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SPATIAL VARIABILITY OF HYDROLOGIC RESPONSE ON NATURALLY VEGETATED HILLSLOPES IN A SEMI-ARID ENVIRONMENT

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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

SPATIAL VARIABILITY OF HYDROLOGIC RESPONSE ON NATURALLY VEGETATED HILLSLOPES IN A SEMI-ARID ENVIRONMENT

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

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BY

ALAN T. PILGRIM

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SPATIAL VARIABILITY OF HYDROLOGIC RESPONSE ON
NATURALLY VEGETATED HILLSLOPES IN A
SEMI-ARID ENVIRONMENT

APPROVED BY

DISSERTATION COMMITTEE

TABLE OF CONTENTS

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LIST OF TABLES

TABLE Page

LIST OF ILLUSTRATIONS

SPATIAL VARIABILITY OF HYDROLOGIC RESPONSE ON NATURALLY VEGETATED HILLSLOPES IN A SEMI-ARID ENVIRONMENT

CHAPTER I

INTRODUCTION TO THE RESEARCH PROBLEM

Early research on overland flow was based on the underlying postulates of the Hortonian overland flow model, with most research designed to measure overland flow and sediment yield on experimental field plots. Working within this paradigm, researchers sought causal relationships between overland flow and geomorphic parameters such as distance from the interfluve, slope angle, and slope length. Short slope lengths of the experimental field plots, and early research by geomorphologists on badland slopes, helped to ensure general acceptance of this model of overland flow.

During the 1960's, the general applicability of Hortonian theory was challenged by the concept of 'partial area contribution'. Evolving from field measurements of both overland flow and throughflow in small catchments in the humid northeast of the United States, the concept of partial area contribution identified stream hydrograph response as a general extension of the drainage system through zones of concentrated 'return throughflow'.

The Hortonian and partial area models thus represent two quite different explanations for the generation of overland flow, with their applicability a function of the environment under consideration. Hortonian overland flow is now considered to be most applicable to arid/semi-arid environments, notably on short slopes with minimal soil development.

Deterministic hydrologic models of catchment discharge traditionally employed the Hortonian model, though several recent models have used the partial area concept. In the past few years it has been argued that a major flaw in most deterministic hydrologic models (whether employing the concept of Hortonian flow or partial area contribution) is their assumption of catchments as spatially homogenous areas. Knowledge of the spatial and temporal variations in hydrologic response within hillslopes (and catchments), requires a knowledge of the spatial distribution of soil/slope characteristics. A mapping strategy such as the nine unit landsurface model (Conacher et al., 1977) offers an appropriate methodological framework for an examination of these spatial patterns in focusing attention on the interrelationships between geomorphic form, pedologic characteristics, and process.

The Research Problem and Research Aims

The research proposed in this study examines the spatial variability of overland flow and sediment yield on hillslopes in a semi-arid environment and relates this variability to the spatial distribution of soil/slope characteristics. The following specific research aims define the scope of this study.

(a) To measure the volume of overland flow and sediment movement by overland flow and rainsplash on three catenas to determine the presence/ absence of differences in hydrologic response within each of the three catenas.

(b) To show the appropriateness of using the nine unit landsurface model as a mapping scheme for the delimitation of areas of potentially different hydrologic response within the hillslope system.

(c) To establish geomorphic and pedologic criteria that can be used in the field identification and mapping of variations in hydrologic response.

This research includes, in Chapter II, a review of relevant literature to demonstrate the evolution of the present 'state of the art' in overland flow, rainsplash, and catenary research, and to illustrate the need for the integration of the two research areas. The physical environment of the study areas is described in Chapter III and the research methodology in Chapter IV. Included in the latter are descriptions of the sampling, mapping and statistical procedures used, the techniques employed to measure overland flow and rainsplash, and a discussion of the pedologic and geomorphic mapping criteria.

Overland flow and sediment yield data are analysed to determine the presence/absence of differences in hydrologic response between erosional and depositional slope environments in Chapter V. Validity of the landsurface unit classification developed in this study is tested using discriminant analysis and these results are discussed in Chapter VI. In the final chapter (VII) the research results are summarised and their application to other environments considered.

The results should provide substantive evidence of both spatial variability in hydrologic response in a semi-arid environment and the relationship of hydrologic response to spatial patterns of soil/slope characteristics. Ability to delimit spatial differences in hydrologic response by patterns of soil/slope characteristics offers potentially useful input for the modelling of catchment hydrology. In using the nine unit landsurface model as the methodological framework, the significance lies not solely in the nine unit model, but rather in the potential contribution of any appropriate mapping scheme. Equally important is the evaluation of potentially useful mapping criteria for the identification of erosional and depositional areas within hillslopes and the application of these criteria to the mapping of differences in hydrologic response.

Finally, as noted by Young (1972:70) almost a decade ago, there has been little research under conditions of natural vegetation, with most research on experimental plots or short slope lengths. It is hoped that this research project will make a positive contribution to our understanding of hillslope hydrology under conditions of natural vegetation.

CHAPTER II

LITERATURE REVIEW

Although most of the landsurface is comprised of hillslopes, the detailed examination of slope form and process has a recent history. This is well illustrated by the publications of Young (1972) and Carson et al. (1972) which represent the first books devoted solely to an examination of hillslopes. As an integral part of this development the discipline of geomorphology has adopted methodology and concepts from pedology, agricultural engineering and hydrology. Recent trends in process studies of overland flow and rainsplash and soil/slope research suggest that this is particularly true during the last twenty years. Increased emphasis on process studies has orientated a good deal of geomorphic research to the micro scale and, as a result, has kindled several important avenues of enquiry. Included are a re-examination of traditional theory (for example, Hortonian overland flow) and a growing awareness of the significance to hydrologic modelling of spatial patterns in soil/slope characteristics.

This review of the literature covers two main avenues of research: 1) overland flow and rainsplash research, and 2) studies of slope morphology and the catena. The review also serves to highlight the separate development of these two research fields and notes their recent integration.

Rainsplash Erosion and Overland Flow

The movement of sediment on slopes by raindrop impact and overland flow is dependent on the interplay of four factors: the detachability and transportability of the soil particles and the detaching and transporting capacity of the eroding agents. Given slopes composed of easily erodible soil, the factor limiting soil loss will be the efficacy of the agent of erosion. Alternately, where raindrop impact and runoff velocity are high (during any one rainfall event) the factor controlling sediment loss will be soil erodibility. Carson et al. (1972) identified these two conditions as 'transport limited' and partly 'weathering limited' respectively. The variables which largely control the interaction of the above four factors are climate, topography, vegetation, land use practices and specific soil characteristics such as soil texture, structure, and soil microroughness.

Historically, the investigation of the relative importance of these variables has been an area of research for agricultural engineers and hydrologists. As already noted it is only in recent years that geomorphologists have actively engaged in the measurement of these processes. In the U.S.A., government sponsored field measurement of surface water erosion commenced on a large scale in 1929 (Young,1972:62) and of all slope processes, overland flow and rainsplash have received by far the greatest attention. The field research has been conducted on soil plots ranging in size from 0.002 to 0.808 of an hectare with most of the research on rainsplash erosion completed in the laboratory.

An important point to note is that all of this research is understandably related to agricultural land and land use practices leaving the measurement of rates of erosion under natural vegetative cover as an area of research for geomorphologists.

So that the research efforts of geomorphologists may be viewed in perspective, and because much of the research by agricultural engineers and others have provided an important basis for geomorphic research, their work is included in this review. For the purposes of discussion the literature relating to soil erosion by rainsplash and overland flow will be examined separately, though obviously there is considerable overlap.

Rainsplash Erosion

Most of the research into rainsplash erosion has been conducted in the laboratory and commenced in the 1940's with the work of Laws (1941), Laws et al. (1943), Ellison (1944, 1947, 1952) and Ekern (1950). In some of the early studies simulated rainfall did not replicate natural rainfall characteristics, but it was not long before attention was focused on rainfall characteristics considered significant - raindrop size, size distribution, shape and attainment of terminal velocity. The plots used were usually small. Ekern (1950) for example, simulated rainfall on a metal soil tray 7.5 cms wide, 7.5 cms deep and 15 cms long. To record the sensitivity of soil loss to slope angle, the tray was simply tilted.

The early research on rainsplash (and overland flow) erosion was integrated by Smith and Wischmeier (1962), their work providing an important assessment of the 'state of the art' at the time. Over the past two decades rainsplash simulation studies have continued to attract agricultural engineers including the work of Free (1960), Rose (1960), Moldenhauer et al. (1964), Palmer (1965), Bubenzer et al. (1971), Lattanzi et al. (1974) and Romkens et al. (1975).

As a result of these research efforts (the above mentioned studies are only a sample) by agricultural engineers, rainsplash erosion is now well documented as a mechanism capable of high rates of soil detachment, but with a low transporting capacity. Not surprisingly, raindrop impact is often referred to as the first stage of the soil erosion process, with the second stage, overland flow providing the transporting medium.

Rainsplash research has generally taken one of four directions. As already noted, the research objective has often been to examine those rainfall and raindrop characteristics most significant to soil detachment. Other work such as that by McIntyre (1958a, 1958b), Tackett et al. (1965), Barnett et al. (1966), and Epstein et al. (1967) have examined the formation of soil crusts and subsequent reduction in infiltration rates following the commencement of rainfall. Palmer (1963), Shen (1973) and others have studied the influence of a thin film of surface water (for example, overland flow or surface detention storage) on the reduction of splash erosion.

The fourth area of research relates directly to land use and the effectiveness of crop residue in reducing soil loss. Recent research includes that by Lattanzi et al. (1974) and Singer et al. (1978). In both cases soil trays approximately 60 cms square were used for laboratory rainfall simulation studies. The experimentation by

Lattanzi et al. (1974) illustrated (as has been done before) that a surface layer of mulch results in a significant reduction in the influence of slope gradient on increasing soil erosion. Their study also showed that a surface mulch equivalent to 0.5 metric tons/ha reduced erosion by 40% and that 2.0 metric tons/ha reduced erosion by 80%.

In recent years geomorphologists have commenced investigating rainsplash erosion, and although the literature already cited would suggest that the mechanics of rainsplash erosion are reasonably well documented, a considerable amount of the geomorphic work deals with laboratory simulations. Work by Bryan (1974a, 1974b, 1976, 1979), Young et al. (1973), Moeyersons (1975) and Luk (1977, 1979) would appear to duplicate existing research.

A potentially more rewarding avenue of research, and one outside the realm of agricultural engineers, is the measurement of rainsplash on undisturbed soils, especially under conditions of natural vegetation. A review of the literature reveals a mere handful of such studies - Moeyersons (1975), Moeyersons et al. (1976), Kwaad (1977), Imeson (1977), and Morgan (1978). The study by Kwaad (1977) examined the significance of rainsplash as a mechanism for colluviation on wooded slopes in dry valleys of the Luxembourg Ardennes. As part of his study Kwaad recorded separately the amount of sediment dislodged upslope and downslope. Working in the same region, Imeson (1977) concluded that rainsplash efficacy was seasonal - a function of both litter cover and the activity of burrowing animals. The measurement techniques used in these field studies are almost as numerous as the authors and include tracing the movement of painted soil particles and a variety of collecting containers ranging from funnels, cylinders, and the splash boards of Ellison (1944).

Overland Flow

In contrast to the research on rainsplash erosion, much of the overland flow research undertaken by agricultural engineers has utilized field plots. Their investigations of the relationships between geomorphic parameters, different agricultural practices, and the resultant rates of soil erosion has generated an enormous amount of data. Both field plot and laboratory simulation data has been used in the subsequent development of empirical equations. Research by Zingg (1940), Smith et al. (1957), Olsen et al. (1963), Swanson et al. (1965), Young et al. (1969), Foster et al. (1972), Muzik (1974) and D'Souza et al. (1976) represents only a sample of this work.

The first empirical equation developed from this research was that by Zingg (1940) who related slope length and slope gradient to soil loss. Subsequent addition of soil erodibility, crop and conservation factors (Musgrave, 1947), and further refinement by Smith and Wischmeier (1962) resulted in the Universal Rainfall-Erosion Equation. More recently, agricultural engineers have worked with the theoretical mathematical modelling of overland flow (for example, David et al., 1975; Onstad et al., 1975).

Initial research on overland flow by geomorphologists was of a rather more indirect nature. Schumm (1956, 1962, 1964) and Leopold et al. (1966) measured rates of soil erosion by recording changes in the exposure of stakes inserted in the ground. This technique, and others such as the use of painted stone lines (Kirkby et al., 1974) have been used in a variety of studies and continue to be used today. An alternate and more direct method is the use of runoff troughs to collect sediment yield and in some cases to record overland flow. Almost without exception this has involved the use of fairly simple and inexpensive equipment in contrast to the more elaborate field plots used by agricultural engineers.

Most of the geomorphic field plots are small. Typical dimensions are of the order of 1 x 2 metres (Pearce, 1976) to 1.5 x 3 metres (Hayward, 1968, 1969). While these two researchers relied on natural rainfall events, simulated rainfall on similar sized field plots has also been used (Yair et al., 1973, 1976, 1980; De Ploey et al.,1975). The replication of natural rainfall characteristics is often regarded to be of minor importance in some of these studies. Other researchers, such as Williams (1969a), have relied on natural rainfall events and used boundary free sediment traps. A description of the various techniques used in the measurement of overland flow is provided by Toy (1977).

The slow rates of geomorphic change associated with overland flow has motivated a number of researchers to monitor badland slopes as these, in contrast to the general landscape, are characterised by high rates of erosion. A variety of researchers have used badland slopes as hardware models including Schumm's (1956, 1962) work on the South Dakota badlands; Campbell (1970, 1974) and Bryan et al. (1978) in Alberta; and Lam (1977) working on the badlands of Hongkong.

Geomorphologists have also used laboratory flumes to simulate overland flow. Examples include the work of Savat (1977), Kilinc et al. (1973) and De Ploey et al., (1976). Unfortunately, few studies have successfully integrated laboratory simulation and field measurements. One notable exception is Emmett's (1970) investigation of the hydraulics of overland flow where detailed laboratory flume studies preceded elaborate rainfall/overland flow simulation in the field.

In both field and laboratory research the role of several environmental variables is well documented - notably the relationships of slope angle and slope length to the generation of overland flow. Soil characteristics such as infiltration rates have also received considerable attention (for example, Selby 1967; Arnett 1976). Knapp (1978) provides a current overview of infiltration research while Hills (1970) has documented the variety of measurement techniques used in infiltration studies. By contrast, aside from the work by Emmett (1970), soil micro-roughness has received little attention from geomorphologists. Some work has been undertaken by agricultural engineers (Burwell et al., 1963; Monteith, 1974).

The emphasis given to factors such as slope angle, slope length, and infiltration characteristics is not surprising when consideration is given to the popularly accepted theory of overland flow - Horton's (1945) theory of infiltration excess overland flow. Simply stated Horton assumed that rainfall intensity in excess of infiltration capacity was the sole source of overland flow; providing a ubiquitous film of water over the slopes. Overland flow was also assumed to be the sole agent of surface fluvial erosion. Chorley (1978) notes that the early research by Schumm on short, unvegetated badland slopes characterised by low infiltration rates, served to re-enforce Horton's theory.

In recent years the universal applicability of the Hortonian overland flow model has been questioned, initially by hydrologists. This reassessment has resulted from at least two lines of investigation, the first of which has been the growing number of studies measuring overland flow and throughflow (Whipkey, 1965; Weyman, 1973).

The second line of investigation concerns the notion that the generation of overland flow is in fact not ubiquitous throughout a catchment. This concept of 'partial area contribution' was first proposed by Betson (1964). Later Dunne et al. (1970), working on forested slopes in the humid temperate environment of the north-east U.S.A., concluded that throughflow contributed significantly to the maintenance of overland flow, by return flow (or saturation overland flow) low on the slope profile. These researchers concluded that the Hortonian model was inappropriate for this environment, and that Horton overland flow, rather than having universal applicability, simply represents one of a range of possibilities.

Several years earlier Kirkby et al. (1967) had in fact suggested that the Hortonian model was probably most appropriate to arid and semi-arid areas with minimal soil development and low infiltration rates; the best example provided by badland slopes. Few studies have assessed the applicability of Hortonian flow in arid regions; though, Yair et al. (1973) and De Ploey et al. (1976), working in the arid environment of Israel, question it's validity. Results of other research on instrumented watersheds in Israel (Gerson et al., 1974) indicate that the partial area concept is also applicable to arid regions but that infiltration-excess overland flow is also important.

In addition several recent publications have highlighted the importance of spatial patterns of soil/slope parameters to process studies. Vorst et al. (1977) make several pertinent observations in relation to catchment studies and the Australian Representative Basins Programme. These authors reviewed the significance of catchment geomorphology to hydrologic investigations and noted that a major deficiency of most deterministic hydrologic models is their tendency to treat catchments as single spatially homogenous units. This they attributed to the oversimplified traditional concepts of runoff generation. Clearly, the future development of hydrologic models requires more input on the spatial variability of processes and pedogeomorphic parameters within a catchment, to enable prediction of the spatial and temporal variability of source areas. Kirkby (1978) also recognised the need for field observations of the spatial pattern of hillslope sediment production, a point noted by Vorst et al. (1977) as particularly important in enabling extrapolation to ungauged catchments.

Two recent studies, Bello et al. (1978) and Yair et al. (1978), have instrumented sections of small catchments. Bello et al. (1978) reported on a project on three small catchments in the New England district of New South Wales, Australia, where one subcatchment was monitored with several overland flow and subsurface flow interceptors. The other research project by Yair et al. (1978) involved the instrumentation of one side of a small first order drainage basin. These authors concluded that spatial variations in runoff processes can be expected. This suggests that the location of monitoring equipment should be such that these spatial variations in hydrologic response are monitored separately, although neither of the above two studies achieved this.

The investigation of spatial variability in overland flow and sediment yield within hillslopes clearly requires integration with the research centred on mapping slope morphology and the catena. A review of the literature in these two areas reveals partial integration of morphometric slope studies and catenary studies with the development of three dimensional landsurface mapping strategies that offer a useful methodological framework for the examination of spatial patterns of hydrologic response.

Slope Morphology and Catenary Research

Landsurface Mapping

The introduction of morphological mapping by Waters (1958) and particularly Savigear (1965) provided the impetus for a new field of landform study, namely parametric mapping. Morphological mapping is concerned solely with the identification and delimitation of variations in landsurface geometry. The technique provides a standardised field method for mapping the three dimensional nature of slope form, but due to the lack of rigour in the definition of the technique, it has proved unreliable for replication of results. Today the technique has essentially evolved into a more comprehensive research tool, that of geomorphological mapping.

On the basis of the same assumption that underlies morphological mapping (i.e., that the facets and curved surfaces comprising the landsurface adjoin in breaks of slope or inflexions) a number of geomorphologists have developed comprehensive parametric mapping strategies for classifying the landsurface into discrete geometric elements. Early work by Ollier (1967), although qualitative, provided a classification of landsurface form devoid of 'Davisian stage names', thus avoiding the inevitable genetic connotations. Speight (1968), Ahnert (1970b), and Parsons (1978), all derived quantitative classifications by combining classes of slope angle with profile and plan form (that is, concave, convex, and rectalinear). This geometric approach to landsurface classification has shown considerable promise as a technique for mapping landsurface form from aerial photographs (generally at a scale of approximately 1:40,000). Examples of Australian research in this field include the work of Speight (1968, 1976) and Scott et al. (1971).

As an end in itself the mapping of surface form would appear to be of little value. However, the application of this research to related topics such as drainage status (for example Troeh, 1964) and soil patterns (Bridges et al., 1963) suggests there are some valuable areas of research. More recently, in his work on the rugged terrain of New Guinea, Speight (1976) recognised the potential application to land use surveys in the prediction of soil patterns from surface form elements mapped by photogrammetry.

The primary objective of all the above mentioned studies is quite clear - the division of the landsurface into discrete categories of geometric shape. A far less restrictive approach has been taken by Ruhe and Walker (1968) and Dalrymple et al. (1968) in the development of hillslope models based on the interrelationships between geomorphic and pedologic form and process. With the inclusion of soil parameters, these models need to be considered in relation to research on soil/slope studies, in addition to the literature already cited. Thus before discussing these more recent models the development of soil/slope studies in geomorphology will be examined. The starting point is in fact in pedology with the inception of the catena concept.

The Catena

The term catena was originally used by Milne (1935), a pedologist to describe the soils around a residual granite hillock in the plateau region south of Lake Victoria (an area with a tropical semi-arid climate). Milne adopted the term because of the lack of a suitable soils term having a cross country dimension. The term 'profile' was regarded as unsuitable as this was already used by geomorphologists and pedologists to denote vertical differentiation in soils.

In the study by Milne surface transportation of soil by overland flow was considered to be the basic process leading to the differential sorting of soils. A skeletal soil forming around the base of the residual outcrop provided the source, with the end members of the catena being a zone of washed sand; a zone of silty or clayey sand and below these a level clay floor (playa). In all, a sequence of seven soil 'zones' was found to recur over a large area of the Central Plateau of Tanganyika.

Milne recognised that such soil relationships could occur over both uniform and varied parent material, although he never provided an unambiguous definition of the term. Millar et al. (1965:463) limited the use of the term to uniform lithology in defining a soil catena as "a sequence of soils from similar parent material and of similar age in areas of similar climate but whose characteristics differ because of variations in relief and drainage". This definition is probably a little restrictive and it is likely that Milne's general concept is more clearly reflected by Bushnell (1942:466) who noted that the soil catena implies "areal associations and gradations of soils related to drainage conditions or the transect of a valley". This is the essence of the catena concept in that it provides a convenient mapping unit and a type of classification.

A systematic approach to classifying such differences in soils within a hillslope was forwarded by Morison (1949). He suggested that any catena could be considered by analogy with an individual soil profile as containing an eluvial complex (high level sites, material lost in solution and by water transport); a colluvial complex (receives water and sediment from eluvial sites and loses material to the sites below); and an illuvial complex (receives material from the entire catena and loses material to the river). Hallsworth (1965) identifies a fourth unit - the alluvial complex on which sediment derived from upstream is deposited.

A similar soil landscape model was proposed by Ruhe (1960), though the terminology was geomorphic. Ruhe also constructed hypothetical graphs illustrating the most likely variations in A horizon thickness and the diminishing influence of local parent material, with increasing distance from the interfluve.

The catena concept has proved a useful framework for pedologic and geomorphic research though it's incorporation into geomorphologic research designs has evolved rather slowly. Examples of catenary research include the work of Watson (1964), Webster (1965), Young (1969a, 1969b), and Gunn (1974). The soil variations originally described by

Milne were essentially textural differences resulting from surface wash. Clearly, the concept is equally applicable to other geomorphic processes such as throughflow (Ruxton, 1958) and to the study of soil geo-chemical catenas (Ball et al., 1968; Glazovskaya, 1970). A number of researchers have also applied a catenary approach in assessing the agricultural potential of soil (for example, Moss, 1963).

All of the previously mentioned catenary studies investigated soil/slope interrelationships in terms of a slope transect, focusing attention on downslope changes in pedologic and geomorphic properties, without incorporating the third dimension of across slope variations. This latter group of areal studies, as illustrated by Walker et al. (1968a, 1968b) and Alexander (1969) reflect more closely Bushnell's (1942) notion of areal associations.

At this point, it is worth noting a number of studies which serve to illustrate the growing integration of the landform mapping techniques discussed earlier and the catenary approach. Curtis et al. (1965) discussed the need for developing a systematic method to describe relief when studying soil patterns. Also explored was the value of land-form parameters as predictors of soils (for example, Bridges et al., 1963) and of drainage conditions. Early work by Glentworth et al. (1950) described the hydrologic sequence characteristic of soil catenas in part of north-east Scotland. More recently Chiang et al. (1970) reexamined the use of relative position within the soil catena as an indicator of moisture status. Using slope gradient, rate of change of slope gradient, and radius of curvature, Troeh (1964) developed mathematical equations to describe the three dimensional nature of hillslopes and was able to correctly classify 90% of the drainage conditions in his study area.

Spatial Patterns of Soil and Slope Parameters

Though much of the early catenary work in geomorphology examined the nature of soil/slope interrelationship in an essentially two dimensional manner, the catena concept embodies, as already noted, the notion of areal associations. Research by Ruhe (1956), Butler (1959), and Dan et al. (1968) fully incorporated the three dimensional nature of the landsurface in their examination of chronological soil/slope sequences.

The application of statistical techniques has provided further refinement in catenary studies, both in the examination of soil/slope transects (for example, Furley, 1968) and of areal patterns (Walker et al., 1968a, 1968b) at the level of the individual hillslope. The work of Walker et al. (1968a, 1968b) is a good example of the application of statistical techniques to an examination of variations in soil properties in relation to areal changes in landform parameters.

In their study, the slope parameters used were gradient, length, direction, curvature, distance from the hillslope summit, and elevation relative to the summit. The soil properties measured included thickness of the A horizon; depth to grey mottles; depth to 50% grey mottles and depth to reddish or brownish mottles; depth to carbonate horizon; and depth of the surficial deposit above the glacial drift. Elevation and slope were the parameters most strongly related to the soil properties measured. A division was also made at two of the sites into convex and concave units - again producing significant regressions. Considerable soil variation remained unaccounted for and the authors concluded that this was probably due to the relict nature of some of the subsoil features. Considerable local variation in the depth of the A horizon was attributed to faunal activity.

In general, all of the research discussed so far has focused attention on the linear and/or areal interrelationships of soil properties and geomorphic form. Often inferences have been made regarding geomorphic precesses, however, these are of a general nature and not supported by field measurement. Clearly, geomorphic and pedologic studies of soil/slope interrelationships share much in common, and in the following discussion several papers are examined which have brought the two fields even closer together with an increased attention to geomorphic processes.

The Interrelationships of Slope Form and Development, Soil Formation and Geomorphic Processes

Up to this point, two basic threads of enquiry have been explored: the description of slope form, and the inception of the catenary concept in pedology and subsequent adoption in geomorphic research. The recent integration of these aspects of pedologic and geomorphic research, namely the interrelationships between slope form and development, soil formation, and geomorphic processes is well illustrated in the research by Furley (1968), Ruhe and Walker (1968), Dalrymple et al. (1968), and Conacher et al. (1977). Work by Alexander (1969) is also discussed in relation to the nine unit landsurface model.

Furley (1968) looks directly at the interrelationships between slope development, soil formation, and geomorphic processes. Presumably because Furley was primarily interested in downslope variations of soil/

slope parameters he used a slope transect rather than areal units. He examined Penck's suggestion that 'slope' (gradient angle) acts as a major control on 'reduction' (degree of weathering) and aimed at exploring the conditions under which there is a consistent relationship between gradient angle and selected criteria of soil maturity. After completing this research Furley noted that there appeared to be relationships between the soil properties and zones of erosion and deposition within the hillslope - that is to say the soil properties were reflecting the geomorphic processes of erosion and deposition.

Working within the framework of the maturity (time dependent) sequence, Furley was restricted to an unsaturated energy state (erosional sites). A further restriction of the concept was that the relationship between the stage of soil formation and gradient angle could only be expected to be consistent on slopes where "the surface and subsurface factors of the soil environment were approximately uniform over the entire sampled area" (Furley, 1968:25). Surface soil criteria selected by Furley were pH, organic carbon percent, total nitrogen percent and particle size. These criteria were selected because in the maturity sequence they should have reflected differences in soil development. Furley concluded that in the erosion zone there were significant associations between gradient angle and the soil properties examined; these were not reflected in the accumulation zone. Organic carbon percent, total nitrogen percent, silt and clay size particles of calcareous soils, and the pH of acidic soils all decreased with an increase in gradient angle while the pH of calcareous soils increased with an increase in gradient angle.

The criteria forwarded by Furley for identifying the erosional/depositional junction were three-fold: visual evidence of those parts of the slope that were respectively gaining and losing soil; graphical analyses of slope angle; and the corresponding changes in slope angle and soil parameters. The first of the three criteria, visual evidence, presents the biggest problem, as Furley infers a change of process from form, without giving any insight into the nature of his 'visual evidence'. Young (1969) rightly maintains that such a deduction can only be made in association with quantitative measurements of the process(es) involved.

Erosion and deposition are both intermittent down a slope and any area defined as erosional will usually contain some areas of deposition. Similarly depositional areas will most probably contain some areas of erosion, however small they may be. Therefore in looking at visual evidence of erosion and deposition the delimitation of erosional and depositional segments must in part be dependent on the areal dominance of the one over the other (Pilgrim, 1972). Field measurements of process(es) involved could then be used to validate or disprove the location of the junction or boundary. Research similar to that by Furley (1968) is discussed by Furley (1969, 1971), Whitfield et al. (1971), Anderson et al. (1975) and Davidson (1977).

Ruhe and Walker (1968) and Walker and Ruhe (1968) formulated models of open and closed systems for hillslopes and soil formation and forwarded a five unit hillslope model - the five units extending from the interfluve to the thalweg are the summit, shoulder, backslope, footslope, and toeslope respectively. The basic thesis of these two papers is centred on the interrelation of geomorphic and pedologic processes.

Open systems hillslopes are defined as having an incomplete sedimentologic record relating to the valley side slopes while closed systems are encircled, so that all erosional debris is trapped within a common depository.

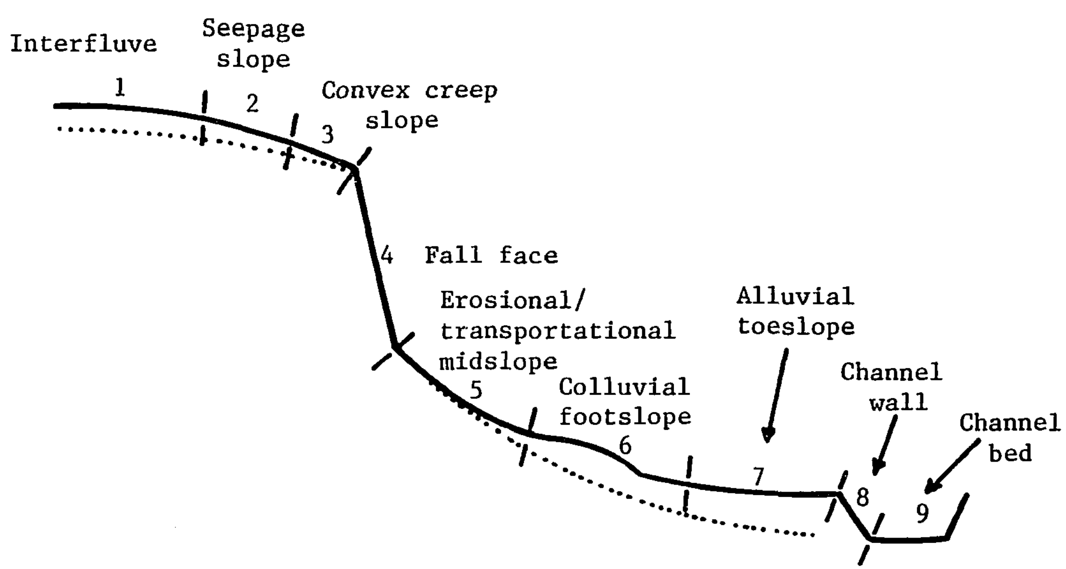
The two hillslope models are summarised as regression equations enabling the statistical testing of soil properties in relation to the hillslope landscape. Also, individual units within the hillslope model can be represented as mathematical subsets. The value of the two models lies in their predictive qualities as to the type of soil trends to be found within a particular area. Marked divergence from the predicted soil distribution may then suggest the influence of past processes or the presence of relict landsurfaces. Ruhe and Walker have employed general systems theory terminology to distinguish between the two models. An important distinction between this model and previous models of slope form is that all five slope components need not occur on every hillslope and that any one of the components may represent a small or large part of the slope profile.

Also in 1968, Dalrymple, Blong and Conacher developed a more comprehensive model of landsurface description. These authors proposed a nine unit landsurface model (Figure 2.1) based on five years of observations in the humid temperate northern half of the North Island of New Zealand. The nine units are the interfluve (unit 1); seepage slope (2); convex creep slope (3); fall face (4); transportational midslope (5); colluvial footslope (6); alluvial toeslope (7); channel wall (8); and channel bed (9); In a later paper Conacher et al. (1977:101) notes that "process and response together define each landsurface unit. The

Figure 2.1

THE HYPOTHETICAL NINE UNIT LANDSURFACE MODEL

(adapted from Dalrymple et al., 1968:62)



.... Approximate lower limit of soil formation processes refer to soil/water/gravity interactions on a landsurface catena and the responses to the pedogeomorphic properties which result from those processes".

The nine unit landsurface model is concerned with the total landsurface and not just hillslopes; concentrating on geomorphic form and contemporary geomorphic and pedogenetic processes rather than on concepts of slope evolution. As such the nine unit landsurface model does not represent a form towards which all hillslopes are evolving in the North Island of New Zealand. The only unit that must be present in any one landsurface is unit 1, the interfluve. All other units may or may not be present and may recur more than once in any one landsurface.

The nine unit model implies an interrelationship between soil properties and surface morphology as theoretically each landsurface unit should exhibit clustering of soil and geomorphic properties characteristic of the unit, with large variations between it and a population of another unit. There is then an assumption of modality underlying the basic concept of the nine unit model and, in the field recognition of the landsurface units, attention is focused on identifying core areas or modal zones, rather than on boundary drawing. Though the conceptual basis of, and applicability of the nine unit model has been considerably amplified by Conacher et al. (1977) there has been little detailed research statistically testing the modality of specific landsurface units. Alexander (1969) worked within the framework of the nine unit model though the variables he tested were solely pedologic.

Alexander identified units 1, 2, and 6 of the hypothetical nine unit landsurface model to delineate soil populations in order to test the hypothesis of soil property clustering. In his analysis Alexander avoided soil chemical properties as Ball and Williams (1968) showed that certain chemical properties of soils were subject to tremendous variation over short distances. Emphasis was placed on soil physical properties that could be readily measured and quantified - horizon thickness, moisture content, and organic matter content. The statistical analyses carried out by Alexander did show the clustering of soil properties into discrete populations related to units 1, 2, and 6 and a dendrogram of soil site similarity coefficients supported the contention of soil property clustering.

The strength of the nine unit model lies in the integration of pedogeomorphic form and process. However, the operation of processes is still inferred from detailed observations of form and to date there is still no published research relating the field measurement of landforming processes to the identification of specific landsurface units. Indeed, research in soil/slope interrelationships in general shows a lack of integration with the quantitative measurement of geomorphic processes. Nevertheless, the basic thesis of the model promises a suitable methodology for the study of process, particularly when considering the current status of research in overland flow and rainsplash.

CHAPTER III

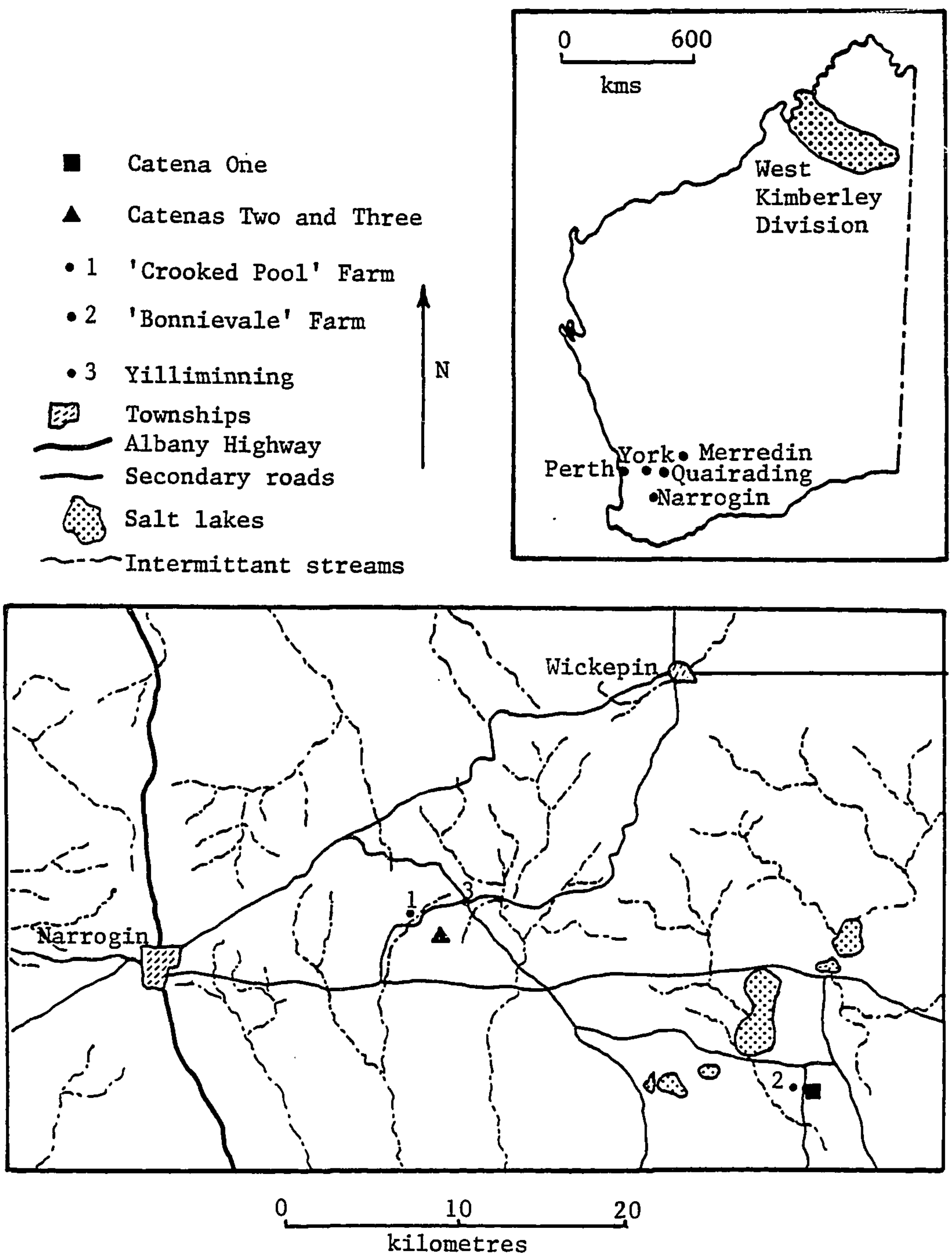
THE STUDY AREA

Field data collection was conducted on three catenas east of Narrogin (Figure 3.1), an agricultural town 190 kilometres southeast of Perth, Western Australia. Catena One is 40 kilometres east of Narrogin and Catenas Two and Three are 24 kilometres east of the town. Together, the three catenas are representative of the landscape common to the southwestern region of Western Australia.

The regional setting of the research sites is essentially that of a landscape of low relief with broad flat-floored valleys and generally long low angle valley side slopes (Pilgrim, 1979). Maximum variations in local relief are of the order of 90 metres over several kilometres; lateritic breakaways (mesas) and outcrops of country rock as domed inselbergs are the most prominent topographic features. Evidence of laterization dominates the landsurface with the formation of the laterites attributed to wetter and warmer conditions during the Tertiary. A subsequent change to drier climatic conditions resulted in the demise of extensive river systems and alluviation of the valleys; many of the major river valleys are now occupied by chains of salt lakes. These lakes function as local internal drainage areas although the river basins

Figure 3.1

LOCATION OF STUDY AREAS



still function as integrated systems during periods of prolonged heavy rainfall.

Present day climatic conditions in the area of the study sites is semi-arid, with an annual rainfall of approximately 400 mm. The area has a strong seasonal maxima with 50% of the rainfall recorded in the three winter months and 80% during the period May to October. Analysis of the frequency and magnitude of rainfall events recorded during the six years of fieldwork (June 1972 to August 1978), revealed general similarity between the rainfall data for the three catenas and the Narrogin townsite (Table 3.1). The data also suggests an inverse correlation between the magnitude of extreme rainfall events and total annual rainfall.

Table 3.1

MAGNITUDE AND FREQUENCY OF RAINFALL EVENTS

(June 1972 to August 1978)

	Recording Stations (rainfall totals in mm)		
	Narrogin Post Office	Catenas Two and Three 'Crooked Pool' Farm	Catena One 'Bonnievale' Farm
Average Annual Rainfall	506.0	429.0	402.0
Percentile			
50	7.5	7.3	7.0
90	21.0	19.0	17.5
95	25.0	25.8	22.5
98	34.0	32.0	33.0
99	41.0	44.5	49.7

Geologically the area forms part of the Yilgarn Block, an extensive area of Archaean granites, gneisses, and greenstones. Outcrops of greenstone are absent in the study areas; gneiss is the most common. The general description given to the soils of this region is that of dominantly yellow and mottled yellow duplex soils (Jarvis, 1979:75), reflecting the dominant influence of laterization. Essential features of these soils are the strong textural contrast between the thick sandy A horizon (which has often been removed by erosion) and the mottled yellow-brown and red clay B horizon. Below the B horizon is the dominantly white kaolin clay above kaolinised parent rock (Stace, 1968). On individual hillslopes lateritic breakaways (or their remnants) cap the interfluves with the only exception provided by extensive outcrops of country rock as domed inselbergs. Subsoil horizons of the lateritic profile are often exposed on the valley side slopes. Weathering of areas of exposed and near surface bedrock produces a coarse textured sandy soil and provides the only soils not dominated by the characteristics of laterization.

The finer textured and medium textured soils of the region are dominated by woodlands of York gum (*Eucalyptus loxophlebia*), salmon gum (*E. salmonophloia*), and wandoo (*E. redunca*). Sheoak (*Casuarina*) is associated with the coarse textured sandy soils surrounding outcrops of gneissic bedrock. Heath and low heath communities, particularly species of *Dryandra*, *Hakea*, and *Xanthorrhoeae* are commonly associated with lateritic soils of the breakaway slopes. The relatively open canopy characteristics of these woodlands is well illustrated in Jarvis (1979: 63).

There is no detailed published research on the soils, geology, geomorphology, vegetation, or climate of the area encompassing the research sites. In a regional context the only research of any significance is that undertaken for the Commonwealth Scientific and Industrial Research Organisation (CSIRO) by Bettenay et al. (1964) in the Merredin district and Mulcahy et al. (1961) in the York-Quairading area. Both these study sites are more than 100 miles to the north of my areas with the research more concerned with soils and landuse.

General Physical Characteristics of the Three Catenas

Catena One is approximately 1100 metres long and 250 metres wide. The dominant feature of this area is a long low angle (1-3 degrees) landsurface unit which occupies the lower two-thirds of the catena. Surface horizons of the laterite profile have been eroded to expose a heavy clay subsoil. Between this landsurface unit and the interfluve there is a small lateritic breakaway remnant, a short colluvial slope and an area of bedrock outcrop. The landsurface unit map (Figure 3.2) illustrates the relative topographic position of each of these landsurface units and includes slope angles representative of each unit. Differences in vegetation also help in identifying the different landsurface units. *Dryandra* dominates the gravelly soil of the breakaway; sandy textured soils such as the colluvial areas and the soils derived directly from the exposed bedrock are more suited to sheoak; while salmon gum dominate the heavier soils of the lower slopes. The erosional and depositional landsurface units also demonstrate marked differences in the percent of vegetative ground cover (grasses) with a virtual absence of grasses on the erosional unit. A similar distinction in vegetative ground cover is also present on Catena Two.

Both Catenas Two and Three occupy the upper portion of a small catchment with the two catenas (Figure 3.3) separated by a shallow poorly defined first order drainage line. Catena Two is approximately 220 metres long and 120 metres wide and is divided into two distinct land-

Figure 3.2

CATENA ONE: LANDSURFACE UNIT MAP

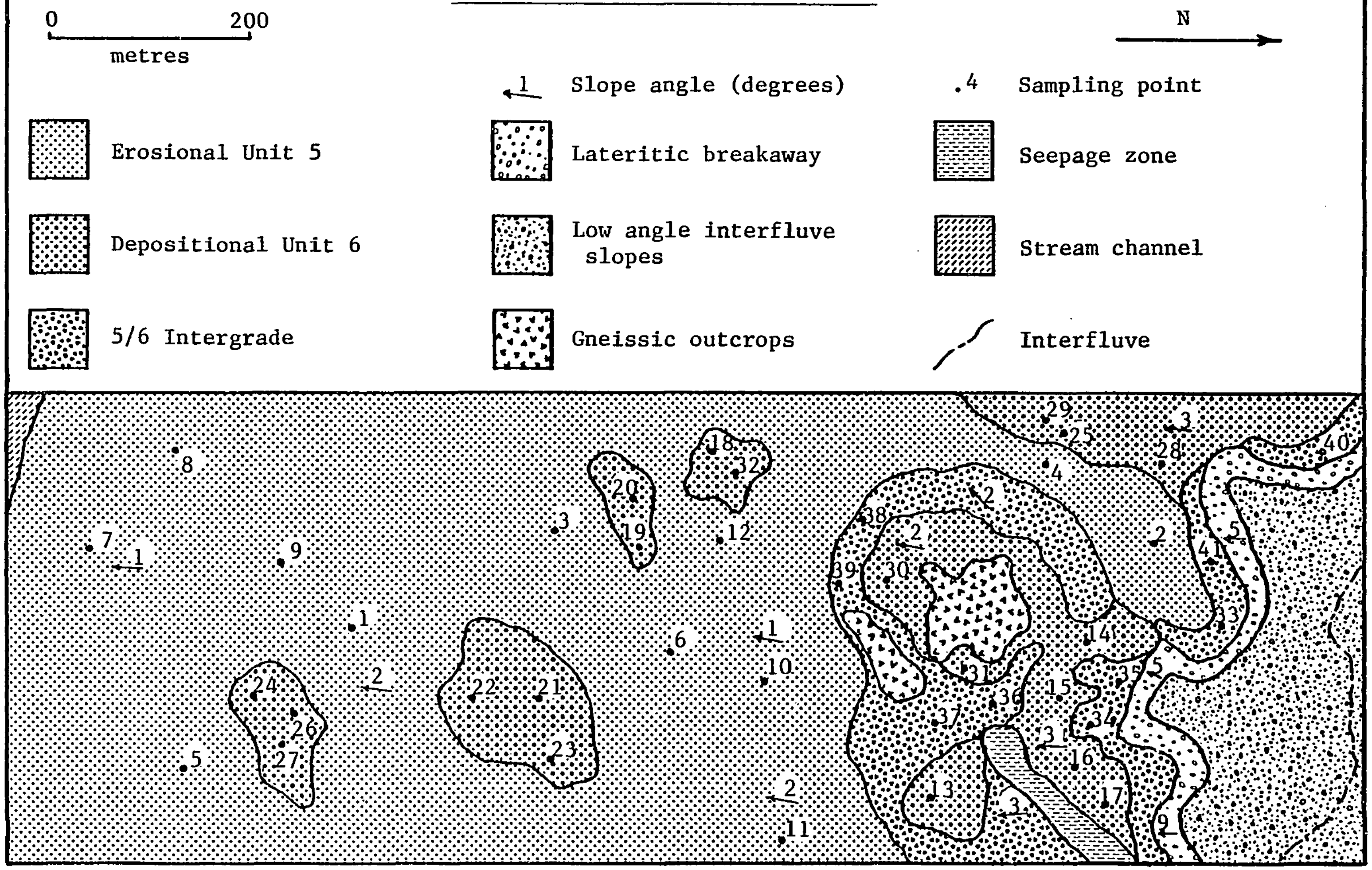
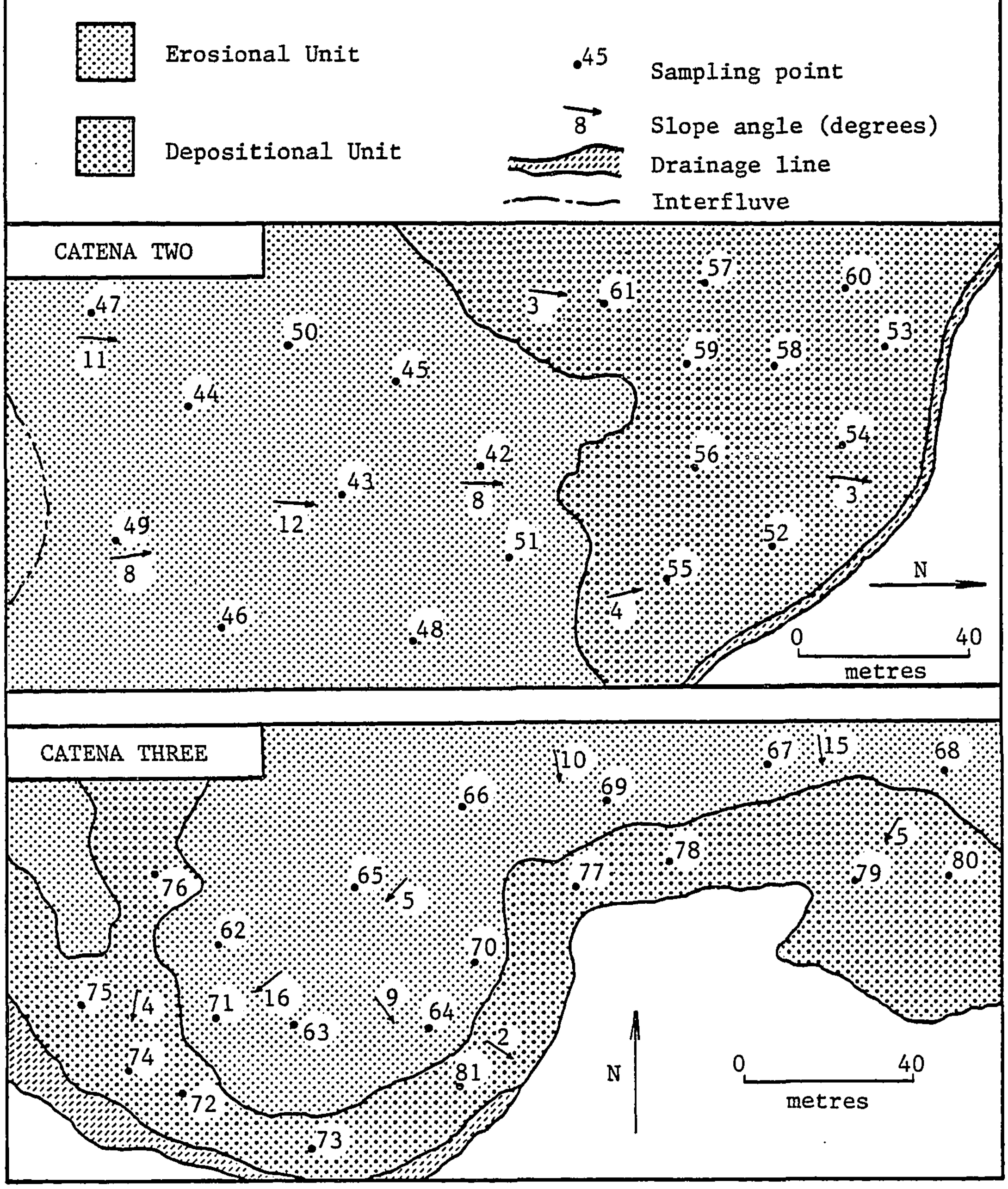


Figure 3.3

CATENAS TWO AND THREE: LANDSURFACE UNIT MAPS



surface units. The upper portion of the slope is a lateritic breakaway remnant though maximum slope angles are only of the order of 13 degrees (Figure 3.3). A coarse textured gravel comprises the surface soil with dryandra the dominant vegetation. Below the breakaway slope is a short colluvial footslope, the lower end of which abutts the drainage line. Soils of the footslope are sandy textured with some small gravels. Relative relief on this catena is approximately 25 metres.

Catena Three, immediately to the north of Catena Two, is the only area not capped by laterite. The upper portion of the catena comprises gneissic outcrops with slope wash forming a distinct and coarse textured colluvial slope along the margin of the outcrop. Several small alluvial fans denote areas of concentrated overland flow. This catena is approximately 90 metres by 200 metres in size.

CHAPTER IV

RESEARCH DESIGN

Discussion of the research design is divided into four sections: the selection of field sites; landsurface mapping and sampling within units; techniques used to measure overland flow and sediment yield; and selection and measurement of geomorphic and pedologic variables.

Selection of Field Sites

To satisfy the research aims the field sites had to meet the following prerequisites:

(a) A semi-arid environment where surface wash could be assumed to be the dominant geomorphic agent;

(b) Conditions of natural vegetation (that is, land which has not been cleared for cultivation or unduly altered from a natural condition);

(c) The field sites, when considered together, should be representative of the landscape common to the southwestern region of Western Australia.

Aerial photographs (1:40,000) were used to locate the scattered areas of uncleared land with a small number of potential field sites selected prior to field reconnaissance. Three catenas east of Narrogin (Figure 3.1) were selected for study, their choice was in part subjective in order to meet the stated criteria.

Landsurface Mapping and Sampling within Landsurface Units

The technique used in landsurface mapping has now been discussed in some detail by Conacher et al. (1977:111). Mapping of landsurface units in the field is dependant upon the identification of geomorphic and pedologic properties which reflect the dominant contemporary geomorphic process operating on that landsurface. Inherent in the definition of a landsurface unit is the concept of modality; that is to say the statistical clustering of the surface morphologic and soil properties identified as indicative of a particular geomorphic process.

Initially, it is necessary to establish those pedologic and morphologic variables that reflect, in this case, the differences between landsurface units 5 (erosional) and 6 (depositional) in a dominantly overland flow environment. Later in this chapter, reference is made to research carried out in the Kimberley Division of Western Australia which, together with field reconnaissance in the Narrogin and surrounding districts, suggested that soil microroughness, the areal distribution of micro soil surfaces, and thickness of the A_1 horizon were suitable mapping criteria.

Field mapping proceeded along radials drawn from centrally located areas of the landsurface units, with the unit boundary (or more probably the intergrade zone) marked by a rapid spatial change in the properties being measured. The mapping process is commenced in centrally located areas of each unit as the interest lies more with the landsurface unit than with the intergrade zones.

The landsurface units as delimited in the field were used as the sampling population. To reduce possible contamination from sample sites located at the boundary (intergrade zone) of two units the sampling population of each unit was reduced in size by one-tenth the distance from the centre to the boundary of each unit. For units 5 and 6 on Catena One, 12 and 20 sampling points respectively, were randomly marked on the landsurface map and their location in the field determined by compass and tape. Nine sampling points were similarly selected within the 5/6 intergrade. On Catenas Two and Three the sample size was reduced to ten due to the relatively small size of the sampling population and the presence of more clearly defined differences between units 5 and 6.

At each sampling point observations were recorded using the techniques outlined in the following sections. A 50 centimetre square pit was used for soil profile descriptions and sampling. Representative soil samples were collected by taking 'grab samples' across the soil profile face. Surface soils were sampled in addition to profile samples at depths of 2-3, 7-8, 14-15, 22-23 centimetres and, where appropriate, at depths to 1.2 metres. Identifiable changes in soil horizons not already included were also sampled. General field descriptions were recorded of colour, texture, structure, presence/absence of humic staining, moisture status, and faunal activity.

Measurement of Overland Flow, Sediment Transport, and Rainsplash Response

In order to monitor the hydrologic response of the different landsurface units three measurement techniques were employed. Overland flow and sediment movement were recorded using washtrays (sediment traps); splashboards were installed to record soil movement by rainsplash; and, grids of metal pins were used in an attempt to measure changes in elevation resulting from erosion or deposition of sediment. The one metre quadrat maps discussed later in this chapter illustrated that the processes of erosion, transportation, and redeposition by overland flow are extremely local in nature. This suggested that process measurements should also be conducted at the scale of the individual quadrat. A brief outline follows of the three measurement techniques used in the study, including the technique used to estimate the catchment area of the washtrays. The availability of rainfall records is also discussed.

Washtrays

To record sediment movement and volume of overland flow on the two landsurface units, a total of 13 washtrays were installed on the three catenas. Distribution of the washtrays throughout the catenas is detailed in Table 4.1. The washtrays were all randomly located at previously selected quadrat sampling points. Each tray drained into a sealed plastic storage drum via a buried length of rubber hosing. Dimension of the washtrays and storage drums are shown in Figure 4.1(a).

Table 4.1

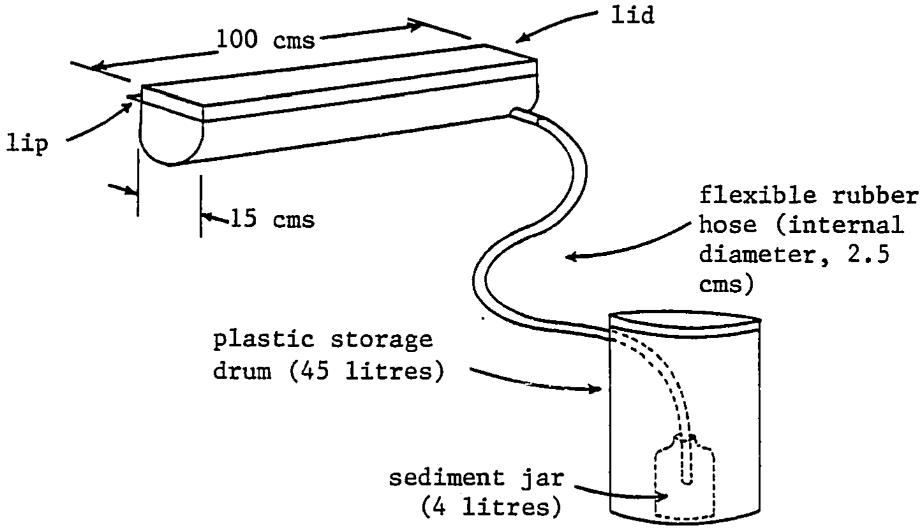
DISTRIBUTION OF WASHTRAYS

Catena	Landsurface Unit	Number of Washtrays	Site Identification
One	Erosional	2	9, 10
	Depositional	2	15, 20
Two	Erosional	2	45, 51
	Depositional	2	56, 59
Three	Erosional	2	70, 71
	Depositional	3	73, 75, 80

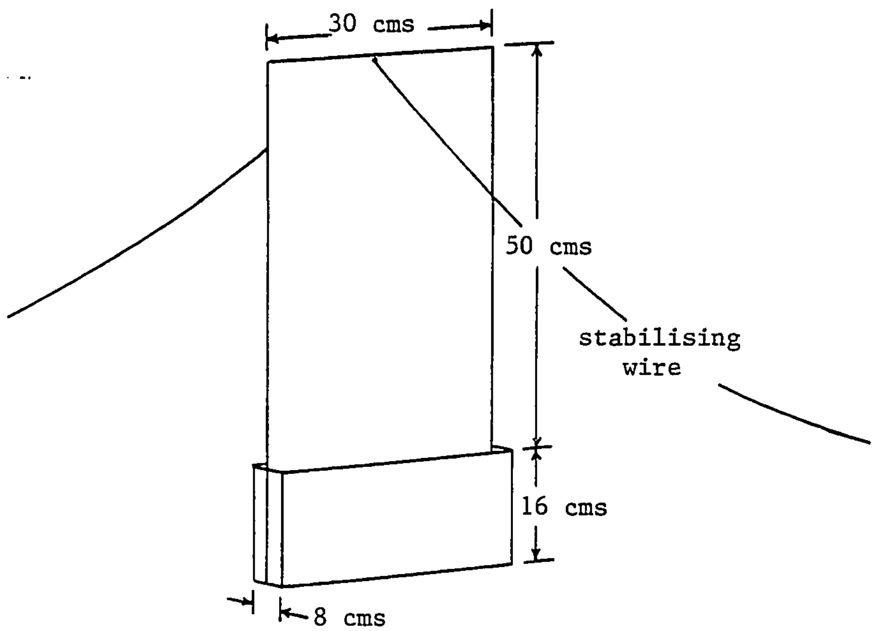
Figure 4.1

FIELD EQUIPMENT

(a) Washtray



(b) Splashtray



The problems associated with the physical installation and maintenance of this type of equipment is well documented (for example, Hayward, 1969). My own experience highlighted several difficulties, including problems of lip contact in gravelly soil and accelerated erosion of the bared surface crusted soil immediately upslope of the washtray. The lip of the washtray was inserted just below the level of the groundsurface and, in general, proved to be a satisfactory contact. Every effort was taken to minimize undue disturbance of the sites and in the initial excavation of a trench for each washtray care was taken not to disturb the upslope soil surface. In addition, the heavy clay subsoil of some sites made pit excavations for the storage drums a difficult task, and more importantly, resulted in occasional flooding of the pits and contamination of the sediment samples.

During periods of fieldwork the washtrays were monitored following each rainfall event. In collecting the sediment samples, soil held in the washtrays was scooped into a plastic bag with the washtray and hose then flushed clean of sediment, and the discharge captured in a four litre plastic screw top jar. The volume of overland flow was recorded in litres. Following periods of absence from the field sites, only sediment load was collected as the water storage capacity of the drums had generally been exceeded.

Splashboards

In an attempt to evaluate the relative efficacy of rainsplash in sediment movement, nine rainsplash boards were installed for the duration of the 1978 winter. The splashboards were installed on June 4 and removed on August 28 and during this period these sites were not monitored. Each splashboard was located adjacent to a washtray, and distributed within the three catenas as shown in Table 4.2. Design of the traps is similar to those used by Ellison (1944) and more recently by Kwaad (1977). Dimensions of the splashboards are shown in Figure 4.1(b), with the splashboards having an upslope and downslope collection trough. When installing each device in the field great care was taken to excavate a trench to the exact dimensions of the trap to avoid soil disturbance both upslope and downslope.

Table 4.2

DISTRIBUTION OF SPLASHBOARDS

Catena	Landsurface Unit	Number of Splashboards	Site Identification
One	Erosional	2	9, 10
	Depositional	1	15
Two	Erosional	2	45, 51
	Depositional	2	56, 59
Three	Erosional	1	71
	Depositional	1	75

To overcome sediment contributions from overland flow, the lip of each splashtray protruded 2-3 millimetres above the groundsurface. This may have resulted in a small percentage of splashed particles not landing in the traps. Kwaad (1977) inserted his splashtrays so that the tray lips were flush with the groundsurface. If Kwaad's assumption is correct that overland flow doesn't occur within his study area then he is indeed measuring sediment dislodged by rainsplash (and most likely creep as the slope angles ranged from 3-40 degrees). Such an assumption is not valid for the Narrogin study sites.

Estimation of Washtray Catchment Areas

Most field research measuring overland flow by the use of sediment traps has utilized some form of artificial catchment boundary such as boards or strips of metal buried in the ground. This has the advantage of defining sediment loss and surface wash to a known area of slope, although the boundaries themselves may have a significant effect on the generation of runoff (Hayward, 1969). More importantly, the use of boundaries generally precludes any investigation of the 'natural' catchment area of individual washtrays (Yair, et al., 1976).

Much of my interest in identifying different landsurface units focuses on the response of each unit to rainfall events. Part of this response relates to the physical nature of microcatchment areas within hillslopes. This requires that some attempt be made to estimate the 'natural' catchment area of each washtray. After some experimentation in the field the following technique was adopted.

Commencing on each side of the washtray the likely catchment boundary was estimated visually for a distance of approximately three metres upslope. Twine and metal pins were used to mark the boundary on the groundsurface. Flourescene dye and watering cans were then used to initiate overland flow across the delimited area. Boundary changes were made where necessary and the process repeated until the catchment was defined. Unfortunately rainstorms were of neither sufficient frequency nor reliability to assist in much of this tedious procedure. Catchments so defined, ranged in area from one square metre to approximately 450 square metres, with the technique providing invaluable observations on the role of microrelief in the pattern of overland flow.

The potential catchment area of each washtray can also be expressed as enclosing an area approximating to the width of the washtray multiplied by the distance from the interfluve (assuming a linear interfluve). However, field observations of overland flow initiated during rainfall events at the Narrogin sites, suggests that the potential catchment area of a washtray is an inadequate measure of the actual contributing area. The latter can be viewed as a function of both soil/slope properties, and temporal variations in rainfall intensity and duration. For the purposes of this research, the fluorescene dye estimates are considered sufficiently accurate and useful in demonstrating the significant role played by specific soil/slope variables.

Metal Pin Grids

A one metre grid of 25 pins (30 centimetre lengths of 10 gauge galvanised iron) was installed on each washtray site on Catena One in April, 1972. The height above the groundsurface of each pin was measured using a millimetre scale affixed to a length of rigid transparent tubing 30 centimetres long, with an internal diameter one millimetre greater than that of the pins. This enabled the measuring tube to be slipped over each pin providing a standardised measurement procedure. Similar use of erosion pins on badland slopes is documented in the work of Schumm (1956, 1962) and Campbell (1970, 1974).

Rainfall Records

During periods of fieldwork rainfall was monitored by a standard raingauge located on each catena. Daily rainfall records for the period June 1972 to September 1978 were also obtained from the

'Bonnievale' and 'Crooked Pool' farms adjacent to Catena One and Catenas Two and Three respectively. 'Crooked Pool' is the official weather recording station for this immediate area although it is not equipped with an automatic rainfall recorder (pluviograph).

A pluviograph loaned by the Perth Office of the Commonwealth Bureau of Meteorology was installed on Catena One during two three week periods of fieldwork in 1975 and 1977 to record rainfall intensity and duration. Unfortunately, the permanent installation of pluviographs on each catena was beyond the financial resources of the research project. Therefore, in an attempt to monitor both rainfall intensity and duration the 'Bonnievale' and Crooked Pool' farmers were provided with recording sheets. Rainfall intensity was to be classified using a five scale intensity rating, with duration period marked directly on the sheets. This did not prove successful.

Rainfall intensity estimates for the field sites were derived by using the pluviograph records from Narrogin, the nearest official weather recording station equipped with a pluviograph. Located 24 kilometres directly west of Catenas Two and Three the Narrogin data was considered sufficiently reliable for two reasons. The station has a rainfall pattern similar to that of the three catenas, as most rainstorms are the result of the west-east passage of fronts. In addition, the limited rainfall intensity data recorded on the catenas, closely matched that of the Narrogin recordings.

Selection and Measurement of Geomorphic and Pedologic Variables

The selection of appropriate geomorphic and pedologic variables was governed by three considerations: (a) the potential value of a variable in distinguishing between the geomorphic processes of erosion/ transportation and sedimentation by overland flow; (b) probable significance as an environmental variable influencing the generation of overland flow and sediment movement; and, (c) the relative ease of field measurement.

A wide range of potentially useful variables were selected, in anticipation that several of these would emerge as key diagnostic mapping criteria. Eighteen variables were measured on all three catenas and are grouped into six descriptive categories: slope, soil microroughness, areal extent of micro soil surfaces, general soil characteristics, soil texture and soil infiltration rates (Table 4.3). Soil compaction and shear strength measurements were also undertaken on Catenas One and Three. The soil characteristics of Catena Two precluded the inclusion of these variables. Other soil characteristics (colour, pH, and structure) were recorded for descriptive purposes only and are not included in the analysis of results.

The rationale in the selection of specific geomorphic and pedologic variables for this research project is of particular significance to landsurface mapping. Consequently, the following discussion includes a justification for selection of these variables, in addition to a brief description of the field and laboratory procedures.

The theoretical basis for selection of some of the soil properties is analagous to the development of an individual soil profile.

Table 4.3

VARIABLE LIST AND DESCRIPTION

Variable Name	Description
Soil Texture	
EGRAVELS	Percentage gravels in surface soil
ESAND	Percentage sand in surface soil
ECLAY	Percentage clay in surface soil
Microroughness	
MEANMICR	Mean microroughness (mm)
DOMMICRO	Microroughness of dominant soil surface (mm)
MMRTRUSL	Mean microroughness in true slope (mm)
MMR90SLP	Mean microroughness 90 degrees to true slope (mm)
MRANGETS	Downslope range in microroughness (mm)
MRANGE90	Across slope range in microroughness (mm)
Slope	
TRUSLOPE	Slope angle (degrees)
SLOPE90	Slope angle 90 degrees to true slope (degrees)
Infiltration	
PREWETHR	Prewetting soil infiltration rate (cc/cm^2/hour)
INFILTHR	Soil infiltration rate (cc/cm^2/hour)
Areal Coverage	
COHESION	Areal percentage soil cohesionless lenses
CRUSTED	Areal percentage soil bare/crusted
VEGCOVER	Areal percentage vegetative ground cover
Soil	
HARDEPTH	Soil depth to hardpan/bedrock (cms)
AHORIZON	Average thickness of A_1 horizon (cms)

Using Morison's (1949) original classification, the erosional unit (unit 5), would represent the eluvial complex and the depositional unit (unit 6), the colluvial complex of a hillslope. Unit 6 is thus the sump area for soil transported across unit 5 from higher up the catena and for material eroded from unit 5. Continuing the analogy, it was hypothesised that unit 5 surface soils would reflect more the characteristics of the subsurface soil horizons - B or possibly even C horizon, or exposed bed-rock. As an area of accumulation from upslope, surface soil properties on unit 6 are hypothesised to be more representative of soil properties common to the A horizon, with the B horizon at greater depth on unit 6 than on unit 5.

Areal Extent of Micro Soil Surfaces

With the exception of the interfluve, all three processes of erosion, transportation, and redeposition of soil and rock material occur throughout any given slope environment. Interfluves are essentially zones of erosion and in general terms, we conceive of the upper portions of hillslopes as zones of erosion and transportation, with sediment accumulation dominating the footslopes. The determination of whether a particular hillslope segment is eroding, aggrading, or functioning as a 'transport slope' is dependant upon the net balance of these geomorphic processes.

In the short term, this 'net balance' may in fact be expressed by the spatial dominance of identifiable visual evidence of either erosion/transportation or redeposition of sediment within the hillslope system. As a working hypothesis it was proposed that differences in 'type' and in areal dominance of this visual evidence should assist in the delimitation of landsurface units 5 and 6.

To test this hypothesis, fieldwork was conducted during 1971 in the West Kimberley Division of Western Australia (Figure 3.1). This region has a semi-arid monsoonal climate and was selected as a suitable study area due to the occurrence of reasonably predictable high intensity rainfall events, in comparison to the semi-arid environment of south-western Australia. Field research on three catenas (two on granite and one on basalt) in the King Leopold Ranges showed clear visual evidence for distinguishing between recent erosion/transportation and redeposition of sediment by overland flow (Pilgrim, 1972). Recent deposition by overland flow was characterised by lenses of cohesionless soil up to six millimetres deep on the granitic catenas while recent deposition on the finer volcanic soils was identified by surface cracking and curling of the clay plates. The erosional/transportational soil surfaces were characterised by an organically stained surface crusting three millimetres thick. Raindrop impact craters contributed to the pitted nature of this surface.

To obtain a quantitative measure of the areal distribution of these various micro surfaces the groundsurface was mapped using a one metre metal frame quadrat, subdivided into a grid of 10 cms by 10 cms squares. The quadrat frame was aligned on the groundsurface so that two sides paralleled the direction of true slope. An example of a quadrat map is included in Chapter V (Figure 5.2).

In selecting an appropriately sized quadrat attention was focused on the scale of the various micro soil surfaces. The quadrat needed to be sufficiently large to enable production of a meaningful 'distribution map' and at the same time provide a repetitive sampling procedure that would not prove too cumbersome in the field.

Results from the Kimberley research on the two granitic catenas showed a much higher areal proportion of cohesionless lenses of soil on the unit 6 sites (mean of 60.5% with a range from 42% to 87.7%) in relation to the bared/surface crusted surfaces. Conversely unit 5 sites reflected a larger proportion of bare/surface crusted soil (mean of 93.7% and range from 90% to 96.4%).

This sampling technique proved viable on all three Narrogin catenas with the exception of the area of granitic outcrops on Catena Three where five metre quadrats were mapped in addition to the one metre areas. A larger mapping unit was selected as the scale of some bedrock outcrops raised doubts as to the validity of the one metre quadrat. This proved to be particularly useful for the calculation of average infiltration rates.

Microroughness

The topographic contrast between an erosional and a depositional landform (for example a range of hills and a floodplain) is essentially a contrast in surface roughness. The West Kimberley fieldwork suggested that the same basic distinction can be made on the micro scale. In the Kimberley catenas where recent erosion had occurred miniature fall faces up to two centimetres high increased the microtopography in comparison to the smoother depositional lenses of soil. Outcropping of parent material also distinguished the erosional/transportational areas, adding further to the surface roughness. The results of these measurements are summarised by Pilgrim (1972).

As a result of the Kimberley research it was hypothesised that differences in surface microroughness could be a useful diagnostic criteria in distinguishing between landsurface units 5 and 6. Measurements of soil microroughness have previously been used in the calculation of depression storage such as in the study by Burwell et al. (1963). More recently, in his study on depression storage, Monteith (1974) used a point quadrat frame, one metre long, with 40 needles 30 centimetres long, spaced 2.5 centimetres apart. A modified version of Monteith's device was adopted for use on the Narrogin catenas. To provide a more detailed roughness profile, the number of needles along the one metre frame was increased to 80. The needles used were 30 centimetre lengths of 10 gauge galvanised iron.

Recordings were taken adjacent to two sides of the one metre mapping quadrat; the downslope side at right angles to the direction of true slope, and the left hand side in the direction of true slope when facing downslope. This then provided a measure of microroughness both in the direction of true slope and at right angles to the direction of true slope. As mentioned in the previous discussion on mapping, it was anticipated that within any one quadrat there would be both areas of erosion/transportation and deposition (as well as vegetation mounds). Accordingly, when marking the height of each needle on the backing board the nature of the groundsurface was also noted.

An index of roughness was then calculated by measuring the difference in the height between successive needles (recorded on millimetre graph paper) and calculating the mean of all differences. The maximum range between any two needles on each set of measurements was also recorded.

Thickness of the A_1 Horizon

Working within the hypothesis that unit 5 and 6 should reflect more the characteristics of A and B soil horizons respectively, it was postulated that the thickness of the A_1 horizon would differ between erosional/transportational and depositional sites with unit 6 sites characterised by thicker A_1 horizons. Other researchers have included depth of the A horizon in studies of variations in soil physical and chemical properties within catenas. Alexander (1969), for example, worked within the framework of the nine unit landsurface model while Walker et al. (1968a, 1968b) and Furley (1968) related depth of the A horizon to changes in slope angle.

In measuring the thickness of the A_1 horizon a mean value was obtained for each site by calculating the average thickness of five evenly spaced measurements across a 50 centimetre profile face. Marked differences were recorded between the two landsurface units. Erosional/transportational sites showed little or no organic staining. In contrast, although the horizon was generally poorly developed, unit 6 soils were organically stained to a maximum depth of 10 centimetres.

Soil Texture Analysis

The inclusion of soil texture as a potentially useful discriminator between erosional and depositional landsurface units is based on the underlying assumption of the catena: that soil texture differences occur along a slope profile as a result of sediment redistribution by overland flow.

Mechanical sieve analysis and the hydrometer method (Day, 1965: 555-556 and 562-566) were used to determine particle size distributions for all soil samples. Initial dry sieve results showed marked discrepancies in the percentage clay/silt fraction when compared to the results obtained by hydrometer analysis. This was attributed to the failure of mortar and pestle preparation of the dry sieve samples to separate the smaller aggregates. The problem was solved by first wet sieving the samples (with a 53 micron sieve) and then dry sieving.

Wet and dry sieving thus provided the percentage silt/clay, sand and gravel, with the relative percentage of silt and clay determined by hydrometer. The textural classification used in this research is that used by the U.S. Department of Agriculture (Birkeland, 1974:12). A wide range of sieve mesh sizes was used in the dry sieving. Several large meshes were particularly useful in separating the coarser textured samples (notably those containing lateritic gravels).

Table 4.4

SOIL SIEVE MESH SIZES SELECTED

8.00 mm	710 microns
5.60 "	500 "
3.35 "	355 "
2.00 "	250 "
1.00 "	106 "
	75 "
	53 "

Soil Infiltration Rate

Infiltration rate was measured using a cylinder-type infiltrometer similar to that used by Selby (1967). A galvanised iron cylinder 23 centimetres in diameter was inserted into the soil to a depth of 10 centimetres. A buffer cylinder 30 centimetres in diameter was placed concentrically around the smaller one and inserted to the same depth.

The soil was pre-wetted by flooding both cylinders and timing the period required for complete infiltration. A constant head of 2.5 centimetres was then maintained with readings taken at one, three, and five minutes and then at five minute intervals for a period of one hour. Soil moisture sampling and penetrometer and shear vane tests were also conducted in association with the infiltration tests and are discussed later in this chapter.

This technique for measuring infiltration rate is relatively simple and inexpensive, and in its application to the Narrogin field sites provided repetitive results of the relative infiltration differences between landsurface units. Useful discussions of the application and limitations of cylinder infiltrometers are provided by Bertrand (1965: 202-207), Hills (1970), and Gregory et al. (1973).

Slope Angle

The Narrogin slope angle data is grouped into three categories, with all observations made with an abney level. The data included in the statistical analyses was recorded at the one metre quadrat sampling sites. By standing the abney level on the quadrat frame, slope angle was measured in the direction of true slope and at right angles to true slope. For general descriptive purposes one detailed slope profile was surveyed through a representative section of each catena using a prismatic compass, 50 metre tape and ranging rods. Slope readings were recorded over 10 metre intervals and at each discernible change of slope. Within each landsurface unit additional readings were taken and entered onto catenary maps.

Soil Compaction and Cohesion

On sandy textured soil, the breakdown of aggregates into smaller aggregates and/or individual soil particles prior to transportation downslope by overland flow, should result in surface soils on depositional sites with lower degrees of compaction and cohesion in contrast to the exposed subsurface horizons of erosional sites. It was therefore hypothesised that differences in compaction and cohesion would assist in the delimitation of contemporary landsurface units 5 and 6.

Penetrometer measurements were used to test for differences in soil compaction. A Proctor needle type penetrometer (Davidson, 1965:472-484) was used on Catena One although its use was limited by several factors. The presence of stones in the subsoil made recordings on some sites erratic and unreliable. The necessity for penetration of the probe to a depth of at least 7.5 centimetres further aggravated this problem. Compaction test were also redundant on a few unit 5 sites due to the presence of bedrock outcrops at the surface.

To help minimize the problems associated with gravels, a pocket penetrometer (Davidson, 1965: 473-474) was used on Catenas Two and Three. Although the required penetration for this particular instrument is only six millimetres, it was still unsuited to the lateritic gravels of the Catena Two erosional unit.

Soil cohesion was measured using a portable torsional shear vane device (Sibley et al., 1965: 39-47). The small size of this instrument enabled separate cohesion tests on the bare surface crusted soils and the cohesionless lenses. With the exception of tests associated with the infiltration measurements on Catena One, shear strength tests were limited to Catenas Two (depositional unit only) and Three.

As soil compaction and cohesion are in part a function of soil moisture, soil moisture content samples were taken at the time of testing. The method used is outlined in the following section.

Soil Moisture Sampling

Soil moisture samples were collected when recording soil cohesion and soil compaction and before and after infiltration tests. The gravimetric technique was used (Gardner, 1965: 92-93) with the soil tins weighed in the field to minimize error from potential moisture loss prior to laboratory analysis. Surface samples were taken for both soil cohesion and compaction. Three moisture samples were collected for the infiltration tests - the top centimetre of soil and at depths of 10-12 and 18-20 centimetres.

Distance from Interfluve to Washtray Sites

Distance from the interfluve to the washtray sites was measured in the field using a 50 metre tape and ranging rods.

Soil Structure, Soil Colour and pH

These three soil characteristics were recorded for descriptive purposes only. The U.S. system of soil structure classification as outlined by Clarke (1971:57) was adopted in all field descriptions with colour recorded using the Munsell Soil Colour Charts. Soil pH was measured using an inexpensive pH test kit produced by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

CHAPTER V

OVERLAND FLOW, SEDIMENT YIELD AND RAINSPLASH RESPONSE ON EROSIONAL AND DEPOSITIONAL LANDSURFACE UNITS

Introduction

In this chapter the field measurements of overland flow and sediment transport are examined to test the hypothesised difference in hydrologic response between erosional slope environments (landsurface unit 5) and depositional slope environments (landsurface unit 6). The respective geomorphic and pedologic characteristics of landsurface units 5 and 6 suggest that the erosional unit should generate more overland flow and a higher sediment yield. This relationship is hypothesised for Catenas One and Two. A reversal in response is hypothesised on Catena Three due to the high variability in rates of overland flow within the gneissic outcrops (erosional unit). This spatial variability is manifest in zones of concentrated overland flow that originate within the gneissic outcrops and flow across the colluvial footslope. The most concentrated lines of overland flow are evidenced by small alluvial fans.

Four aspects of the hydrologic data are considered: the relationships of precipitation (individual rainfall events) to overland flow; precipitation (individual events) to sediment yield; total sediment yield over the six years of recording; and the relative efficacy of rain-splash and overland flow to sediment transport. Selection of these four criteria as suitable measures of differences in hydrologic response, reflects both the methodology of previous soil erosion research (reviewed in Chapter II) and the physical characteristics of erosional and depositional landsurface units (discussed in Chapter IV).

It had been hoped that the use of a grid of pins corresponding to the dimensions of the quadrat maps would yield some interesting changes in pin exposure, enabling the formulation of a balance sheet of soil 'gains' and 'losses' for each site. The results proved to be inconclusive and are not included in the analysis of results. The lack of success of this technique on the Narrogin catenas was attributed to two main factors. Unlike the field sites of Schumm's (1956) early work, the Narrogin catenas are not characterised by abnormally high rates of sediment movement. As a consequence, measurement error (calculated by three successive measurements of each grid of pins) generally exceeded any discernible change in pin exposure or burial. In addition, although all sites were protected by six line ringlock fences, kangaroos still managed to bend numerous pins on all sites.

The diagnostic characteristics of the two landsurface units identify differences in soil/slope parameters such as soil texture, microroughness, soil depth, soil compaction and thickness of the A_1 horizon. All of these variables are pertinent to an analysis of over-land flow and sediment movement because of their importance to soil infiltration rates, surface detention storage, and the relative detachability of soil particles. Consequently, in analysing overland flow and soil loss response to individual rainfall events, it is anticipated that the distinctive soil/slope characteristics of the two landsurface units will at least result in hydrologic responses that differ in 'quantity'. In addition, specific response thresholds resulting from factors such as differences in surface detention storage may also distinguish the two units from one another.

On Catena One, 19 observations were recorded of sediment yield and overland flow from individual rainfall events (Table 5.1). Ten observations were recorded for Catenas Two and Three (Table 5.2). Due to the small sample size for Catenas Two and Three some of the regressions are not statistically significant, especially when the data are grouped into two subsets. This precludes any conclusive statement as to the geomorphic significance of several of the regression lines. It does, however, suggest some directions for future research, most notably in reference to testing the precipitation thresholds identified within the range of observed rainfall events, and for events of greater magnitude.

For the rainfall events recorded, a noticeable difference was measured between Catena One and Catenas Two and Three in correlating rainfall amount with intensity. The rainfall events sampled on Catena One showed a high correlation (r = 0.93) between rainfall amount and maximum 30 and 60 minute intensity (inferred from the official Narrogin rainfall records). Of these three parameters, rainfall amount was the most highly correlated with volume of overland flow and sediment yield. Intensity and rain amount were less correlated (r = 0.53) for the rainfall events sampled on Catenas Two and Three, with overland flow and

Table 5.1

CATENA ONE

RAINFALL, SEDIMENT YIELD AND OVERLAND FLOW DATA

Obs.	Rainfall (mm) Amount	In.30	In.60	Site 9 Ov.	Sd	Site 10 Ov.	Sd	Site 15 Ov.	Sd	Site 20 Ov.	Sd
1	6.80	5.50	3.50	2.40	5.81	2.40	10.48	0.30	2.71	0.45	1.18
2	19.50	12.50	8.00	55.00	61.00	20.00	33.08	6.00	30.00	1.10	2.75
3	6.00	3.50	2.00	2.75	6.40	1.25	7.45	0.25	3.10	0.20	0.75
4	9.50	10.50	7.00	16.00	0.95	6.50	4.34	1.33	3.23	0.75	0.71
5	7.20	8.50	4.50	20.00	24.00	16.00	38.50	1.00	9.33	1.10	6.62
6	8.80	4.00	3.00	14.00	21.00	9.00	23.39	1.40	12.00	1.30	8.00
7	3.60	1.80	1.40	4.00	10.16	3.40	7.00	0.25	3.84	0.30	1.00
8	5.00	4.00	2.20	6.20	13.00	5.00	8.96	0.25	5.00	0.30	1.23
9	9.50	9.00	6.00	15.00	10.00	9.50	24.00	1.50	13.00	0.70	1.13
10	3.80	2.20	2.00	1.80	6.13	1.00	9.47	0.60	3.36	0.20	0.30
11	21.00	13.00	7.00	28.00	26.00	22.80	45.91	18.00	9.03	7.80	12.50
12	6.00	3.50	3.00	0.50	4.70	0.75	18.50	0.15	3.23	0.25	2.56
13	26.00	16.00	13.00	33.00	23.03	21.60	22.07	18.00	21.89	8.40	12.27
14	18.00	14.00	9.00	6.60	19.55	12.60	21.65	0.90	12.52	1.80	5.86
15	3.00	1.40	1.10	0.40	1.00	0.40	2.81	0.10	1.00	0.15	0.28
16	3.50	1.70	1.20	0.40	2.00	0.50	4.00	0.10	1.45	0.15	0.50
17	10.80	6.50	4.00	12.00	11.00	9.00	18.00	1.80	6.00	0.90	1.50
18	7.80	5.00	3.00	2.60	3.92	3.00	12.37	0.30	2.13	0.10	1.00
19	5.20	1.60	1.00	1.00	3.00	1.20	4.00	0.20	2.00	0.05	0.45

In.30 Maximum 30 minute rainfall intensity (mm)

In.60 Maximum 60 minute rainfall intensity (mm)

Ov. Overland Flow (litres)

Sd Sediment Yield (grams)

Table 5.2

RAINFALL, SEDIMENT YIELD AND OVERLAND FLOW DATA

(a) CATENA TWO

Obs.	Rainfall (mm)			Site 45		Site 51		Site 56		Site 59	
	Amount	In.30	In.60	Ov.	Sd	Ov.	Sd	Ov.	Sd	Ov.	Sd
1	7.50	12.00	6.00	33.00	4.43	10.00	3.29	1.80	2.42	1.00	2.10
2	19.10	12.50	8.00	75.00	26.11	25.00	30.84	5.40	10.71	7.00	16.50
3	6.00	7.50	4.70	24.00	4.84	7.00	8.42	0.50	2.19	0.75	2.40
4	12.00	13.00	8.00	51.00	60.45	9.00	8.41	2.20	10.36	2.50	21.48
5	3.00	1.50	1.00	1.50	0.50	0.50	0.20	0.05	0.10	0.10	0.20
6	4.40	2.00	2.00	5.00	1.60	1.00	0.50	0.10	0.25	0.15	0.30
7	5.20	5.00	3.50	8.00	2.80	1.30	1.20	0.20	1.30	0.25	1.80
8	8.00	4.00	3.00	6.00	3.50	2.20	1.50	0.10	0.90	0.15	1.70
9	17.00	9.00	6.00	65.00	38.00	10.50	6.00	2.50	8.52	4.50	29.00
10	20.00	6.00	5.00	48.00	20.23	7.00	3.40	1.70	5.50	2.20	21.00

(b) CATENA THREE

Obs.	Site 70		Site 71		Site 73		Site 75		Site 80	
	Ov.	Sd	Ov.	Sd	Ov.	Sd	Ov.	Sd	Ov.	Sd
1	1.50	4.83	0.40	6.90	1.00	0.49	11.30	18.88	3.30	2.35
2	5.00	8.00	4.00	9.00	22.00	31.32	63.0	222.00	27.00	74.93
3	0.40	0.90	0.20	1.20	1.00	8.00	1.00	9.00	2.00	9.75
4	1.75	4.73	1.00	3.73	2.00	2.65	13.00	30.10	6.75	8.99
5	0.05	0.05	0.05	0.08	0.05	0.10	0.10	0.25	0.10	0.20
6	0.05	0.07	0.05	0.20	0.05	0.10	0.15	0.30	0.10	0.20
7	0.15	0.30	0.10	0.40	0.08	0.14	0.40	2.00	0.20	0.90
8	0.15	0.20	0.10	0.30	0.10	0.25	1.50	2.50	1.20	1.31
9	2.20	4.50	1.50	6.50	3.50	2.80	17.00	30.00	9.00	17.00
10	1.20	3.00	1.00	4.00	2.50	2.10	13.00	22.14	7.50	10.00

In.30 Maximum 30 minute rainfall intensity (mm)
In.60 Maximum 60 minute rainfall intensity (mm)
Ov. Overland Flow (litres)
Sd Sediment Yield (grams)

sediment yield most highly correlated with rainfall intensity. Relatively high correlations were achieved on all catenas (on both the erosional and depositional landsurface units) by the regression of sediment yield and volume of overland flow on either rainfall amount or rainfall intensity.

Smith and Wischmeier (1962:124), in reviewing soil loss data for agricultural plots, noted generally poor correlations using rainfall amount and rainfall intensity. Higher correlations were obtained for their fallow plots by a linear regression of soil loss with rainfall energy (kinetic energy of the storm multiplied by maximum 30 minute intensity). Soil loss from these plots was also highly correlated with the product of, rainfall amount and maximum 30 minute intensity. The latter rainfall index was applied to the rainfall data for Catenas Two and Three (due to the low correlation between rainfall amount and intensity) but failed to improve the coefficients of determination for overland flow or sediment yield.

A comparison of the erosional and depositional sites within each catena, based on the total sediment yield for the six years, is warranted for two main reasons. Given the physical characteristics of Catenas One and Two, the six year sediment loads recorded on the erosional units, should, as already hypothesised, exceed those of the depositional units with a reversal in response on Catena Three. The long term results are also valuable as supportive evidence for the relatively small number of observations recorded for individual rainfall events.

The fourth aspect of the hydrologic data included in this analysis is the relative efficacy of rainsplash transport. As already noted in the literature review, rainsplash is well established as a mechanism capable of high rates of soil detachment, but relatively low rates of sediment transport. Research by agricultural engineers has also identified significant reductions in splash erosion associated with vegetative ground cover and the presence of organic matter in the surface soil horizon. As differences in both the percentage of vegetative ground cover and thickness of the A_1 horizon are postulated as diagnostic of erosional and depositional landsurface units, differences in rainsplash response are also hypothesised with rainsplash a more significant factor in sediment transport on the erosional units. One of the measures used in this study to assess rainsplash response is a comparison of net downslope sediment transport by rainsplash with total sediment yield. Defined as rainsplash efficacy, the index is calculated as follows.

$$\text{Rainsplash Efficacy (\%)} = \frac{\text{Downslope Splash} - \text{Upslope Splash}}{\text{Net Downslope Splash} + \text{Washtray Sediment}}$$

In the following discussion of results, the three catenas are considered separately, as each represents a different soil/slope environment. As already noted, it is hypothesised that each catena will be characterised by a difference in hydrologic response between the erosional and depositional landsurface units. It is this difference in response between landsurface units that is the subject of investigation. Variations in hydrologic response between the catenas is not a major consideration in this study.

Catena One

Results for both sediment yield and overland flow for individual rainfall events support the hypothesised relationship between the two landsurface units. In comparison to the depositional sites, the two erosional sites are more responsive in both volume of overland flow and weight of sediment transported, with mean values for both variables significantly different between the two landsurface units (Table 5.3). Variations in hydrologic response between the two recording sites on each landsurface units show no significant difference, with the exception of sediment yield (0.05) on the depositional unit (Table 5.3). The latter may be in part a reflection of the higher percentage vegetative ground cover of site 20.

The general physical characteristics of each landsurface unit have already been discussed (Chapter III), and in evaluating the inter-unit intra-unit variations attention will be focused more on the specific site characteristics of each of the four recording stations. Those site characteristics that contribute to, or correlate with differences in hydrologic response on Catena One are listed in Table 5.4. The most distinctive physical differences between the erosional and depositional sites are infiltration rates (also reflected in the soil compaction values), soil microroughness, vegetative ground cover, soil depth, thickness of the A_1 horizon and the percentage areal dominance of micro soil surfaces. These and other relevant physical characteristics are considered more fully in the following discussion of the hydrologic data for the two landsurface units.

Table 5.3

CATENA ONE: SUMMARY STATISTICS

Variable	Sample	N	Mean	Standard Deviation	't' Value	Level of Significance
Sediment Yield (grams)	Erosional Unit	38	14.96	13.25	4.00	0.01
	Depositional Unit	38	5.40	6.40		
Overland Flow (litres)	Erosional Unit	38	9.67	1.43	3.84	0.01
	Depositional Unit	38	2.10	4.27		
Erosional Unit						
Sediment Yield	Site 9	19	13.29	14.19	-0.77	*
	Site 10	19	16.63	12.40		
Overland Flow	Site 9	19	11.66	14.25	1.08	*
	Site 10	19	7.67	7.57		
Depositional Unit						
Sediment Yield	Site 15	19	7.62	7.64	2.25	0.05
	Site 20	19	3.18	3.94		
Overland Flow	Site 15	19	2.75	5.53	1.00	*
	Site 20	19	1.36	2.42		

't' Values

Sediment Yield

Site	10	15	20
9	* (1.08)	0.01 (2.54)	0.01 (3.10)
10		0.05 (2.29)	0.01 (3.46)
15			* (1.00)

Overland Flow

Site	10	15	20
9	* (0.77)	* (1.53)	0.01 (2.99)
10		0.01 (2.70)	0.01 (4.50)
15			0.05 (2.25)

* Asterisk denotes lack of statistical significance

Table 5.4

CATENA ONE: PHYSICAL CHARACTERISTICS OF WASHTRAY SITES

Variable	Erosional Sites		Depositional Sites	
	9	10	15	20
Soil infiltration rate ($cc/cm^2/hour$)	4.00	7.52	31.28	29.20
Areal percentage soil bare/crusted	88.00	87.00	1.50	0.20
Areal percentage soil cohesionless lenses	12.00	13.00	93.00	83.50
Areal percentage vegetative ground cover	0.00	0.00	5.50	16.30
Mean microroughness (mm)	0.96	1.16	0.74	1.94
Downslope range in microroughness (mm)	3.00	4.00	3.00	9.00
Across slope range in microroughness (mm)	5.00	10.00	3.00	17.00
Soil depth to hardpan/bedrock (cms)	6.00	7.50	65.00	50.00
Soil compaction (lbs/sq.in.)	1600.00	1200.00	180.00	100.00
Percentage gravels in surface soil	11.12	14.10	7.26	4.22
Percentage clay at 2.5 cms depth	10.10	15.00	8.20	7.80
Average thickness of A_1 horizon (cms)	0.00	0.50	7.00	10.00
Estimated catchment area (sq. metres)	13.20	8.02	33.58	3.58
Slope angle (degrees)	1.20	1.00	1.50	2.80

Overland Flow

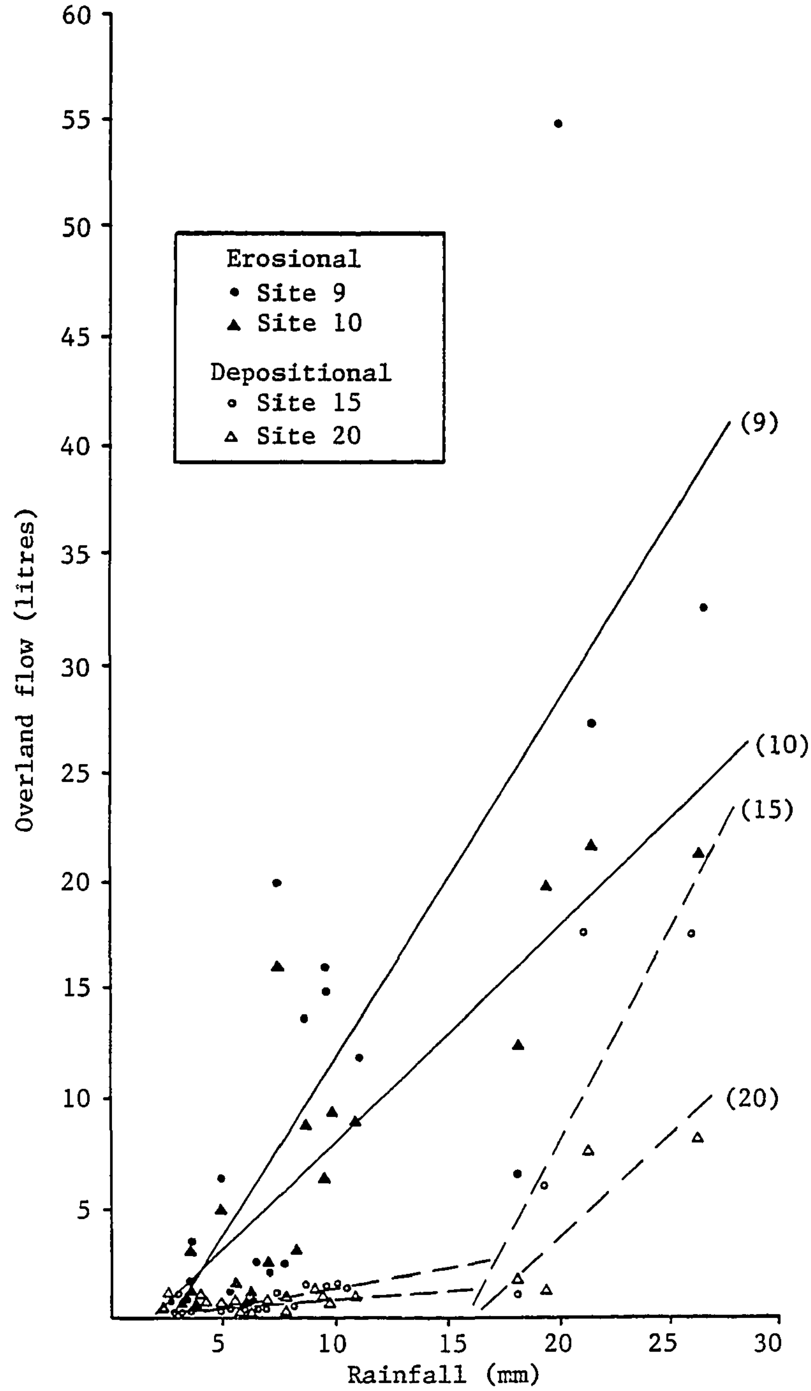
Reference to Figure 5.1 illustrates the distinctly different overland flow responses of the two units. Sites 9 and 10, on the erosional unit are both characterised by a linear increase in overland flow in response to larger rainfall events. In contrast negligible amounts of overland flow were recorded by sites 15 and 20 for all but the higher magnitude events. The response differences reflect the physical charactristics of the two units.

Conditions favourable to overland flow typify the erosional landsurface unit, in particular, the low infiltration rates; low soil microroughness and a total absence of vegetative ground cover (Table 5.4). The surface characteristics of site 9, the most responsive of the erosional sites, offer the least impediment to overland flow and, in addition, the estimated catchment area of this washtray is approximately 60% larger than that of site 10.

Markedly different physical properties characterize the depositional landsurface unit. Noticeably higher infiltration rates (reflected in lower soil compaction readings) and a greater percentage of vegetative ground cover (primarily a short needle grass generally less than 10 centimetres in height) combine to impede the generation of overland flow. The vegetative cover serves two important functions in protecting some of the soil surface from rainsplash impact and in increasing surface microroughness. The latter is a critical component in the overland flow threshold, characteristic of this unit (Figure 5.1) in that the 'barrier effect' of the vegetation, manifested in semi-enclosed depressions, increases surface detention storage. This is well

Figure 5.1

CATENA ONE: OVERLAND FLOW RESPONSE TO RAINFALL



illustrated by the one metre quadrat map for site 20 (Figure 5.2). The role of vegetation in detention storage is further supported by site 20, the less responsive of the two depositional sites, which has a noticeably higher percentage of vegetative ground cover.

Regression equations for all four sites are included in Table 5.5. The regressions for sites 15 and 20 were generated using a dummy variable to identify rainfall events greater than and less than 18 millimetres. The equations took the following form,

$$Ov = a + P_1 + D_1 + D_1P_1$$

where, Ov = overland flow in litres

P_1 = precipitation amount in millimetres

D_1 = dummy variable.

Table 5.5

CATENA ONE REGRESSIONS: OVERLAND FLOW WITH RAINFALL AMOUNT

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
9	19	$Ov = -4.15 + 1.66P_1$	0.60	9.21	26.07	0.01
10	19	$Ov = -1.96 + 1.01P_1$	0.80	3.50	66.90	0.01
15 (<18 mm)	15	$Ov = -0.68 + 0.20P_1$	0.86	2.30	29.33	0.01
(>18 mm)	4	$Ov = -31.85 + 2.0P_1$	0.86	2.30	29.33	0.01
20 (<18 mm)	15	$Ov = -0.26 + 0.11P_1$	0.84	1.04	27.11	0.01
(>18 mm)	4	$Ov = -14.23 + 0.89P_1$	0.84	1.04	27.11	0.01

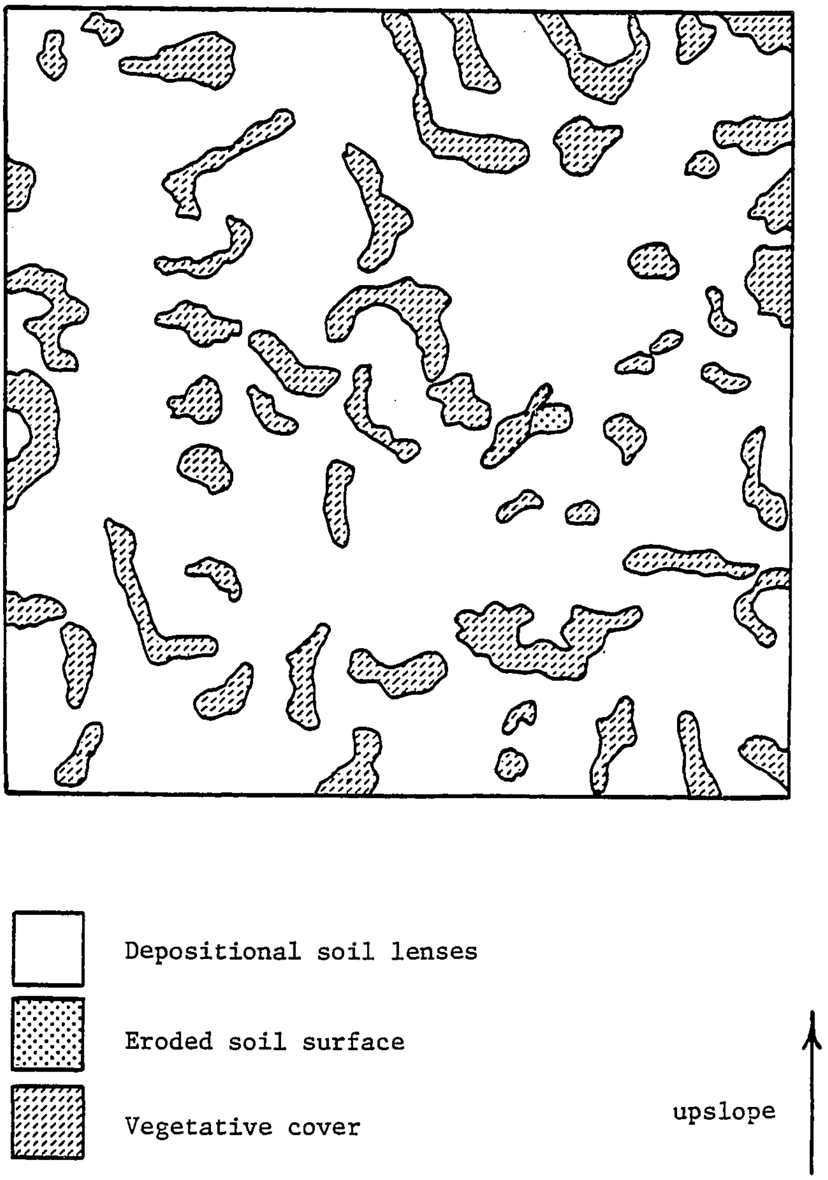
Ov = Overland flow (litres)
P_1 = Rainfall amount (mm)

Use of the dummy variable places emphasis on the precipitation threshold and provides an overall correlation coefficient for the total data set. This procedure has one minor drawback. Due to the nature of

Figure 5.2

CATENA ONE: SITE 20

ONE METRE QUADRAT MAP



the data, the standard error is underestimated for the larger events. However, this is not considered a critical factor as these regressions are used here to primarily illustrate differences in overland flow response, rather than as predictive models. Results obtained by calculating separate linear regressions for the two subsets are included in Table 5.6.

Table 5.6

CATENA ONE: SITES 15 AND 20

REGRESSION: OVERLAND FLOW WITH PRECIPITATION

Site	N	Regression	r^2	Standard Error	F	Level of Significance
15(a)	4	$Ov = -31.85 + 2.01P_1$	0.65	6.20	3.78	*
15(b)	15	$Ov = -0.68 + 0.2P_1$	0.72	0.33	32.75	0.01
20(a)	4	$Ov = -14.23 + 0.89P_1$	0.65	2.77	3.80	*
20(b)	15	$Ov = -0.26 + 0.11P_1$	0.50	0.29	12.75	0.01

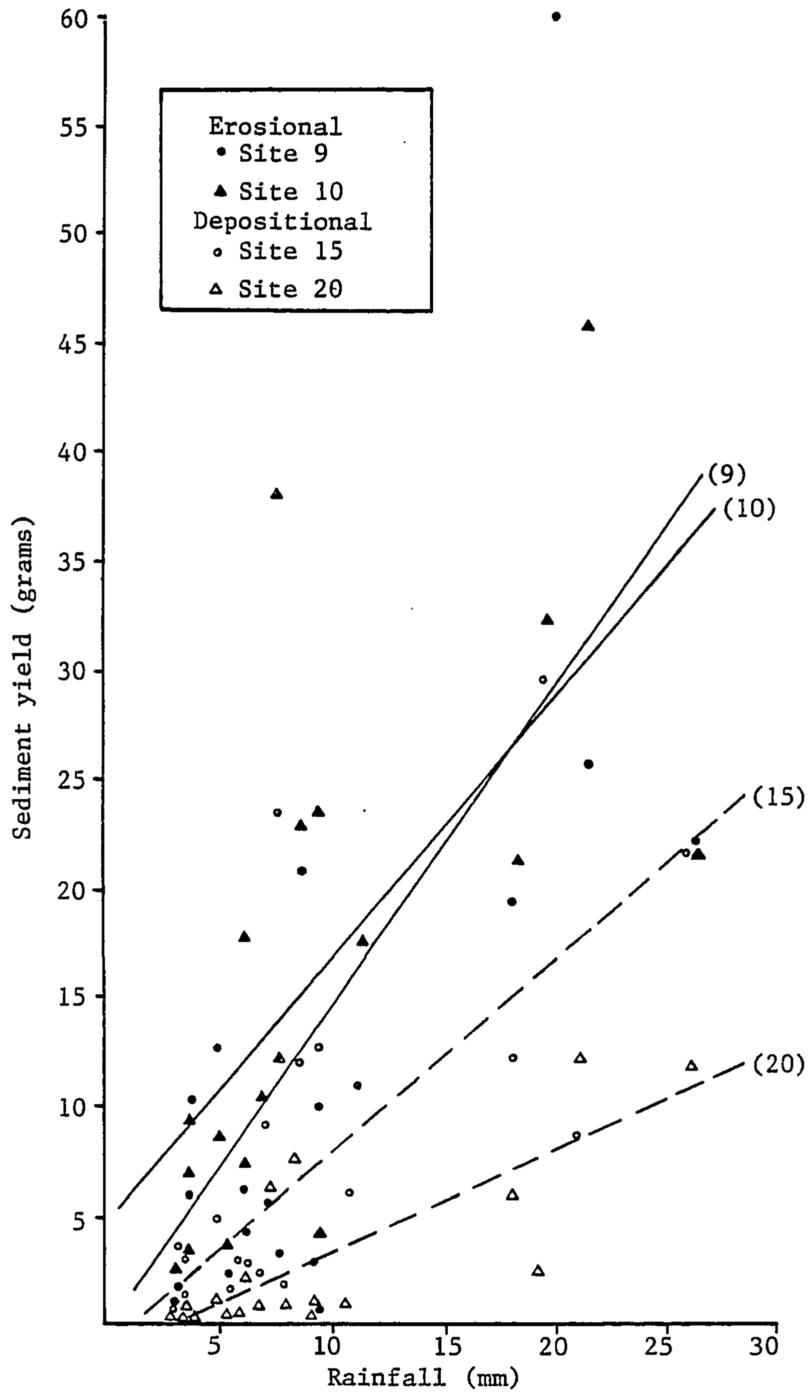
Ov Overland Flow (litres)
P_1 Precipitation Amount (mm)
(a) Rainfall Events > 18mm
(b) Rainfall Events < 18mm
* Not Significant

Sediment Transport

Bivariate regressions of sediment yield with precipitation amount for each of the four sites (Figure 5.3) show that the erosional landsurface unit has an overall higher sediment yield with sediment transport more sensitive to increases in precipitation. Linear regression provides a 'best fit curve' for the data although the coefficients

Figure 5.3

CATENA ONE: SEDIMENT YIELD RELATED TO RAINFALL



of determination are noticeably lower than for overland flow (Table 5.7). This may be due in part to the combined influences of rainsplash and overland flow in sediment transport. Smith and Wischmeier (1962:120) for example, note maximum splash of 150 cms with stone fragments of 4 mm diameter splashed 20 cms.

Table 5.7

CATENA ONE REGRESSIONS: SEDIMENT YIELD WITH RAINFALL AMOUNT

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
9	19	$Sd = -0.31 + 1.43P_1$	0.45	10.80	14.01	0.01
10	19	$Sd = 4.98 + 1.22P_1$	0.43	9.60	12.99	0.01
15	19	$Sd = -0.97 + 0.90P_1$	0.62	4.83	27.98	0.01
20	19	$Sd = -1.16 + 0.46P_1$	0.60	2.57	25.27	0.01

Sd = Sediment weight (grams)
P_1 = Rainfall amount (mm)

Comparison of the overland flow and sediment regressions for the depositional unit (Figures 5.1 and 5.3) clearly illustrates the presence of sediment movement in the absence of general overland flow. Further evidence supporting the efficacy of rainsplash was provided by field measurements of sediment movement by rainsplash during the 1978 winter. These results are summarised in Table 5.8 and compared with the washtray sediment yields for the same time period. Sediment weights from the 30 cms splash trays were adjusted to enable direct comparison with samples from the one metre washtrays.

Though the sample is too small to be conclusive, the results do suggest that rainsplash is an important agent in sediment detachment on

Table 5.8

CATENA ONE: SPLASHTRAY AND WASHTRAY SEDIMENT YIELDS

Unit	Site Number	Splash (gms) Downslope	Splash (gms) Upslope	% Splashed Downslope	Net Downslope Splash (gms)	Washtray (gms)	Rainsplash Efficacy (%)
Erosional	9	161.10	104.96	60.50	56.14	146.86	27.65
Erosional	10	89.20	74.60	54.40	14.60	76.61	16.00
Depositional	15	8.70	1.63	84.20	7.07	39.40	15.40
Depositional	20	no splash data available					

Note: All data recorded for the period June 4 - August 28, 1978

the erosional landsurface unit in that a higher sediment yield was obtained from downslope splash than from the washtrays. The latter have protective lids such that sediment collected is assumed to be primarily a function of overland flow transport. A comparison of sediment (by weight) splashed upslope and downslope does show a downslope bias ranging from 54.4% for site 10 to 84.2% for site 15.

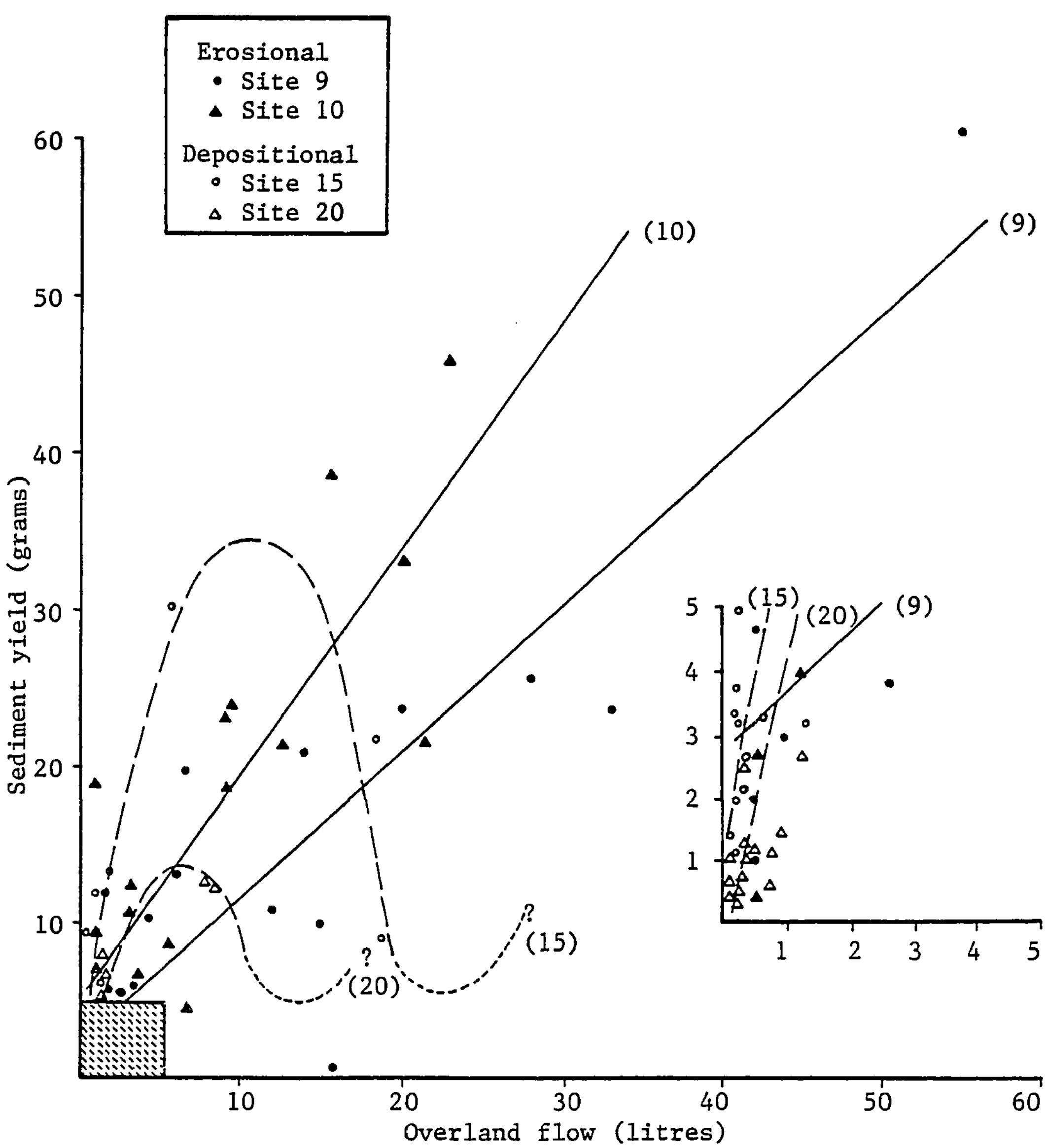
More importantly, the calculation of rainsplash efficacy relative to overland flow (Table 5.8) shows a net downslope movement of sediment by rainsplash ranging from 15.4% to 27.65%. The results suggest that rainsplash is a more important transport agent on the erosional unit compared to the depositional unit, but that overland flow remains the most significant agent of sediment transport. The low slope angles associated with this catena support this conclusion. Thus the most significant role of rainsplash remains one of detachment (mobilisation) of sediment enabling transport by overland flow. This is clearly more evident on the bare soil surface of the erosional sites where total rainsplashed sediment is more than twenty fold (by weight) that recorded for site 15.

The relationship between overland flow and sediment yield for the four recording stations also reveals distinctly different responses for the two landsurface units (Figure 5.4). Linear regression (Table 5.9) provides a best fit for the erosional sites with the positive intercept on the Y axis interpreted as a function of rainsplash transport with negligible amounts of overland flow.

In contrast, the depositional units show a curvilinear trend, with considerable sediment transport associated with minimal overland

Figure 5.4

CATENA ONE: SEDIMENT YIELD RELATED TO OVERLAND FLOW



flow conditions and decreasing sediment transport recorded for the larger runoff events. The 'best fit curve' for both sites 15 and 20 is a second order polynomial (Table 5.9). This curvilinear relationship is consistent with the physical characteristics of the depositional land-surface unit (in particular, the soil microroughness) and it is hypothesised that the sediment threshold is a response to reduced rainsplash detachment, due primarily to surface depression storage.

Table 5.9

CATENA ONE REGRESSIONS: SEDIMENT YIELD WITH OVERLAND FLOW

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
9	19	$Sd = 2.84 + 0.890v$	0.81	6.36	72.47	0.01
10	19	$Sd = 5.85 + 1.400v$	0.74	6.60	46.72	0.01
15	19	$Sd = 1.33 + 6.460v - 0.320v^2$	0.80	3.68	30.70	0.01
20	19	$Sd = -0.14 + 4.200v - 0.330v^2$	0.88	1.44	59.45	0.01

Sd = Sediment weight (grams)
Ov = Overland flow (litres)

Under conditions of negligible overland flow it is postulated that sediment transport is primarily a function of short range movement by rainsplash. Increased rates of overland flow, while transporting some loose sediment, are accompanied by an increase in the depth of water protecting the soil surface from rainsplash, thus reducing soil detachment. In support of this hypothesis, the less responsive of the two sites has the higher percentage vegetative cover and microroughness and as a result greater potential depression storage and a smaller estimated catchment area.

The significance of the depth of surface water in protection of the soil surface from rainsplash has been noted by a number of researchers including Smith and Wischmeier (1962:120) and more recently by Bryan (1976:107). There is general concensus among these and other researchers that soil detachment by splash increases until the depth of surface water exceeds raindrop diameter. The efficacy of rainsplash transport at low flow conditions may also be enhanced by the early displacement of the most easily eroded material. For the less frequent, but higher magnitude rainfall events not included in this data set it is hypothesised that a second threshold would appear in regressing sediment with overland flow, in response to the increased turbulence associated with increased runoff (Figure 5.4).

Comparison of the particle size range of the splashed and overland flow sediments for all three sites reveals the more selective nature of splash erosion, with sand sized particles predominating (Table 5.10). The largest particles splashed were less than 3.35 mm in diameter, with a correspondingly low percentage of splashed silt and clay sized particles.

Analysis of overland flow and sediment yield for individual rainfall events has clearly demonstrated differences in hydrologic response between the two landsurface units with the erosional landsurface generating significantly more overland flow and sediment. These results are supported by a comparison of the total sediment yield for the two landsurface units over the six year period of records. Total sediment yield on the erosional landsurface unit was greater than that of the depositional unit by a factor of 2.5 (Table 5.11).

Table 5.10

CATENA ONE

WASHTRAY AND SPLASHTRAY SEDIMENT PARTICLE SIZE ANALYSIS

JUNE 4 - AUGUST 28, 1978

Diameter	Site 9		Site 10		Site 15	
(mm)	(a)	(b)	(a)	(b)	(a)	(b)
+8.000		0.57				
5.600		0.22				
3.350		1.04		0.51		
2.000	0.31	1.09	0.15	1.37		3.30
1.000	7.13	9.61	11.87	10.43	9.92	20.66
0.710	14.00	11.13	14.69	10.76	10.68	13.63
0.500	16.55	12.88	17.63	10.70	14.88	12.94
0.355	12.78	10.44	14.28	7.64	14.50	10.53
0.250	13.51	10.36	12.01	8.78	16.79	9.72
0.106	22.00	18.93	18.04	15.86	22.90	14.26
0.075	5.13	5.36	2.94	4.61	3.82	3.17
0.053	3.74	5.17	2.12	3.76	1.90	3.02
<0.053	4.84	13.21	6.25	25.58	4.58	8.76

(a) Downslope splashtray sample (expressed as a percentage)

(b) Washtray sample (expressed as a percentage)

Table 5.11

CATENA ONE: TOTAL WASHTRAY SEDIMENT YIELD
(June, 1972 to August, 1978)

Site	Sediment Weight (gms)
9	2740
10	1930
15	1443
20	369

Catena Two

The lateritic breakaway (the erosional unit) and colluvial footslope of Catena Two represent distinctly different soil/slope environments as illustrated by the marked differences in soil texture (especially the percentage gravels), soil depth, thickness of the A_1 horizon, vegetative ground cover, and the areal percentage of micro soil surfaces (Table 5.12). In addition, and in contrast to Catena One, the lateritic breakaway has noticeably steeper slopes. The estimated size of the contributing area for each washtray reflects these steeper slopes with large elongate catchments on the lateritic breakaway.

As anticipated the hydrologic response of the two landsurface units differs, with the erosional laterite slope (sites 45 and 51) generating more overland flow and sediment. Mean values for the sediment yield recorded from individual rainfall events are not, however, significantly different between the two landsurface units (Table 5.13).

Comparison of the two depositional sites (56 and 59) shows no significant difference in overland flow or sediment yield (Table 5.13). Sites 45 and 51 (the erosional sites) are significantly different in terms of runoff - attributable to the much steeper slope angle and larger estimated catchment area of the sediment trap for site 45 (Table 5.12).

Overland Flow

Although the erosional lateritic breakaway is significantly more responsive than the colluvial footslope, there is no noticeable difference, such as a threshold, in the form of the overland flow response on the two units. All four recording stations revealed an

Table 5.12

CATENA TWO: PHYSICAL CHARACTERISTICS OF WASHTRAY SITES

Variable	Erosional Sites		Depositional Sites	
	45	51	56	59
Soil infiltration rate (cc/cm2/hour)	36.81	27.06	50.52	71.57
Areal percentage soil bare/crusted	85.90	84.00	2.00	4.60
Areal percentage soil cohesionless lenses	14.00	14.00	74.10	69.80
Areal percentage vegetative ground cover	0.10	2.00	23.90	25.60
Mean microroughness (mm)	5.04	3.69	3.54	2.13
Downslope range in microroughness (mm)	45.00	36.00	72.00	30.00
Across slope range in microroughness (mm)	34.00	19.00	26.00	22.00
Soil depth to hardpan/bedrock (cms)	3.00	10.00	72.00	55.00
Percentage gravels in surface soil	69.08	28.00	3.34	1.19
Percentage sand in surface soil	18.22	62.42	82.96	91.34
Average thickness of A_1 horizon (cms)	1.50	2.00	6.50	9.00
Estimated catchment area (sq. metres)	83.15	68.00	19.06	17.10
Slope angle (degrees)	13.00	6.50	3.70	3.20

Table 5.13

CATENA TWO: SUMMARY STATISTICS

Variable	Sample	N	Mean	Standard Deviation	't' Value	Level of Significance
Sediment Yield (grams)	Erosional Unit	20	11.31	15.98	1.08	*
	Depositional Unit	20	6.93	8.60		
Overland Flow (litres)	Erosional Unit	20	19.50	22.90	3.47	0.01
	Depositional Unit	20	1.65	1.97		
Erosional Unit						
Sediment Yield	Site 45	10	16.25	20.04	1.42	*
	Site 51	10	6.38	9.12		
Overland Flow	Site 45	10	31.65	26.94	2.75	0.01
	Site 51	10	7.35	7.32		
Depositional Unit						
Sediment Yield	Site 56	10	4.22	4.21	2.75	0.01
	Site 59	10	9.65	11.06		
Overland Flow	Site 56	10	1.45	1.68	-0.45	*
	Site 59	10	1.86	2.29		

't' Values

Sediment Yield

Site	51	56	59
45	* (1.42)	0.05 (1.86)	* (0.91)
51		* (0.68)	* (-0.72)
56			* (-1.45)

Overland Flow

Site	51	56	59
45	0.01 (2.75)	0.01 (3.54)	0.01 (3.48)
51		0.05 (2.48)	0.05 (2.26)
56			* (-0.45)

* Asterisk denotes lack of statistical significance

exponential relationship with precipitation such that a log-normal plot of overland flow with maximum one hour rainfall intensity provided the best correlation (Figure 5.5 and Table 5.14).

Table 5.14

CATENA TWO REGRESSIONS: OVERLAND FLOW WITH RAINFALL INTENSITY

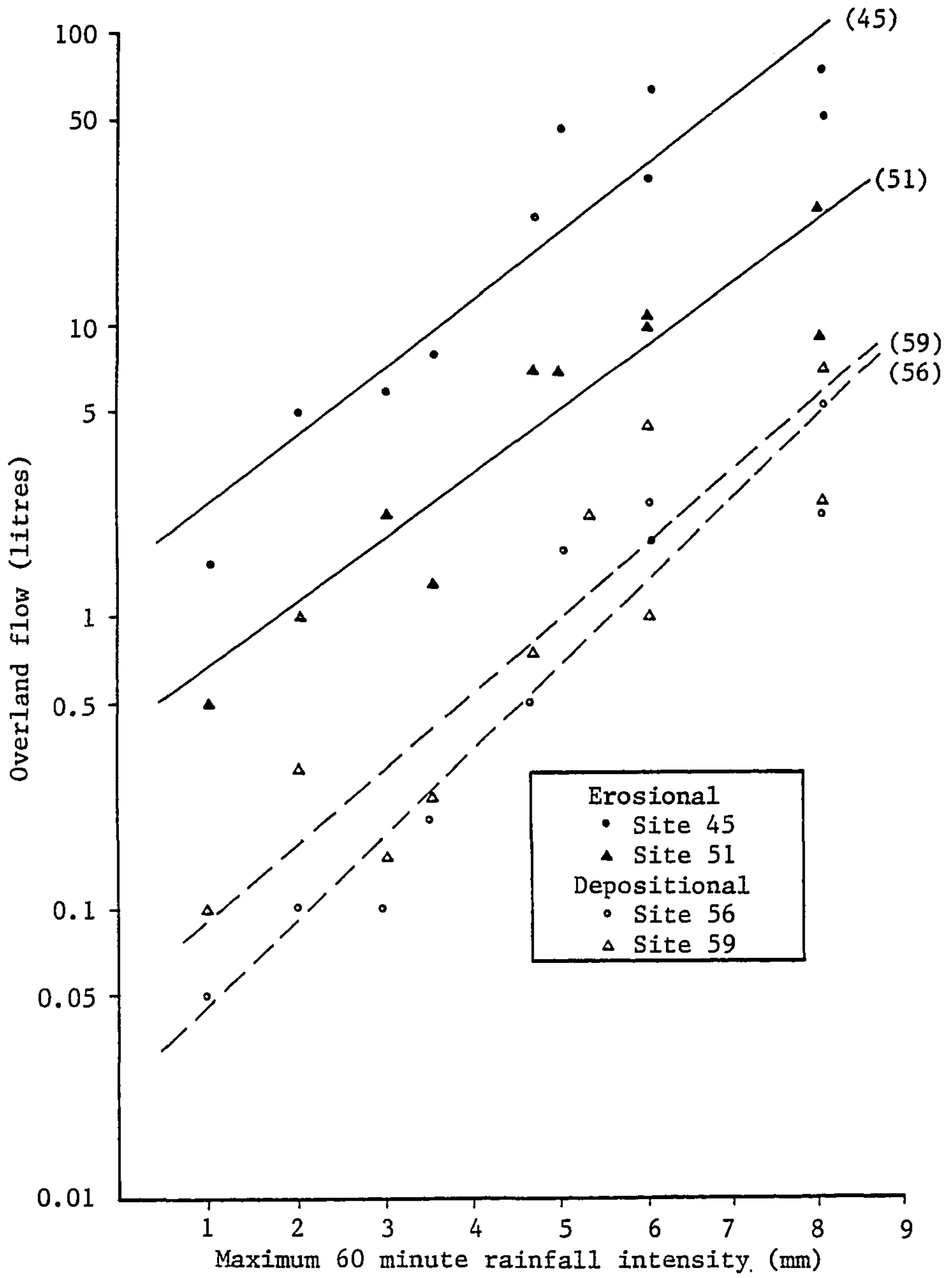
Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
45	10	$\text{Log Ov} = 0.18 + 0.23In_{60}$	0.87	0.22	52.87	0.01
51	10	$\text{Log Ov} = -0.39 + 0.22In_{60}$	0.88	0.20	56.54	0.01
56	10	$\text{Log Ov} = -1.59 + 0.29In_{60}$	0.90	0.23	73.40	0.01
59	10	$\text{Log Ov} = -1.34 + 0.26In_{60}$	0.85	0.28	44.24	0.01

Ov = Overland flow (litres)
In_{60} = Maximum one hour rainfall intensity (mm)

Differences in soil/slope characteristics between the two land-surface units support the observed variations in overland flow response (Table 5.12). The steeper slopes, lower infiltration rates, shallow depth to an indurated laterite horizon, and minimal vegetative ground cover are all characteristics of the erosional unit conducive to the generation of overland flow. By contrast, physical characteristics of the colluvial footslope (such as higher infiltration rates) are much less conducive to runoff. The greater microroughness of the erosional unit is primarily due to lateritic gravels, not vegetation, and field observations suggest that the gravels are of little importance in surface detention storage. However, the gravels do serve to subdivide the overland flow into rivulets, thus increasing frictional effects.

Figure 5.5

CATENA TWO: OVERLAND FLOW RELATED TO RAINFALL



Closer examination of the overland flow/precipitation relationship for each site suggests two separate responses within the data; one for rainfall events greater than approximately 16.5 mm and a second for events less than 16.5 mm. This division of the data is most clearly shown by regressing overland flow on maximum 30 minute rainfall intensity (Figure 5.6) and is in large part a function of the low correlation between rainfall amount and intensity ($r = 0.54$). In comparing the scatterplots in Figure 5.6 it should be noted that some of the sites are scaled differently to accommodate variations in response. The overall pattern of response suggests that for rainfall events of less than 16.5 mm overland flow is relatively insensitive to changes in rainfall intensity. Site 45 is an exception to this rule, most likely because of the steeper slopes. The two fold division of the data improves the coefficients of determination for all sites (Table 5.15), although a number of the correlations are not statistically significant due to the small sample size.

Sediment Transport

As already noted, the sediment yield recorded for individual rainfall events showed no significant difference between the two landsurface units, although total sediment yield over the six year period of measurements was 2.7 times greater on the lateritic breakaway (Table 5.16).

Several factors that may contribute to the lack of statistical significance for the sediment response measured for individual rainfall events include the small sample size and the large standard deviations. The latter is due to the wide range of sediment yields associated with

Figure 5.6

CATENA TWO: OVERLAND FLOW RESPONSE TO RAINFALL, THE 16.5 MM POTENTIAL THRESHOLD

EROSIONAL SITES

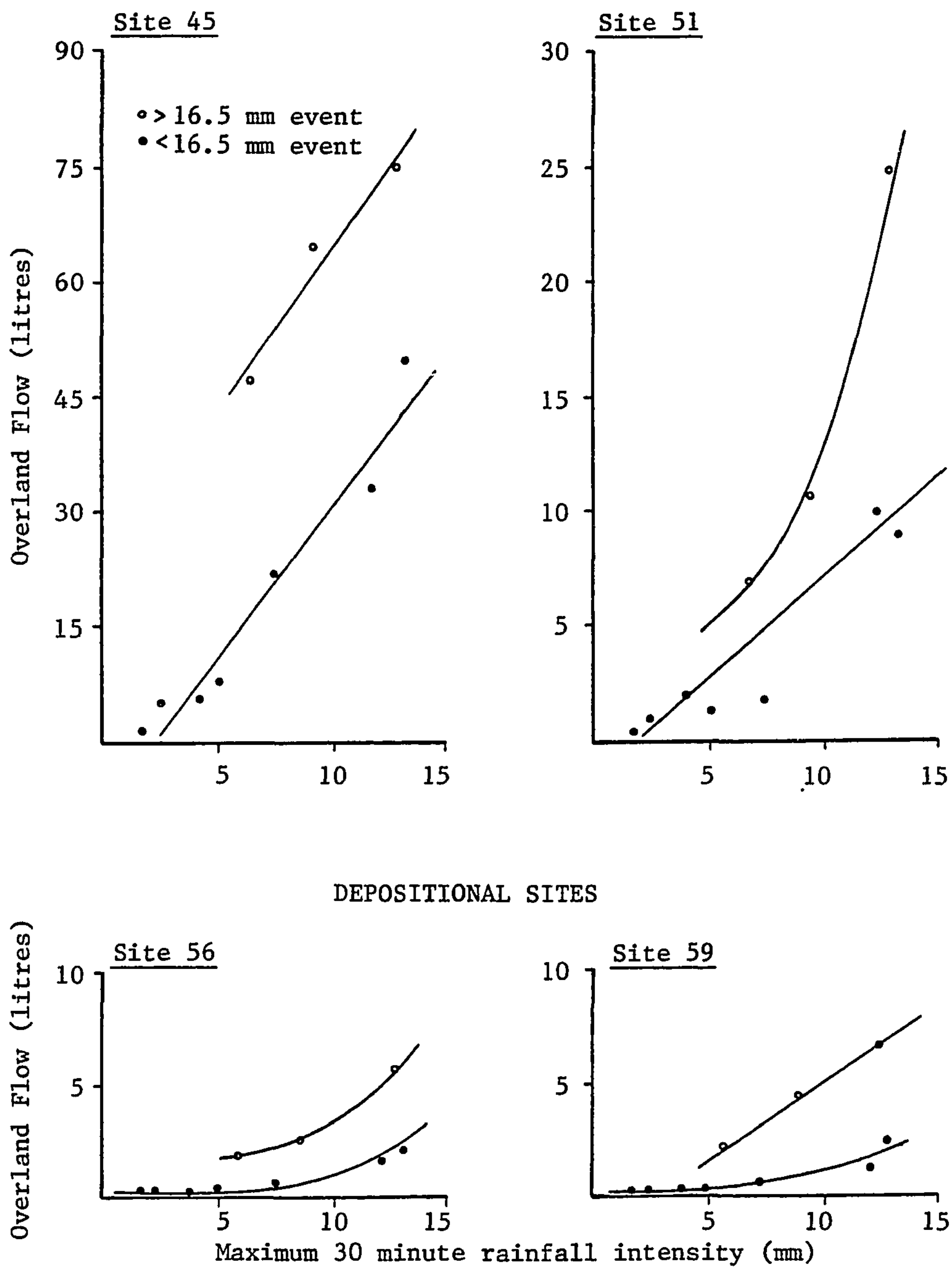


Table 5.15

CATENA TWO REGRESSIONS: OVERLAND FLOW WITH RAINFALL INTENSITY, THE 16.5 MM POTENTIAL THRESHOLD

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
45(a)	3	$Ov = 24.9 + 4.12In_{30}$	0.96	3.70	26.19	*
45(b)	7	$Ov = -6.36 + 3.84In_{30}$	0.92	5.53	61.34	0.01
51(a)	3	$Log\ Ov = 0.30 + 0.08In_{30}$	0.97	0.06	37.35	*
51(b)	7	$Ov = -1.04 + 0.85In_{30}$	0.92	1.29	55.12	0.01
56(a)	3	$Log\ Ov = -0.26 + 0.07In_{30}$	0.98	0.05	46.66	*
56(b)	7	$Log\ Ov = -1.42 + 0.14In_{30}$	0.97	0.10	221.20	0.01
59(a)	3	$Ov = -2.19 + 0.74In_{30}$	0.99	0.07	2418.00	0.01
59(b)	7	$Log\ Ov = -1.12 + 0.11In_{30}$	0.93	0.14	72.46	0.01

(a) = Rainfall events >16.5 mm
(b) = Rainfall events <16.5 mm

Ov = Overland flow (litres)
In_{30} = Maximum 30 minute rainfall intensity (mm)
* = Lack of statistical significance

Table 5.16

CATENA TWO: TOTAL WASHTRAY SEDIMENT YIELD
(June, 1972 to August, 1978)

Site	Sediment Weight (gms)
45	7632.3
51	5627.6
56	1726.1
59	3260.0

rainfall events of different magnitude and intensity. Soil texture differences may also be important, especially in terms of sediment detachment by rainsplash. Results discussed later in this chapter clearly suggest that the sandy textured soils of the colluvial footslope are more easily transported by rainsplash than the coarser textured lateritic soils. The soil texture differences are analogous to the sediment transport conditions identified by Carson and Kirkby (1972:190) as 'transport limited' and 'partly weathering limited', respectively.

Scatterplots for each site of sediment yield with precipitation show an exponential relationship similar to that observed with overland flow. A log-normal regression of sediment with maximum one hour rainfall intensity provides a good overall fit, although the coefficients of determination are slightly lower than those observed for overland flow (Figure 5.7 and Table 5.17).

Table 5.17

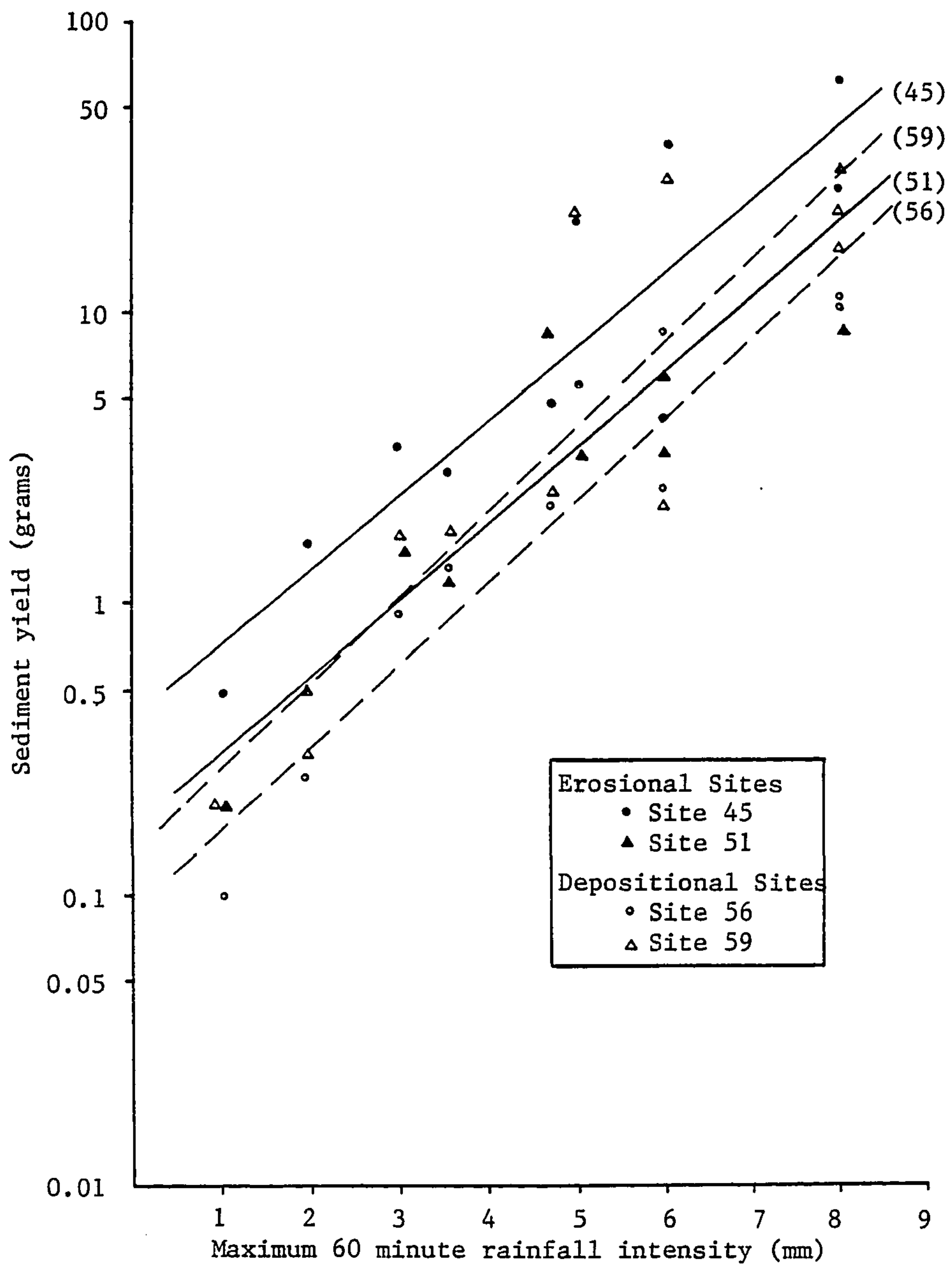
CATENA TWO REGRESSIONS: SEDIMENT YIELD WITH RAINFALL INTENSITY

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
45	10	Log Sd = -0.36 + 0.25In_{60}	0.81	0.31	33.79	0.01
51	10	Log Sd = -0.74 + 0.25In_{60}	0.85	0.26	47.19	0.01
56	10	Log Sd = -1.00 + 0.27In_{60}	0.89	0.25	62.77	0.01
59	10	Log Sd = -0.81 + 0.28In_{60}	0.74	0.42	23.12	0.01

Sd = Sediment weight (grams)
In_{60} = Maximum one hour rainfall intensity (mm)

Figure 5.7

CATENA TWO: SEDIMENT YIELD RELATED TO RAINFALL



The preciptiation threshold identified in the overland flow data is not as evident in the sediment results although division of the observations into two subsets does result in higher correlation coefficients for the smaller rainfall events. For sites 45, 56, and 59 sediment yield is relatively insensitive to increased rainfall intensity for events less than 11.5 mm (Figure 5.8). A similar response is evident on site 51 for events smaller than 16.5 mm. The resultant regression analyses are all statistically significant and with the exception of site 51 improved the explained variance (Table 5.18). Sediment yield appears far more sensitive to larger rainfall events (Figure 5.8) although the small sample size precludes general statistical significance (Table 5.18). The unexpected negative slope of the regression line for site 59 is not statistically significant and its occurrence is attributed to the small sample size.

Table 5.18

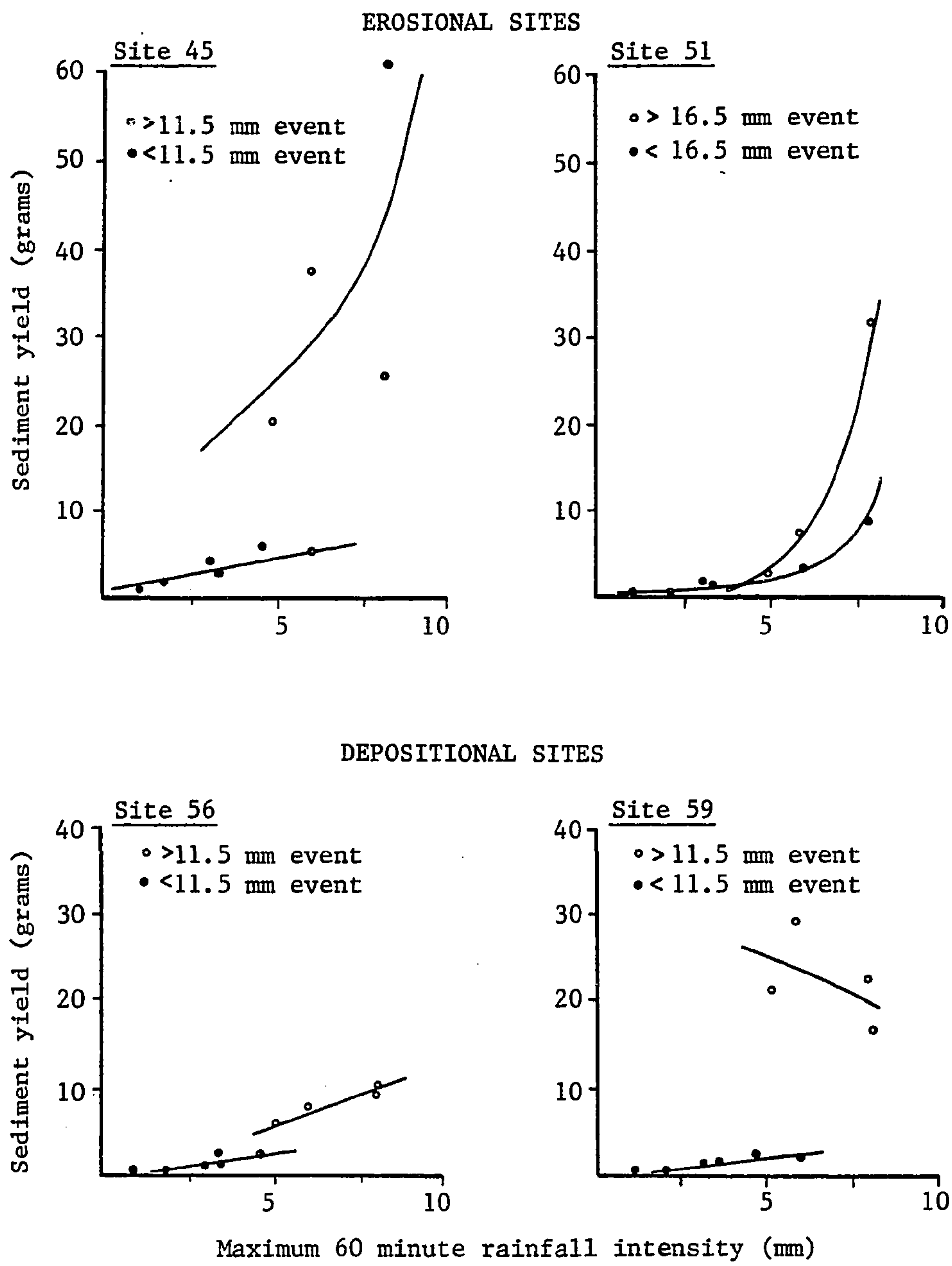
CATENA TWO REGRESSIONS: SEDIMENT YIELD WITH RAINFALL INTENSITY, POTENTIAL THRESHOLDS

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
45(a)	4	$\text{Log Sd} = 0.99 + 0.08In_{60}$	0.32	0.21	0.94	*
45(b)	6	$\text{Sd} = 0.09 + 0.85In_{60}$	0.84	0.74	21.50	0.01
51(a)	3	$\text{Log Sd} = -1.12 + 0.32In_{60}$	0.99	0.05	145.20	*
51(b)	6	$\text{Log Sd} = -0.67 + 0.22In_{60}$	0.79	0.30	19.14	0.01
56(a)	4	$\text{Sd} = -1.55 + 1.53In_{60}$	0.93	0.79	25.03	0.05
56(b)	6	$\text{Sd} = -0.57 + 0.52In_{60}$	0.96	0.22	91.02	0.01
59(a)	4	$\text{Log Sd} = 1.56 - 0.03In_{60}$	0.24	0.11	0.65	*
59(b)	6	$\text{Sd} = -0.12 + 0.46In_{60}$	0.78	0.49	13.94	0.05

(a) = Rainfall events >11.5 mm (>16.5 mm for site 51)
(b) = Rainfall events <11.5 mm (<16.5 mm for site 51)
Sd = Sediment weight (grams)
In_{60} = Maximum one hour rainfall intensity (mm)
* = Lack of statistical significance

Figure 5.8

CATENA TWO: SEDIMENT YIELD RELATED TO RAINFALL, POTENTIAL THRESHOLDS



Examination of the limited data available for rainsplash and comparison with the washtray results suggest differences between the two landsurface units in the relative efficacy of rainsplash and overland flow. Measurements of rainsplash over the 1978 winter showed average sediment movement (including upslope transport) to be twice as great on the depositional unit (Table 5.19). The data thus suggests that the sandy colluvial soils are more susceptible to detachment and short range transport by rainsplash.

Equally important is consideration of the relative amount of sediment actually splashed downslope. On the steeper slopes of the erosional unit an average of 75% of the sediment was splashed downslope compared with 56% on the colluvial footslope. Site 45 on a 13 degree slope recorded 84% downslope movement. An approximate calculation of differences in sediment weight between downslope and upslope transport shows an even greater discrepancy between the two landsurface units with greater downslope sediment transport on the lateritic breakaway (by a factor of 2.5). The calculation of rainsplash efficacy (that is, in comparison to overland flow transport) reveals an overall two fold increase in downslope splash transport on the steeper lateritic slopes, compared to the colluvial sites. Thus while the colluvial soils are more easily detached by rainsplash, there is more net downslope transport of soil by rainsplash associated with the steeper slopes of the lateritic breakaway. In addition, the washtray results for the same time period suggest that overland flow is a more important transport mechanism on the laterite slopes than on the colluvial footslope. This is particularly evident on the steeper slopes and coarser textured soil

Table 5.19

CATENA TWO: SPLASHTRAY AND WASHTRAY SEDIMENT YIELDS

Unit	Site Number	Splash (gms) Downslope	Splash (gms) Upslope	% Splashed Downslope	Net Downslope Splash (gms)	Washtray (gms)	Rainsplash Efficacy (%)
Erosional	45	29.30	5.46	84.43	24.84	92.40	20.50
Erosional	51	20.13	9.86	67.10	10.27	27.48	27.20
Depositional	56	17.10	13.50	55.88	3.60	35.82	9.13
Depositional	59	45.60	35.60	56.10	10.00	60.35	14.20

Note: All data recorded for the period June 4 - August 28, 1978

of site 45 (Table 5.19). Also worthy of note is the difference in the range of particle sizes collected from the splashtrays and washtrays. All splashed sediment was less than 3.35 mm in diameter and predominantly sand sized fractions (Table 5.20).

Table 5.20

CATENA TWO

WASHTRAY AND SPLASHTRAY SEDIMENT PARTICLE SIZE ANALYSIS

JUNE 4 - AUGUST 28, 1978

Diameter	Site 45		Site 51		Site 56		Site 59	
(mm)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
+10.000		11.93		10.04				
8.000		8.72		5.82				
5.600		12.00		6.11				
3.350		14.06		5.60				0.22
2.000	1.82	7.39	0.33	2.98	0.39	0.39	0.51	1.94
1.000	16.72	12.74	15.06	14.99	16.57	17.67	20.80	22.42
0.710	11.26	6.31	11.26	9.32	28.26	27.02	20.14	15.21
0.500	12.97	6.37	12.75	8.66	26.70	26.02	17.52	16.77
0.355	12.96	5.36	12.91	7.86	13.06	13.93	17.59	15.41
0.250	14.56	5.03	15.56	8.33	5.65	5.50	11.46	10.69
0.106	20.02	6.23	22.52	13.17	4.48	4.05	8.03	9.28
0.075	3.18	0.90	3.47	2.47	0.58	0.78	0.80	1.52
0.053	1.59	0.58	2.32	1.38	0.58	0.67	0.58	1.41
<0.053	4.89	2.37	3.80	3.24	3.70	3.96	2.55	5.15

(a) Downslope splashtray sample (expressed as a percentage)

(b) Washtray sample (expressed as a percentage)

Regression analysis of sediment yield with overland flow adds further support to the significance of rainsplash as an agent of mobilization on the sandy textured soils of the colluvial footslope. Both sites 56 and 59 show similar curvilinear relationships, with a third order polynomial providing the best fit (Figure 5.9 and Table 5.21). The low runoff volumes generated on this landsurface unit suggest in themselves that most washtray sediment is the result of rainsplash transport. However, the data also suggests maximum rainsplash activity at low overland flow conditions. Decreased sediment yield with greater overland flow volume, may be due to the presence of a protective film of water across the soil surface. For rainfall events larger than those recorded in this study, another threshold is postulated with increased turbulence increasing the sediment load.

In contrast, sites 45 and 51 show distinctly different relationships between sediment and overland flow (Figure 5.9, Table 5.21). Linear regression provides a best fit for the site 51 data with one extreme observation increasing the coefficient of determination from 60% to 88%. Results from site 45 are unclear. The highest correlation between the two variables is a log-log transformation (Table 5.21). A third order polynomial provides a reasonable fit although there is no reason to expect such a response considering the apparent importance of overland flow to sediment transport.

It is possible, given the relatively steep slopes and the high percentage of gravels in the soil at site 45, that the one observation that recorded a high sediment yield associated with 50 litres of runoff, resulted from a sudden washing of sediment into the washtray in response

Figure 5.9

CATENA TWO: SEDIMENT YIELD RELATED TO OVERLAND FLOW

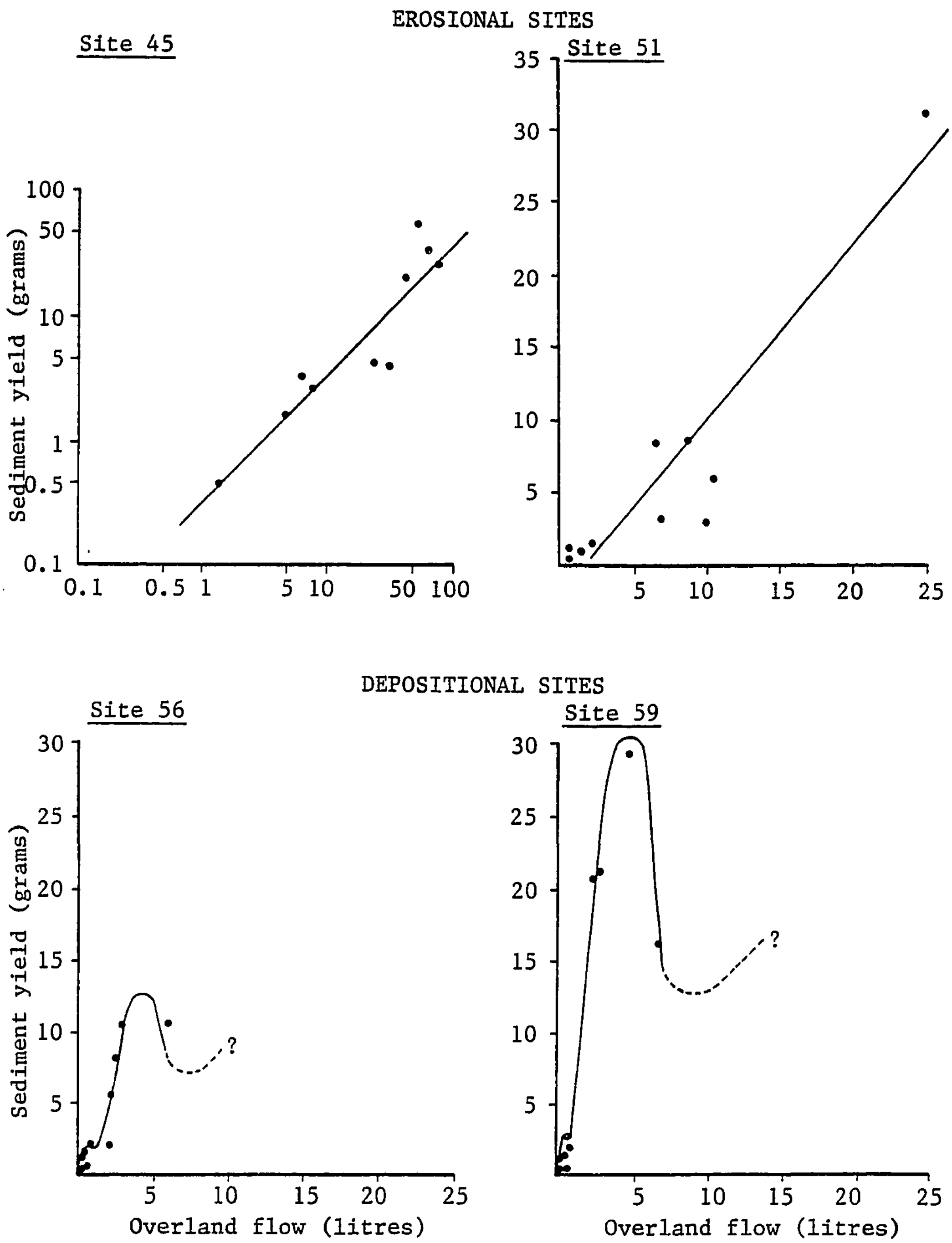


Table 5.21

CATENA TWO REGRESSIONS: SEDIMENT YIELD WITH OVERLAND FLOW

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
45(a)	10	Log Sd = $-0.50 + 1.060v$	0.85	0.27	45.75	0.01
45(b)	10	Sd = $10.12 - 2.280v + 0.100v^2 - 0.0010v^3$	0.75	12.20	6.09	0.05
51	10	Sd = $-2.19 + 1.160v$	0.88	3.40	56.60	0.01
56	10	Sd = $0.86 - 1.120v + 2.840v^2 - 0.430v^3$	0.87	1.85	13.45	0.01
59	10	Sd = $-1.01 + 6.900v + 1.250v^2 - 0.270v^3$	0.95	2.94	40.57	0.01

Sd = Sediment weight (grams)

Ov = Overland flow (litres)

to one or more pulses of overland flow. In comparative terms this was an intense storm with the possibility of short duration rainfall intensities considerably higher than those calculated for the 30 minute and 60 minute intervals. Removal of this one aberrant observation results in a reasonably linear or slightly exponential relationship as might be expected. A clearer pattern may also be revealed if data for much larger rainfall events were available.

Catena Three

As hypothesised, the overland flow and sediment yield results for Catena Three demonstrate an inverse relationship to that hypothesised and substantiated for Catenas One and Two (Table 5.22). Average overland flow response on the depositional unit is significantly higher (0.05). Sediment yield is also greater on this unit, though only significant at 0.1. This reversal in hydrologic response denotes an important difference in soil/slope characteristics between this area and Catenas One and Two. Both catenas discussed thus far included an erosional landsurface unit characterised by a truncated or eroded soil profile. In contrast, the erosional unit on Catena Three comprised outcrops of gneissic rock interspersed with small depositional pockets of coarse textured soil. The colluvial footslope is most readily distinguished from the erosional unit by the absence of rock outcrops; presence of deeper soils; noticeably less variability in soil depth; and gentler slopes (Table 5.23). Differences in other soil characteristics, such as texture, are more subtle with slightly coarser material associated with the gneissic outcrops.

Relative areal homogeneity of the landsurface units on Catenas

Table 5.22

CATENA THREE: SUMMARY STATISTICS

Variable	Sample	N	Mean	Standard Deviation	't' Value	Level of Significance
Sediment Yield (grams)	Erosional Unit	20	2.94	2.98	-1.50	0.10
	Depositional Unit	30	17.02	41.76		
Overland Flow (litres)	Erosional Unit	20	1.04	1.37	-2.08	0.05
	Depositional Unit	30	6.99	12.72		
Erosional Unit						
Sediment Yield	Site 70	10	2.65	2.77	-0.45	*
	Site 71	10	3.23	3.30		
Overland Flow	Site 70	10	1.24	1.53	0.65	*
	Site 71	10	0.84	1.22		
Depositional Unit						
Sediment Yield	Site 73	10	4.79	9.63	(see table below)	
	Site 75	10	33.72	67.21		
	Site 80	10	12.56	22.63		
Overland Flow	Site 73	10	3.23	6.70		
	Site 75	10	12.04	19.08		
	Site 80	10	5.71	8.18		

't' Values

DEPOSITIONAL UNIT

Sediment Yield

Site	75	80
73	* (-1.35)	* (-1.00)
75		* (0.94)

Overland Flow

Site	75	80
73	* (-1.38)	* (-0.74)
75		* (0.96)

EROSIONAL UNIT WITH DEPOSITIONAL SITES

	Site	73	75	80
Erosional Unit	Sediment Yield	* (0.80)	0.05 (2.08)	0.05 (1.90)
	Overland Flow	* (1.42)	0.01 (2.61)	0.05 (2.53)

* Asterisk denotes lack of statistical significance

Table 5.23

CATENA THREE: PHYSICAL CHARACTERISTICS OF WASHTRAY SITES

Variable	Erosional Sites		Depositional Sites		
	70	71	73	75	80
Soil infiltration rate (cc/cm^2/hour)	25.30	43.30	40.80	31.30	24.70
Areal percentage bare soil/rock	18.00	34.00	7.00	6.00	56.70
Areal percentage rock (five metre quadrat)	42.00	45.00	0.00	0.00	0.00
Areal percentage cohesionless lenses	79.50	65.00	10.00	75.00	40.00
Areal percentage vegetative ground cover	2.50	1.00	83.00	19.00	2.70
Mean microroughness (mm)	3.81	3.70	2.10	1.60	1.90
Downslope range in microroughness (mm)	77.00	62.00	23.00	25.00	18.00
Across slope range in microroughness (mm)	48.00	45.00	23.00	14.00	24.00
Soil depth to hardpan/bedrock (cms)	14.80	14.00	45.00	76.00	58.10
Range in soil depth (cms)	37.00	38.00	3.00	4.50	2.00
Percentage gravels in surface soils	15.90	18.20	8.90	19.60	4.70
Average thickness of A_1 horizon (cms)	2.00	3.50	10.00	4.50	3.00
Estimated catchment area (sq. metres)	12.08	75.20	82.00	448.00	129.50
Slope angle (degrees)	10.50	16.00	5.50	4.00	4.30

One and Two enabled assumptions of relative uniformity in response across each landsurface unit. Though the gneissic outcrops constitute a clearly identifiable landsurface unit, the presence of rock outcrops introduces greater internal variability in slope angle, microroughness, and soil depth. Consequently, much of the overland flow (observed during relatively intense rainfall) quickly coalesces to form concentrated flow lines that are generally indefinable in the absence of runoff. Sites 70 and 71, located on pockets of coarse textured weathered gneiss, are not associated with any of these concentrated flow lines and consequently are characterised by low hydrologic response; even though the general area of both sites has a relatively high percentage of rock outcrops (42% and 45% respectively) suggesting potentially high rates of runoff. Both erosional sites recorded similar sediment yield and overland flow responses with no significant differences in the mean values for each site (Table 5.22).

In contrast, three levels of response were hypothesised on the colluvial footslope. Sediment and runoff responses ranged in magnitude for sites 73, 75, and 80, although none of the sites had significantly different means (Table 5.22). The lack of statistical significance is in part a result of the large standard deviations for sites 75 and 80. Site 75 was the most responsive with an estimated potential catchment area of 448 square metres extending into the gneissic outcrops. Located on a small alluvial fan, the washtray includes in its catchment area a zone of concentrated overland flow. Site 73 was the least responsive to overland flow and sediment movement, reflecting the high percentage vegetative cover (interception rather than surface depression storage) and comparatively small estimated catchment area (Table 5.23). Mean values for overland flow and sediment yield on site 73 are not significantly different to the average response for the erosional unit (Table 5.22).

Overland Flow

Though the two landsurface units differ significantly in the volume of overland flow recorded, all five sites share an exponential relationship with precipitation, similar to that already discussed for Catena Two. A log-normal plot of overland flow with maximum one hour rainfall intensity provided the best correlation (Figure 5.10 and Table 5.24).

Table 5.24

CATENA THREE REGRESSIONS: OVERLAND FLOW WITH RAINFALL INTENSITY

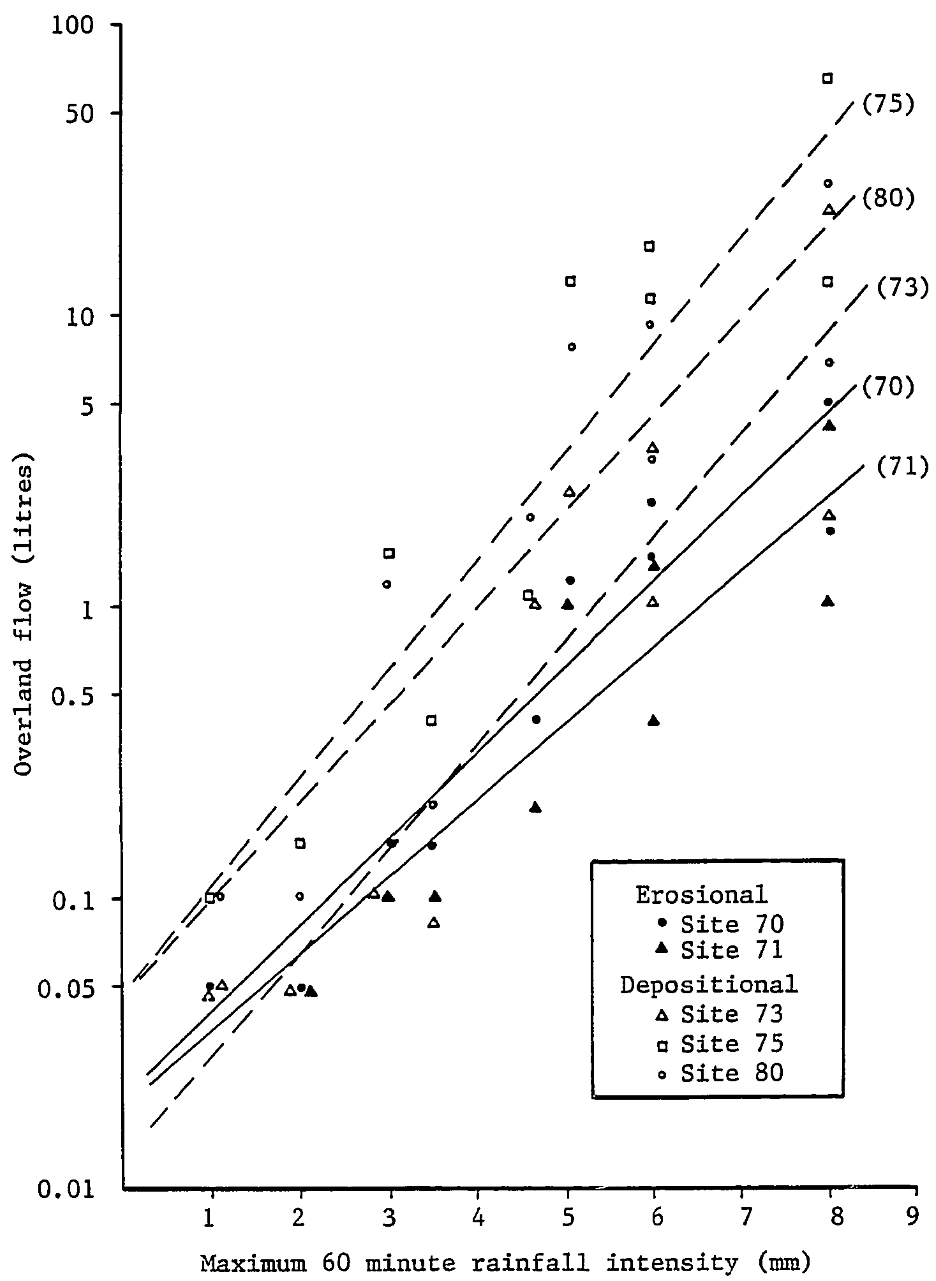
Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
70	10	$\text{Log Ov} = -1.67 + 0.29\text{In}_{60}$	0.91	0.23	78.25	0.01
71	10	$\text{Log Ov} = -1.70 + 0.26\text{In}_{60}$	0.84	0.28	41.32	0.01
73	10	$\text{Log Ov} = -1.85 + 0.35\text{In}_{60}$	0.82	0.41	36.79	0.01
75	10	$\text{Log Ov} = -1.34 + 0.37\text{In}_{60}$	0.85	0.40	43.62	0.01
80	10	$\text{Log Ov} = -1.33 + 0.33\text{In}_{60}$	0.82	0.39	35.88	0.01

Ov = Overland flow (litres)
In_{60} = Maximum one hour rainfall intensity (mm)

Higher correlations between overland flow and rainfall intensity were achieved by decomposing the data into two subsets, using the same rainfall threshold (16.5 mm) that was applied to the Catena Two data.

Figure 5.10

CATENA THREE: OVERLAND FLOW RESPONSE TO RAINFALL



The resultant regression analyses (Figure 5.11 and Table 5.25) clearly demonstrate the greater sensitivity of overland flow to the larger, more intense rainfall events and suggests an exponential relationship with rainfall intensity. Due to the small sample size three of the regressions are not statistically significant. For rainfall events of less than 16.5 mm overland flow is much less responsive, with a generally linear to slightly curvilinear correlation with rainfall intensity.

Table 5.25

CATENA THREE REGRESSIONS: OVERLAND FLOW WITH RAINFALL INTENSITY, THE 16.5 MM POTENTIAL THRESHOLD

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
70(a)	3	$Ov = -5.34 + 1.29In_{60}$	0.99	0.21	168.70	0.05
70(b)	7	$\text{Log } Ov = -1.64 + 0.25In_{60}$	0.94	0.17	74.80	0.01
71(a)	3	$\text{Log } Ov = -1.02 + 0.20In_{60}$	0.99	0.02	491.80	0.05
71(b)	7	$\text{Log } Ov = -1.61 + 0.20In_{60}$	0.98	0.07	238.10	0.01
73(a)	3	$\text{Log } Ov = -1.31 + 0.32In_{60}$	0.96	0.13	27.30	*
73(b)	7	$Ov = -0.57 + 0.29In_{60}$	0.88	0.29	35.90	0.01
75(a)	3	$\text{Log } Ov = -0.12 + 0.24In_{60}$	0.97	0.09	32.40	*
75(b)	7	$\text{Log } Ov = -1.28 + 0.32In_{60}$	0.86	0.34	30.90	0.01
80(a)	3	$\text{Log } Ov = -0.13 + 0.19In_{60}$	0.96	0.08	23.90	*
80(b)	7	$Ov = -1.85 + 0.94In_{60}$	0.87	0.93	35.70	0.01

(a) = Rainfall events >16.5 mm
(b) = Rainfall events <16.5 mm

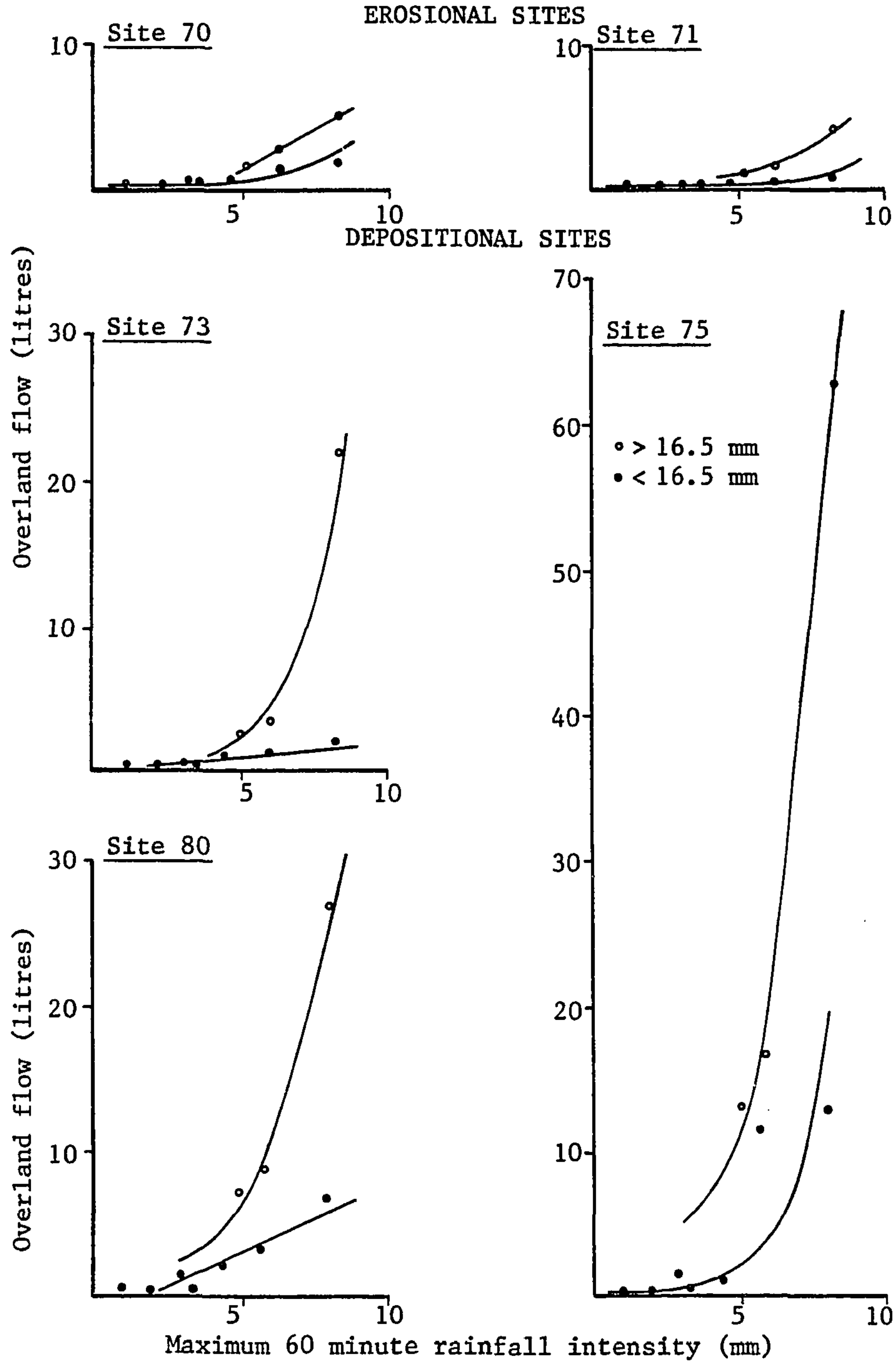
Ov = Overland flow (litres)
In_{60} = Maximum one hour rainfall intensity (mm)

Sediment Transport

The total weight of sediment collected over the six year period of recordings showed an average of 4.5 times as much sediment transported across the colluvial footslope, compared to the gneissic outcrops

Figure 5.11

CATENA THREE: OVERLAND FLOW RESPONSE TO RAINFALL, THE 16.5 MM POTENTIAL THRESHOLD



(Table 5.26). Even greater variation is to be found within the depositional unit, with the order of magnitude related to overland flow response for the three sites. An approximate ratio of total sediment movement for sites 73, 80, and 75 is 1 : 2.5 : 12, respectively. Similar long term responses are also suggested by differences in soil depth between the three colluvial sites (Table 5.23) and clearly indicate that the high sediment transport rates of the colluvial footslope relate more to redeposition than erosion of soil.

Table 5.26

CATENA THREE: TOTAL WASHTRAY SEDIMENT YIELD
(June, 1972 to August, 1978)

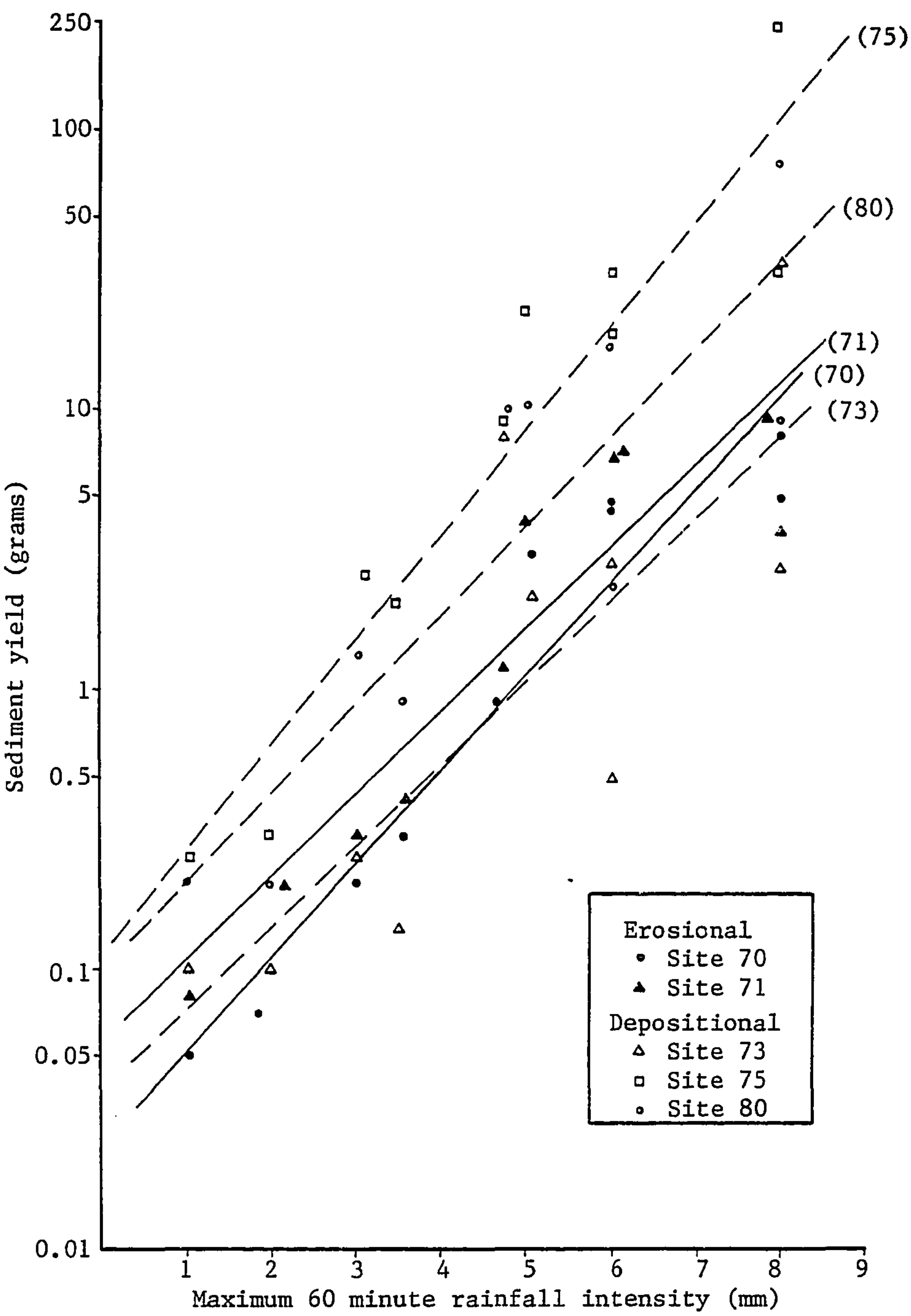
Site	Sediment Weight (gms)
70	2,026
71	2,356
73	1,988
75	23,013
80	4,442

Although total sediment yield varies markedly throughout the catena, all five sites have a similar exponential relationship between sediment yield and individual rainfall events. A log-normal regression analysis of sediment yield with maximum one hour rainfall intensity produced the highest correlation between the two variables (Figure 5.12). Site 73 has a noticeably lower coefficient of determination (Table 5.27), most likely a function of the high percentage vegetative cover (83%) associated with this washtray.

Improved correlation coefficients were obtained by using the precipitation threshold (16.5 mm) employed with the overland flow results and by regressing sediment yield against maximum thirty minute

Figure 5.12

CATENA THREE: SEDIMENT YIELD RELATED TO RAINFALL



rainfall intensity. To accommodate the wide variations in response, some of the graphs are scaled differently. Consequently the regression equations listed in Table 5.28 should be used for comparison of differences in rates of change. The relationship between sediment yield and rainfall is similar to that obtained for overland flow and precipitation. An exponential increase in sediment yield is associated with the larger rainfall events with an anticipated, less sensitive relationship between sediment yield and the smaller rainfall events (Figure 5.13).

Table 5.27

CATENA THREE REGRESSIONS: SEDIMENT YIELD WITH RAINFALL INTENSITY

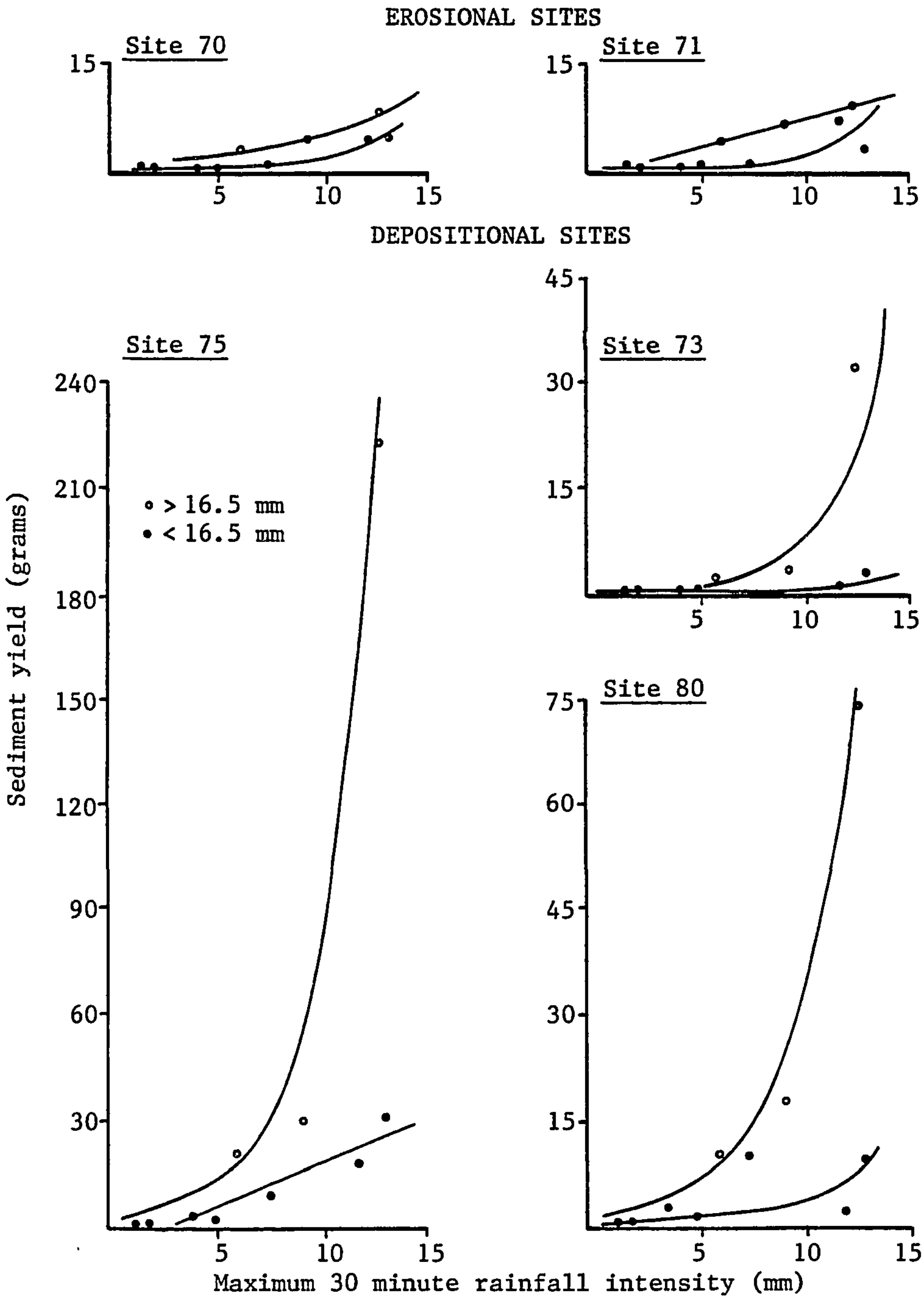
Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
70	10	$\text{Log Sd} = -1.60 + 0.33\text{In}_{60}$	0.91	0.26	79.90	0.01
71	10	$\text{Log Sd} = -1.25 + 0.29\text{In}_{60}$	0.85	0.29	47.40	0.01
73	10	$\text{Log Sd} = -1.42 + 0.29\text{In}_{60}$	0.67	0.53	16.10	0.01
75	10	$\text{Log Sd} = -0.93 + 0.37\text{In}_{60}$	0.90	0.31	72.10	0.01
80	10	$\text{Log Sd} = -0.98 + 0.31\text{In}_{60}$	0.78	0.42	28.20	0.01

Sd = Sediment weight (grams)
In_{60} = Maximum one hour rainfall intensity (mm)

Measurement of sediment transport by rainsplash was limited to sites 71 and 75. Nevertheless, the available data supports the results obtained from Catenas One and Two in terms of the more selective nature of sediment splash. Sand sized particles predominated, with the maximum particle sizes recorded in the splash trays ranging between 2.0 and 3.35 mm in diameter. In contrast, small pieces of weathered gneiss within

Figure 5.13

CATENA THREE: SEDIMENT YIELD RELATED TO RAINFALL, THE 16.5 MM POTENTIAL THRESHOLD



the range of 3.35 to 5.6 mm in diameter were deposited in the washtray for site 71.

Table 5.28

CATENA THREE REGRESSIONS: SEDIMENT YIELD WITH RAINFALL INTENSITY, THE 16.5 MM POTENTIAL THRESHOLD

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
70(a)	3	Log Sd = 0.07 + 0.06In_{30}	0.99	0.01	326.40	0.05
70(b)	7	Log Sd = -1.40 + 0.17In_{30}	0.99	0.10	370.60	0.01
71(a)	3	Sd = -0.53 + 0.76In_{30}	0.99	0.15	507.00	0.05
71(b)	7	Log Sd = -1.13 + 0.15In_{30}	0.95	0.17	92.80	0.01
73(a)	3	Log Sd = -0.93 + 0.18In_{30}	0.86	0.34	6.19	*
73(b)	6	Log Sd = -1.17 + 0.09In_{30}	0.82	0.25	18.80	0.05
75(a)	3	Log Sd = 0.29 + 0.16In_{30}	0.88	0.27	7.20	*
75(b)	7	Sd = -6.21 + 2.36In_{30}	0.91	3.83	48.50	0.01
80(a)	3	Log Sd = 0.12 + 0.14In_{30}	0.95	0.14	19.60	*
80(b)	7	Log Sd = -0.65 + 0.12In_{30}	0.67	0.43	10.40	0.05

(a) Rainfall events >16.5 mm
(b) Rainfall events <16.5 mm

Sd = Sediment weight (grams)
In_{30} = Maximum 30 minute rainfall intensity (mm)

The calculation of rainsplash efficacy, though limited in number, also suggests that rainsplash sediment transport is much more important on the erosional unit (Table 5.29) though the size of splashed particles does not exceed 3.35 mm in diameter (Table 5.30). Scatter-plots for sites 70 and 71 of sediment yield with volume of overland flow supports this hypothesis (Figure 5.14). Both sites recorded a decrease in sediment yield rates with increased overland flow such that a division of the data on the basis of a precipitation threshold (11.5

Table 5.29

CATENA THREE: SPLASHTRAY AND WASHTRAY SEDIMENT YIELDS

Unit	Site Number	Splash (gms)		% Splashed Downslope	Net Downslope Splash (gms)	Washtray (gms)	Rainsplash Efficacy (%)
		Downslope	Upslope				
Erosional	70	no splash data available					
Erosional	71	51.00	42.00	55.00	9.00	23.86	27.38
Depositional	73	no splash data available					
Depositional	75	10.60	11.50	48.00	-0.90	27.29	-0.30
Depositional	80	no splash data available					

Note: All data recorded for the period June 4 - August 28, 1978

Figure 5.14

CATENA THREE: SEDIMENT YIELD RELATED TO OVERLAND FLOW

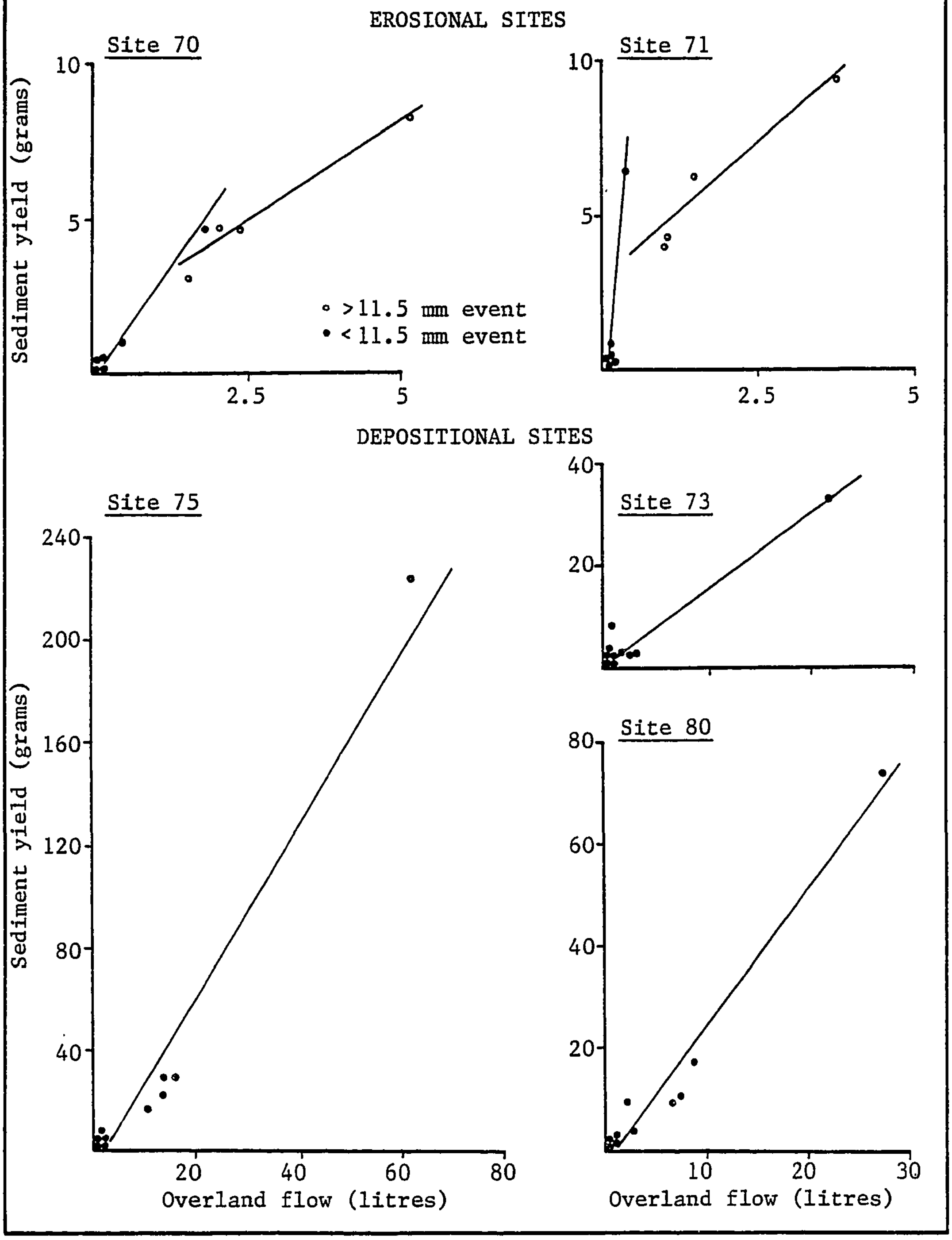


Table 5.30

CATENA THREE

WASHTRAY AND SPLASHTRAY SEDIMENT PARTICLE SIZE ANALYSIS

JUNE 4 - AUGUST 28, 1978

Diameter (mm)	Site 71 (a)	Site 71 (b)	Site 75 (a)	Site 75 (b)
+5.600		3.31		0.79
3.350		5.11		5.24
2.000	1.66	13.41	2.82	11.10
1.000	22.14	28.50	17.87	20.85
0.710	.14.90	12.57	14.42	11.32
0.500	14.42	9.77	14.11	9.60
0.355	11.24	6.75	11.28	7.15
0.250	9.84	4.90	12.22	6.96
0.106	15.09	7.12	17.55	11.65
0.075	3.46	1.59	3.13	3.59
0.053	2.19	1.42	2.19	2.93
<0.053	5.05	5.53	4.39	8.83

(a) Downslope splashtray sample (expressed as a percentage)

(b) Washtray sample (expressed as a percentage)

mm) yields higher coefficients of determination (Table 5.31). The precipitation threshold of 16.5 mm yields slightly lower correlation coefficients though the slope of the regression lines are similar. The apparent decrease in sediment yield with increased overland flow may be due to the protective effect of a surface film of water. Alternatively the relationship between sediment and overland flow may be due to a third variable - the specific siting of the washtrays in locations of low overland flow response. On the depositional unit, sediment and overland flow are linearly correlated, with the correlation coefficients improved (most noticeably on site 73) by one extreme observation (Figure 5.14).

Table 5.31

CATENA THREE REGRESSIONS: SEDIMENT YIELD WITH OVERLAND FLOW

Site Number	N	Equation	r^2	Standard Error	F	Level of Significance
70(a)	4	Sd = 1.97 + 1.21Ov	0.95	0.55	41.80	0.05
70(b)	6	Sd = -0.15 + 3.0Ov	0.99	0.14	866.00	0.01
71(a)	4	Sd = 2.80 + 1.60Ov	0.87	1.08	13.60	*
71(b)	6	Sd = -1.35 + 19.13Ov	0.93	0.81	49.60	0.01
73	10	Sd = 0.30 + 1.39Ov	0.94	2.50	124.80	0.01
75	10	Sd = -7.97 + 3.46Ov	0.96	13.24	223.70	0.01
80	10	Sd = -2.85 + 2.69Ov	0.95	5.37	151.40	0.01

(a) = Rainfall events >11.5 mm　　Sd = Sediment weight (grams)
(b) = Rainfall events <11.5 mm　　Ov = Overland flow (litres)

Summary

Comparison of the overland flow and sediment yield data for each catena clearly demonstrates that significant differences in hydrologic response are associated with the respective soil/slope characteristics of depositional and erosional landsurface units. On Catena One, the mean values of overland flow and sediment yield recorded for individual rainfall events, were significantly different between the two landsurface units. Total sediment yield for the six years of observations also showed a higher yield on the erosional unit by a factor of 2.5. Distinct differences in soil/slope properties, most notably the greater surface microroughness and higher infiltration rates of the depositional unit, were reflected in regression analyses of the hydrologic data. Regression analyses of overland flow against rainfall and sediment yield with overland flow, both revealed the presence of thresholds on the depositional unit. In addition, the virtual absence of vegetative ground cover on the erosional unit was identified as a major contributing factor to the observed twenty fold difference between the two units in total rainsplashed sediment.

The Catena Two results revealed an overall similarity in response to that observed on Catena One. Total sediment yield (for the six years of observations), from the erosional unit exceeded soil loss from the depositional unit by a factor of 2.7. Correlations of sediment yield with individual rainfall events, and overland flow with rainfall, also revealed the erosional unit as more responsive in both sediment yield and overland flow. Division of the rainfall events into two subsets (approximately, greater than and less than 16.5 mm) clearly illustrated a low sediment and overland flow response on both land-surface units to the smaller rainfall events. One notable exception was the overland flow response on site 45, which was attributed to the steeper slopes and larger estimated catchment area of this site. Compared to the colluvial sites, the erosional unit was more responsive to the larger rainfall events, both in sediment yield and overland flow. In addition, the calculation of rainsplash efficacy in downslope sediment transport showed a two fold difference between the two units.

Although total splash transport was greater on the depositional landsurface unit, the greater efficacy of rainsplash on the erosional unit reflected the steeper slopes and markedly lower vegetative ground cover. A final distinction in the hydrologic response of the two landsurface units was identified in correlating sediment yield with overland flow. A curvilinear regression line indicated two thresholds in the observations for the depositional unit. Both thresholds are interpreted as indicative of the high rates of sediment mobilization by rainsplash and the reduction in splash transport associated with surface pooling of water.

For Catena Three, the hypothesised reversal in hydrologic response between the two landsurface units was substantiated for both overland flow and sediment yield, although the difference in sediment yield means was not highly significant (0.1). In part this reflected the wide range in hydrologic response recorded for the three depositional sites. Total sediment yield, for the six year period, varied between sites 73, 80, and 75 in the approximate ratio of 1 : 2.5 : 12, respectively. Similarly, sites 73 and 75 were respectively, the least and most responsive to overland flow. The overall mean of the six year sediment totals for the three depositional sites exceeded the mean value recorded for the two erosional sites by a factor of 4.5. A two fold division of the rainfall events (with the same approximate threshold of 16.5 mm) improved the correlation coefficients for all five sites and more clearly identified the greater sensitivity of overland flow and sediment yield to the higher magnitude, and higher intensity, rainfall events. Although only two sites (71 and 75) were monitored, measurement of rainsplash transport suggested much higher net downslope transport on the erosional unit.

The variability in hydrologic response recorded within each of the three catenas has clearly demonstrated significant differences between the depositional and erosional landsurface units. All four of the attributes measured: overland flow response to individual rainfall events; sediment yield for individual rainfall events; total sediment yield for the six year period of recording; and rainsplash efficacy, substantiated the hypothesised relationships.

A comparison of Catena One and Two reveals an overall similarity in hydrologic response. The erosional unit on both catenas was the most responsive, recording higher rates of overland flow, sediment yield and rainsplash efficacy. In contrast, the overland flow and sediment results substantiated the hypothesised response for Catena Three; attributed to the presence of gneissic outcrops within the erosional unit and the subsequent development of concentrated zones of overland flow within both the erosional and depositional landsurface units.

In the following chapter, discriminant analysis is employed to test the validity of the landsurface unit classification on each catena. Verification of the spatial variability in soil/slope characteristics will then enable generalizations to the spatial differences in hydrologic response within each catena.

CHAPTER VI

CATENARY SPATIAL PATTERNS OF SOIL/SLOPE CHARACTERISTICS

Introduction

The results discussed in Chapter V clearly identify differences in hydrologic response between sites located on erosional and depositional landsurface units. As demonstrated, these distinct hydrologic responses reflected differences between the soil/slope characteristics of the erosional and depositional sites. In this chapter, results are presented of discriminant analysis performed to evaluate the statistical significance of these pedologic and geomorphic differences among the mapped landsurface units. Statistical validation of the landsurface unit classification will enable spatial generalisation of the observed variations of hydrologic response.

Landsurface units are defined as spatially contiguous areas characterised by relative internal homogeneity (modality) of pedologic and geomorphic parameters. Discriminant analysis and cluster analysis are appropriate statistical procedures for testing the significance of the differences among the mapped units. However, as one of the research aims focuses on the identification of the most useful mapping criteria, discriminant analysis was selected. The stepwise selection of variables available in discriminant analysis, provides a ranking of the variables in order of discriminating power, thus enabling reduction of the list of potential discriminators to a smaller set of key diagnostic mapping criteria. Wilk's lambda was the criterion selected to determine the order of entry; the smaller the value of Wilk's lambda, the better the discrimination.

A total of 81 sites were sampled across the three catenas. In addition to the erosional and depositional units on each catena, a third area, a 5/6 intergrade was also mapped on Catena One. As the name implies, an intergrade is a transition zone; in this case a transition zone between the erosional (unit 5) and depositional (unit 6) landsurface units. The number of sites on each catena and the group number (label) used for each landsurface unit in the discriminant analyses is outlined in Table 6.1.

Table 6.1

DISTRIBUTION OF SAMPLING SITES AMONG LANDSURFACE UNITS AND CATENAS

Catena	Group Number	Number of Sites	Landsurface Unit	Description
One	1	12	Erosional	Long low angle pediment slope
	2	20	Depositional	Colluvium
	3	9	Transitional	5/6 intergrade
Two	4	10	Erosional	Lateritic breakaway
	5	10	Depositional	Colluvium
Three	6	10	Erosional	Gneissic outcrops
	7	10	Depositional	Colluvium

The 18 variables measured on all three catenas were defined in Chapter IV (Table 4.3) and grouped into six soil and/or slope categories; soil texture, microroughness, slope, infiltration, areal extent of micro soil surfaces, and general soil characteristics. Group means and standard deviations for all 18 variables are listed in Tables 6.2 and 6.3 respectively. Table 6.4, the correlation matrix indicates that few variables are affected by collinearity.

The fundamental hypothesis underlying selection of all the pedogeomorphic criteria discussed in this study is that all are potentially useful criteria for distinguishing between the physical characteristics of erosional and depositional environments in a semi-arid climatic regime. The ability to 'generalise results' to other semi-arid soil/slope environments is in part a function of the success of the research data to support the hypotheses underlying the original selection of mapping criteria. Statistically, this requires that not only should the mean values for variables measured on each of the two landsurface units be significantly different, but that they also differ in the direction hypothesised. The variable means listed in Table 6.2 generally show similar values among the three erosional groups and the three depositional groups such that composite means for all erosional and depositional sites support the hypothesised directional bias (Table 6.5).

A one tailed 't' test was used to test for statistical significance between: the composite means for all variables (that is, groups 1, 4, and 6 compared to groups 2, 5, and 7); the mean values for each variable on individual catenas; and a comparison of the variable means of the three erosional groups with one another, and the three deposition-

Table 6.2

GROUP MEANS

Variable Name	Group 1	2	3	4	5	6	7
Slope							
TRUSLOPE	1.76	2.35	2.12	9.50	3.46	8.30	4.02
SLOPE90	0.65	0.66	0.77	1.45	0.73	1.25	0.90
Microroughness							
MEANMICR	1.20	1.37	1.40	4.53	2.25	3.86	1.86
DOMMICRO	1.30	0.56	1.26	4.16	1.62	3.28	1.57
MMRTRUSL	1.21	1.28	1.52	4.52	2.12	3.85	1.80
MMR90SLP	1.18	1.44	1.27	4.54	2.40	3.86	1.93
MRANGETS	5.42	5.95	8.00	52.10	31.40	74.90	22.80
MRANGE90	6.66	7.65	5.66	37.10	32.40	58.20	22.10
Areal Coverage							
COHESION	19.29	77.31	31.06	14.55	85.23	41.00	59.48
CRUSTED	80.16	10.85	57.63	84.47	4.26	44.94	26.02
VEGCOVER	0.54	11.84	10.63	0.98	10.54	14.01	14.50
Soil Characteristics							
HARDEPTH	11.33	49.87	32.44	4.40	63.30	14.38	54.80
AHORIZON	0.21	6.30	2.72	1.50	7.75	3.25	6.75
Soil Texture							
EGRAVELS	7.86	5.60	7.26	64.59	2.23	15.86	8.90
ESAND	76.38	86.83	84.47	83.61	89.80	82.97	82.71
ECLAY	15.44	7.80	9.13	9.28	6.12	8.88	8.29
Infiltration							
PREWETHR	15.28	44.02	N/A	63.00	109.59	37.82	49.99
INFILTHR	8.01	26.49	N/A	29.71	60.28	20.38	26.81

Table 6.3

GROUP STANDARD DEVIATIONS

Variable Name	Group						
	1	2	3	4	5	6	7
Slope							
TRUSLOPE	0.78	0.71	0.54	2.06	0.91	4.82	1.09
SLOPE90	0.33	0.24	0.79	0.72	0.48	0.75	0.65
Microroughness							
MEANMICR	0.26	0.38	0.37	0.71	0.75	1.06	0.41
DOMMICRO	0.35	0.14	0.54	0.82	0.19	1.13	0.39
MMRTRUSL	0.30	0.42	0.53	0.85	0.83	1.04	0.44
MMR90SLP	0.31	0.44	0.24	1.02	1.28	1.35	0.66
MRANGETS	1.78	1.87	2.78	31.08	16.29	33.79	6.69
MRANGE90	3.36	3.80	1.87	18.41	21.94	21.60	8.36
Areal Coverage							
COHESION	10.75	8.60	16.05	4.93	10.05	21.39	24.79
CRUSTED	10.55	10.38	23.17	4.98	2.70	22.46	20.08
VEGCOVER	0.62	8.22	11.43	0.92	10.69	21.36	24.88
Soil Characteristics							
HARDEPTH	3.04	7.63	5.98	2.79	7.41	6.73	10.81
AHORIZON	0.26	2.43	1.69	0.91	1.89	0.89	2.85
Soil Texture							
EGRAVELS	5.98	4.29	8.53	20.26	2.33	5.14	6.18
ESAND	4.85	4.08	3.19	9.60	3.71	1.98	2.82
ECLAY	3.28	2.32	2.33	5.23	1.65	1.96	1.53
Infiltration							
PREWETHR	6.88	13.04	N/A	47.94	26.01	7.74	22.06
INFILTHR	3.83	7.26	N/A	13.69	19.51	3.56	15.25

Table 6.4

CORRELATION MATRIX

	TRUSLOPE	COHESION	CRUSTED	VEGCOVER	MEANMICR	DOMMICRO	HARDEPTH	AHORIZON	EGRAVELS	ESAND
TRUSLOPE	-									
COHESION	0.01	-								
CRUSTED	-0.11	-0.52	-							
VEGCOVER	0.09	-0.54	-0.43	-						
MEANMICR	0.13	-0.17	-0.12	0.30	-					
DOMMICRO	0.19	0.09	-0.38	0.27	0.35	-				
HARDEPTH	-0.02	0.21	-0.09	-0.14	-0.21	-0.02	-			
AHORIZON	0.01	-0.15	0.16	-0.01	-0.05	-0.06	-0.01	-		
EGRAVELS	0.06	0.04	-0.01	-0.02	0.14	0.18	-0.06	-0.02	-	
ESAND	-0.07	0.09	-0.01	-0.08	-0.19	-0.25	0.02	0.09	-0.29	-
ECLAY	0.15	-0.06	-0.01	0.07	0.16	0.27	-0.02	-0.13	0.21	-0.93
SLOPE90	0.08	0.24	-0.18	-0.08	-0.07	-0.12	-0.07	-0.01	-0.11	-0.11
MMRTRUSL	0.19	-0.13	-0.09	0.23	0.73	0.31	-0.11	-0.13	0.11	-0.16
MMR90SLP	0.04	-0.14	-0.10	0.26	0.85	0.26	-0.22	0.02	0.10	-0.15
MRANGETS	0.21	-0.15	0.06	0.09	0.52	0.39	-0.10	0.01	0.14	-0.14
MRANGE90	-0.14	-0.16	-0.11	0.27	0.57	0.35	-0.17	0.08	0.25	-0.33
PREWETHR	0.05	-0.13	-0.02	0.16	0.06	-0.05	0.15	-0.08	-0.05	0.23
INFILTHR	0.02	-0.15	0.01	0.14	-0.02	-0.07	0.29	0.01	-0.09	0.24

	ECLAY	SLOPE90	MMRTRUSL	MMR90SLP	MRANGETS	MRANGE90	PREWETHR	INFILTHR
ECLAY	-							
SLOPE90	0.16	-						
MMRTRUSL	0.17	0.12	-					
MMR90SLP	0.10	-0.19	0.28	-				
MRANGETS	0.15	-0.10	0.73	0.17	-			
MRANGE90	0.27	-0.15	0.14	0.71	0.15	-		
PREWETHR	-0.24	0.09	0.19	-0.05	0.08	-0.17	-	
INFILTHR	-0.23	0.19	0.09	-0.11	0.06	-0.20	0.68	-

Table 6.5

COMPOSITE MEANS AND STANDARD DEVIATIONS
FOR THE EROSIONAL AND DEPOSITIONAL GROUPS

Variable Name	Mean		Standard Deviation	
	Erosional	Depositional	Erosional	Depositional
Soil Texture				
EGRAVELS	28.091	5.589	27.859	4.977
ESAND	80.702	86.444	6.918	4.361
ECLAY	11.466	7.508	4.763	2.119
Microroughness				
MEANMICR	3.073	1.713	1.655	0.618
DOMMICRO	2.815	1.080	1.467	0.573
MMRTRUSL	3.073	1.626	1.666	0.653
MMR90SLP	3.070	1.802	1.776	0.859
MRANGETS	41.718	16.525	38.902	14.054
MRANGE90	32.281	17.450	26.758	15.695
Slope				
TRUSLOPE	6.221	3.047	4.557	1.117
SLOPE90	1.090	0.740	0.691	0.436
Infiltration				
PREWETHR	37.237	61.912	33.203	33.688
INFILTHR	18.657	35.021	12.146	19.630
Areal Coverage				
COHESION	24.609	74.834	17.654	17.104
CRUSTED	70.503	12.990	22.429	14.580
VEGCOVER	4.887	12.180	13.112	14.290
Soil				
HARDEPTH	10.118	54.462	5.971	9.941
AHORIZON	1.562	6.775	1.457	2.436
N=	32	40	32	40

al groups with one another (Table 6.6). With the exception of the variable VEGCOVER, the composite means for all erosional and depositional sites are significantly different at the 0.01 level. VEGCOVER is significant at 0.05. However, not all variable means for the two landsurface units are significantly different on individual catenas. The greater degree of similarity among the erosional groups, and in particular, the depositional groups was anticipated to be evident in the absence of statistical significance in more variables. The smallest number of significant variables is manifest in a comparison of groups 4 and 6 (Table 6.6, column 10).

Initially, discriminant analysis was applied to the total data set for the three catenas (excluding the 5/6 intergrade) to test the validity of the six group classification and to identify the most significant discriminators. Using the same data set, single variable analyses were then computed to identify distinctive physical characteristics of each landsurface unit. Finally, discriminant analysis was applied separately to each of the three catenas to test for the presence/absence of modality in individual variables measured on adjacent landsurface units. Included in this discussion is an analysis of the 5/6 intergrade mapped on Catena One. Hence, the following discussion of results is divided into three separate sections.

Stepwise Discriminant Analyses of the Six Groups

In order to determine if the six groups could be correctly classified and to ascertain which variables were the 'best discriminators', all variables measured on all three catenas were used as input. Results of the analysis are summarised in Table 6.7. Fifteen variables were entered before the minimum tolerance for entry was exceeded, though a correct classification of all sites was achieved with the first 10 variables. Slope was the only variable category not included in the first 10 variables.

Table 6.6

STATISTICAL SIGNIFICANCE OF VARIABLE MEANS

Variable	Overall	Catenas			Unit 6			Unit 5		
	Means	1	2	3	2/5	2/7	5/7	1/4	1/6	4/6
Soil Texture										
EGRAVELS		*			0.05	0.05				
ESAND			0.05	*	*			0.05		*
ECLAY			0.05	*	0.05	*				*
Microroughness										
MEANMICR		*					*			*
DOMMICRO							*			0.05
MMRTRUSL		*					*			*
MMR90SLP		0.05				0.05	*			*
MRANGETS		*	0.05				*			*
MRANGE90		*	*				*			0.05
Slope										
TRUSLOPE		0.05					*			*
SLOPE90		*		*	*	*	*		0.05	*
Infiltration										
PREWETHR				*		*				*
INFILTHR				*		*				0.05
Areal Coverage										
COHESION				0.05	0.05			*		
CRUSTED				0.05				*		
VEGCOVER	0.05			*	*	*	*	*	0.05	0.05
Soil										
HARDEPTH						*	0.05		*	
AHORIZON					*	*	*			
N=	72	32	20	20	30	30	20	22	22	20

* not significant
0.05 significant at 0.05
all other variables significant at 0.01

Table 6.7

STEPWISE ANALYSIS - WILK'S LAMBDA

CATENAS 1, 2 and 3

Step	Variable	F ratio	Wilk's Lambda	% Correctly Classified	% Correctly Grouped 1	2	4	5	6	7	Misclassification 1	2	4	5	6	7
1	HARDEPTH	149.89	0.08094	59.72	33	65	80	70	70	40	6 4	7 5	1	7 2	1 4	2 5
2	EGRAVELS	84.05	0.01794	70.83	84	65	80	80	80	40	6	7 5	6	2	1	2 5
3	MEANMICR	62.69	0.00618	80.56	100	75	80	80	90	60		7 5	6	7	1	2 5
4	CRUSTED	48.44	0.00326	86.11	100	85	90	90	90	60		7 5	6	2	1	2 5
5	DOMMICRO	41.06	0.00186	90.28	100	95	90	90	90	70		5	6	2	1	5 2
6	INFILTHR	36.54	0.00112	91.67	100	95	90	90	90	80		7	6	7	1	2 5
7	MRANGE90	32.57	0.00078	95.83	100	95	100	90	100	90		7		7		2
8	MRANGETS	30.18	0.00052	95.83	100	95	100	90	100	90		7		7		2
9	ECLAY	28.01	0.00038	94.44	100	90	100	90	100	90		7		7		2
10	ESAND	26.31	0.00028	100.00	100	100	100	100	100	100						
11	SLOPE90	24.77	0.00021	100.00												
12	VEGCOVER	23.21	0.00017	100.00												
13	TRUSLOPE	21.85	0.00014	100.00												
14	AHORIZON	20.65	0.00012	100.00												
15	PREWETHR	19.22	0.00011	100.00												
	N=			72	12	20	10	10	10	10						

Note: Only the two most important groups are listed for the misclassifications.

The second major objective of this analysis was reduction of the variable set to a smaller group of key diagnostic mapping criteria. Achievement of a 100% correct classification with only 10 variables represents the first step in the identification of the most useful discriminators, and provides a sizeable reduction in the original variable list. For field mapping purposes, an even smaller number of variables is desirable, but this reduction requires the acceptance of a less than 100% correct classification.

Reference to Table 6.7 shows that the first four variables entered (HARDEPTH, EGRAVELS, MEANMICR and CRUSTED) provide for an overall 86% correct grouping. All 12 group 1 sites are correctly classified and with the exception of group 7 (60%), all groups have at least an 85% correct classification. Each of the first four variables selected measure different characteristics of the landsurface units: soil depth (HARDEPTH); soil texture (EGRAVELS); soil microroughness (MEANMICR); and the percentage of bare/eroded soil surface (CRUSTED).

The addition of the next three variables (Table 6.7) improves the overall classification to almost 96% and in so doing makes two important contributions to the discriminant results. The seven-variable analysis correctly classifies all three erosional groups (1, 4, and 6) and markedly improves correct classification of the group 7 sites, from 60% to 90%. DOMMICRO and MRANGE90 are both measures of soil microroughness requiring little, if any, additional fieldwork. However a considerable amount of fieldwork is required in measuring soil infiltration rates (INFILTHR). While this does add a fifth characteristic to the soil/slope data it is probably more desirable and practical to establish a set of classificatory/mapping criteria enabling relative infiltration rates to be inferred. Examination of the correlation matrix for the 72 sites suggests no suitable surrogate for INFILTHR. The highest correlation (r = 0.29) is with HARDEPTH, already in the analysis. Entered as the sixth variable, INFILTHR is not vital to the discriminant results. A considerable amount of additional fieldwork is required to yield a small percentage increase in the sites correctly grouped. For these reasons a second stepwise analysis was performed omitting both infiltration variables (INFILTHR, PREWETHR).

As shown in Table 6.8 the removal of INFILTHR changes the order of entry for variables at steps 6 through 10. The two measures of soil microroughness range (MRANGETS and MRANGE90) are displaced by soil texture variables (ESAND and ECLAY). Inclusion of the two soil texture variables (steps 6 and 7, Table 6.8) actually yields a slightly better classification than that offered by the inclusion of INFILTHR. However a correct classification of all groups requires 12 variables (compared to 10).

The results of this six group analysis have demonstrated that of the original 18 variables selected as discriminators, only 10 are required for a correct classification of all sites. Further economy is possible by accepting an overall 95% correct classification in which all erosional groups are correctly classified (Table 6.7). Omission of the two infiltration variables (INFILTHR and PREWETHR) and execution of a stepwise analysis with the remaining 16 variables improved the seven variable outcome (Table 6.8).

Further examination of the results of this six group analysis

Table 6.8

STEPWISE ANALYSIS - WILK'S LAMBDA
(omission of INFILTHR and PREWETHR)

CATENAS 1, 2 and 3

Step	Variable	% Correctly Classified	% Correctly Grouped						Misclassifications					
			1	2	4	5	6	7	1	2	4	5	6	7
1	HARDEPTH	59.72	33	65	80	70	70	40	6 4	7 5	1	7 2	1 4	2 5
2	EGRAVELS	70.83	83	65	80	80	80	40	6	7 5	6	2	1	2 5
3	MEANMICR	80.56	100	75	80	80	90	60		7 5	6	7	1	2 5
4	CRUSTED	86.11	100	85	90	90	90	60		7 5	6	2	1	2 5
5	DOMMICRO	90.28	100	95	90	90	90	70		5	6	2	1	5 2
6	ESAND	91.67	100	95	90	100	90	70		5	6		1	5 2
7	ECLAY	97.22	100	95	100	100	100	90		5				5 2
8	MRANGETS	97.22	100	95	100	100	100	90		5				5
9	MRANGE90	98.61	100	100	100	100	100	90						5
10	SLOPE90	98.61	100	100	100	100	100	90						5
11	TRUSLOPE	98.61	100	100	100	100	100	90						5
12	AHORIZON	100.00	100	100	100	100	100	100						
	N=	72	12	20	10	10	10	10						

Note: Only the two most important groups are listed for misclassifications also show that in the stepwise addition of variables, the erosional groups (1, 4, and 6) are more readily classified than any of the depositional groups (2, 5, and 7). This greater distinctiveness in pedogeomorphic form is well illustrated by the territorial map (Figure 6.1) for the initial 15 variable analysis. The map represents the 'distance' between group centroids and the individual cases within each group. A discrete cluster of values identifies each erosional group. In contrast, the depositional groups (2, 5, and 7), although all correctly classified, show a higher degree of homogeneity among the three groups.

Another measure of the relative 'distance' between groups is provided by the size of the F ratio between each pair of groups. For example, the relative distinctiveness of the groups is well illustrated by reference to the F statistics at steps 4 and 15 in the stepwise analysis (Table 6.9). All are significant at the 0.01 level. At step 4 there are some extremely large F ratios, all of which are noticeably smaller by the final step in the analysis (Table 6.9b). This may be the result of the loss in degrees of freedom and it may also indicate that the first four variables entered are the strongest discriminators between an erosional and depositional environment. As already shown in Table 6.7, subsequent variables offer only small increments in explanation. As anticipated, the larger F ratios are generally between pairs of erosional and depositional groups. The largest values are those pairing group 4 (the lateritic breakaway) with the depositional environments (groups 2, 5, and 7). Not surprisingly, the smallest F ratios (indicative of the greatest similarity) occur between groups 2, 5, and 7, as the three colluvial footslopes have similar soil/slope characteristics.

Figure 6.1

TERRITORIAL MAP (TABLE 6.7 ANALYSIS)

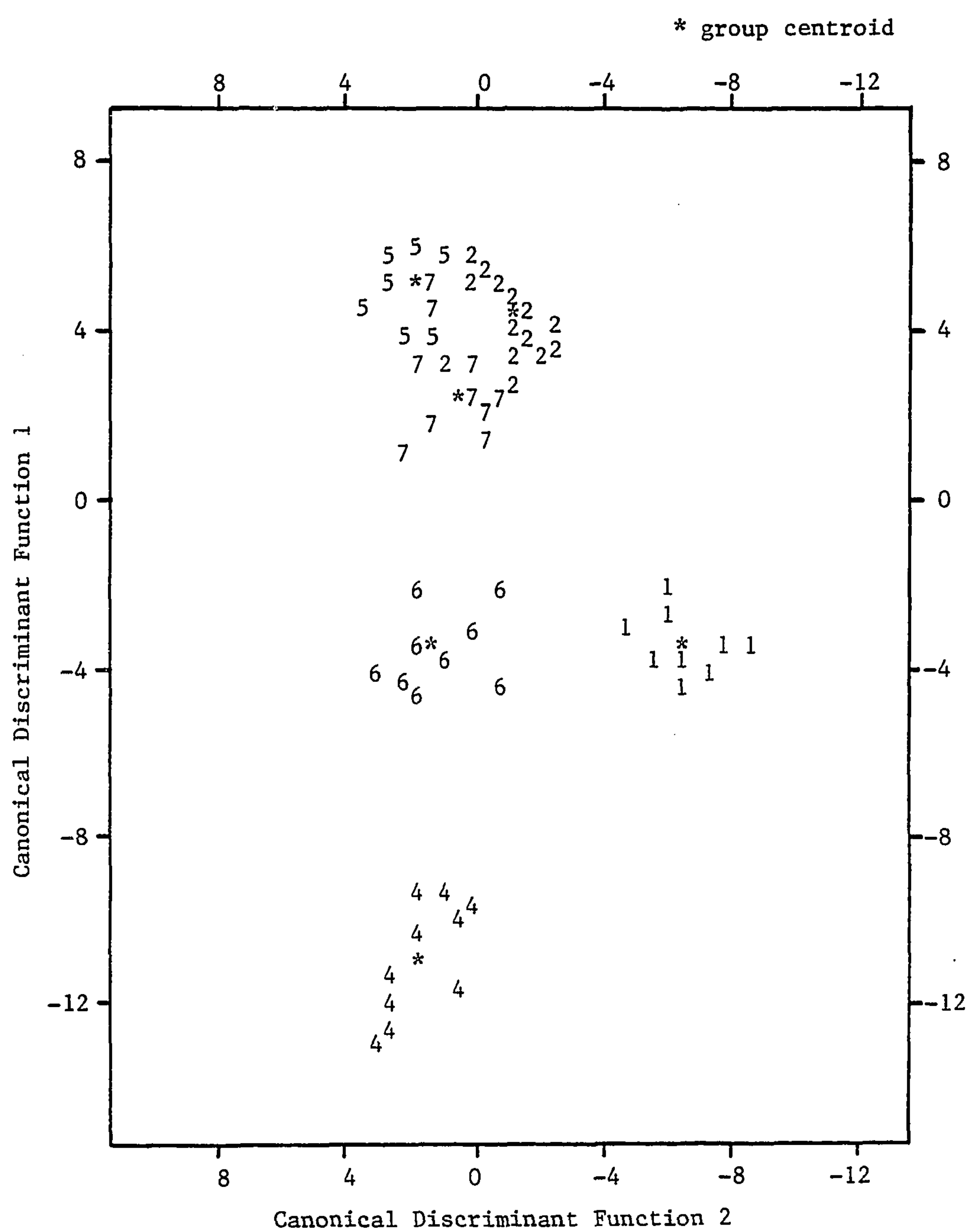


Table 6.9

F STATISTICS

(a) Four Variable Step

Group	1	2	4	5	6
2	97.78				
4	82.65	192.90			
5	116.67	12.06	173.80		
6	33.55	65.94	48.68	68.72	
7	73.71	4.99	129.75	5.58	46.73

(b) Fifteen Variable Step

Group	1	2	4	5	6
2	37.58				
4	40.19	90.38			
5	43.29	9.09	72.76		
6	21.72	35.72	26.26	27.36	
7	27.42	6.11	54.02	7.37	17.24

A stepwise discriminant analysis of the three depositional groups revealed soil depth and soil infiltration rates to be the weakest discriminators among the different depositional environments. A correct classification of the three groups required five variables, measuring microroughness (DOMMICRO), areal extent of micro soil surfaces (CRUSTED), slope (TRUSLOPE), and soil texture (EGRAVELS and ESAND). In contrast, only three variables (EGRAVELS, AHORIZON, and CRUSTED) were required for a correct classification of the more distinctive erosional groups. The results of these analyses are summarised in Table 6.10.

Table 6.10

STEPWISE ANALYSIS OF EROSIONAL AND DEPOSITIONAL UNITS

(a) EROSIONAL UNITS

Variable	Wilk's Lambda	F Ratio	% Correctly Classified	% Correctly Classified by Group		
				1	4	6
EGRAVELS	0.179	66.14	78.13	67	80	90
AHORIZON	0.041	54.83	96.88	100	90	100
CRUSTED	0.015	63.61	100.00	100	100	100

(b) DEPOSITIONAL UNITS

Variable	Wilk's Lambda	F Ratio	% Correctly Classified	% Correctly Classified by Group		
				2	5	7
DOMMICRO	0.167	91.99	77.50	100	50	60
CRUSTED	0.103	37.84	90.00	100	100	60
TRUSLOPE	0.068	32.77	95.00	100	100	80
EGRAVELS	0.052	28.86	97.50	100	100	90
ESAND	0.033	29.58	100.00	100	100	100

For the purposes of mapping landsurface units the data could be viewed as four, rather than six groups: the three erosional groups and an amalgam of the depositional sites. Field evidence supports this generalisation as the depositional groups are all colluvial footslopes and similar in terms of overall pedogeomorphic form. In contrast, the erosional groups are representative of three distinct erosional landscape elements: a lateritic breakaway (group 4); an interfluve area characterised by outcrops of gneissic bedrock and shallow pockets of soil (group 6); and a long low angle pediment slope (group 1). Further generalisation is available if the assumption is accepted that the key issue is simply the differentiation between erosional and depositional landsurface units, reducing the number of required groups to two. In terms of the classification such a grouping presents no problem. Reference to Table 6.7 shows that the dominant grouping of misgrouped sites is such that erosional sites are always matched with one of the erosional groups. Similarly, depositional sites are always allocated to one of the depositional groups.

This twofold division between the erosional and depositional sites is further illustrated by reference to Table 6.11, from the original 15 variable stepwise analysis. Under P(G/X) is printed the probability of group membership based on the established classification. The second highest probability for group membership is printed in the next column to the right. All depositional sites on all three catenas are allocated to an alternate depositional group and with one exception (in group 1) the same rule applies to the erosional sites on Catenas One and Two. However, on Catena Three eight of the group 6 sites are allocated to group 7, indicating a higher degree of similarity between the Catena Three erosional and depositional sites than with either of the other two erosional groups. This 'second order misclassification' may also be interpreted as an indicator of considerable variation within

Table 6.11

PREDICTED GROUP MEMBERSHIP

Actual Group	Predicted Group Membership	Highest Group Probability P(X/G)	P(G/X)	2nd Highest Group	P(G/X)	Scores on First Discriminant Function
1	1	0.85	1.00	6	0.00	-3.05
1	1	0.97	1.00	6	0.00	-2.42
1	1	0.41	1.00	6	0.00	-2.89
1	1	0.02	1.00	2	0.00	-3.01
1	1	0.96	1.00	6	0.00	-3.31
1	1	0.97	1.00	6	0.00	-3.40
1	1	0.74	1.00	6	0.00	-2.48
1	1	0.68	1.00	6	0.00	-3.13
1	1	0.94	1.00	6	0.00	-3.81
1	1	0.88	1.00	6	0.00	-4.24
1	1	0.86	1.00	6	0.00	-3.47
1	1	0.76	1.00	6	0.00	-1.92
2	2	0.70	0.99	7	0.00	4.52
2	2	0.95	0.99	7	0.00	5.31
2	2	0.38	0.99	7	0.00	6.26
2	2	0.04	0.53	7	0.46	5.53
2	2	0.71	1.00	7	0.00	4.46
2	2	0.16	0.99	5	0.00	6.17
2	2	0.31	0.99	7	0.00	3.52
2	2	0.52	0.99	7	0.00	5.55
2	2	0.18	0.94	7	0.05	3.53
2	2	0.70	1.00	5	0.00	4.67
2	2	0.86	0.99	7	0.00	3.61
2	2	0.93	0.99	7	0.00	5.27
2	2	0.80	1.00	7	0.00	4.83
2	2	0.60	1.00	7	0.00	4.02
2	2	0.61	0.99	7	0.00	4.36
2	2	0.67	0.97	7	0.02	3.37
2	2	0.70	0.99	7	0.00	5.94
2	2	0.79	0.99	7	0.00	4.63
2	2	0.69	1.00	5	0.00	5.61
2	2	0.95	0.99	7	0.00	4.54
4	4	0.12	1.00	6	0.00	-9.04
4	4	0.57	1.00	6	0.00	-10.54
4	4	0.18	1.00	6	0.00	-12.49
4	4	0.18	1.00	6	0.00	-12.82
4	4	0.00	1.00	6	0.00	-11.64
4	4	0.16	1.00	6	0.00	-9.24
4	4	0.45	1.00	6	0.00	-10.08
4	4	0.33	1.00	6	0.00	-11.06
4	4	0.40	1.00	6	0.00	-12.16
4	4	0.09	1.00	6	0.00	-9.40

Actual Group	Predicted Group Membership	Highest Group Probability P(X/G)	P(G/X)	2nd Highest Group	P(G/X)	Scores on First Discriminant Function
5	5	0.77	1.00	7	0.00	5.78
5	5	0.82	1.00	2	0.00	6.36
5	5	0.37	1.00	2	0.00	5.62
5	5	0.60	1.00	2	0.00	5.80
5	5	0.68	1.00	7	0.00	4.83
5	5	0.30	0.92	2	0.07	5.92
5	5	0.86	0.99	2	0.00	5.48
5	5	0.91	0.99	2	0.00	4.57
5	5	0.97	1.00	2	0.00	5.49
5	5	0.56	0.99	2	0.00	4.22
6	6	0.07	1.00	1	0.00	-2.14
6	6	0.56	1.00	1	0.00	-4.41
6	6	0.17	1.00	7	0.00	-4.26
6	6	0.93	1.00	7	0.00	-3.13
6	6	0.88	1.00	7	0.00	-3.71
6	6	0.26	1.00	7	0.00	-4.11
6	6	0.51	1.00	7	0.00	-3.27
6	6	0.08	1.00	7	0.00	-2.61
6	6	0.25	1.00	7	0.00	-2.08
6	6	0.61	1.00	7	0.00	-4.17
7	7	0.41	0.99	2	0.00	2.63
7	7	0.74	0.99	2	0.00	3.55
7	7	0.21	0.95	2	0.03	5.46
7	7	0.11	0.99	2	0.00	4.97
7	7	0.04	0.99	2	0.00	1.26
7	7	0.71	1.00	2	0.00	3.55
7	7	0.65	1.00	2	0.00	2.03
7	7	0.25	1.00	5	0.00	1.80
7	7	0.26	1.00	2	0.00	1.76
7	7	0.98	0.99	2	0.00	2.65

the group 6 sites. The latter is illustrated in Table 6.11 in the column headed P(X/G). These values represent the probability of a case in each group having a location so far from the group centroid. Some of the group 6 probabilities are quite low.

The division between the erosional and depositional sites is nevertheless strong and is perhaps best illustrated by the scores on the first discriminant function (Table 6.11) which accounts for 68% of the total variance in the six groups. All erosional sites have large negative values in contrast to the positive values for the depositional sites. Subsequent discriminant functions do not provide the same division between erosional and depositional sites, but rather, account for some of the variance among the depositional and erosional groups.

However, the rationale in identification of these landsurface units is not simply to provide a twofold grouping of erosional and depositional environments. The markedly different pedogeomorphic form of each erosional group and the differences in hydrologic response of the three areas requires at least a fourfold grouping of the data. In addition, although the three colluvial groups share general physical characteristics, they are also different; in part a reflection of their catenary relationship with distinctly different erosional units. As such, the investigation of hydrologic response within the three catenas is considered best handled by maintenance of the original six groups.

Single Variable Analysis of the Six Groups

Discriminating Power of Individual Variables

The ability of individual variables to discriminate between the different landsurface units is largely disguised in a multiple variable analysis. To ascertain the relative discriminating power of individual variables, single analyses were computed for all 18 variables. A summary of the results, including the percentage of cases correctly classified in each group and the dominant allocation of misgrouped sites, is given in Table 6.12.

DOMMICRO (62.5%) proved the strongest discriminator, with SLOPE90 and VEGCOVER (26.39%) the weakest. No one category of variables was noticeably weaker in discriminating power, although those variables measuring general soil characteristics and several of the microroughness variables provide better discrimination. All of the variables misclassify erosional and depositional sites with each other. Interestingly, the first four variables selected in the stepwise analysis (HARDEPTH, EGRAVELS, MEANMICR, and CRUSTED) ranked second, eighth, thirteenth, and fourteenth in terms of the percentage correctly classified in the single variable analyses. This suggests that the latter two, at least, are correlated with other variables that were entered earlier in the stepwise analysis.

'Stepwise' Analysis Using the Single Variable Results

To evaluate the efficiency of the Wilk's lambda selection, all variables were ranked in order of their ability, as single discriminattors, to correctly group sites. The variables were then added, one at

Table 6.12

CATENAS 1, 2 and 3

SINGLE VARIABLE ANALYSES

Variable	F ratio	Wilk's Lambda	% Correctly Classified*	% Correctly Classified						Misclassification of Groups**					
				1	2	4	5	6	7	1	2	4	5	6	7
Soil Texture															
EGRAVELS	75.39	0.1489	49 (5)	8	30	80	90	90	20	5 6 7 2	5 6 1 7	6	1	2	2 5 6 1
ESAND	9.48	0.5819	44 (8)	67	25	10	70	40	70	7 4	5 4 7	2 5 1 6	2 7	7 2 4	6 5
ECLAY	14.69	0.4732	47 (6)	33	30	20	70	60	30	4	4 5 6 7	2 5 1	2 4	1 4 5 7	4 5 2 6
Microroughness															
MEANMICR	57.56	0.1865	42 (9)	75	15	50	30	50	50	2 7	1 7	6	7 6	4 5 7	5 1 2
DOMMICRO	69.81	0.1590	63 (1)	58	100	70	50	40	20	5 2 7		6	1 7	4 1 5	1 5
MMRTRUSL	50.55	0.2070	35 (11)	50	15	60	20	50	30	2 7	1 7 5	6	7 4	4 2	5 2 1
MMR90SLP	28.25	0.3184	38 (10)	67	25	60	30	30	20	2 7	1 7 5	6 5	2 4 6 7	4 5 7	5 1 2 6
MRANGETS	26.57	0.3319	54 (3)	58	55	20	50	60	80	2	1	6 7 5	7 2 6	4 7	2 5
MRANGE90	24.19	0.3530	44 (8)	67	40	30	00	70	60	2	1 7	5 7 6	7 6 4	4 5 7	2 4
Slope															
TRUSLOPE	27.58	0.3237	49 (5)	83	40	50	40	10	70	2 7	1 5	6	2 7	4 7 1	5 1
SLOPE90	4.63	0.7401	26 (12)	67	00	70	10	00	30	5 4 7	1 5 7 6	1 7	1 4 7	4 1 7	1 4 5
Infiltration															
PREWETHR	20.04	0.3970	50 (4)	92	30	30	90	60	10	2	7 1 6 4	1 5 2 6 7	7	2 7 5	6 1 2 4
INFILTHR	24.71	0.3481	46 (7)	92	15	30	80	80	00	6	4 6 7 1	6 5 1 7	4 7	2 7	4 1 2 5 6
Areal Coverage															
COHESION	51.46	0.2041	50 (4)	42	55	70	60	40	30	4 6	5 7	1	2	1 7 2 4	2 5 6 4
CRUSTED	79.82	0.1419	42 (9)	42	20	60	90	30	30	4 6	5 7	1	2	7 1 2	5 6 2
VEGCOVER	2.46	0.8427	26 (12)	67	10	50	10	00	30	4	7 4 5 1 6	1	4 7 1	4 7 1 5	4 5 1
Soil															
HARDEPTH	149.90	0.0809	60 (2)	33	65	80	70	70	40	6 4	7 5	1	7 2	1 4	2 5
AHORIZON	31.25	0.2983	50 (4)	100	30	60	50	70	00		5 6 7	1 6	2 7	4 2	5 6 2
N=			72	12	20	10	10	10	10						

* Variables ranked in order of percentage correctly classified

** Groups listed in order of importance for misclassifications a time and in order of discriminating power, into a discriminant analysis. Results of this predetermined 'stepwise' analysis are summarised in Table 6.13 with the first four variables (DOMMICRO, HARDEPTH, MRANGETS, and COHESION) yielding an overall correct grouping of 87.5%. However, to achieve a correct grouping of all erosional sites 11 variables are required. A 100% correct classification of all sites demands 14 variables. One final illustration of the relative inefficiency of this analysis is provided by the variable AHORIZON. Included at step 5, AHORIZON actually reduces the percentage of correct groupings.

Perusal of Table 6.12 illustrates that most variables provide good discrimination for at least one group and, in some instances (for example, EGRAVELS) for several groups. Four variables (EGRAVELS, ECLAY, DOMMICRO, and MRANGETS) were selected so that all groups were represented by at least one strong discriminator. Discriminant analysis with these four variables yielded the highest overall percentage correct classification of all analyses discussed in this chapter (90.28%), but failed to correctly group either all the erosional or all the depositional groups. In addition, misclassifications occurred between the erosional and depositional landsurface units and the F ratio between groups 5 and 7 was not significant. This result may be explained by the use of only two physical characteristics, soil texture and microroughness, to differentiate between the groups. The results of this four variable analysis are included in Table 6.14.

Clearly, the Wilk's lambda selection provides a more efficient grouping of key diagnostic variables. In addition, the relative distinctiveness of the six soil/slope groups was revealed in the Wilk's

Table 6.13

'STEPWISE' ANALYSES - ENTRY BY SINGLE VARIABLE RESULTS

CATENAS 1, 2 and 3

Step	Variable	% Correctly Classified	% Correctly Grouped 1	2	4	5	6	7	Misclassifications 1	2	4	5	6	7
1	DOMMICRO	62.50	58	100	70	50	40	20	5 2		6	1 7	4 1	1 5
2	HARDEPTH	77.78	100	90	80	70	40	70		5	6	7	4 1	5 2
3	MRANGETS	83.33	100	90	80	70	80	70		5	6	7	1 4	5 2
4	COHESION	86.11	100	90	80	90	80	70		5 7	6	7	1 4	5 2
5	AHORIZON	83.33	100	90	80	80	80	60		5	6	7	1 4	5 2
6	PREWETHR	91.67	100	95	80	100	80	90		7	6		1 4	2
7	EGRAVELS	94.44	100	95	90	100	90	90		7	6		1	2
8	TRUSLOPE	94.44	100	95	90	100	90	90		7	6		1	2
9	ECLAY	95.83	100	95	90	100	100	90		7	6			2
10	INFILTHR	94.44	100	95	90	90	100	90		7	6	7		2
11	ESAND	97.22	100	95	100	90	100	100		7		2		
12	MRANGE90	98.61	100	95	100	100	100	100		7				
13	MEANMICR	98.61	100	95	100	100	100	100		7				
14	CRUSTED	100.00	100	100	100	100	100	100						
	N=	72	12	20	10	10	10	10						

Note: Only the two most important groups are listed for misclassifications

Table 6.14

STEPWISE ANALYSIS - EGRAVELS, ECLAY, DOMMICRO AND MRANGETS

CATENAS 1, 2 and 3

(a) Classification Results

Group	N	Predicted Group Membership 1	2	4	5	6	7
1	12	11 91.7%	1 8.3%	0 0.0%	0 0.0%	0 0.0%	0 0.0%
2	20	0 0.0%	20 100.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%
4	10	0 0.0%	0 0.0%	9 90.0%	0 0.0%	1 10.0%	0 0.0%
5	10	0 0.0%	0 0.0%	0 0.0%	8 80.0%	0 0.0%	2 20.0%
6	10	0 0.0%	0 0.0%	0 0.0%	2 20.0%	7 70.0%	1 10.0%
7	10	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	10 100.0%

Percent of 'grouped' cases correctly classified: 90.28%

(b) F Ratios Between Groups

Group	1	2	4	5	6
2	14.34				
4	103.83	123.46			
5	19.57	9.17	76.17		
6	41.75	45.45	45.94	13.43	
7	11.42	5.36	67.25	1.68	15.51

lambda results and in particular by examination of the F ratios (Table 6.9) between pairs of groups and the territorial map (Figure 6.1).

Pedogeomorphic Characteristics of the Landsurface Units Revealed by Single Variable Analyses

The potential value of the single variable analyses lies more in the ability to identify the most distinctive physical characteristics of each landsurface unit. As already illustrated, the discriminating power of most variables varies markedly between the six groups, with both 'strong' and 'weak' variables associated with each group (these are summarised in Table 6.15). In the discussion that follows the 'strongest' and 'weakest' discriminators for each of the six data groups are compared to the main physical characteristics of the respective landsurface units.

The Erosional Sites

As previously noted, the erosional groups are clearly different from one another in certain physical attributes and, for this reason, these groups are discussed first.

Group 1: The Low Angle Pediment Slope of Catena One

This group has already been identified as the soil/slope unit most easily classified and the most discrete of the six groups. As anticipated, the single variable analyses (Table 6.12) reveal a number of strong discriminators associated with the group 1 sites. In all, there are six variables with a minimum 75% correct classification. One variable, AHORIZON, correctly groups all 12 sites. Five of the six variable categories are included in the list of strong discriminators

Table 6.15

SUMMARY OF SINGLE VARIABLE DISCRIMINATORS

CATENAS 1, 2 and 3

	% Correctly Classified	Groups 1	2	4	5	6	7
Strongest Discriminators	⩾90%	PREWETHR	DOMMICRO		EGRAVELS	EGRAVELS	
		INFILTHR			PREWETHR		
		AHORIZON			INFILTHR		
					CRUSTED		
	⩾75%	ECLAY		EGRAVELS		INFILTHR	MRANGETS
		MEANMICR		HARDEPTH			
		TRUSLOPE					
	⩾70%			DOMMICRO	ESAND	MRANGE90	ESAND
				SLOPE90	ECLAY	HARDEPTH	TRUSLOPE
				COHESION	HARDEPTH	AHORIZON	
Weakest Discriminators	⩽25%	EGRAVELS	ESAND	ESAND	MMRTRUSL	TRUSLOPE	EGRAVELS
			MMR90SLP	ECLAY	MRANGE90	SLOPE90	DOMMICRO
			MEANMICR	MRANGETS	SLOPE90	VEGCOVER	MMR90SLP
			MMRTRUSL		VEGCOVER		PREWETHR
			CRUSTED				INFILTHR
			INFILTHR				AHORIZON
			VEGCOVER				
			SLOPE90				

with VEGCOVER (66.7%) the most useful in the remaining category.

Reference to the group means and standard deviations (Tables 6.2 and 6.3) illustrates why these variables are such good discriminators. Taken as a group they identify the major physical attributes of this landsurface unit: low angle slopes (a mean of 1.75 degrees); a relatively high clay content in the surface soil (15.44%) with correspondingly low infiltration rates (8.01 cms/hour); a thin or absent A_1 horizon (0.2 cms thick); and a flat eroded micro soil surface broken only by low (1.5 to 2.0 cms) miniature erosional scarps and characterised by a general absence of vegetative cover (0.54%).

Only one variable, EGRAVELS (percentage gravels in the surface soil) is a poor discriminator (defined as a 25% or less correct classification). This variable does, however, provide good results for the other two erosional groups and, as already noted, ranked second in the Wilk's lambda analysis. The failure of EGRAVELS to provide better grouping for these sites is most likely the result of differences in the topographic position of the landsurface units within the catena. The percentage of gravels in the surface soils of southwestern Australia is essentially a function of distance from the interfluve, where the percentage gravels decreases downslope. Both groups 4 and 6 are erosional units located at, or immediately below, the interfluve and as a result are easily distinguished by coarser textured soils (Table 6.2). By contrast, the low angle pediment (group 1) sites are further downslope on the catena and, in terms of percentage gravels in the surface soil, are more closely associated with the depositional group means.

One other variable, HARDEPTH, was expected to provide good discrimination. However, although soil depth clearly differentiates between erosional and depositional environments, the similarities in mean values for groups 1, 4, and 6 yields a high percentage (67%) of misclassification in the group 1 sites.

<u>Group 4: The Lateritic Breakaway of Catena Two</u>

Five different variables, EGRAVELS, DOMMICRO, HARDEPTH, COHESION, and SLOPE90, provided the best single variable discrimination for the group 4 data. Each variable correctly classified between 70% and 90% of the sites. Mean values for the first four of these describe the main physical characteristics of this lateritic breakaway: a coarse textured surface soil (average of 64% gravels); high values of microroughness (4.16 mm), due primarily to the surface gravels; shallow depth to an indurated horizon (4.4 cms); and a general absence of cohesionless lenses of soil (14.55%). One other geomorphic characteristic, slope (TRUSLOPE), was anticipated as a key diagnostic criterion for this landsurface unit as it is a significant classificatory variable for this unit when considered in isolation with its downslope catenary member (group 5). Misclassifications by TRUSLOPE result from similarity in the group 4 (9.5 degrees) and group 6 (8.3 degrees) means. In relative terms these two erosional units have much steeper slopes in comparison to the depositional groups and the low angle group 1 sites (Table 6.2). In contrast, SLOPE90 provides good discrimination (70%) suggesting that on steeper slopes, the across slope values are likely to be greater.

The general absence of vegetative ground cover (VEGCOVER) on the breakaway was also expected to be a useful diagnostic criterion. However, both the low angle pediment and lateritic breakaway have low mean values for VEGCOVER (respective means of 0.54% and 0.98%) and misclassifications are common between the two groups. VEGCOVER is a stronger discriminator when considering the Catena Two data in isolation.

MRANGETS (20%), ECLAY (20%), and ESAND (10%) are the weakest variables. As already noted, the mean microroughness of the lateritic gravels (DOMMICRO) is a strong discriminator for this unit. However, a measure of microroughness range (MRANGETS) proved of little use due to similar mean and standard deviation values for groups 4, 5, and 6. For the group 5 sites the high range values are largely the result of needle grass clumps while the group 6 values result from gneissic rock outcrops and needle grass clumps.

Variability in surface soil texture is greater among the group 4 sites than in any other group (Table 6.3) and is the most likely explanation for the inability of ESAND and ECLAY to produce a satisfactory grouping of these sites. In addition the relatively poor performance of INFILTHR (30%) and PREWETHR (30%) may be partially explained by the texture characteristics of the surface soil; notably the high percentage of gravels, and the wide variability in soil texture. Both infiltration variables have large standard deviations and mean values close to the overall means (Tables 6.2 and 6.3). On sites characterised by a high concentration of gravels some difficulty was encountered with the insertion of infiltration rings. The resultant soil disturbance is assumed to have introduced some measurement error and increased the variability of the results. Part of this variability may also be a function of the overall variability in surface soil texture and the presence of an indurated laterite horizon at relatively shallow depth.

Group 6: The Gneissic Outcrops of Catena Three

Results of the single variable analyses suggest four distinctive physical characteristics of this landsurface unit (Tables 6.12 and 6.15). Two of these, the percentage gravels in the surface soil (EGRAVELS) and soil depth (HARDEPTH) were also the strongest single discriminators for the lateritic breakaway. In the erosional environment of Catena Three, the relatively high percentage of soil fraction greater than two millimetres in diameter represents weathered fragments of gneissic bedrock; primarily quartz and feldspars. This relatively coarse textured material is washed off the exposed outcrops of bedrock to accummulate as shallow pockets of soil. As a consequence soil depth is highly variable when compared to the erosional environments of Catenas One and Two. The thickness of the A_1 horizon (AHORIZON) is also considerably greater. A fourth major characteristic of this landsurface unit, the outcropping of gneissic bedrock, is reflected in the range of microroughness (MRANGE90).

The F statistic has already been discussed as a useful measure of the relative differences between groups. A second perusal of Table 6.9b serves to illustrate that of the three catenas, the largest F ratio occurs on Catena Two (groups 4 and 5) with the smallest F ratio, and therefore the least significant differences, on Catena Three (groups 6 and 7).

Though important physical differences allow the delimitation of erosional and depositional landsurface units on Catena Three, the noticeably smaller F statistic suggests that these two groups share a greater number of similar physical characteristics than those of Catenas One and Two. Misclassifications between groups 6 and 7 are common. The most frequent are associated with the variables COHESION, VEGCOVER, ESAND, ECLAY, and to a lesser extent PREWETHR and INFILTHR (Table 6.12). All of these variables have relatively similar means for the two groups (Table 6.2). These incorrect groupings are essentially a function of the overall physical characteristics of the erosional unit: an area dominated by outcrops of gneissic bedrock, interspersed with shallow pockets of coarse textured soil. The latter, while too small to be individually mapped, share a number of physical properties with the colluvial footslope (most noticeably, the characteristics measured by the variables already mentioned).

However, with the exception of VEGCOVER (0.0%), these six variables are not the weakest discriminators for this group. The two slope variables TRUSLOPE (10%) and SLOPE90 (0.0%) are primarily misclassified with the lateritic breakaway sites due to similarity in the group means. VEGCOVER is most commonly misclassified into groups 4 (50%) and 7 (30%). This misgrouping is somewhat surprising considering the magnitude of difference between the VEGCOVER means for groups 4 and 7, but can be accounted for by the large standard deviations for groups 6 and 7 and the broad range of values (59%) in the group 6 data.

The Depositional Sites

In contrast to the three discrete erosional areas, the territorial map (Figure 6.1) revealed a high degree of homogeneity between the three colluvial landsurface units. In response to their similarity it was anticipated that groups 2, 5, and 7 would be less well-defined by a suite of strong discriminators. As illustrated in Table 6.15 this generalisation only holds true for groups 2 and 7 with the colluvial footslope below the breakaway well defined in seven single variable analyses. The following discussion identifies the strongest and weakest discriminators for each group and considers the significant physical characteristics revealed by the results.

Group 2: Catena One Colluvium

The most distinctive feature of this landsurface unit is the long list of variables which, as single discriminators, fail to correctly classify 25% or more of the sites (Tables 6.12 and 6.15). One measure of soil microroughness correctly groups all 20 sites with soil depth the next best discriminator (HARDEPTH, 65%). DOMMICRO successfully classifies all sites as it is only measuring the mean microroughness of the cohesionless soil lenses; the dominant micro soil surface on this landsurface unit (refer to COHESION, Table 6.2). The low mean value for microroughness (0.56 mm) reflects the essentially flat surface topography of the sand sized lenses.

Three other measures of microroughness, MEANMICR (15%), MMRTRUSL (15%) and MMR90SLP (25%) yielded poor results. All three represent values for the total soil surface microroughness and serve to illustrate a fundamental problem with measures of microroughness. The type of microtopography characteristic of this landsurface unit is cohesionless lenses of soil interspersed with low soil mounds associated with needle grass clumps. A contrasting microtopography is that of the low angle pediment (group 1) sites. This area is dominated by a bare eroded soil surface broken only by miniature erosional scarps. Though distinctly different in 'type', the resultant mean values for MEANMICR, MMRTRUSL, and MMR90SLP are similar for groups 1 and 2. As a result, misclassification of group

2 sites into group 1 are high; MEANMICR (55%), MMRTRUSL (50%) and MMR90SLP (45%). Most of the remaining misclassifications for these three variables were included in group 7 where the microroughness values represent a microtopography similar to the group 2 sites.

Another five variables, CRUSTED, VEGCOVER, ESAND, SLOPE90, and INFILTHR are poor discriminators. For example, the areal percentage criteria CRUSTED and VEGCOVER are primarily misgrouped into other depositional landsurface units; the result of similarities in group means. CRUSTED correctly grouped only 15% of the sites with the remaining 85% distributed within groups 5 (60%) and 7 (25%). Similarly, VEGCOVER correctly classified only 10% with 60% included in groups 5 and 7. The remaining 30% was distributed between the unit 5 groups; largely as a result of the relatively high standard deviation for the group 2 data.

Two categories of variables, slope and microroughness yield considerable misclassification between group 2 and its catenary member, group 1. As already noted values for some of the microroughness variables are similar for the two landsurface units even though the 'type' of microroughness differs markedly. Differences in slope are subtle. The remaining four categories of variables produce little misclassification between these two groups (Table 6.12).

Group 5: Catena Two Colluvium

The summary table of single variable analyses (Table 6.15) lists seven variables, each of which correctly groups no less than 70% of these sites. Two of these, EGRAVELS and PREWETHR have a 90% correct grouping. Located downslope of the lateritic breakaway, the major physical characteristics of this colluvial footslope are summarised by the list of strong discriminators. This area has the deepest soils of all the units with a high percentage sand fraction in the surface soil (89%); correspondingly high infiltration rates (60.28 cms/hour); and a predominance of cohesionless lenses of soil (85.23%).

Both infiltration variables (PREWETHR and INFILTHR) have by far the largest means of all groups, so that even with large standard deviations the percentage of sites correctly grouped is high. These high infiltration rates reflect a number of factors including the thickness of sandy textured soil that overlies the indurated lateritic gravels. The high mean value for HARDEPTH (63.3 cms) makes this a relatively good criterion for discrimination from the other five groups. Additional factors influencing soil infiltration rates on this landsurface are the relatively low angle slopes and general absence of a bare/eroded, soil crusted surface (CRUSTED, 6% of surface area). This variable is a good discriminator by virtue of a low mean and low variability in areal occurrence across the landsurface unit.

The weakest discriminators include measures of microroughness (for example MRANGE90, 0.0% and MMRTRUSL, 20%) where the same problems of classification arise as were discussed for the group 2 data. With VEGCOVER (10%), the high variability in vegetative ground cover (Table 6.3) led to misclassifications in both erosional and depositional groups.

Group 7: Catena Three Colluvium

The strongest single discriminators for this landsurface unit, MRANGETS, ESAND, and TRUSLOPE (Table 6.15) reveal little in the way of distinctive landsurface characteristics. However, these variables do assist in accounting for the poor performance of the group 7 data in the Wilk's lambda analysis. In the stepwise analysis (Table 6.7), MRANGETS, ESAND, and TRUSLOPE were not entered until steps 8, 10, and 12 respectively, making TRUSLOPE redundant, as a correct grouping was achieved with 10 steps. Furthermore, of the first six variables entered in the analysis, EGRAVELS, DOMMICRO, and INFILTHR are weak single variable discriminators for group 7 (20%, 20%, and 0.0% respectively). A final factor, already addressed in the group 6 discussion is the similarity in a number of variables between the two Catena Three landsurface units.

Discriminant Analysis Results for Each Catena

In the identification and mapping of landsurface units a primary concern is the catenary relationship between units. Of particular interest is the presence/absence of modality in specific variables measured on adjacent landsurface units. The following discussion summarises the most distinctive physical differences revealed by single variable analyses between erosional and depositional landsurface units on each catena. A number of additional variables specific to Catenas One and Three are included in the analyses. These are defined in Table 6.16 with means and standard deviations for each variable in Table 6.17.

Results of the single variable analyses are summarised in Tables 6.19, 6.20, and 6.21. Also included are the results of a one tailed 't' test between the group means for all variables on each catena. Prior to examination of these tables, results of the four variable stepwise analyses are considered (Table 6.14). The variables used were the first four selected in the six group stepwise analysis (Table 6.7).

Table 6.16

DEFINITION OF VARIABLES

(a) CATENA ONE

Variable	Description
Soil Texture	
DGRAVELS	% gravels in cohesionless soil lenses
DSAND	% sand in cohesionless soil lenses
INCHGRAV	% gravels at depth of 2.5 cms
INCHSAND	% sand at depth of 2.5 cms
INCHCLAY	% clay at depth of 2.5 cms
Soil Compaction	
COMPACTN (lbs/sq. inch)	surface soil compaction

(b) CATENA THREE

Variable	Description
Soil Texture	
DGRAVELS	% gravels in cohesionless soil lenses
DSAND	% sand in cohesionless soil lenses
Soil	
SOLDEPRA	range in soil depth (cms)
Soil Compaction (kg/sq. cm)	
PREPEND	depositional lenses, pre-infiltration
PREPENE	bare eroded soil surface, pre-infiltration-
PREPENED	average value of PREPEND and PREPENE
POSPEND	depositional lenses, post-infiltration
POSPENE	bare eroded soil surface, post-infiltration
POSPENED	average value of POSPEND and POSPENE
Shear Strength (tons/sq. ft)	
PRESHED	depositional lenses, pre-infiltration
PRESHEE	bare eroded soil surface, pre-infiltration
PRESHEED	average value of PRESHED and PRESHEE
POSSHED	depositional lenses, post-infiltration
POSSHEE	bare eroded soil surface, post-infiltration
POSSHEED	average value of POSSHED and POSSHEE

Table 6.17

GROUP MEANS AND STANDARD DEVIATIONS

(a) CATENA ONE

Variable	Group Means			Group Standard Deviations		
	1	2	3	1	2	3
DGRAVELS	33.24	19.38	27.03	24.10	9.29	12.68
DSAND	97.35	95.74	97.47	1.38	2.49	0.81
INCHGRAV	7.89	2.94	12.44	4.32	1.62	15.55
INCHSAND	79.96	86.97	85.52	4.19	1.91	3.08
INCHCLAY	14.02	8.62	8.73	3.22	1.36	1.81
COMPACTN	1500.00	202.50	272.22	304.50	67.64	76.24

(b) CATENA THREE

Variable	Group Means		Group Standard Deviations	
	6	7	6	7
SOLDEPRA	36.40	3.10	11.85	1.41
DGRAVELS	48.69	30.13	11.27	12.64
DSAND	94.92	95.37	2.29	3.06
PREPEND	0.94	0.90	0.35	0.36
PREPENE	0.72	1.14	0.25	0.39
PREPENED	0.83	1.02	0.29	0.32
POSPEND	0.95	0.59	0.39	0.43
POSPENE	0.84	0.51	0.32	0.23
POSPENED	0.89	0.54	0.33	0.32
PRESHED	0.06	0.09	0.01	0.04
PRESHEE	0.11	0.28	0.03	0.09
PRESHEED	0.08	0.18	0.02	0.06
POSSHED	0.04	0.06	0.02	0.04
POSSHEE	0.09	0.18	0.05	0.06
POSSHEED	0.06	0.13	0.04	0.04

Stepwise Analysis: HARDEPTH, EGRAVELS, MEANMICR, CRUSTED

Two analyses were executed for the Catena One data, to include consideration of the 5/6 intergrade (group 3). Three variables, CRUSTED (areal percentage of bare/eroded soil surface), HARDEPTH (soil depth), and EGRAVELS (percentage gravels in the surface soil) were entered (in the order listed) before the mininum tolerance for entry was exceeded in the two group analysis. The resultant F statistic between the two units was 286.84. Inclusion of the 5/6 intergrade still only required three variables for a correct grouping (HARDEPTH, CRUSTED, and MEANMICR). Not surprisingly, the F statistics between the two landsurface units and the intergrade are noticeably smaller, indicative of the greater degree of similarity between both landsurface units and the 5/6 intergrade. This point is further illustrated by the territorial map (Figure 6.2) for this analysis, with the 5/6 intergrade cases (group 3) located between groups 1 and 2. In addition, the intergrade ranked as the second highest probability for group membership for all group 1 and 2 cases.

Table 6.18

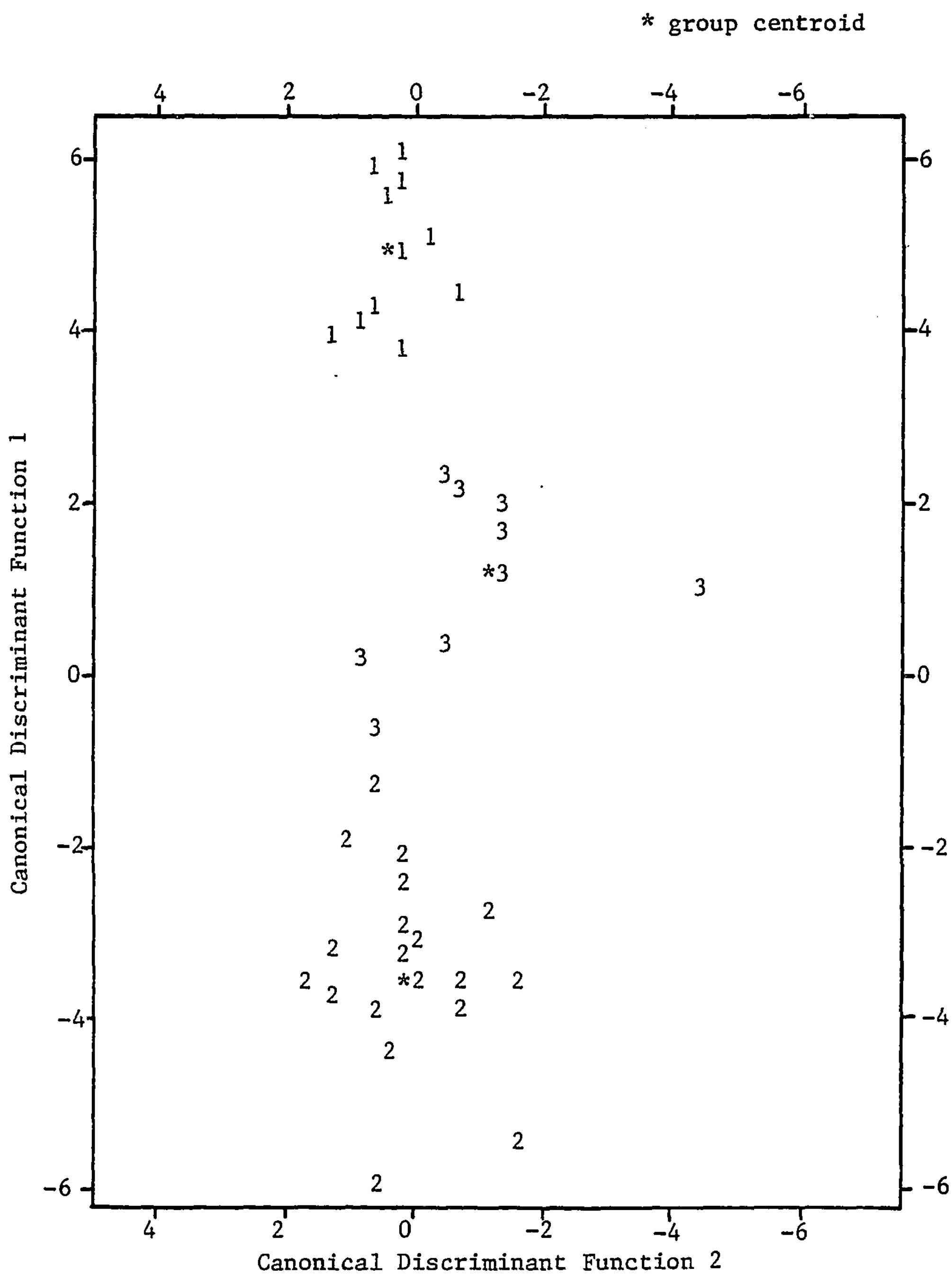
CATENA ONE: F STATISTICS

Group	1	2
2	171.28	
3	26.46	44.88

The territorial map for the 15 variable analysis (Figure 6.1) clearly illustrated the presence of even more distinct physical differences between the erosional and depositional units on Catena Two. Only two variables, CRUSTED and HARDEPTH, were entered before the minumum

Figure 6.2

CATENA ONE TERRITORIAL MAP



tolerance for entry was exceeded. The resultant F ratio was 1139.5.

Landsurface modality is least evident on Catena Three although all sites are correctly classified by the three variables HARDEPTH, EGRAVELS, and MEANMICR. The F ratio, though much smaller than the values for Catenas One and Two is still statistically significant (40.637).

Single Variable Analyses

Results for the Catena One analyses are summarised in Table 6.19, with the two and three group results in the left and right hand columns respectively. Four variables, COHESION (areal percentage of cohesionless soil lenses), CRUSTED, HARDEPTH, and COMPACTN (soil compaction), each correctly classify all sites in the two groups case. A 't' test of significance (0.01) between group means (Table 6.19) identified four variable categories (general soil characteristics; areal extent of micro soil surfaces; infiltration rates; and, soil compaction) as measuring the most significant differences between erosional and depositional landsurface units on Catena One. Addition of the 5/6 intergrade sites decreased the discriminating power of each variable due to misclassification between the two landsurface units and the intergrade zone. No single variable correctly classified all sites for the three groups.

Statistically, the least significant variables on Catena Two (Table 6.20) were those measuring soil texture (with the exception of EGRAVELS) and soil microroughness range, although only one variable, MRANGE90 was not significant at the 0.05 level. Six variables correctly classified all sites, indicative of the distinct physical differences between the two landsurface units.

In contrast, soil depth was the only variable to correctly

Table 6.19

CATENA ONE - SINGLE VARIABLE ANALYSES

Variable	't'	% Correctly Classified						
		Two Groups	Unit 5	Unit 6	Three Groups	Unit 5	Unit 6	5/6
Soil Texture								
EGRAVELS	*	66	50	75	53	42	75	22
DGRAVELS	0.05	69	58	75	54	58	70	11
ESAND		91	92	90	63	75	60	56
DSAND	*	59	67	55	49	25	55	67
ECLAY		91	83	95	63	83	60	44
INCHSAND		84	67	95	59	67	60	44
INCHGRAV		78	58	90	63	33	90	44
INCHCLAY		87	67	100	54	67	55	33
Microroughness								
MEANMICR	*	56	75	45	37	75	5	56
DOMMICRO		97	92	100	66	33	95	44
MMRTRUSL	*	50	50	50	34	50	15	56
MMR90SLP	0.05	55	67	55	49	58	50	33
MRANGETS	*	56	58	55	46	58	30	66
MRANGE90	*	53	67	45	37	00	45	67
Slope								
TRUSLOPE	*	72	83	65	54	67	60	22
SLOPE90	*	56	67	50	**	**	**	**
Infiltration								
PREWETHR		91	92	90	N/A			
INFILTHR		91	100	85	N/A			
Areal Coverage								
COHESION		100	100	100	76	67	100	33
CRUSTED		100	100	100	83	92	100	33
VEGCOVER		81	100	70	61	100	60	11
Soil								
HARDEPTH		100	100	100	93	100	90	89
AHORIZON		94	100	90	80	100	75	25
Soil Compaction								
COMPACTN		100	100	100	80	100	75	67
N=		32	12	20	41	12	20	9

* not significant
0.05 significant at 0.05
all other variables significant at 0.01

** variable did not qualify for analysis
N/A data not available

Table 6.20

CATENA TWO

SINGLE VARIABLE ANALYSES

Variable	't'	% Correctly Classified	% Correctly Classified Unit 5	Unit 6
Soil Texture				
EGRAVELS		95	90	100
ESAND	0.05	55	40	70
ECLAY	0.05	70	50	90
Microroughness				
MEANMICR		90	100	80
DOMMICRO		100	100	100
MMR90SLP		90	90	90
MMRTRUSL		90	90	90
MRANGETS	0.05	70	50	90
MRANGE90	*	55	40	70
Slope				
TRUSLOPE		100	100	100
SLOPE90		75	70	80
Infiltration				
PREWETHR		85	80	90
INFILTHR		80	80	80
Areal Coverage				
COHESION		100	100	100
CRUSTED		100	100	100
VEGCOVER		75	100	50
Soil				
HARDEPTH		100	100	100
AHORIZON		100	100	100
N=		20	10	10

0.05 significant at 0.05
* not significant
all other variables significant at 0.01

group all sites on Catena Three (Table 6.21). A number of the Catena Three variables, most noticeably those measuring soil texture and soil infiltration rates, failed to be statistically significant; due primarily to an absence of marked soil texture differences between the two land-surface units. Six other variables were only significant at the 0.05 level. The most distinct differences between the erosional and depositional environments of Catena Three are indicated by soil microroughness, general soil characteristics, and shear strength of the surface soil.

The Catena One and Three results suggests that in the absence of gravelly soil, soil compaction and shear strength are useful diagnostic criteria. Also identified are a number of variables that fail to show any statistically significant difference in group means for one or more catenas. Close examination of the 't' scores for these variables suggests that the lack of significance is most probably not a reflection of the small sample size.

Summary

The application of discriminant analysis to the landsurface unit data verified the field mapping and classification of units on all three catenas. Results of the six-group stepwise analysis (Tables 6.7 and 6.8) identified each of the groups as distinct soil/slope entities, while also illustrating the greater homogeneity of the three depositional groups. The stepwise analysis of the six groups also demonstrated that of the original 18 variables, only 10 were required for a correct grouping of all sites. The omission of both infiltration variables yielded an overall 97% correct grouping (with correct classification of all

Table 6.21

CATENA THREE

SINGLE VARIABLE ANALYSES

Variable	't'	% Correctly Classified	% Correctly Classified Unit 5	Unit 6
Soil Texture				
EGRAVELS		85	90	80
DGRAVELS	0.05	75	70	80
ESAND	*	65	60	70
ECLAY	*	70	80	60
DSAND	*	55	50	60
Microroughness				
MEANMICR		95	90	100
DOMMICRO		90	80	100
MMRTRUSL		95	90	100
MMR90SLP		80	70	90
MRANGETS		90	80	100
MRANGE90		85	80	90
Slope				
TRUSLOPE		80	60	100
SLOPE90	*	60	40	80
Infiltration				
PREWETHR	*	70	80	60
INFILTHR	*	70	80	60
Areal Coverage				
COHESION	0.05	70	70	70
CRUSTED	0.05	60	50	70
VEGCOVER	*	50	70	30
Soil				
HARDEPTH		100	100	100
AHORIZON		75	90	60
SOLDEPRA		95	90	100

Variable	't'	% Correctly Classified	% Correctly Classified Unit 5	Unit 6
Soil Compaction				
PREPEND	*	65	60	70
PREPENE		70	80	60
PREPENED	*	70	70	70
POSPEND	0.05	80	80	80
POSPENE		65	50	80
POSPENED	0.05	85	80	90
Shear Strength				
PRESHED		80	100	60
PRESHEE		90	100	80
PRESHEED		85	100	70
POSSHED	0.05	55	60	50
POSSHEE		80	80	80
POSSHEED		90	90	90
N=		20	10	10

* not significant
0.05 significant at 0.05
all other variables significant at 0.01

erosional sites) with seven variables; resulting in a substantial reduction in the number of required mapping criteria. This seven variable set included measures of soil depth, soil texture, microroughness, and the areal percentage coverage of bare/eroded soil surfaces.

Single variable analyses of the six group data further demonstrated the more distinctive soil/slope characteristics of the three erosional groups (Table 6.12). The single variable results also identified the strongest single discriminators to be (in order of decreasing importance) measures of soil microroughness, soil depth, thickness of the A_1 horizon, infiltration rates, and the areal percentage ground cover of cohesionless lenses of soil. Weak discrimination by a single variable may indicate an absence of modality within the six groups, or it may simply be the result of several groups sharing similar mean values (as demonstrated by the homogeneity of the depositional groups).

To avert the problem of relative homogeneity among the three depositional groups, and to enable closer examination of the catenary interrelationship between the erosional and depositional landsurface units, separate discriminant analyses were computed for each catena. The results (summarised in Tables 6.19, 6.20, and 6.21) showed the most clearly defined physical differences to be between the erosional lateritic breakaway and colluvial footslope of Catena Two. One variable, soil depth, correctly classified all sites on all three catenas. On Catena One, the inclusion of the 5/6 intergrade in a discriminant analysis markedly reduced the percentage of correct classifications, with misclassifications common between the erosional and depositional sites and the intergrade.

The discriminant results discussed in this chapter have clearly demonstrated the presence of modality in specific pedogeomorphic characteristics within each of the landsurface units. The integration of these spatial patterns of soil/slope characteristics with the observed differences in hydrologic response is examined in Chapter VII.

CHAPTER VII

SUMMARY AND IMPLICATIONS FOR OTHER ENVIRONMENTS

The hypothesis examined in this study suggests that spatial variability in overland flow and sediment yield on hillslopes in a semi-arid environment are related to the spatial distribution of specific soil/slope characteristics. Analysis of overland flow, sediment yield, and soil/slope data supports the research hypothesis by validating the field classification of erosional and depositional landsurface units, and in identifying distinctly different hydrologic responses between two landsurface units on three separate catenas.

Four measures of hydrologic response were used to test for differences in overland flow and sediment yield between the landsurface units; overland flow response to individual rainfall events, sediment yield from individual rainfall events, total sediment yield for the six year period of recording, and rainsplash efficacy. All four attributes substantiated the hypothesised relationships.

On both a lateritic breakaway and a low angle pediment slope, the erosional unit was significantly more responsive to rainfall events, yielding higher rates of overland flow, sediment yield and rainsplash efficacy. This similarity in response reflected several physical characteristics common to these erosional units. Relative to their respective depositional units, both the lateritic breakaway and low angle pediment slope have noticeably lower soil infiltration rates due to shallow soils and a higher percentage clay fraction. In addition, the minimal vegetative ground cover of the two erosional units is considered a significant factor in the higher sediment yield observed for rainsplash and overland flow.

In contrast, a reversal in hydrologic response was hypothesised and substantiated for a third catena; outcrops of gneissic rock characteristic of the erosional unit produced channelization of overland flow. As a result, lines of concentrated overland flow traversed the colluvial footslope with the most concentrated flow lines denoted by small alluvial fans. Spatial variability in overland flow within the colluvial footslope was evidenced in the high variance in response observed among the three recording stations.

Application of discriminant analysis to the soil/slope data validated the landsurface unit classification and identified the most useful mapping criteria. Seven variables measuring soil depth, soil texture, microroughness, and the areal percentage coverage of bare/eroded micro soil surfaces provided satisfactory discrimination of the six soil/slope groups. Separate analyses of soil/slope data for the low angle pediment and the gneissic outcrop also suggested that in the absence of gravelly soils, soil compaction and shear strength are useful diagnostic criteria for delimiting erosional and depositional landsurface units. The discriminant results for the six groups also revealed the more distinctive physical characteristics of the three erosional landsurface units, in contrast to the relative homogeneity of the depositional units.

Potential contributions of this research to hillslope hydrology relate in part to the scale of inquiry. Citing the inherent inadequacies of treating catchments as spatially homogenous areas, recent research (as outlined in Chapter II) identified the need for field observations of spatial variability in overland flow, sediment production, and soil/slope characteristics within hillslopes. Results of this investigation provide substantive evidence of both spatial variability in hydrologic response within hillslopes, and the relationship of hydrologic response to spatial patterns of soil/slope characteristics.

Specific characteristics of the observed differences in overland flow and sediment yield are assumed to reflect a degree of uniqueness to the physical environment of southwestern Australia. However, the research results suggest that the identification of spatial patterns of soil/slope characteristics associated with different hydrologic responses should be applicable to other semi-arid environments. In particular, measures of soil depth, soil texture, microroughness, and the areal percentage coverage of either a bare/eroded soil surface or cohesionless lenses of soil are considered appropriate for similar environments beyond Australia. This contention is supported by the abundant literature documenting correlations between hydrologic response and geomorphic/pedologic criteria. Catenary research (for example, Furley, 1971; Anderson, 1975; and Davidson, 1977) provide further support in demonstrating spatial and/or linear patterns of soil/slope properties on hillslopes other than those of southwestern Australia. Furthermore, as noted in Chapter IV, the initial field identification of potentially useful mapping criteria was conducted in the semi-arid environment of the West Kimberley Division of northern Australia. Thus, although an element of uniqueness is assumed in the relative importance of the mapping criteria identified within the study areas, they are considered appropriate for other semi-arid regions.

There are several general implications of the research results. Identification of key soil/slope criteria diagnostic of spatial variations in hydrologic response provides a potentially useful method of mapping the spatial variability in hydrologic response of small catchments and offers potentially useful input for the modelling of catchment hydrology. As such, the results suggest an alternative approach to hillslope hydrology to that available in traditional hydrologic models.

Although this research was restricted to landsurface units 5 and 6 the results suggest that the nine unit landsurface model is an appropriate methodological framework for such an investigation, at least under conditions of natural vegetation. Analysis of the soil/slope data supports the notion of modality inherent in the definition of a landsurface unit with the measurement of overland flow and sediment yield supporting the inferred interrelationships between form and process.

In investigating spatial variability in hydrologic response and the interrelationship with spatial patterns of soil/slope properties, several lines of inquiry for future research have become apparent. An immediate problem unanswered by the research data is the nature of the hydrologic response of both erosional and depositional landsurface units to rainfall events of higher magnitude and intensity than those observed. A larger sample (both in number and in range) of overland flow and sediment response to single rainfall events would also enable a more rigorous statistical assessment of the numerous threshold conditions identified on the three catenas. In addition, similar research projects need to be undertaken on slopes where the natural vegetation has been removed to assess the applicability of the results established for vegetated slopes. Finally, successful application of hydrologic mapping to small catchments also requires the development of mapping criteria that will enable integration with large scale aerial photography.

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