

Datapoint 157 in the Te Arai (lrl) data is unusually high in terms of percentage bare ground compared to its immediate neighbours. Further investigation revealed this not to be a true outlier, as such, but a data point with a low number of pixels at that aspect, leading to artificial buoyancy in the percentage bare ground figures. Issues relating to the trend of buoyancy within the calculated percentage bare ground figures are discussed in the next chapter (Chapter 6 Discussion). Data point 337 in the Te Arai (mrj) dataset is similarly further away from the fitted curve compared to all of the preceding data values. Investigation revealed this to be a genuine observation caused by a noticeably higher value of percentage bare ground for this particular aspect class. Two outliers exist in the Wharerata dataset around aspect values 202 and 225. As just explained for the other datasets these are aspect values represented by a low number of pixels, yet are sufficiently high to warrant their inclusion in the plot, rather than remove them as outliers.

Table 5.3 also details the quantitative characteristics of the percentage bare ground when examined against the aspect variable. Two anomalies are immediately visible, these appear to be the relatively high figure for PBG in the Waihora landsystem as a minimum or baseline figure when compared to the 1, 2, and 3% average values for the other landsystems. This could well be a function of the long linear slopes of the Waihora and their influence on surface hydrology. The other visible anomaly is the high percentage of bare ground in the Te Arai (mrj) dataset which reaches 15% maximum percentage bare ground, a good 5% higher than the other landsystems. This could possibly be explained as being lithologically determined and that it illustrates the unstable nature of the close jointed mudstone at what are maximum or near maximum slope angles.

Radar plots in Figure 5.5 display these figures rotationally and permits comparisons to be made between landsystems for both the vector and the magnitude of the erosion. There is clearly a strong North/South dichotomy when interpreting the data on a broad scale, but what explains the minor rotations within the illustrated susceptible ranges of aspect for hillslope failure? It could be that the storm and the uplift characteristics influencing the resultant ridge and valley orientation characteristics provide an explanation for the variation.

Aspect has previously received attention within the NZ mass movement erosion context. The literature identifies two major seasonal patterns (and influences) of hillslope failure. Eyles (1971), working in the Central Hawke's Bay, attributed the importance of aspect to the predisposition of the hillslopes to desiccation with actual failure induced by fissuring and the subsequent interception of the catchment run off. The level of soil moisture in the more stable southerly aspects was found to have a compounding influence on overall stability by ameliorating the potential for fissuring, and by supporting a denser vegetation cover.

Crozier *et al.* (1980) also found that northerly aspects were strongly correlated with hillslope failure during their study of a winter 'storm' event in the Wairarapa, East Coast, North Island, New Zealand. However, the failures were not attributed to desiccation, as the antecedent moisture conditions were extremely high. The authors stated that aspects affected by failure were not any wetter than the more stable aspects. The quantity of material available for movement was cited as a controlling factor in relation to aspect. It was found that historically the (seasonally) wetter southerly aspects had suffered a greater degree of regolith stripping, thus reducing the budget available for movement

Fransen (1996) (working in the Central Hawke's Bay) more recently identified a similar pattern to that of Eyles (1971), and referred to the significance of aspect in relation to soil

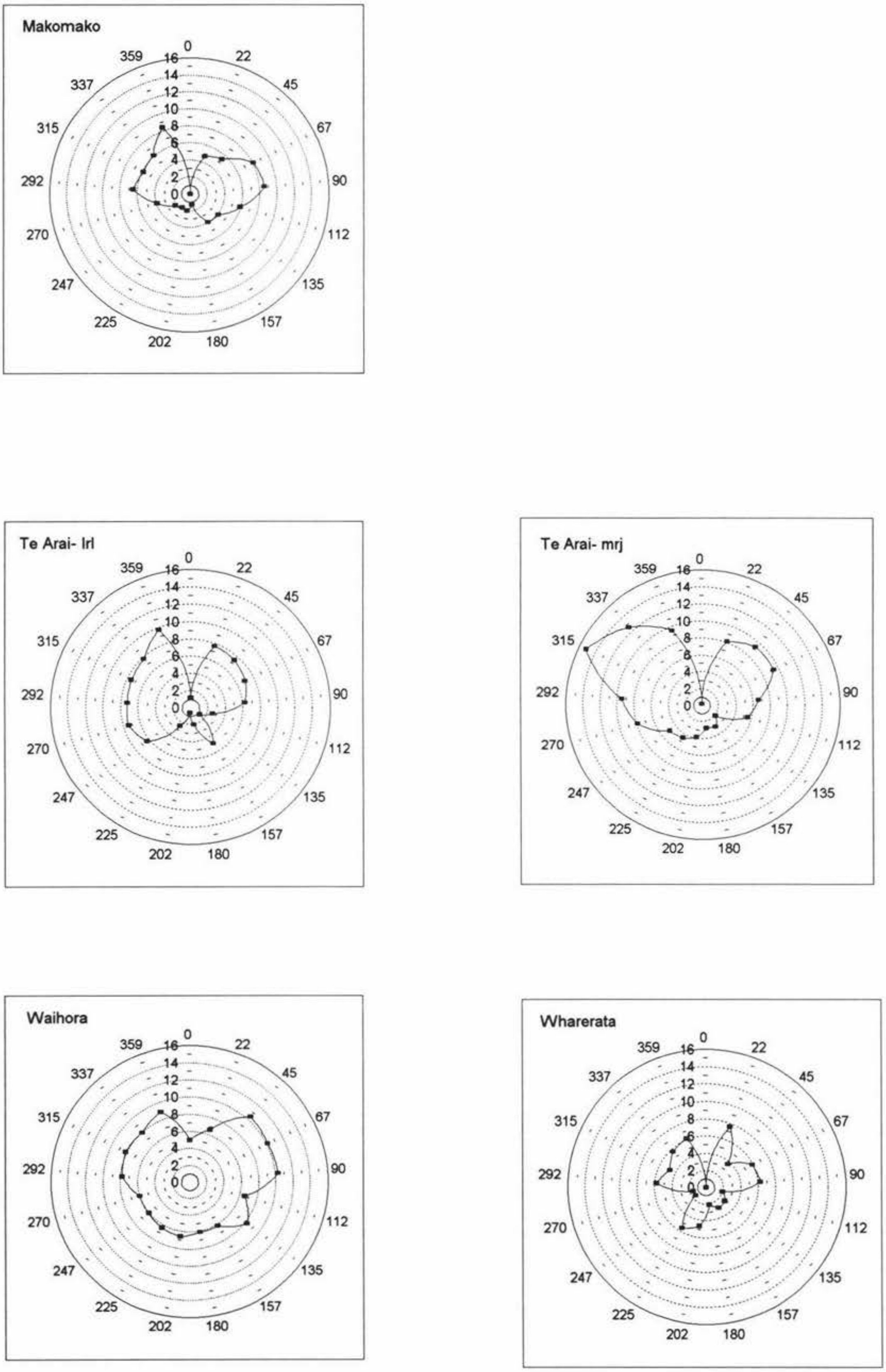

Figure 5.5 Percentage Bare Ground of Erosion vs Aspect (ρ = PBG, θ = Ave of aspect class.)

slip erosion risk. He observed that the highest density of failures occurred on the northerly and westerly aspects, with other significant failures in the easterly aspects. Overall, the southerly aspects were found to be far more stable. This project shows a similar trend or predisposition for hillslope failure as related to slope aspect, although no investigation has been made into the antecedent moisture conditions or *in-situ* regolith budgets.

5.2.3 Elevation.

Figure 5.6 illustrates the plots of percentage bare ground versus elevation. Elevation values are a mean based upon a 10m wide level slicing approach similar to that applied to the other independent variables. For reasons outlined earlier the level slicing approach was used mainly to assist in noise removal. In datasets such as aspect and elevation where actual values cover a wide range it facilitates interpretation by the reader, with minor adjustment to the original data. Table 5.4 details the range of percentage bare ground, and critical range (assuming a 4% PBG threshold) for each landsystem.

Landsystem	PBG (%)	Critical elevation
Makomako	1-9	380 - 480
Te Arai (lrl)	0-16	100 - 360
Te Arai (mrj)	2-11	80 - 280
Waihora	4-13	80 - 400
Wharerata	2-10	100 - 340

Table 5.4 PBG data for the elevation variable.

Strong linear correlation exists for both the Makomako and Te Arai (lrl) datasets, while the Te Arai (mrj) and Waihora datasets are more parabolic. The Wharerata dataset could also be described as parabolic, however, the curve is fitted with much less certainty. The parabolic curves conform well to those published by Gao (1993). At higher elevations for some of the datasets (Te Arai (mrj), Waihora) there appears to be less material available for displacement, and thus Figure 5.6 displays a declining percentage bare ground. Other authors have used this point to analyse the initial volume of the slide mass as a controlling influence upon the initiation of landsliding. However, this condition is not universal in the datasets as exampled by the Makomako and Te Arai (lrl) which display increasing bare ground at higher elevations.

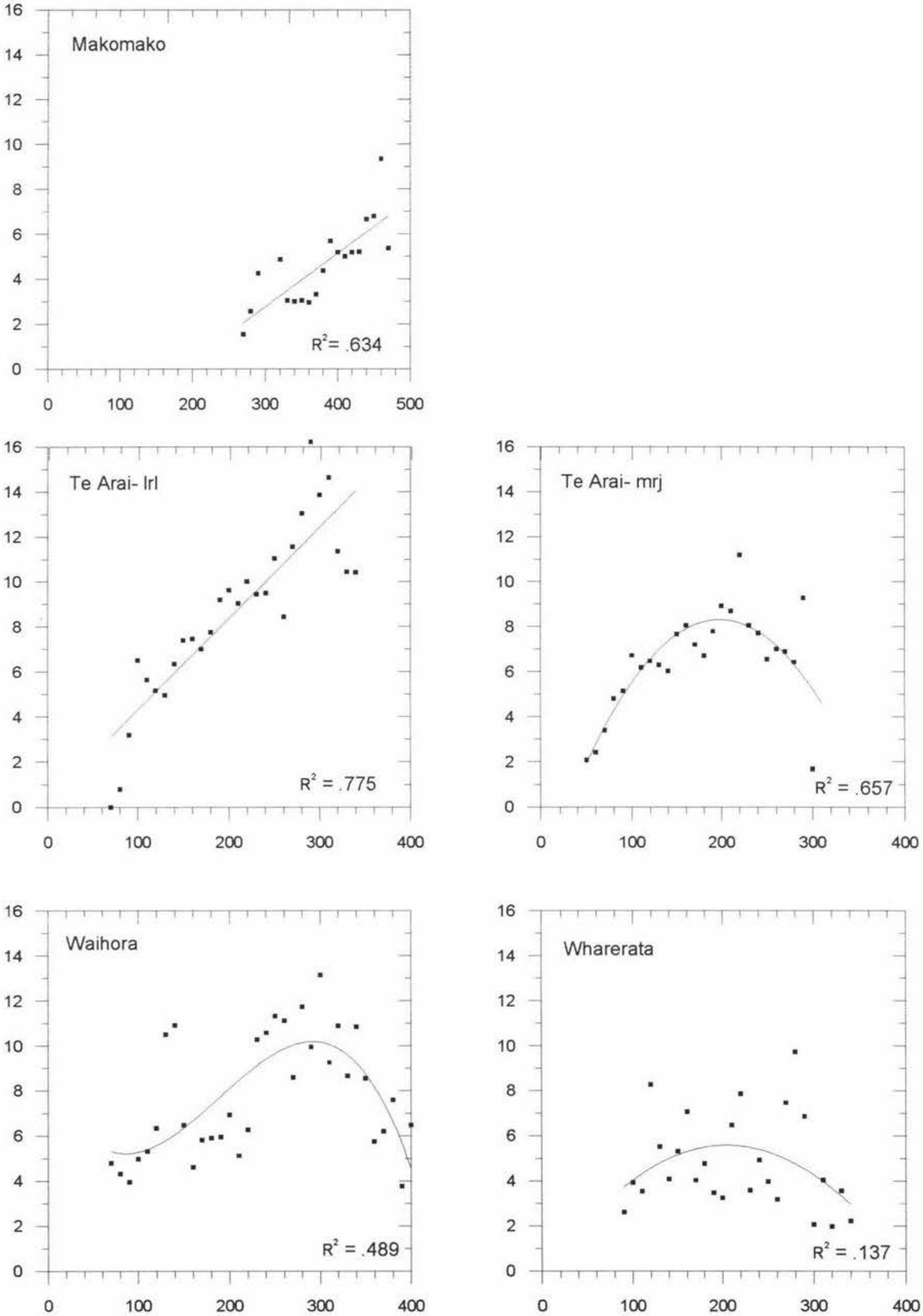

Figure 5.6 Percentage Bare Ground of Erosion Scars vs Elevation
(X axis = elevation in metres, Y axis = PBG).

Again there is an anomaly between the two Te Arai datasets which, as previously found, can be explained reasonably well by the presence of an interbedded sandstone mudstone sequence in the study site. Similar to the bedded lithology of the Makomako landsystem it allows steeper slope angles to develop, which tend to be more stable at higher elevations. Thus the sequence is creating an artefact in the context of the Te Arai landsystem which is defined purely as a close jointed mudstone lithology. As was found with the aspect datasets the Waihora landsystem has a higher minimum percentage bare ground, yet fits well with the overall data trends.

Elevation was chosen as a topographic attribute to investigate because of the need to examine whether or not it determined a critical elevation range for landsliding. A secondary purpose was to use the results to determine if the concept of hillslope regolith budgets can be identified and applied to the given landsystems, as well as to see if historic excavation can be considered to have had any effect on these budgets.

The Makomako and Te Arai (lrl) datasets both show increased bare ground at higher elevations (and thus a negative response to a regolith budget becoming the limiting factor upon failure), whilst all other datasets display a drop off in percentage bare ground. From field examination of the Te Arai (lrl) study site this is attributed to the shallow lithic contact of the soil profile. Thus the soil profile is able to conduct less storm rainfall than a soil profile with a greater weathering depth, leaving the upper layers super saturated and exacerbating failure. Post storm event the erosion scar then migrates upslope gradually following the initial failure. It appears to require less significant triggers to gradually nibble away at the headscarp successively rather than the clearly defined failure planes in other lithologies. Thus the bare ground figure tends to increase with time following the storm event.

There is a notion that higher elevations can and do sustain higher overall slope angles. This implies that any relationship between percentage bare ground and elevation is really controlled by slope. Figure 5.7 is a plot for each landsystem to investigate the range of slope angles for elevation class intervals to test this hypothesis. As we can see the fitted curve illustrates a tendency for the Te Arai (lrl) data to support slightly greater slope angles at higher elevations. However this trend is not consistent across all of the datasets.

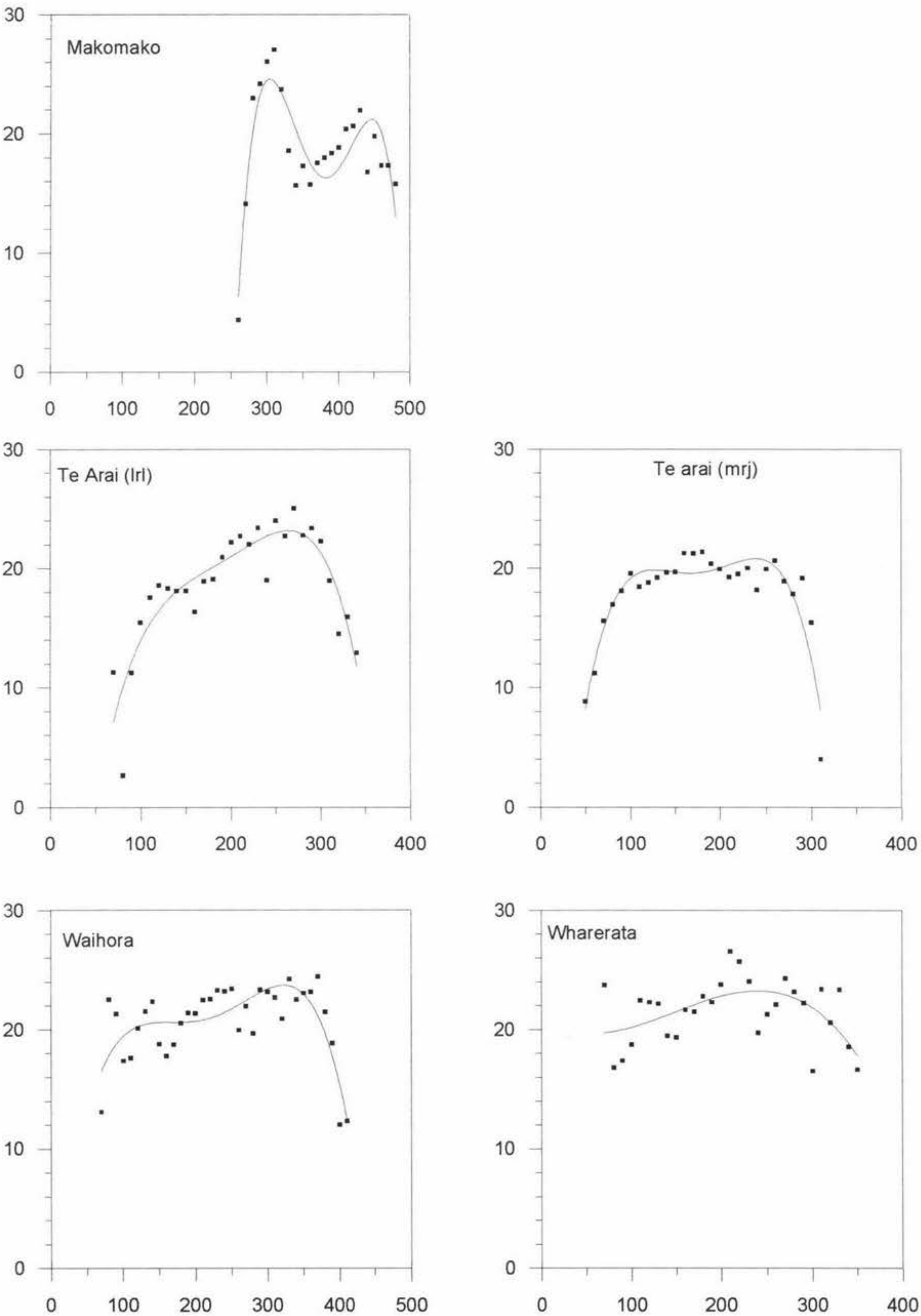

Figure 5.7 Slope Angle vs Elevation.
(X axis = elevation in metres, y axis = slope angle in degrees).

Generally, steeper slope angles occur at low to medium elevations, and are not strongly associated with higher elevations.

5.2.4 Slope configuration.

Previous authors (eg Gao, 1993) have identified slope configuration or the slope morphometry as being statistically significant upon the initiation of landsliding. Slopeforms which are concave-concave have been judged to be the most susceptible to landsliding, followed by those with concave planform curvature. These slope forms promote the convergence of overland flow, or the concentration of runoff within swales. These quantified investigations of slope configuration have been supported by field observations (eg Trustrum *et al.*, 1990; DeRose *et al.*, 1991; Hendriksen, 1996).

Slopeform.aml (Appendix I) was written to investigate slope configuration as an independent variable to see what effect it had upon landsliding. Slope curvatures were extracted from the DEM for the profile (upslope) direction, and planform (alongslope) direction. The values for each cell were then reclassed into one of three domains: 1. concave, 2. linear, 3. convex, depending upon the relative change in elevation along the direction of sampling. Combining the values for both curvatures provided for each cell an indication of the three dimensional slope form. Figure 5.8 illustrates the nine possible slope form elements. However, the previously identified trends are not consistent with the spatial distribution of landsliding as investigated within this project, using slope curvatures derived from 12.5m resolution DEMs.

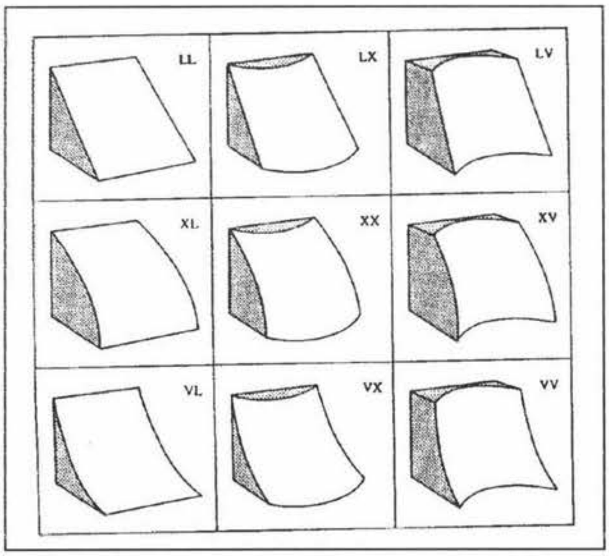

Figure 5.8 Slope Form elements. From Gao and Lo, (1995).
(LL = Profile/Planform curvature)

Figure 5.9 provides an illustration of the percentage bare ground figures extracted for each type of slope form. Strong trends are not immediately visible for any particular slope form, only the Waihora landsystem shows a predominance of landsliding within concave-concave slope elements. However, the Makomako and Waihora show relatively high percentage bare ground figures for slope elements with a concave planform curvature. One feature that does become apparent is the consistency which slope elements having a convex planform curvature return high values of percentage bare ground for each study site.

It is pertinent at this point to question whether the 12.5 resolution of the DEM can adequately define dissected topography for the purpose of representing a three dimensional land surface as a categorised slope element form. Geomorphologists using larger resolution DEMs (25m) to establish channel head locations have found that some finer drainage channels are poorly detected by the DEM (Jessen, 1997, pers comm). It is suggested that the 12.5m DEM is similarly of insufficient resolution to identify fine textured channels. Whereas spurs tend to be larger, more dominant features which are more easily identified from the DEM in the form of slope curvature, and thus appear consistently with high percentage bare ground values in Figure 5.9.

5.2.5 Flow accumulation.

The project not only investigated geomorphic topographic attributes but also sought to examine the effect of overland hydrological flow on landsliding in relation to catchment size. Ellis (1996) believed that flow accumulation and flow path length influenced the location and severity of soil erosion. The aim was to ascertain whether similar observations could be made for the Waipaoa River catchment. Flow accumulation which is defined as the number of upslope contributing pixels for a given pixel was computed for each pixel in the images and used as a surrogate for catchment area. The objective was to test if a relationship existed between catchment area and the occurrence of landsliding, or in this context, percentage bare ground. The ARC/INFO GIS software used to calculate flow accumulation employs the algorithm outlined by Jenson and Dominique (1988), based upon the D8 flow routing concept of O'Callaghan and Mark (1984).

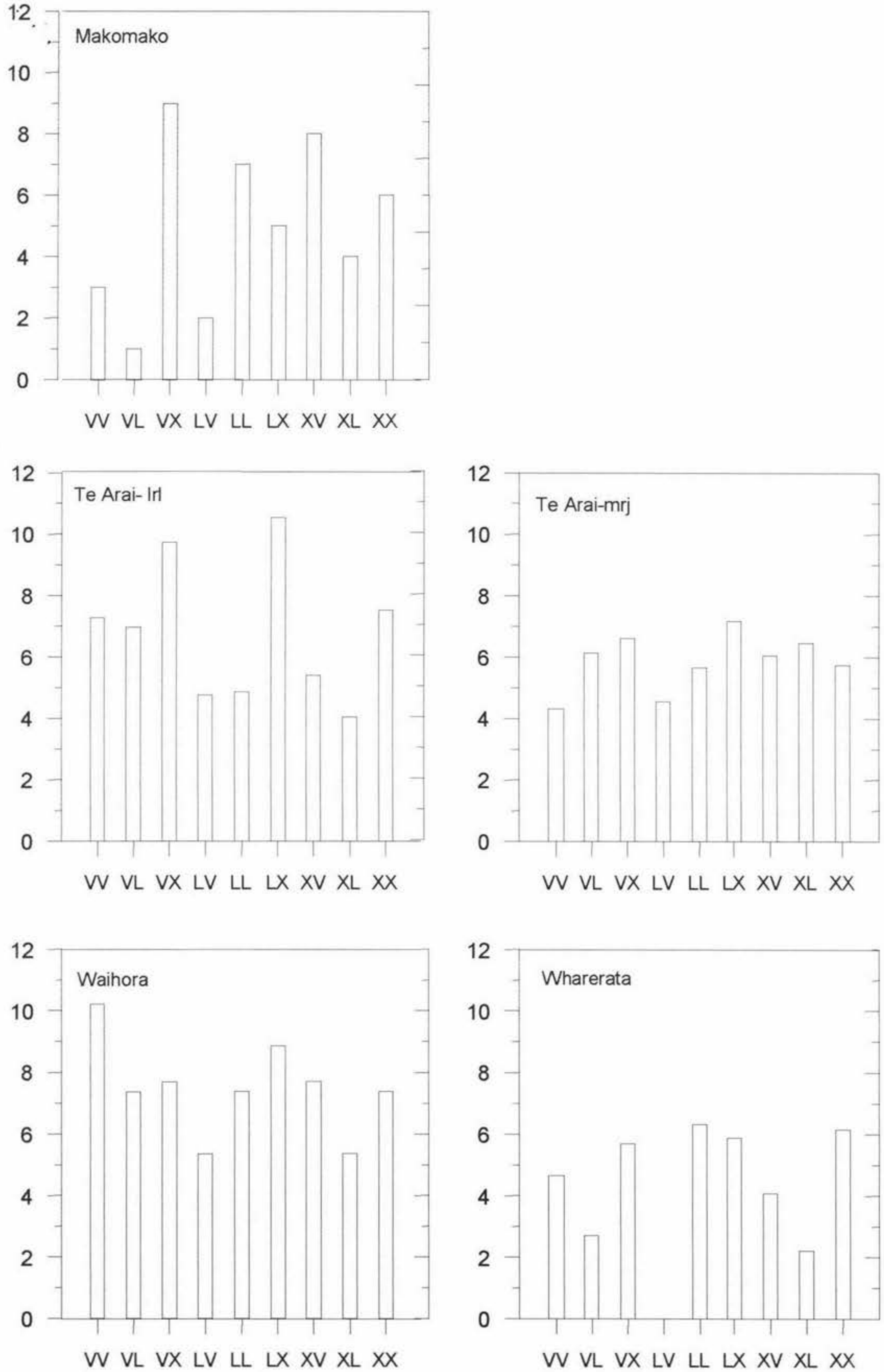

Figure 5.9 Percentage Bare Ground of Erosion vs. Slope configuration (X axis = slope form (profile/planform), Y axis = PBG).

Figure 5.10 is a cumulative frequency distribution of catchment area for each study site. Assuming a threshold of 65 for channel head location (Jessen,1997, pers comm) we can see that the zero order catchments in which erosion tends to predominate (as observed from stereo airphotos) occupy some 10% of each study site.

Characteristically, overland flow accumulation images span several orders of magnitude, and display a sigmoidal curve. For the convenience of graphing the results a log transform $40 \log_{10}(x + 1)$ was applied to the data to keep it within an 8 bit display (0-255) range, and to facilitate general file handling. The log transformed data plots (Figure 5.11 highlight an interesting characteristic trend of data spread. The percentage bare ground figures versus flow accumulation, initialise themselves with a relatively constant rate of percentage bare ground for smaller catchment areas, then after what appears to be a threshold like value in the data spread rapidly. The overall trend for the entire datasets is for percentage bare ground to decline with increasing catchment area (if we fit a linear curve). However, the maximum values for percentage bare ground, tend to increase with catchment area.

Similarly, the range of variability increases greatly with catchment area. This is a logical observation if we consider that as catchment area increases in size the pattern of hillslope failures would vary greatly as other more localised controls become a controlling influence upon hillslope failure. This represents the fact that the catchment area variable essentially becomes less independent with increasing size, forming interdependence with other variables. Although the data is highly variable we can use the flow accumulation data to determine the initial percentage bare ground values for smaller catchments i.e. those associated with ridges and other local topographic maxima (Table 5.5).

Landsystem	Initial PBG (%)
Makomako	6
Te Arai (lrl)	7
Te Arai (mrj)	7
Waihora	9
Wharerata	6

Table 5.5 Initial PBG values.

Looking at the plots in Figure 5.11 a number of flow accumulation values have zero percentage bare ground values. Further investigation of these data points revealed them to be associated very closely with either a stream channel, the shoulder of the channel, or vegetation growing directly in or over the channel. Thus in the percentage bare ground

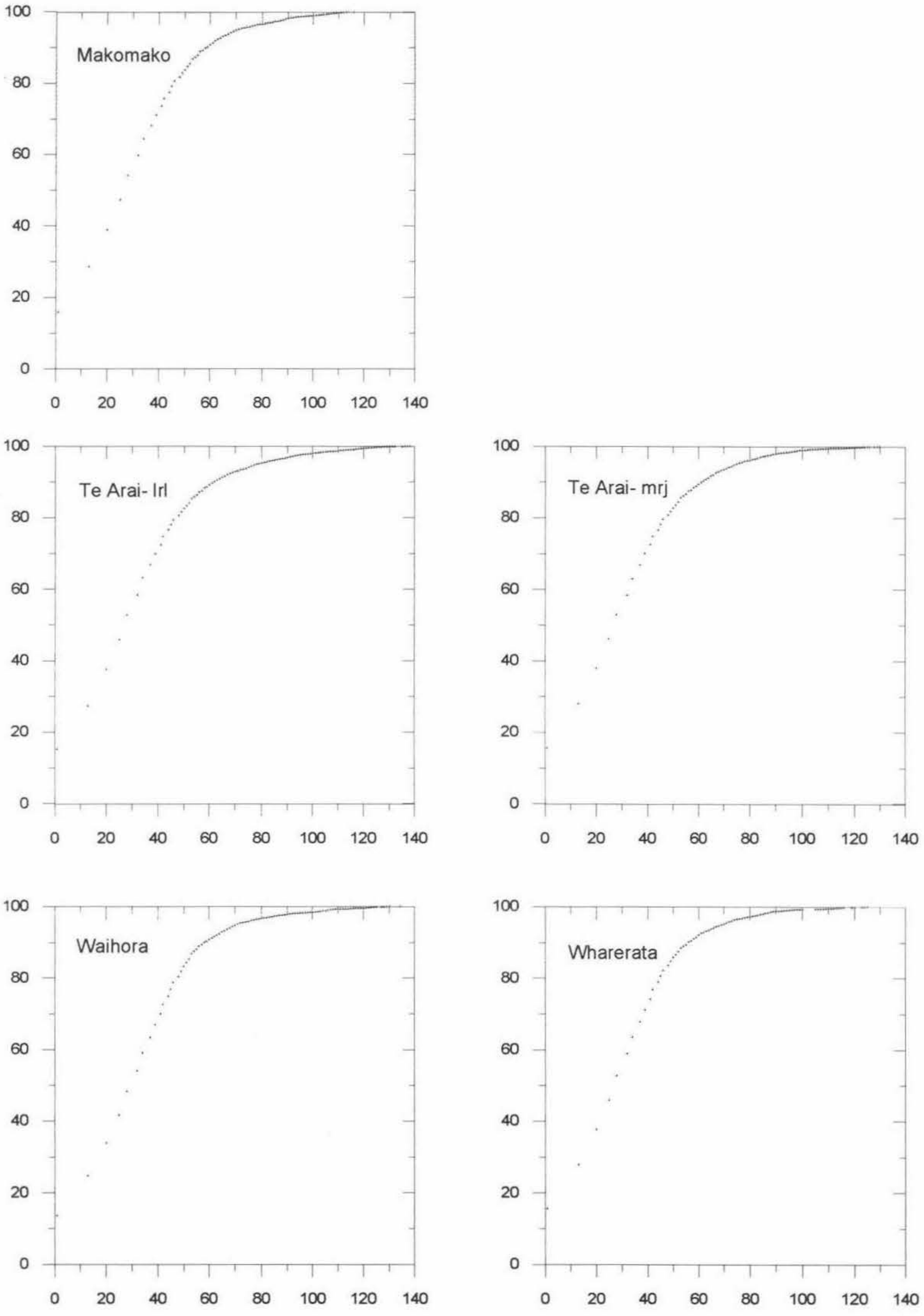

Figure 5.10 Catchment Area Cumulative Frequency Distribution (X axis = log transformed flow accumulation, Y axis = cumulative frequency in %).

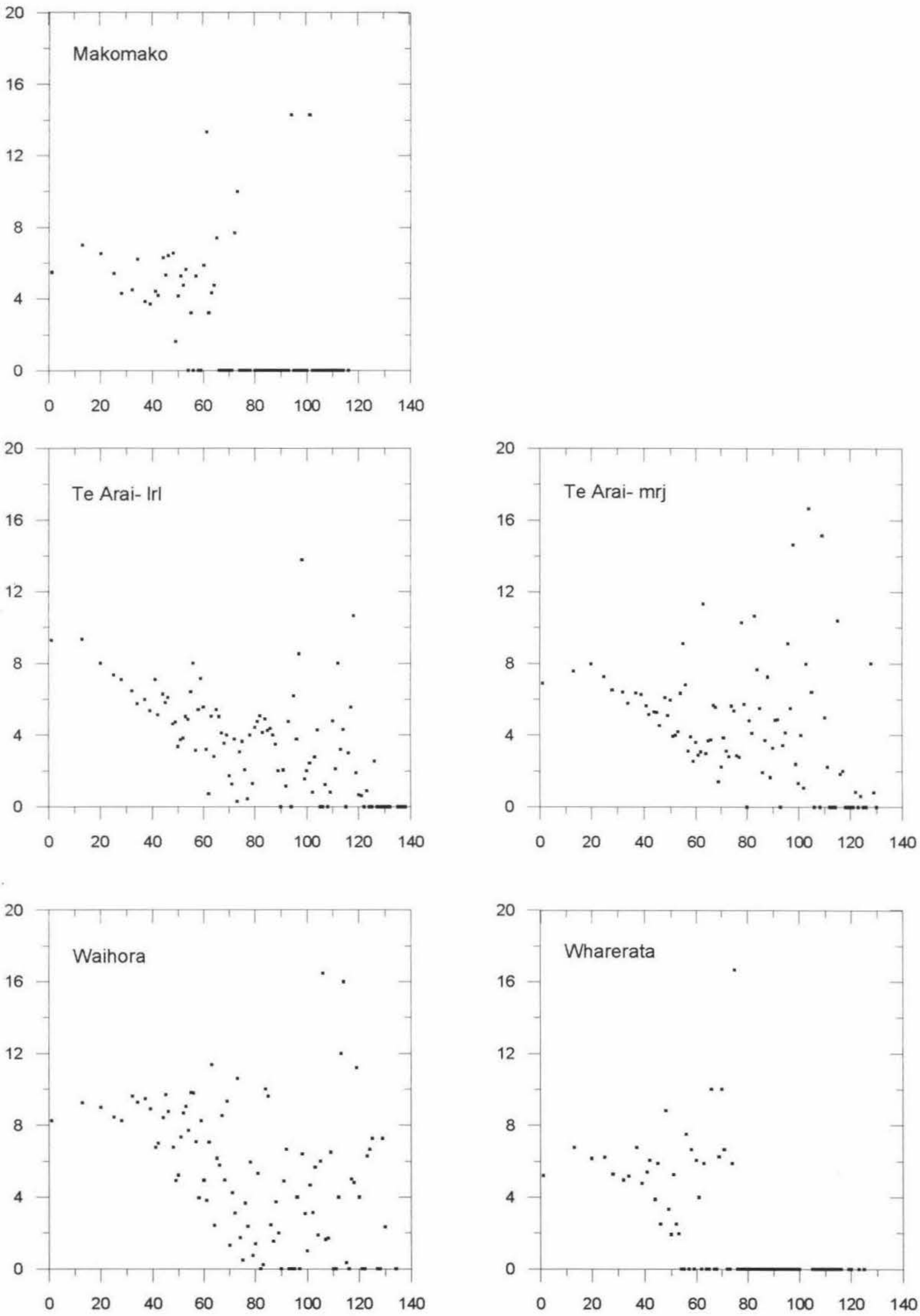

Figure 5.11 Percentage Bare Ground of Erosion Scars vs Catchment Area (flow accumulation) (X axis = log transformed flow accumulation, Y axis = PBG).

versus catchment area plots we can identify a progression from the ridge crest to stream channel.

Several authors have alluded to the difficulty of extracting channel networks from DEMs (Moore *et al.*, 1991; Tribe, 1991; Quinn *et al.*, 1995), using a threshold of flow accumulation because of the migrational nature of the channel under different intensity rainstorms and discharge cycles. The process appears to be somewhat subjective (see the valley-head locations selected independently in Tribe 1991), often with geomorphologists being employed to locate channel heads from DEM's at different thresholds, and ultimately choosing a single threshold value (e.g. those with a flow accumulation greater than 65 (Jessen pers comm, 1997)), for an entire river catchment.

The zero PBG values can then be used to represent the physical entity of the stream channel, and thus a channel initiation threshold specific to the landsystem under observation can be identified. The benefit of using the erosion map method to identify channel initiation thresholds is that it represents an objective method of identifying stream channel networks. Images of channels identified by thresholds more appropriate to the geomorphic characteristics and erosion distribution can then be mosaiced together for the study area to produce more accurate representation of a channel network for an entire river catchment.

5.2.6 Flow Path Length.

The flow accumulation variable gave an indication of the incidence rate of landsliding in relation to catchment area. From that it was possible to determine how the variability of percentage bare ground increased with increasing catchment areas, and by implication the distance from the ridge crests. However, this applies within an areal context and not a true Euclidean distance from ridge crest measurement.

It became necessary to compute the upslope flow path lengths for any given pixel, and thus a true indication of linear measurement. The graphs for percentage bare ground versus flow path length are shown in Figure 5.12. We can see that the plots show a similar trend in variability as the flow accumulation plots. The ARC/INFO software calculates the upslope flow path pixels from the same D8 flow routed output grid derived from the DEM, for

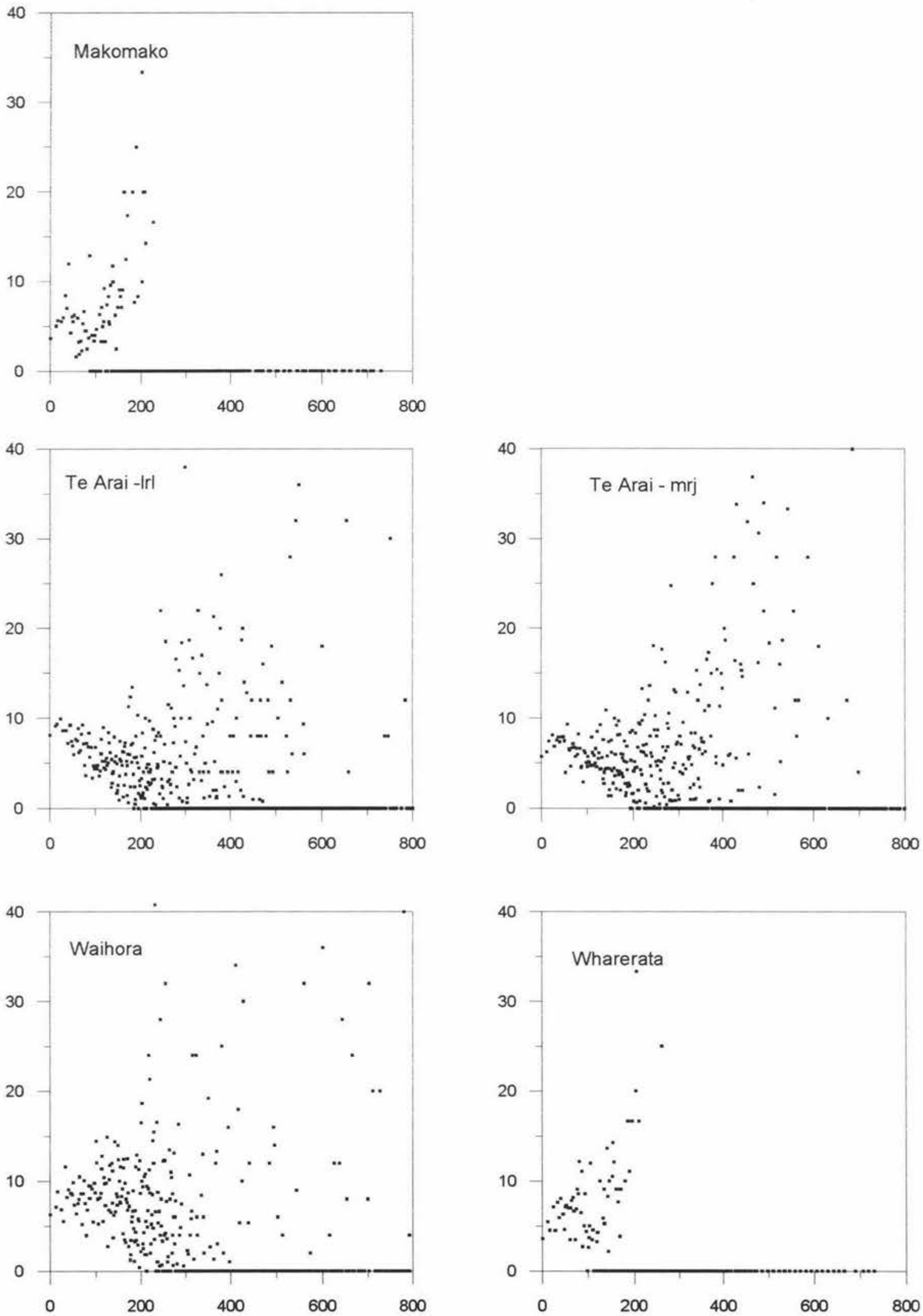

Figure 5.12 Percentage Bare Ground of Erosion Scars vs Flow Path Length (X axis = flow path length(pixels), Y = PBG).

which the flow accumulation is also calculated. Thus, the dominance of the D8 characteristics are inherited through all of the derived products.

5.2.7 Soil Moisture Index.

The Soil Moisture Index (SMI) was computed for each landsystem to enable us to examine what effect soil water content had upon the incidence of landsliding. Specifically we wanted to see if the results could be used to support the preferential removal of regolith within swales, or if landsliding occurred higher up the hillslope under conditions of lower soil water content. From the plots (Figure 5.13), we can see a strong negative trend for percentage bare ground versus the computed SMI, and thus a strong relationship between drier soils and landsliding. The Waihora data shows a slight exception to this, although it should be noted that the data point where SMI = 10 is represented by a low frequency in the histogram.

The SMI is a useful tool for any bare ground analysis because it places greater consideration upon slope angles in addition to catchment size. So in comparison with the flow accumulation images where variability tended to impair precise interpretation, the influence of slope in the SMI (effectively a slope weighting for soil moisture) gives a reasonable picture of the spatial distribution of erosion as it relates to soil moisture conditions.

The higher SMI values represent greater catchment areas and generally lower slope angles. Thus for the plots in Figure 5.13, it becomes apparent that landsliding occurs in the smaller catchments with greater slope angles. By implication this reinforces the notion that landsliding predominates in close proximity to the ridge crest on the upper portions of the hillslopes, even though the previous flow accumulation analysis wasn't able to pinpoint this. Although we can identify the ridge crest and stream channel entities from these images, it still doesn't pinpoint swale location without further investigation. However, it is a relatively simple procedure to identify SMI values which represent specific landform components given a modicum of time.

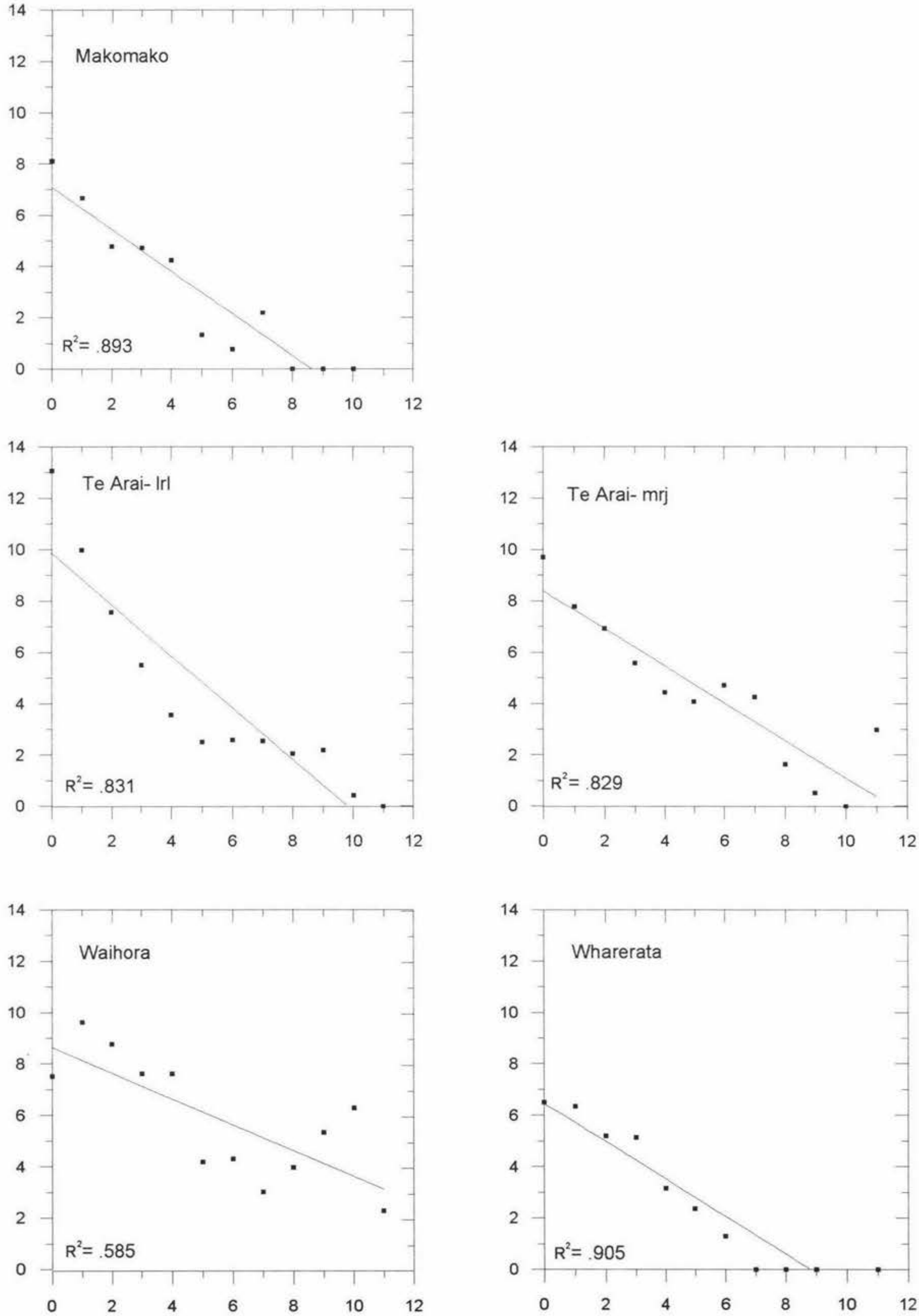

Figure 5.13 Percentage Bare Ground of Erosion vs Soil Moisture Index (X axis = soil moisture index, Y axis = PBG).

5.3 Sediment budgeting.

The second major objective of the project was to calculate a sediment budget for selected landsystems of the Waipaoa River catchment, pertaining to the Cyclone Bola storm event. As previous authors (Page *et al.*, 1994) have indicated, a sediment budget usually contains a significant temporal component. In contrast this project provides an instantaneous sediment budget for a single storm event. Volumes for the displaced sediment were derived by multiplying the area of bare ground (representing the scar surface) by the average scar depth using depth measurements taken soon after the Cyclone Bola storm event. Table 5.6 illustrates the average scar depth for each landsystem. Volumes have been calculated for the classified images relating to the components of the sediment budget: inputs (landsliding), deposition (material deposited on the hillslope and not reaching a stream channel), and outputs (material delivered to the stream network).

Landsystem	Ave Scar depth (m)
Makomako	0.75
TeArai	0.76
Waihora	0.75
Wharerata	0.81

Table 5.6 Average scar depth measurements. (Page, 1997, pers comm).

Table 5.7 is the sediment budget calculated from the classified images for each landsystem study site. As the primary objective of the project investigated the quantified topographic attributes rather than landform components, no attempt has been made to subdivide the study sites into their various geomorphic constituents, moreso the aim was to provide an absolute volumetric figure.

Landsystem	Component	Location	Process	Sediment flux (m^3)
Makomako	Inputs	All landform elements	Landsliding	40,247
	Storage	All landform elements	Deposition	18,590
	Output	Incised Stream channel	Fluvial reworking	21,657
Te Arai (lrl)	Inputs	All landform elements	Landsliding	186,889
	Storage	All landform elements	Deposition	65,518
	Output	Incised Stream channel	Fluvial reworking	121,371
Te Arai (mrj)	Inputs	All landform elements	Landsliding	187,844
	Storage	All landform elements	Deposition	106,280
	Output	Incised Stream channel	Fluvial reworking	81,564
Waihora	Inputs	All landform elements	Landsliding	166,484
	Storage	All landform elements	Deposition	44,394
	Output	Incised Stream channel	Fluvial reworking	121,550
Wharerata	Inputs	All landform elements	Landsliding	37,614
	Storage	All landform elements	Deposition	8,080
	Output	Incised Stream channel	Fluvial reworking	29,534

Table 5.7 Landsystem Study Site Sediment Budget.

The third objective was to produce a sediment delivery ratio (SDR) to quantify the relationship between total sediment produced and sediment delivered to the stream channels for each landsystem. Table 5.8 provides these figures. Standard error of the mean figures for the 100 debris tail measurements investigated in the field (Page,1997, pers comm.), allowed construction of error limits for the assumed debris tail depth (0.18m) of ±2 standard errors of the mean. Sediment delivery ratios had previously been calculated for these landsystems, although the technique employed was slightly more generalised. The purpose was to investigate how much more accurate figures provided by a Remote Sensing/GIS approach could be in determining these ratios.

Landsystem		**Sediment Delivery Ratio**	
	Lower (- 2 s.e.)	Mean	Upper (+ 2 s.e.)
Makomako	0.63	0.54	0.44
Te Arai (lrl)	0.72	0.65	0.57
Te Arai (mrj)	0.54	0.43	0.31
Waihora	0.78	0.73	0.67
Wharerata	0.83	0.79	0.74

Table 5.8 Sediment Delivery Ratios.

The figures reflect the morphometric characteristics of each landsystem. From Table 5.8 it appears that landsystems with longer, more planar slopes (Makomako, Waihora, Wharerata), all produce a higher sediment delivery ratio. This could be attributed to the fewer topographic constraints which impede the transport of the flowing mass. By comparison the Te Arai (mrj) sediment delivery ratio clearly identifies the more irregular topography and higher incidence of topographic constraints such as bends, deflections, run-ups, and opposing channel walls etc. These all serve to dampen the rate of travel for the flowing mass and lessen the overall distance travelled, thus providing lower sediment delivery ratios, as more material is deposited upon the hillslope.

Earlier in the results section the combination of lithologies within the Te Arai (lrl) dataset became apparent when investigating individual topographic attributes. This combination has been identified very well by the method used to calculate the SDR. The greater component of steeper, more planar slopes generate a higher sediment delivery ratio more in line with the purely planar hillslope type landsystems. Contrary to the earlier situation whereby the combination of lithologies was less than ideal during the spatial analysis, here it provides a good test for the validation of the sediment delivery ratio.

5.4 Landslide probability.

The fourth objective of the project was to predict the spatial distribution of erosion for the four selected landsystems of the Waipaoa River catchment. The results obtained in Section 5.2, gave a good indication of what the most appropriate independent variables were for inclusion in the predictive model. The approach was to primarily identify the significant variables, and then lump them together in a conceptual model which could be used to predict the probability of erosion in the form of percentage bare ground. Equation 5.1 illustrates the conceptual model for predicting the percentage bare ground.

$$y = \sum w_i y_i / \sum w_i$$

$$w_i = \frac{1}{S_i^2}$$

where s_i = (standard error of estimate)
y_i = independent variable function

Equation 5.1 Conceptual model for erosion prediction.

The results presented in section 5.2 on the spatial analysis of independent show that slope, aspect, elevation and the SMI were the most suitable variables to be used in the model. The flow accumulation derived variables were not conclusive enough to be included. Although they did illustrate interesting trends, we couldn't use the results as anticipated in response to Ellis' (1996) observations.

Carrara *et al.* (1991) alluded to the optimism of models warning that they (models) often fit the sample from which they are derived far better than the population. Thus we were concerned with ensuring that any variables having been quantified from our study sites (the sample) and included in the model for extrapolation were truly indicative of conditions elsewhere within the catchment (the population).

The range of slope angles encountered for the study sites (0-45°) were considered to be an adequate range for the greater catchment. Naturally, there will be hillslopes which are steeper than 45°, although, above this point the hillslopes tend to be quite denuded anyway. The potential for the greater catchment to contain slopes over 45° was not considered to have a deleterious effect within the context of this project (Crippen, 1997, pers. Comm). Similarly aspect was considered to be a stable variable within the model because all study sites encompassed the complete range of possible slope orientations.

Originally, it was considered appropriate to include elevation as another independent variable within the model to add to the specificity already defined by slope and aspect. However, the range of values for elevation amongst the five study sites illustrated in Figure 5.6 differs markedly from the range of elevation defined for each landsystem in Table 3.3. The study sites for this project were generally located in the middle reaches of the catchment. As Figure 3.2 shows, the conditions that help define each landsystem are distributed widely throughout the catchment. The uplift conditions of the catchment vary and thus so do the potential range of elevation values for any given landsystem.

The Soil Moisture Index contains well fitted curves and has an inherently dimension less character which makes it well suited for application to the population. However, it is questionable whether the SMI can be considered to be totally independent of the other variables because of the use of slope in the SMI calculation process.

After the variables chosen for inclusion in the model had been selected, the fitted curve functions, the correlation coefficients and standard error of estimates were obtained from the curve fitting program. Table 5.9. presents the correlation coefficients and standard error of estimates for each landsystem whilst Tables 5.10, 5.11, and 5.12 present the fitted curve functions for each independent variable (topographic attribute) included within the model.

Landsystem	**Slope**		**Aspect**		**SMI**	
	R^2	s.e.	R^2	s.e.	R^2	s.e.
Makomako	0.856	2.02	0.611	2.42	0.893	0.985
Te Arai	0.957	0.402	0.918	1.05	0.829	1.57
Waihora	0.462	1.70	0.729	0.644	0.585	2.55
Wharerata	0.701	1.70	0.421	2.09	0.905	0.757

Table 5.9 Correlation coefficients and standard error of estimates.

Landsystem	Fitted curve function (Equation 5.2)
Makomako	$y = (0.300 * x) + (-0.936)$
Te Arai	$y = (0.441) + (1.266 * x) + (-0.241 * x^2) + (0.0183 * x^3) + (-0.000531 * x^4) + (5.05E - 006 * x^5)$
Waihora	$y = (0.094 * x) + (5.466)$
Wharerata	$y = (0.157 * x) + (1.00)$

Table 5.10 Fitted curve functions for the slope variable.

Landsystem	Fitted curve function (Equation 5.3)
Makomako	$y = (-0.123) + (0.243 * x) + (-0.00215 * x^2) + (2.78E - 006 * x^3) + (1.87E - 008 * x^4) + (-4.12E - 011 * x^5)$
Te Arai	$y = (4.35) + (0.248 * x) + (-0.00375 * x^2) + (1.69E - 005 * x^3) + (-2.31E - 008 * x^4)$
Waihora	$y = (4.05) + (0.199 * x) + (-0.00220 * x^2) + (8.23E - 006 * x^3) + (-9.85E - 009 * x^4)$
Wharerata	$y = (8.53) + (-0.0771 * x) + (0.000380 * x^2) + (-8.52E - 007 * x^3) + (9.556E - 010 * x^4)$

Table 5.11 Fitted curve functions for the aspect variable

Landsystem	Fitted curve function (Equation 5.4)
Makomako	$y = (-0.818 * X) + (7.076)$
Te Arai	$y = (-0.728 * x) + (8.38)$
Waihora	$y = (-0.501 * x) + (8.63)$
Wharerata	$y = (-0.731 * x) + (6.45)$

Table 5.12 Fitted curve functions for the SMI variable.

The technique used to calculate the probability of percentage bare ground used the functions derived from the fitted curves for each independent variable, because of the high correlation coefficients achieved. The standard error of estimate was obtained for each fitted curve to act as the weighting coefficient for each component in the model. Essentially this rendered the importance of the independent variable within the model proportional to the certainty of the fitted curve for percentage bare ground. weights for each variable were then normalised by dividing by the sum of weights, so that the weights summed to unity. The resulting components were then introduced to Equation 5.1 producing the predictive model (Equation 5.5) for each landsystem. Table 5.13 lists the models to assign a probability value for the percentage bare ground of any given pixel in the image at cell location $x_i y_i$:

Landsystem	Predictive probability functions (Equation 5.5).
Makomako	$PBGx_iy_i = \dfrac{\left(\frac{1}{2.02^2}\right)(Equation5.2) + \left(\frac{1}{2.42^2}\right)(Equation5.3) + \left(\frac{1}{0.985^2}\right)(Equation5.4)}{\left(\frac{1}{2.02^2} + \frac{1}{2.42^2} + \frac{1}{0.985^2}\right)}$
Te Arai	$PBGx_iy_i = \dfrac{\left(\frac{1}{0.402^2}\right)(Equation5.2) + \left(\frac{1}{1.05^2}\right)(Equation5.3) + \left(\frac{1}{1.57^2}\right)(Equation5.4)}{\left(\frac{1}{0.402^2} + \frac{1}{1.05^2} + \frac{1}{1.57^2}\right)}$
Waihora	$PBGx_iy_i = \dfrac{\left(\frac{1}{1.70^2}\right)(Equation5.2) + \left(\frac{1}{0.644^2}\right)(Equation5.3) + \left(\frac{1}{2.55^2}\right)(Equation5.4)}{\left(\frac{1}{1.70^2} + \frac{1}{0.644^2} + \frac{1}{2.55^2}\right)}$
Wharerata	$PBGx_iy_i = \dfrac{\left(\frac{1}{1.70^2}\right)(Equation5.2) + \left(\frac{1}{2.09^2}\right)(Equation5.3) + \left(\frac{1}{0.757^2}\right)(Equation5.4)}{\left(\frac{1}{1.70^2} + \frac{1}{2.09^2} + \frac{1}{0.757^2}\right)}$

Table 5.13 Predictive erosion model for each landsystem.

CHAPTER 6

DISCUSSION

6.1 Achievements of the project.

The initial objectives of the project were to identify the most significant variables that influenced the spatial distribution of landsliding within the four selected landsystems of the Waipaoa River catchment. Of the seven DEM derived topographic attributes or independent variables analysed in Section 5.2 a more clear understanding of their relationship with the extent of landsliding was determined. High correlation coefficients were observed for the independent variables: slope, aspect, elevation and soil moisture index when plotted against the incidence of landsliding in the form of percentage bare ground.

Clear patterns were not able to be derived from the flow accumulation, flow length and slope configuration independent variables. They did, however, provide a new insight into the spatial variation of the relative extent of bare ground. Although the flow accumulation and its derived attributes were not specific at the pixel level, they did allow us to view the Cyclone Bola induced erosion from a hillslope continuum point of view whereby we could identify trends within the data relating to geomorphic features. The analysis of the slope configuration topographic attribute also provided us with an indication of the upper limits of topographic sensitivity for the 12.5m DEM when examining topographic features within the Waipaoa River catchment.

The use of spatially explicit data in the form of digitally rectified orthophotos enabled a far more accurate classification of erosion induced bare ground to be achieved by eliminating the radial distortion characteristically associated with relief displacement in aerial photograph scenes. The areal figures derived for actual scar affected areas were far more precise than figures derived from non-orthorectified imagery. Combining the more accurate figures for the areal extent of bare with the scar depth measurements gave a good measurement indication for the total volume of sediment displaced from each study site. Likewise, the use of orthophotos also permitted better identification of the spatial connectivity for sediment delivery systems within each study site, allowing more accurate and realistic sediment delivery ratios to be derived for each site. Under conditions of changing lithology and geomorphic expression the sediment delivery ratios were found to accurately depict these variations within study sites.

The project also succeeded in providing a model for the prediction of the spatial distribution of erosion. The structure of the model avoided the use of variables whereby any interdependence between them would have compromised its overall integrity. Beven (1989) identified a tendency to over parameterise models in many studies. Including only the most significant and stable variables produced a simple, but robust model. The model predicted the potential extent of any bare ground by assigning a probability to each pixel according to the topographic characteristics of the location.

The process of assigning a 'data driven' weighted probability to each variable (topographic attribute) helped to avoid any subjective categorisation when identifying the extent of each variable the extent of bare ground. It weighted the individual components of the model according to their relationship with landsliding, rather than assigning an arbitrary importance based upon their percentile values. Using only the minimum number of combined parameters in the model helped to avoid any potential error propagation, that is commonly associated with multi-parameter models

6.2 Potential Limitations.

As indicated earlier in Chapter Three, rainfall is important in initiating flowing of landslide masses (Varnes, 1979) and is significant upon the spatial distribution of landsliding. The importance of rainfall has been well documented within the New Zealand context. However, no investigation of rainfall has been made within this project. The rainfall figures provided in Table 4.1 were generated from isohyets interpolated by the Gisborne District Council. The generalised nature of these figures in relation to each study site precluded the use of them for any spatial analysis into their influence upon the spatial distribution of landsliding with any certainty.

Although the aerial photographs used in this study were within what was earlier described as a practical scale range for geomorphological interpretation, they are slightly outside the 1:15,000 optimum scale suggested by Mantovani *et al.* (1996). Some New Zealand authors (e.g. Crozier *et al.*, 1980) have found that under conditions of high spatial densities of landsliding the individual scar counts derived from 1:25,000 aerial photographs tended to be greater than those observed and recorded in the field.

To help alleviate any over classification of bare ground, three or four passes were applied to each image to ensure an accurate classification. Bare ground caused by obvious features such as stock ponds, gateways and farm tracks were easily identified and not mis-classified. However, difficulty arose when coalescing landslide complexes were the feature under observation. Generally all failures within these complexes were relatively easily identified by the transportation characteristics of the displaced material. However, subsequent reworking of the material in a channel proved troublesome. In this scenario, any bare ground that was considered to be a function of scouring was not recorded as a scar event. As a control measure, all of the classified images were routinely checked by an independent geomorphologist to identify any erroneous classifications.

A potential inadequacy of the 12.5m DEM was highlighted by the spatial analysis of the slope configuration independent variable, during which there was a perceived inability to identify fine textured drainage channels. A more complete discussion of the issues associated with DEM resolution was presented in Chapter Two, and will not be revisited here. The 12.5m DEM resolution proved to be sufficient for the generation of topographic attributes for spatial analysis within this project, because of the larger nature of the features under observation. It is recognised however, that the 12.5m resolution is still inadequate when examining certain hydrological features. Such features were not central to the outcomes of this project thus rendering the 12.5m DEM resolution appropriate to the method of analysis.

One other potential criticism that has been directed towards the DEM derived data was their inability to represent the surface angle of the erosion scar .Specifically, it was questioned whether or not the 2 degree slope class interval used to calculate the proportion bare ground for the slope independent variable was too narrow to sufficiently represent the range of slope angles that exist within a landslide event. After field observation of the Te Arai(lrl) study site, it became apparent that the failure plane of a single landslide event may well encompass a range of slope angles. These tend to vary greatly between the top and the bottom of the scar. There is no assurance that these failure planes are perfectly representative of the former ground surface, which may well have contained non-uniform slope angles.

Previous authors (e.g. Kingsbury *et al.* 1991) had found that DEM (or TIN) derived slope angles were not necessarily directly related to the field slope angle. The failure of the DEM to perfectly represent the land surface is implicitly assumed and understood in this project. But it is the best estimate of the land surface that we can generate given the size of the Waipaoa River catchment.

For the spatial analysis the AMLs were written to calculate the percentage bare ground relative to the pixel frequency of the particular class interval for each given topographic attribute. The percentage bare ground technique of evaluating the relative extent of erosion was considered to be a practical, unbiased technique applied to the raster based datasets. However, where certain class intervals were represented by exceptionally low values in the frequency distribution, the technique tended to produce abnormally high percentage bare ground figures. Investigation of these artificially buoyant figures revealed such outliers to be instances of 1,2,4, or 8 pixels in the histogram returning PBG figures of 100%, 50%, 25%, and 12.5% respectively. Literally, a hillslope failure occurred directly on or adjacent to and including these slope angle pixels. On the basis of their low frequency it was decided to omit them.

In the sediment delivery ratio calculations there is the assumption that the debris deposited upon the hillslope is of a uniform depth. This, however, doesn't take into account two field conditions identified from the stereo airphotos. Firstly, on convex slope elements the debris was often observed to assume a sheet wash transport process. This by implication suggests that the debris material thins as it spreads out, causing the assumed 18cm figure to overestimate the debris depth. Secondly, the debris material that enters a channel, particularly where the channel is entrenched, may often be of a greater depth because of the lateral confinement within the channel forcing the material to accumulate prior to reworking, and thus be under-estimated by the 18cm figure for debris depth.

Contrary to this assumed condition of uniform debris depth is the fact that several authors have hypothesised that the debris depth actually diminishes during the transportation process. Crozier (1996) favours this situation whereby peripheral thinning and deposition gradually reduce the volume of material for the moving mass causing it to gradually fall below what is considered a 'critical thickness' at which point movement of the debris tail ceases.

Some questions have been raised previously as to whether the empirical modelling approach to landslide analysis is potentially inadequate. Wadge *et al.* (1993) have suggested that the technique of using the spatial and/or temporal characteristics of previous hazard events as an empirical approach to modelling may be inherently flawed by the fact that:

1. *The variables available for measurement may not have the same value as those obtained during the hazard event;*
2. *Choice of what environmental variables to use is largely guesswork, and the model may only explain a fraction of the hazard variance; and*
3. *Cross tabulation ignores potentially useful information in the spatial autocorrelation of data*

Clearly, any surface/subsurface hydrological conditions will be vastly different from the extreme conditions encountered in the Cyclone Bola storm event. However, no attempt has been made during this project to include a temporal component to the analysis or model. As such no effort has been made to provide any indication of potential *hazard*, because of such dependencies upon the quantification of temporal characteristics.

As the project did not employ an engineering geology approach (requiring specific hydrostatic data) to the mechanics of slope failure, and the fact that the main source of data was the DEM, (derived from raw elevation data acquired in 1979 by the former DoSLI organisation as part of an aerial mapping programme and generated prior to the regolith stripping by or the geomorphic response to Cyclone Bola) the issue of post storm analysis is not seen as particularly problematic to the method employed.

It is true that the choice of environmental variables is largely guesswork, which itself assumes some form of subjective analysis as indicated earlier by Mantovani *et al.* (1996). Many different combinations of the independent variables were investigated to examine their influence upon the incidence and proportion bare ground in terms of their magnitude and consistency during the analysis. This approach graphically indicated what topographic attributes were significant influences upon the extent of bare ground. The perceived subjectivity regarding selection of independent variables for analysis and modelling is partly negated in this study by the prominence already attached to those topographic attributes, being identified repeatedly in the literature. New Zealand authors (e.g. Crozier, 1996) have specifically avoided the use of spatial auto-correlation as an analytical tool within landslide studies because of the unrealistically high correlation coefficients that are routinely produced.

Hillel (1986, cited in Moore *et al.*, 1993) specified four goals to assist in model genesis:

1.Parsimony	*A model should not be anymore complex than it needs to be and should include only the smallest number of parameters whose values must be obtained from data.*
2.Modesty	*A model should not pretend to do too much as there is no such thing as THE model.*
3.Accuracy	*We need not have our model depict a phenomenon much more accurately than our ability to measure it.*
4.Testability.	*A model must be testable, and we need to know if it is valid or not, and what are the limits of its validity.*

In answer to the appropriateness of a model, it is believed that the percentage bare ground prediction model contains only the most significant variables that influence landsliding. Part of its simplicity is attributed to the landsystem approach of stratifying the catchment. In modelling landslide distribution it is difficult to apply regression techniques to specific sites because of the binary distribution of landsliding (Shu-Quiang and Unwin, 1992). Hence this model relies upon the use of percentage bare ground for a given variable class as a function of landsliding rather than targeting specific hillslope failures at a given location.

Heerdegen and Beran (1982) state that more generalised studies are the only practical solution when undertaking catchment wide studies. Hence, this model when applied to the 2204km^2 Waipaoa river catchment aligns itself well with the data already available for the catchment and measurement techniques applied to those datasets, rather than being highly specific and difficult to implement in the wider context. In terms of its testability the model has yet to be validated.

6.3 Contribution to existing knowledge.

This study examined some of the topographic attributes which national and international literature have shown to be significant upon the spatial distribution of landsliding. This more detailed spatial analysis of the DEM derived attributes, and the analysis of both affected and unaffected locations, has quantitatively reaffirmed the influence that these have within a New Zealand context. The results produced identified how a more clear understanding of these has been presented for the Waipaoa River catchment. It also identified what previously unexamined topographic attributes such as catchment area (flow accumulation) and flow path length (i.e. distance to steam) were found to have upon the spatial distribution of landsliding. Although these were found to become progressively more interdependent with size, they have allowed the proposal of an objective method for the identification of steam channel networks from a DEM.

The classification of the erosion scars and displaced sediment allowed a more accurate sediment delivery ratio to be determined for each landsystem. Although more general ratios had been established in earlier catchment studies, the ratios produced in this study provide more definitive figures which are suitable for introduction to a decision support system with more certainty because of their greater accuracy. The classified erosion maps and concepts behind the sediment delivery ratios allowed quantified sediment fluxes to be calculated for each study site, which can at a later date possibly be extrapolated to the wider catchment. A simple yet robust probability model specific to each landsystem has been developed for the Waipaoa River catchment in an attempt to assist in the prediction of the spatial distribution of landsliding based upon the predominant topographic attributes for a given location.

CHAPTER SEVEN

CONCLUSIONS

- Slope angles are significant upon the spatial distribution of landsliding within the Waipaoa river catchment. When the known under estimations of the DEM were corrected the range of erosion susceptible slope angles proved consistent with similar hillslope processes reported overseas.
- Slope orientation or aspect showed a high positive correlation with the extent of bare ground during the Cyclone Bola storm event. A strong pattern was found between the northerly and southerly compass orientations, whereby the northerly aspects suffered higher denudation of hillslopes compared to their southerly counterparts.
- Elevation was also shown to be an influence upon landsliding, returning generally high correlation coefficients.
- The notion that higher elevation supports steeper slope angles was not proven in this study. Generally the steeper slope angles were found at median elevation values.
- Slope configuration was not be proven to be a significant factor upon landsliding, although elements with convex planform curvatures which generally corresponded to spur features were found to return consistently high figures for bare ground.
- No direct correlation could be made between catchment area and landsliding. However, when the catchment area variables were investigated in association with an erosion map the results could be used to objectively identify stream channels from the DEM.
- The Soil Moisture Index showed a strong correlation with the incidence of landsliding. The SMI confirmed the location of landsliding in relation to the proximity the ridgeline, and thus the point of slope break. Future work identifying SMI values pertaining to specific swale features will help quantify the preferential removal of soil plasma within swales.
- Sediment delivery ratios specific to each landsystem were identified for the Waipaoa River catchment, and were shown to reflect changing lithological conditions
- Remote Sensing using aerial photographs and their digitally orthorectified derivatives proved successful in a catchment wide erosion mapping and modelling study. However, ground truthing remains an important component of Remote Sensing

applications. There is always the need to relate the digital data to the on ground spatial characteristics of the data. Conducted early in the study helps to avoid any potential erroneous data investigations ensuring focus on the topic.

- The 3.0m pixel size of the Waihora landsystem SN11485F/H20 orthoimage was considered to be slightly too large during the course of this study. It had a tendency for classified scar and debris tail components to display a slightly pixellated outline. Although this was not exceptionally coarse it did detract from the precision achieved with the 2.5m resolution orthoimages.
- The use of orthorectified airphotos in landslide studies is essential for the derivation of precise locational data when examining topographic attributes. The orthophotos avoid the topographic layering found in non-orthorectified imagery due to relief displacement. This also helps to ensure the spatial continuity of classified features such as debris tail paths. The use of orthophotos proved to be rather serendipitous when rule based approaches forced the selection of study sites with off nadir locations.
- The development of a landslide probability for each pixel can be further developed to produce a landslide susceptibility map for the entire catchment, and be used in conjunction with recent observations made from the Nuhaka storm event (1997) to target areas most suitable for the application of soil conservation techniques.

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APPENDIX I AMLs

```
/* ##############################################################################
/*
/*                                  geomorphia.aml
/*
/* ##############################################################################
/*
/* Description:     This ATOOL creates a statistics file for calculating the
/*                  proportion bare ground (PBG) versus each independent geomorphic
/*                  variable according to a user selected zone interval and grid.
/*
/* Created by:      L.R.Lovell June 1997, Massey University
/* Location:        /home/rs3/projects/lrl/atool/arc (LCR-PN)
/* Initiation:      geomorphia
/* Suggestions:
/* FYI:             designed to preserve any pre-existing system files
/* Calls:           aspect, elevation, slope
/*
/* ##############################################################################

&severity &error &routine fallover
&term 9999
&sv work [show workspace]
&type
&type Present workspace is %work%, ATOOL selecting appropriate workspace for processing


/* define the geomorphic attribute of choice
&type
&type     This geomorphia.aml ATOOL generates a statistics file for calculating the
proportion bare ground (PBG) versus a zone of each geomorphic attribute under observation.
First choose your landsystem of interest:
&type
&type     Enter         'K' for Makomako
&type                   'L' for Te Arai (Mangatoetoe Station)
&type                   'M' for Te Arai (Mrj derived data)
&type                   'R' for Wharerata
&type                   'W' for Waihora
&type                   any other key to abort

&sv landsystem [response 'Enter choice...']

&if ^ [locase %landsystem%] in {'k','l','m','r','w'} &then
  &do
    &type You have not entered a K,L,M,R or W correctly, aborting AML... Bye Bye!
    &stop
  &end


/* select appropriate grids for processing and name for stats output files
&select %landsystem%
  &when k
    &do
      &workspace /home/rs3/projects/lrl/wdata/makomako
      &sv aspect makoaspect
      &sv elev makodtm
      &sv scar makoscar
      &sv slope makoslope
      &sv astats makoasp
      &sv estats makoelev
      &sv sstats makoslop
    &end

  &when l
```

```
    &do
      &workspace /home/rs3/projects/lrl/wdata/tearai
      &sv aspect tearaiaspect
      &sv elev tearaidtm
      &sv scar tearaiscar
      &sv slope tearaislope
      &sv astats taaspect
      &sv estats taelev
      &sv sstats taslope
    &end

  &when m
    &do
      &workspace /home/rs3/projects/lrl/wdata/tearai
      &sv aspect mrjaspect
      &sv elev mrjdtm
      &sv scar mrjscar
      &sv slope mrjslope
      &sv astats mrjasp
      &sv estats mrjelev
      &sv sstats mrjslope
  &end

  &when r
    &do
      &workspace /home/rs3/projects/lrl/wdata/wharerata
      &sv aspect wrataaspect
      &sv elev wratadtm
      &sv scar wratascar
      &sv slope wrataslope
      &sv astats wrataasp
      &sv estats wrataele
      &sv sstats wrataslo
  &end

  &when w
    &do
      &workspace /home/rs3/projects/lrl/wdata/waihora
      &sv aspect waihoraaspect
      &sv elev waihoradtm
      &sv scar waihorascar
      &sv slope waihoraslope
      &sv astats waiasp
      &sv estats waiele
      &sv sstats waislope
  &end

  &otherwise
    &do
      &type You goofed buddy.... bye bye!
      &stop
    &end
&end


/* define the geomorphic attribute of choice
&type
&type     Now choose your geomorphic attribute of interest:
&type
&type     Enter         'A' for slope aspect
&type                   'E' for elevation
&type                   'S' for slope angle
&type                   any other key to abort
```

```
&sv attribute [response 'Enter choice...']

&if ^ [locase %attribute%] in {'a','e','s'} &then
  &do
    &type You have not entered an A,E, or S correctly, aborting AML... Bye Bye!
    &stop
  &end

&if [locase %attribute%] = 'a' &then &call aspect
&if [locase %attribute%] = 'e' &then &call elevation
&if [locase %attribute%] = 's' &then &call slope

&return

/*****************************************************************************
&routine aspect                /* processes for 'aspect' as the independent variable

grid

/* create zonegrid based on user selection.
&if [exists %aspect% -grid] &then
  &do
    &type
    &type  The AML now requires you to choose the interval of each aspect zone
    &type  for the chosen variable.
    &type
    &type  Enter    '4' for four compass points
    &type
    &type           '8' for eight compass points
    &type
    &type           '16' for sixteen compass points
    &type
&sv interval [response 'Enter interval...']
&type
  &end


/* Establish remap tables for user specified zones

&select %interval%
  &when 4
    &do
      &sv fu [open zone.rmp sv -write]
      &sv sv [write %fu% '0 45 : 45']
      &sv sv [write %fu% '45 135 : 135']
      &sv sv [write %fu% '135 225 : 225']
      &sv sv [write %fu% '225 315 : 315']
      &sv sv [write %fu% '315 360 : 360']
      &sv sv [write %fu% '361 361 : 361']  /* 361 represents areas of flat land
      &sv sv [close -all]
     &end

  &when 8
    &do
      &sv fu [open zone.rmp sv -write]
      &sv sv [write %fu% '0 45 : 45']
      &sv sv [write %fu% '45 90 : 90']
      &sv sv [write %fu% '90 135 : 135']
      &sv sv [write %fu% '135 180 : 180']
      &sv sv [write %fu% '180 225 : 225']
      &sv sv [write %fu% '225 270 : 270']
      &sv sv [write %fu% '270 315 : 315']
      &sv sv [write %fu% '315 360 : 360']
      &sv sv [write %fu% '361 361 : 361']
      &sv sv [close -all]
     &end

  &when 16
    &do
      &sv fu [open zone.rmp sv -write]
      &sv sv [write %fu% '0 22 : 22']
      &sv sv [write %fu% '22 45 : 45']
      &sv sv [write %fu% '45 67 : 67']
      &sv sv [write %fu% '67 90 : 90']
      &sv sv [write %fu% '90 112 : 112']
      &sv sv [write %fu% '112 135 : 135']
      &sv sv [write %fu% '135 157 : 157']
      &sv sv [write %fu% '157 180 : 180']
      &sv sv [write %fu% '180 202 : 202']
      &sv sv [write %fu% '202 225 : 225']
      &sv sv [write %fu% '225 247 : 247']
      &sv sv [write %fu% '247 270 : 270']
      &sv sv [write %fu% '270 292 : 292']
      &sv sv [write %fu% '292 315 : 315']
      &sv sv [write %fu% '315 337 : 337']
      &sv sv [write %fu% '337 360 : 360']
      &sv sv [write %fu% '361 361 : 361']
      &sv sv [close -all]
     &end

  &otherwise
    &do
      &type Aborting AML.... bye bye!
      &stop
    &end
&end


/*create zonegrid and test for any existing zone grids of the same name
&if [exists zonegrid -grid] &then
  &do
    &sv kill [response 'zonegrid already exists! Do you wish to overwrite it? Enter Y to
NUKE it now']
      &type
      &if [locase %kill%] = 'y' &then kill zonegrid all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
zonegrid = slice (%aspect%,table,zone.rmp)
&type

/* resample zonegrid to align resolution with scar grid.
&if [exists rezonegrid -grid] &then
  &do
    &sv kill [response 'rezonegrid already exists! Do you wish to NUKE it? Enter Y to make
it so']
      &type
      &if [locase %kill%] = 'y' &then kill rezonegrid all
        &else
          &do
```

```
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type resampling  zonegrid to 2.5m resolution...
rezonegrid = resample (zonegrid, 2.5)
&type

/* compute zonal statistics and convert to DBASE file for spreadsheet analysis
&if [exists %astats% -info] &then
  &do
    &type
    &sv nuke [response [translate %astats%]'stats file exists already! Do you wish to
overwrite it?  Enter Y to NUKE it now']
      &select %nuke%
        &when y
          &do
            &sv delete = [delete %astats% -info]
          &end

        &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
      &end
  &end

&type
&type processing aspect data...

%astats% = zonalstats(rezonegrid,%scar%,moment,data)
&type
arc infodbase %astats% %astats%.dbf

&type
&type     Do you wish to peruse the newly created stats file?
&sv peruse [response 'Enter either Y or N']
  &if [locase %peruse%] = y &then
    &do
      arc tables
      sel %astats%
      unload %astats%.txt
      q
     &end


&select %peruse%
    &when y
      &do
        &popup %astats%.txt
      &end

    &otherwise
      &do
      &end
&end



/* delete grids, files and variables to release memory
kill (! zonegrid rezonegrid !) all
&sv delete = [delete zone.rmp -file]
&sv delete = [delete %astats%.txt -file]
/*&sv delete = [delete %astats% -info]
&dv work aspect attribute landsystem grid interval fu sv kill nuke delete peruse astats scar

q

&return


/*****************************************************************************
&routine elevation  /* processes for 'elevation' as the independent variable

grid

/* create zonegrid to slice elevation values into 10 metre intervals
&if [exists %elev% -grid] &then
&select %landsystem%
  &when k
    &do
      &sv fu [open zone.rmp sv -write]
        &sv sv [write %fu% '256 260 : 260']
        &sv i = 260
        &sv j = 270
          &do &until %i% = 480
            &sv sv [write %fu% [quote %i% [calc %i% + 10] : %j%]]
            &sv i [calc %i% + 10]
            &sv j [calc %j% + 10]
          &end
      &sv sv [close -all]
    &end

 &when l
    &do
      &sv fu [open zone.rmp sv -write]
        &sv sv [write %fu% '66 70 : 70']
        &sv i = 70
        &sv j = 80
          &do &until %i% = 340
            &sv sv [write %fu% [quote %i% [calc %i% + 10] : %j%]]
            &sv i [calc %i% + 10]
            &sv j [calc %j% + 10]
          &end
      &sv sv [close -all]
    &end



  &when m
    &do
      &sv fu [open zone.rmp sv -write]
        &sv i = 40
        &sv j = 50
          &do &until %i% = 310
            &sv sv [write %fu% [quote %i% [calc %i% + 10] : %j%]]
            &sv i [calc %i% + 10]
            &sv j [calc %j% + 10]
          &end
      &sv sv [close -all]
     &end


  &when r
```

```
    &do
      &sv fu [open zone.rmp sv -write]
        &sv sv [write %fu% '63 70 : 70']
        &sv i = 70
        &sv j = 80
          &do &until %i% = 350
            &sv sv [write %fu% [quote %i% [calc %i% + 10] : %j%]]
            &sv i [calc %i% + 10]
            &sv j [calc %j% + 10]
          &end
      &sv sv [close -all]
    &end


  &when w
    &do
      &sv fu [open zone.rmp sv -write]
        &sv i = 60
        &sv j = 70
          &do &until %i% = 410
            &sv sv [write %fu% [quote %i% [calc %i% + 10] : %j%]]
            &sv i [calc %i% + 10]
            &sv j [calc %j% + 10]
          &end
      &sv sv [close -all]
    &end


  &otherwise
    &do
      &type Aborting AML.... bye bye!
      &stop
    &end
&end


/*test for any existing zone grids of the same name first
&if [exists zonegrid -grid] &then
  &do
    &sv kill [response 'zonegrid already exists! Do you wish to overwrite it? Enter Y to
NUKE it now']
      &type
      &if [locase %kill%] = 'y' &then kill zonegrid all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
zonegrid = slice (%elev%,table,zone.rmp)
&type

/* resample zonegrid to align resolution with scar grid.
&if [exists rezonegrid -grid] &then
  &do
    &sv kill [response 'rezonegrid already exists! Do you wish to NUKE it? Enter Y to make
it so']
      &type
      &if [locase %kill%] = 'y' &then kill rezonegrid all
        &else
```

```
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type resampling  zonegrid to 2.5m resolution...
rezonegrid = resample (zonegrid, 2.5)


/* compute zonal statistics and convert to DBASE file for spreadsheet analysis
&if [exists %estats% -info] &then
  &do
    &type
    &sv nuke [response [translate %estats%]'stats file exists already! Do you wish to
overwrite it? Enter Y to NUKE it now']
      &select %nuke%
        &when y
          &do
            &sv delete = [delete %estats% -info]
          &end

        &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
      &end
  &end


&type
&type processing elevation data...


%estats% = zonalstats(rezonegrid,%scar%,moment,data)
&type
arc infodbase %estats% %estats%.dbf

&type
&type     Do you wish to peruse the newly created stats file?
&sv peruse [response 'Enter either Y or N']
  &if [locase %peruse%] = y &then
    &do
      arc tables
      sel %estats%
      unload %estats%.txt
      q
     &end


&select %peruse%
    &when y
      &do
        &popup %estats%.txt
      &end

    &otherwise
      &do
      &end
&end
```

```
/* release memory
/*kill (!zonegrid rezonegrid!) all
&sv delete = [delete zone.rmp -file]
&sv delete = [delete %estats% -info]
/*&sv delete = [delete %estats%.txt -file]
&dv work attribute landsystem grid interval fu sv i j kill nuke delete peruse estats elev
scar

q

&return



/*****************************************************************************
&routine slope                /* processes for 'slope' as the independent variable

grid

/* create zonegrid based on user input
&if [exists %slope% -grid] &then
  &do
    &type  The AML now requires you to choose the interval of each slope zone
    &type  which will determine the number of sectors for the chosen variable.
    &type
    &type  Enter    '2' for two degree intervals
    &type
    &type           '3' for three degree intervals
    &type
    &type           '4' for four degree intervals
    &type
    &type           '5' for five degree intervals
    &type

&sv interval [response 'Enter interval...']
&type
  &end


/* Establish remap tables for user specified zones
/* these could be easily looped, however, they provide a neat record of classes

&select %interval%
  &when 2
    &do
      &sv fu [open zone.rmp sv -write]
      &sv sv [write %fu% '0 1 : 1']
      &sv sv [write %fu% '1 3 : 3']
      &sv sv [write %fu% '3 5 : 5']
      &sv sv [write %fu% '5 7 : 7']
      &sv sv [write %fu% '7 9 : 9']
      &sv sv [write %fu% '9 11: 11']
      &sv sv [write %fu% '11 13 : 13']
      &sv sv [write %fu% '13 15 : 15']
      &sv sv [write %fu% '15 17 : 17']
      &sv sv [write %fu% '17 19 : 19']
      &sv sv [write %fu% '19 21 : 21']
      &sv sv [write %fu% '21 23 : 23']
      &sv sv [write %fu% '23 25 : 25']
      &sv sv [write %fu% '25 27 : 27']
      &sv sv [write %fu% '27 29 : 29']
      &sv sv [write %fu% '29 31 : 31']
      &sv sv [write %fu% '31 33 : 33']
      &sv sv [write %fu% '33 35 : 35']
      &sv sv [write %fu% '35 37 : 37']
      &sv sv [write %fu% '37 39 : 39']
      &sv sv [write %fu% '39 41 : 41']
      &sv sv [write %fu% '41 43 : 43']
      &sv sv [write %fu% '43 45 : 45']
      &sv sv [write %fu% '45 47 : 47']
      &sv sv [write %fu% '47 49 : 49']
      &sv sv [close -all]
   &end

  &when 3
    &do
      &sv fu [open zone.rmp sv -write]
      &sv sv [write %fu% '0 2 : 2']
      &sv sv [write %fu% '2 5 : 5']
      &sv sv [write %fu% '5 8 : 8']
      &sv sv [write %fu% '8 11 : 11']
      &sv sv [write %fu% '11 14 : 14']
      &sv sv [write %fu% '14 17 : 17']
      &sv sv [write %fu% '17 20 : 20']
      &sv sv [write %fu% '20 23 : 23']
      &sv sv [write %fu% '23 26 : 26']
      &sv sv [write %fu% '26 29 : 29']
      &sv sv [write %fu% '29 32 : 32']
      &sv sv [write %fu% '32 35 : 35']
      &sv sv [write %fu% '35 38 : 38']
      &sv sv [write %fu% '38 41 : 41']
      &sv sv [write %fu% '41 44 : 44']
      &sv sv [write %fu% '44 47 : 47']
      &sv sv [write %fu% '47 48 : 48']
      &sv sv [close -all]
    &end

  &when 4
    &do
      &sv fu [open zone.rmp sv -write]
      &sv sv [write %fu% '0 3 : 3']
      &sv sv [write %fu% '3 7 : 7']
      &sv sv [write %fu% '7 11 : 11']
      &sv sv [write %fu% '11 15 : 15']
      &sv sv [write %fu% '15 19 : 19']
      &sv sv [write %fu% '19 23 : 23']
      &sv sv [write %fu% '23 27 : 27']
      &sv sv [write %fu% '27 31 : 31']
      &sv sv [write %fu% '31 35 : 35']
      &sv sv [write %fu% '35 39 : 39']
      &sv sv [write %fu% '39 43 : 43']
      &sv sv [write %fu% '43 47 : 47']
      &sv sv [write %fu% '47 48 : 48']
      &sv sv [close -all]
    &end

  &when 5
    &do
      &sv fu [open zone.rmp sv -write]
      &sv sv [write %fu% '0 5 : 5']
      &sv sv [write %fu% '5 10 : 10']
      &sv sv [write %fu% '10 15 : 15']
      &sv sv [write %fu% '15 20 : 20']
      &sv sv [write %fu% '20 25 : 25']
      &sv sv [write %fu% '25 30 : 30']
```

```
      &sv sv [write %fu% '30 35 : 35']
      &sv sv [write %fu% '35 40 : 40']
      &sv sv [write %fu% '40 45 : 45']
      &sv sv [write %fu% '45 50 : 50']
      &sv sv [close -all]
     &end

  &otherwise
    &do
      &type Aborting AML... bye bye!
      &stop
    &end
&end

/*test for any existing zone grids of the same name
&if [exists zonegrid -grid] &then
  &do
    &sv kill [response 'zonegrid already exists! Do you wish to overwrite it?  Enter Y to
NUKE it now']
      &type
      &if [locase %kill%] = 'y' &then kill zonegrid all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
zonegrid = slice (%slope%,table,zone.rmp)
&type

/* resample zonegrid to align resolution with scar grid
&if [exists rezonegrid -grid] &then
  &do
    &sv kill [response 'rezonegrid already exists! Do you wish to overwrite it?  Enter Y to
NUKE it now']
      &type
      &if [locase %kill%] = 'y' &then kill rezonegrid all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type resampling  zonegrid to 2.5m resolution...
rezonegrid = resample (zonegrid, 2.5)

/* compute zonal statistics and convert to DBASE file for spreadsheet analysis
&if [exists %sstats% -info] &then
  &do
    &type
    &sv nuke [response [translate %sstats%]'stats file exists already! Do you wish to
overwrite it?  Enter Y to NUKE it now']
      &select %nuke%
        &when y
          &do
            &sv delete = [delete %sstats% -info]
          &end
```

```
        &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
      &end
  &end

&type
&type processing slope data...

%sstats% = zonalstats(rezonegrid,%scar%,moment,data)
&type
arc infodbase %sstats% %sstats%.dbf

&type
&type      Do you wish to peruse the newly created stats file?
&sv peruse [response 'Enter either Y or N']
  &if [locase %peruse%] = y &then
    &do
      arc tables
      sel %sstats%
      unload %sstats%.txt
      q
    &end


&select %peruse%
    &when y
      &do
        &popup %sstats%.txt
      &end

    &otherwise
      &do
      &end
&end



/* release memory
kill (!zonegrid rezonegrid!) all
&sv delete = [delete zone.rmp -file]
&sv delete = [delete %sstats% -info]
/*&sv delete = [delete %sstats%.txt -file]
&dv work attribute landsystem grid interval fu sv kill nuke delete peruse sstats slope scar

q

&return



/*****************************************************************************
/*
&routine fallover
&type      She's breaking up - I cant hold her!!,
Aborting AML.... bye bye!
&stop
&return
/*
/*****************************************************************************
```

```
/* ##############################################################################
/*
/*                                    hydrologia.aml
/*
/* ##############################################################################
/*
/* Description:      This ATOOL creates a statistics file for calculating the
/*                   proportion bare ground (PBG) versus one of a number of
/*                   hydrologically derived independent variables (flowpath length,
/*                   flow accumulation and its subsequent indices SMI, WPI).
/*
/* Created by:       L.R.Lovell August 1997, Massey University
/* Location:         /home/rs3/projects/lrl/atool/arc (LCR-PN)
/* Initiation:       hydrologia
/* Suggestions:
/* Calls:            fallover
/*
/* ##############################################################################

&severity &error &routine fallover
&term 9999
&sv work [show workspace]
&type
&type Present workspace is %work%, ATOOL selecting appropriate workspace for processing


/* define the landsystem under observation
&type
&type     This hydrologia ATOOL generates a statistics file to calculate the proportion bare
ground (PBG) within zonal ranges of hydrologically derived variables, or their compound
indices eg SMI and WPI. Choose your landsystem of interest:
&type
&type     Enter      'K' for Makomako
&type                'L' for Te Arai (Mangatoetoe Station)
&type                'M' for Te Arai (Murray Jessen data)
&type                'R' for Wharerata
&type                'W' for Waihora
&type                any other key to abort

&sv landsystem [response 'Enter choice...']

&if ^ [locase %landsystem%] in {'k','l','m','r','w'} &then
  &do
    &type You have not entered a K,L,M,R or W correctly, aborting AML... Bye Bye!
    &stop
  &end


/* select appropriate GRID files for processing and names for output files
&select %landsystem%
  &when k
    &do
      &workspace /home/rs3/projects/lrl/wdata/makomako
      &sv dtm makodtm
      &sv scar makoscar
      &sv slope makoslope
      &sv flowstat makpbgca
      &sv flength kflength
      &sv smistat maksmi
      &sv wpistat makwpi
    &end
```

```
  &when l
    &do
      &workspace /home/rs /projects/lrl/wdata/tearai
      &sv dtm tearaidtm
      &sv scar tearaiscar
      &sv slope tearaislo e
      &sv flowstat lrlpbg a
      &sv flength lflengt
      &sv smistat lrlsmi
      &sv wpistat lrlwpi
    &end

  &when m
    &do
      &workspace /home/rs /projects/lrl/wdata/tearai
      &sv dtm mrjdtm
      &sv scar mrjscar
      &sv slope mrjslope
      &sv flowstat mrjpbg a
      &sv flength mflengt
      &sv smistat mrjsmi
      &sv wpistat mrjwpi
  &end

  &when r
    &do
      &workspace /home/rs /projects/lrl/wdata/wharerata
      &sv dtm wratadtm
      &sv scar wratascar
      &sv slope wrataslop
      &sv flowstat wrapbg a
      &sv flength rflengt
      &sv smistat wratasm
      &sv wpistat wratawp
  &end

  &when w
    &do
      &workspace /home/rs /projects/lrl/wdata/waihora
      &sv dtm waihoradtm
      &sv scar waihorasca
      &sv slope waihorasl pe
      &sv flowstat waipbg a
      &sv flength wflengt
      &sv smistat waihsmi
      &sv wpistat waihwpi
  &end

  &otherwise
    &do
      &type You goofed bu dy.... bye bye!
      &stop
    &end
&end



grid

&if %landsystem% ne w &th n
  &do
/* compute depressionless DEM and flowdirection grids for said DTM
```

```
&if [exists filled -grid] &then
  &do
    &sv kill [response 'filled already exists! Do you wish to NUKE it? Enter Y to make it
so']
      &type
      &if [locase %kill%] = 'y' &then kill filled all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&if [exists flowdir -grid] &then
  &do
    &sv kill [response 'flowdir already exists! Do you wish to NUKE it? Enter Y to make it
so']
      &type
      &if [locase %kill%] = 'y' &then kill flowdir all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&type computing depressionless DEM and flow direction grid...
fill %dtm% filled sink # flowdir
&type

/* create flowaccumulation grid
&if [exists flowacc -grid] &then
  &do
    &sv kill [response 'flowacc already exists! Do you wish to NUKE it? Enter Y to make it
so']

      &if [locase %kill%] = 'y' &then kill flowacc all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
flowacc = flowaccumulation (flowdir)
&type

/* create log transformed flowaccumulation grid for graph purposes
&if [exists flowacclog -grid] &then
  &do
    &sv kill [response 'flowacclog already exists! Do you wish to NUKE it? Enter Y to make
it so']

      &if [locase %kill%] = 'y' &then kill flowacclog all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&type computing log transformed flow accumulation...
flowacclog = (40 * log10 (flowacc) + 1)
&type


/*create flowlength grid for overland flow paths
&if [exists flowdir -grid] &then
  &do
    &sv kill [response 'flowlength already exists! Do you wish to NUKE it? Enter Y to make
it so']

      &if [locase %kill%] = 'y' &then kill flowlength all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type computing flowpath lengths...
flowlength = flowlength (flowdir, #, upstream)



/* resample flowdirection, flowaccumulation, log flowaccumulation and flowlength /* grids to
align resolution with scar grids.
&if [exists reflowdir -grid] &then
  &do
    &type
    &sv kill [response 'reflowdir already exists! Do you wish to NUKE it? Enter Y to make it
so']

      &if [locase %kill%] = 'y' &then kill reflowdir all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&if [exists reflowacc -grid] &then
  &do
    &sv kill [response 'reflowacc already exists! Do you wish to NUKE it? Enter Y to make it
so']

      &if [locase %kill%] = 'y' &then kill reflowacc all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&if [exists reflowacclog -grid] &then
  &do
    &sv kill [response 'reflowacclog already exists! Do you wish to NUKE it? Enter Y to make
it so']

      &if [locase %kill%] = 'y' &then kill reflowacclog all
```

```
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end
&end

&if [exist reflowlength -grid] &then
  &do
    &type
      &sv kill [response 'reflowlength already exists! Do you wish to NUKE it? Enter Y to
make it so']

      &if [locase %kill%] = 'y' &then kill reflowlength all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&type resampling flow grids to 2.5m resolution...
reflowdir = resample (flowdir, 2.5)
reflowacc = resample (flowacc, 2.5)
reflowacclog = int (resample (flowacclog, 2.5))
reflowlength = int (resample (flowlength, 2.5))
&type

/* compute Soil Moisture Index, (cf. Moore et al, 1991) and convert to an integer grid
&if [exists smi -grid] &then
  &do
    &sv kill [response 'smi already exists! Do you wish to NUKE it? Enter Y to make it so']

      &if [locase %kill%] = 'y' &then kill smi all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&type computing soil moisture index...
smi =  int (ln (flowacc / (tan (%slope% div deg))))
&type

/* compute water power index, (cf. Moore et al, 1991) and convert to integer grid
&if [exists wpi -grid] &then
  &do
    &sv kill [response 'wpi already exists! Do you wish to NUKE it? Enter Y to make it so']

      &if [locase %kill%] = 'y' &then kill wpi all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type computing water power index...
wpi = int (flowacc * (tan (%slope% div deg)))

/* resample wpi amd smi grids to align resolution with scar grids.
&if [exists resmi -grid] &then
  &do
    &type
    &sv kill [response 'resmi already exists! Do you wish to NUKE it? Enter Y to make it
so']

      &if [locase %kill%] = 'y' &then kill resmi all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&if [exists rewpi -grid] &then
  &do
    &sv kill [response 'reflowacc already exists! Do you wish to NUKE it? Enter Y to make it
so']

      &if [locase %kill%] = 'y' &then kill rewpi all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&type resampling indices grids to 2.5m resolution...
resmi =  resample (smi, 2.5)
rewpi =  resample (wpi, 2.5)

&type


/*compute relationship between erosion scar occurrence and above variables
&if [exists %flowstat% -info] &then
  &do
    &type
    &sv nuke [response [translate %flowstat%]' stats file exists already! Do you wish to
NUKE it? Enter Y to make it so']
      &select %nuke%
        &when y
          &do
            &sv delete = [delete %flowstat% -info]
          &end

        &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
      &end
  &end

&type

&type
&type processing log transformed flow accumulation data...
```

```
%flowstat% = zonalstats(reflowacclog,%scar%,moment,data)
&type
arc infodbase %flowstat% %flowstat%.dbf

&if [exists %flength% -info] &then
  &do
    &type
    &sv nuke [response [translate %flength%]' stats file exists already! Do you wish to NUKE
it? Enter Y to make it so']
      &select %nuke%
        &when y
          &do
            &sv delete = [delete %flength% -info]
          &end

        &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
      &end
  &end

&type

&type
&type processing flowpath length data...


%flength% = zonalstats(reflowlength,%scar%,moment,data)
&type
arc infodbase %flength% %flength%.dbf

&if [exists %smistat% -info] &then
  &do
    &type
    &sv nuke [response [translate %smistat%]' stats file exists already! Do you wish to NUKE
it? Enter Y to make it so']
      &select %nuke%
        &when y
          &do
            &sv delete = [delete %smistat% -info]
          &end

        &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
      &end
  &end

&type

&type
&type processing soil moisture index data...


%smistat% = zonalstats(resmi,%scar%,moment,data)
&type
arc infodbase %smistat% %smistat%.dbf

&if [exists %wpistat% -info] &then
  &do
    &type
    &sv nuke [response [translate %wpistat%]' stats file exists already! Do you wish to NUKE
it? Enter Y to make it so']
      &select %nuke%
        &when y
          &do
            &sv delete = [delete %wpistat% -info]
          &end

        &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
      &end
  &end

&type

&type
&type processing water power index data...


%wpistat% = zonalstats(rewpi,%scar%,moment,data)
&type
arc infodbase %wpistat% %wpistat%.dbf



/* clean up info files, grids and variables to release memory
&sv delete = [delete %flowstat% -info]
&sv delete = [delete %flength% -info]
&sv delete = [delete %smistat% -info]
&sv delete = [delete %wpistat% -info]
kill (!filled  flowacc  flowacclog flowdir reflowdir reflowacc reflowacclog flowlength
reflowlength smi wpi resmi rewpi!) all
&dv work landsystem dtm scar slope flowstat flength wpistat smistat kill nuke delete

q

&type

&return


/*****************************************************************************
/*
&routine fallover
&type     She's breaking up - I cant hold her!!,
Aborting AML.... bye bye!
&stop
&return
/*
/*****************************************************************************
```

```
/* ################################################################################
/*
/*                                    slopeform.aml
/*
/* ################################################################################
/*
/* Description:     This ATOOL creates a statistics file for calculating the
/*                  proportion bare ground (PBG) versus slope configuration.
/*
/* Created by:      L.R.Lovell June 1997, Massey University
/* Location:        /home/rs3/projects/lrl/atool/arc (LCR-PN)
/* Initiation:      slopeform
/* Suggestions:
/* FYI:             requires reconciliation by AML user for categorical slope units
/* Calls:
/*
/* ################################################################################

&severity &error &routine fallover
&term 9999
&sv work [show workspace]
&type
&type Present workspace is %work%, ATOOL selecting appropriate workspace for processing
/*&watch slopeform.watch &append

/* define the landsystem under observation
&type
&type     This slopeform ATOOL generates a statistics file representing the magnitude of
bare ground within zones of consistent slope form elements or slope configuration. Choose
your landsystem of interest:
&type
&type     Enter     'K' for Makomako
&type               'L' for Te Arai (Mangatoetoe Station)
&type               'M' for Te Arai (Murray Jessen data)
&type               'R' for Wharerata
&type               'W' for Waihora
&type               any other key to abort

&sv landsystem [response 'Enter choice...']

&if ^ [locase %landsystem%] in ('k','l','m','r','w') &then
  &do
    &type You have not entered a K,L,M,R or W correctly, aborting AML... Bye Bye!
    &stop
  &end


/* select appropriate DTM file for processing and name for stats output
&select %landsystem%
  &when k
    &do
      &workspace /home/rs3/projects/lrl/wdata/makomako
      &sv grid makodtm
      &sv scar makoscar
      &sv stats maconfig
      &sv form makform
    &end

&when l
    &do
      &workspace /home/rs3/projects/lrl/wdata/tearai
      &sv grid tearaidtm
      &sv scar tearaiscar
      &sv stats taconfig
      &sv form taform
    &end

  &when m
    &do
      &workspace /home/rs3/projects/lrl/wdata/tearai
      &sv grid murrdtm
      &sv scar mrjscar
      &sv stats mjconfig
      &sv form mrjform
  &end

  &when r
    &do
      &workspace /home/rs3/projects/lrl/wdata/wharerata
      &sv grid wratadtm
      &sv scar wratascar
      &sv stats wrconfig
      &sv form wratform
  &end

  &when w
    &do
      &workspace /home/rs3/projects/lrl/wdata/waihora
      &sv grid waihoradtm
      &sv scar waihorascar
      &sv stats waconfig
      &sv form waiform
  &end

  &otherwise
    &do
      &type You goofed buddy.... bye bye!
      &stop
    &end
&end


grid


/* calculate hillslope curvature grids for said DTM
&if [exists out -grid] &then
  &do
    &sv kill [response 'out already exists! Do you wish to NUKE it? Enter Y to make it so']
      &type
      &if [locase %kill%] = 'y' &then kill out all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&if [exists prof -grid] &then
  &do
    &sv kill [response 'prof already exists! Do you wish to NUKE it? Enter Y to make it so']
      &type
      &if [locase %kill%] = 'y' &then kill prof all
        &else
          &do
```

```
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&if [exists plan -grid] &then
  &do
    &sv kill [response 'plan already exists! Do you wish to NUKE it? Enter Y to make it so']
      &type
      &if [locase %kill%] = 'y' &then kill plan all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
out = curvature (%grid%, prof, plan)
&type

/* reclass curvature grids to represent concave, linear or convex slope elements
&if [exists profint -grid] &then
  &do
    &sv kill [response 'profint already exists! Do you wish to NUKE it? Enter Y to make it
so']
      &type
      &if [locase %kill%] = 'y' &then kill profint all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end


&if [exists planint -grid] &then
  &do
    &type
    &sv kill [response 'planint already exists! Do you wish to NUKE it? Enter Y to make it
so']
      &type
      &if [locase %kill%] = 'y' &then kill planint all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&type reclassing curvature grids
if (prof < 0) profint = 1
  else if (prof == 0) profint = 2
  else if (prof > 0) profint = 3
endif


if (plan < 0) planint = 1
  else if (plan == 0) planint = 2
  else if (plan > 0) planint = 3
endif
```

```
&type

/* combine profile and planform curvature to identify 3D slope form element
&if [exists element -grid] &then
  &do
    &sv kill [response 'element already exists! Do you wish to NUKE it? Enter Y to make it
so']
      &type
      &if [locase %kill%] = 'y' &then kill element all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
element = combine (profint, planint)
&type

/* resample 3D element grid to align resolution with scar image
&if [exists 3delement -grid] &then
  &do
    &sv kill [response '3delement already exists! Do you wish to NUKE it? Enter Y to make it
so']
      &type
      &if [locase %kill%] = 'y' &then kill 3delement all
        &else
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
  &end

&type
&type resampling slope configuration grid
3delement = resample (element, 2.5)
&type

/* unload 3delement VAT to allow user to identify slope form elements
 &if [exists %form%.txt -file] &then
  &do
    &sv nuke [response [translate %form%.txt]' already exists! Do you wish to NUKE it? Enter
Y to make it so']
        &select %nuke%
         &when y
          &do
            &sv delete = [delete %form%.txt -file]
          &end

         &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
        &end
  &end

&type
&type unloading [translate %form%.txt]
   arc tables
   sel 3delement.vat
   unload %form%.txt
```

```
 q

&type
&type AML USER: You need to be aware of the following. In [translate %form%.txt] thematic
values are given for slope curvatures. PROFILE curvatures are given first, followed by
PLANFORM curvature.
&type
&type     1 represents CONCAVE curvature
&type     2 represents LINEARITY
&type     3 represents CONVEX curvature.
&type
&type     Note these values for reconciliation later on !!
&type
&pause

/*compute relationship between erosion scar occurrence and slope configuration
&if [exists %stats% -info] &then
  &do
    &type
    &sv nuke [response [translate %stats%]' stats file exists already! Do you wish to NUKE
it? Enter Y to make it so']
      &select %nuke%
        &when y
          &do
            &sv delete = [delete %stats% -info]
          &end

        &otherwise
          &do
            &type Aborting AML.... bye bye!
            &stop
          &end
      &end
  &end

&type

&type
&type processing slope form data...


%stats% = zonalstats(3delement,%scar%,moment,data)
&type
arc infodbase %stats% %stats%.dbf

&type
&type     Do you wish to peruse the newly created stats file?
&sv peruse [response 'Enter either Y or N']
  &if [locase %peruse%] = y &then
    &do
      arc tables
      sel %stats%
      unload %stats%.txt
      q
     &end


&select %peruse%
    &when y
      &do
        &term 9999
        &popup %stats%.txt
      &end
    &otherwise
      &do
      &end
&end


/* clean up info files, grids and variables to release memory
&sv delete = [delete %stats%.txt -file]
&sv delete = [delete %stats% -info]
kill (!out prof plan profint planint element 3delement!) all
&dv landsystem grid scar stats form sv kill delete peruse

q

&return


/*****************************************************************************
/*
&routine fallover
&type     She's breaking up - I cant hold her!!,
Aborting AML.... bye bye!
&stop
&return
/*
/*****************************************************************************
```