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SOIL MOISTURE VARIABILITY: IMPLICATIONS FOR THE HYDROLOGY, EROSION AND MANAGEMENT OF GULLIED CATCHMENTS IN CENTRAL SPAIN

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SOIL MOISTURE VARIABILITY: IMPLICATIONS FOR THE HYDROLOGY, EROSION AND MANAGEMENT OF GULLIED CATCHMENTS IN CENTRAL SPAIN.

by

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ABSTRACT

Soil Moisture Variability: Implications for the Hydrology, Erosion and Management of Gullied Catchments in Central Spain

Christopher Fitzjohn

In semi-arid environments, the combination of a non-uniform distribution of vegetation, an often highly irregular terrain and complex geological, pedological and management histories have frequently given rise to considerable spatial variability in the physical and hydrological properties of soils. Heterogeneity within the soil's physical and hydrological properties can result in pronounced differences in infiltration and soil moisture. The hydrological response of semi-arid landscapes to rainfall events may therefore be spatially non-uniform. Quantifying the spatial pattern of hydrological response is important for identifying those areas within the landscape which are vulnerable to runoff and erosion. Since soil moisture is considered to be a key factor in determining hydrological response and its spatial distribution is a function of the soil's physical and hydrological properties, the spatial and temporal measurement of soil moisture may be used to identify contrasting areas of hydrological response. In a badlands environment located approximately 70 km north of Madrid, central Spain, an experiment was established to describe the temporal and spatial variability in soil moisture at three scales, with the primary aim of furthering the understanding of the hydrological and geomorphological processes operating in semi-arid landscapes.

At each measurement scale, the macroscale (25m sampling interval), the mesoscale (gully catchments, 5m sampling interval) and the microscale (1m sampling interval), two distinct groups of soil moisture conditions emerged related to dry and wet weather conditions. At each measurement scale the maximum variability in soil moisture is similar (>20% volumetric content difference between immediately adjacent sampling points). At the meso and microscale the spatial pattern of soil moisture could be described as a mosaic pattern which during the dry period was more fragmented and variable than during the wet period. The spatial pattern of soil moisture during wet conditions is more uniform due to the development of extensive wet areas within the catchments. During these conditions the range of spatial correlation in soil moisture may double (to greater than 30m) compared to dry conditions, indicating an increase in the spatial continuity of soil moisture. The spatial variability in soil moisture therefore displays a temporal dependency; the mosaic soil moisture pattern is more fragmented and spatially discontinuous during dry than wet conditions.

A striking characteristic of the study area is the near horizontal interbedding of sediment horizons which may strongly contrast in their textural composition over relatively short distances. This variability in soil texture and the associated changes in pore size characteristics, were the principal controlling factors in determining the spatial patterns of soil moisture and overrides the known influence of vegetation and topography on soil moisture. During dry conditions the non-uniform uptake of soil moisture by vegetation may partly explain the greater variability in soil moisture observed during this period.

The mosaic patterns of soil moisture represent areas of contrasting hydrological response. During dry periods when the mosaic pattern is more fragmented, source areas of overland flow are spatially isolated and surrounded by 'sink' areas capable of re-absorbing runoff and sediment deposition. Hydrological pathways are therefore discontinuous resulting in minimal runoff reaching the catchments channels. Since soil moisture values during this period are below saturation, any runoff which does occur is generated as infiltration excess overland flow. In semi-arid areas spatial variability in soil properties or vegetation patterns may therefore be beneficial for runoff and erosion control by creating a self-regulating system in which runoff producing areas are surrounded by buffer zones capable of re-absorbing the runoff. During wet periods extensive areas of the catchments may be saturated, source areas are no longer spatially isolated and continuous hydrological pathways may develop rapidly during this period. During the wet period when conditions are above a critical saturation threshold value widespread runoff will occur regardless of the spatial variability in the soil's physical and hydrological properties.

The creation of a mosaic pattern in which buffer zones are adjacent to potential runoff producing areas, as identified from spatial soil moisture patterns, may provide the most effective management strategy in runoff and erosion control for degraded semi-arid environments. The creation of a mosaic pattern is most applicable at the watershed scale allowing several land uses, including those which are potentially degrading, to co-exist. Increasing the critical threshold value above which widespread runoff occurs should also be included as part of this management strategy.

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Chapter 1

Introduction

1.0 Introduction to Soil Variation

Variation arises from interactions within a multi-scale system comprising the lithosphere, the biosphere and the atmosphere through time (Rowell, 1994). Soil forms an important component of the biosphere. Its distribution and properties reflect the continuous processes operating within the biosphere and between the biosphere-lithosphere and the biosphere-atmosphere. It is the varying nature of these processes and the multi-scaled nature of the system which has produced a soilscape continuum, exhibiting varying degrees of change in both space and time (Wilding, 1985; Fitzpatrick, 1986; Kachanoski and De Jong, 1988; Webster and Oliver, 1990; McBratney, 1992; Rowell, 1994). Thus, soil variability is

"*the product of soil forming factors operating and interacting over a continuum of spatial and temporal scales*" (Trangmar *et al.*, 1985).

Soil variation may be encountered as either systematic variation or as random variation (Trangmar *et al.*, 1985; Wilding, 1985). Systematic variation may occur as gradual change, distinct change or as trends in soil properties, which may be explained in terms of soil forming processes operating at a given scale of observation *ie.* soil series or the catena concept (Trangmar *et al.*, 1985; Wilding, 1985). The heterogeneity found in soils which cannot be explained is termed random variation. This at first apparent random variation or unexplained heterogeneity, may however, be found to contain a systematic component as the soil body is studied in greater detail (Trangmar *et al.*, 1985). Therefore the degree of variation encountered is partly dependent upon the extensiveness of the investigation. The accuracy of statements made about soil properties, soil behaviour and land use performance depends upon the degree of variation identified by the investigation and the variation present, as well as the purpose of the study. However, it is almost certain that as soil variation increases, then the precision of statements, particularly those related to the large scale *ie.* catchments, or those concerning soil properties known to be highly variable, will worsen (Trangmar *et al.*, 1985).

It has become increasingly recognised that

"*it is the inability to deal with spatial variability that prevents soil users from accurately matching soil use requirements to soil characteristics*" (Uehara *et al.*, 1985).

Furthermore, fundamental to our understanding of soil behaviour, is the need for knowledge on the interactions between the spatial and temporal scales of soil processes (Kachanoski and De Jong, 1988). To obtain greater precision in statements concerning soil processes, with the aim of improving land use management and to further our understanding of soil behaviour, the spatial and temporal variations of soil properties and the causes of these variations, need to be examined and quantified.

1.1 Causes of Soil Variation

Soil variation is the result of continuous interactions between the soil forming factors given by the formula:

S = a function of (cl, p, r, v, o)t

where S represents the soil or a soil property, 'cl' is climate, 'p' is parent material, 'r' is topography, 'v' is vegetation, 'o' is the biotic component including organisms and human impact and 't' is the time over which these factors have been operating to form soil (Beckett and Webster, 1971; Robert, 1993; Rowell, 1994). Where soil formation occurs in a natural environment, the resulting variation is termed intrinsic variability or natural variability (Cambardella *et al.*, 1994). In most environments however, intrinsic variability is accompanied by extrinsic variability caused by human disturbance within the environment, modifying the soil forming factors singularly or in combination (Cambardella *et al.*, 1994).

Variations in parent materials over short distances may be closely allied with short range variability in soil properties (Beckett and Webster, 1971; Wilding, 1985; Burrough, 1993). Stolt *et al.* (1993) have reported that differences in parent material may be more important in explaining spatial variability in soils than landscape position. Soils formed on transported materials such as alluvium or colluvium will be more variable than those weathered from bedrock *in-situ* (Beckett and Webster, 1971). Furthermore if sediments are deposited under alternating depositional environments, or have differing source areas producing interbedded or regularly interbedded sediments, then patterns of soil variation may be expected to show a trend or be regular reflecting the pattern of deposited sediments (Beckett and Webster, 1971). Geomorphic processes such as soil erosion by surface wash or gullying will increase soil variability, especially if several underlying sediments are exposed by gully dissection (Beckett and Webster, 1971). Changes in plant communities, whose distribution is largely determined by climate, will result in different soil types and hence variability in soil properties (Beckett and Webster, 1971). Further soil variability will occur when variations in species composition and plant structure are present within a single community. Variations in topography and relief, encompassing slope and aspect, will also give rise to variability in soil properties *eg.* the catena concept demonstrates how different soil types are geographically related to and associated with relief features. Variability in the number, type and activity of soil organisms will also produce variability within the soil body *eg.* the presence of worms within the soil environment can markedly change soil structure and resilience (Beckett and Webster, 1971; Brady, 1992; Burrough, 1993). Changes in climate, encompassing precipitation, temperature, solar radiation and evaporation, will also produce gradual changes in soil. It is common to find maps showing the world distribution of soil types which are based on changes in climate (*eg.* Miller and Donahue, 1995). Soil variation and variations in the values of soil properties is also induced by human disturbance, whether this occurs through land use management or simple neglect of the surrounding environment (Beckett and Webster, 1971; Trangmar *et al.*, 1985; Wilding, 1985; Burrough, 1993; Rowell, 1994). Robert (1993) has reported that human disturbance induced variability can be significant. Such disturbance can take the form of ploughing, planting, grazing, fertilization, drainage, pollution and changes in land use *etc.* (Beckett and Webster, 1971; Trangmar *et al.*, 1985). Disturbed soils show significantly more variation than natural soils (Wilding, 1985). Furthermore, certain soil properties which are vulnerable to disturbance and therefore most affected will show greater variation compared to more stable (tolerant) soil properties as a result of land disturbance (Beckett and Webster, 1971; Trangmar *et al.*, 1985; Wilding, 1985). Rowell (1994) has reported that considerably more variation in soil data was found under arable areas when compared to woodland sites. Within natural soils some 50-75% of the total variation in certain soil properties such as texture, colour and root abundance occurs over distances greater than 500m, whereas disturbed soils showed similar magnitudes of variation at distances of less than 10m (Trangmar *et al.*, 1985). Even in edaphically similar sites, differences in the spatial pattern of soil variability can be related to disturbance history (Robertson *et al.*, 1993).

Soil is a dynamic system and this is reflected by the inclusion of time in the soil forming factor's formula, indicating that the rates and importance of each soil forming factor will change through time *eg.* human disturbance has been operating over a relatively short time scale (Rowell, 1994). As soils develop and mature, with the increasing age of the landscape, then soil variability may decrease, since these older soils will have slowly approached an equilibrium with their environment (Soil - Environment Equilibrium concept), where the biotic community reaches a stable climax system and the physical environment becomes balanced (Beckett and Webster, 1971; Rowell, 1994). Young soils and young landscapes will show greater variation since they will be in dis-equilibrium with their environment and the soil forming factors. The soil-environment equilibrium may be brought into dis-equilibrium or held at a stage below equilibrium, and hence greater variability, by human disturbance and geomorphic processes such as erosion and deposition.

Rarely do soil forming processes operate singularly but rather act in combination with other soil forming processes to produce variation. Therefore it is the interactions between these soil forming factors and the multitude of feedback mechanisms between them producing an integrated system which is the cause of soil variability.

1.2 Scale and Nested Structures

With soil forming processes operating and interacting over a continuum of spatial and temporal scales, it is expected that soil variability itself will be scale-dependant. This change in the degree of soil variability with changing scale is known as "*scale heterogeneity*" (Beckett and Webster, 1971; Peck *et al.*, 1977; Uehara *et al.*, 1985; Trangmar *et al.*, 1985; Cambardella *et al.*, 1994). Furthermore the importance of soil forming processes in determining soil variability will vary depending upon the scale of investigation (Rowell, 1994). Change in variability with scale may be linear, curvilinear or irregular and changes as different causes of soil variability exert dominating effects over different spatial scales (Trangmar *et al.*, 1985). Since soil variability is scale dependant, then the soil variation identified and the causes of this variation will be in the form of a nested structure (Trangmar *et al.*, 1985). Identifying the nature of this nested structure depends largely on the scale and frequency of observation (Trangmar *et al.*, 1985). An example of nested soil variability is given by Trangmar *et al.* (1985) in which causes of soil variation which operate over large distances *e.g.* climate, or long time periods *e.g.* soil weathering are modified by other processes which operate over shorter distances *e.g.* erosion, or change more frequently *e.g.* temperature or rainfall.

Nyberg (1996) used a nested sampling design in an attempt to identify the scale at which soil moisture variation was greatest. At the 0.2 x 0.2m and 1 x 1m scale soil moisture variability was very low, compared to the 10 x 10m scale where variability significantly increased and was similar to the catchment wide variability in soil moisture. Hence the process controlling soil moisture variability operated at a scale greater than 10m. These nested structures of soil variation are the result of soil forming processes operating over a range of scales from the megascopic to the microscopic (Wilding, 1985). To move from one level to another level in these nested structures, certain scale boundaries of both distance and time must be overcome by the investigator. The length of this distance and time will depend upon the nature of the environment *ie.* its degree of variability and upon the soil property in question. Such a concept may explain why Burrough (1993) reports that the variation observed over longer distances may be present within the first few metres, and why Beckett and Webster (1971) report that

"*up to half of the variance within a field may already be present within any m^2 in it*".

Complications may arise in identifying nested structures of soil variability, since the scale on which soil variability occurs changes with increasing soil depth (Zhang and Berndtsson, 1988). Several studies have indicated that the subsoil is much more variable than the topsoil (McBratney and Webster, 1983; Wilding, 1985; Zhang and Berndtsson, 1988; Loague, 1992a; Stolt *et al.*, 1993). This is explained in part by management practices such as ploughing which tend to promote homogeneity in surface soils and partly by climatic effects such as temperature which work on larger spatial scales for upper soil layers (Berndtsson and Chen, 1994). However Ritsema and Dekker (1995) have reported greater variability in soil moisture in the upper soil layers due to greater textural and structural differences found in these horizons.

1.3 Soil Variation : Beneficial or Problematic ?

Soil variability may be seen as both problematic and/or as being beneficial (McBratney, 1992; Ibanez *et al.,* 1995). In terms of sampling effort, quality of information (particularly for modelling) and for optimal soil management, soil variability is considered a problem (McBratney, 1992). If several soil properties are to be measured and their nested structure of variability is complex, then potentially large numbers of soil samples will be required to unravel the complexity. Therefore sampling effort will potentially be very high, largely dependent upon the sampling technique and the sampling strategy. The quality of information will also be to some degree dependant upon the extent of soil variation encountered by the investigation (McBratney, 1992). Burrough (1993) has reported that

"*information on spatial variability is essential when modelling soil forming and environmental processes*".

Many models are based on isotropicity and homogeneity of spatial units (Hawley *et al.*, 1983; Price and Bauer, 1984). This is particularly so for drainage basin and hillslope hydrological models for which inhomogeneity and small scale variability has serious consequences (Price and Bauer, 1984; De Roo and Riezebos, 1992). Berndtsson and Larson (1987) and Yair and Lavee (1985) have argued that the high variability encountered in soil properties in semi-arid and arid regions makes the application of models to these regions much more difficult than would be in humid temperate regions. The inclusion of temporal variability operating over a range of scales is also seen as being of increasing importance for modelling (Burrough, 1993). The ignorance of models to spatial and temporal structures operating over various scales may be seen as a fundamental flaw in their physical and mathematical foundation (Sharma *et al.*, 1980).

The more variable a soil is, then the more complicated and more difficult it becomes to manage.

"*Soil is easier to manage if it is uniform*" (McBratney, 1992).

If soil variability is high, then the degree of control and the current management techniques necessary to contain such processes as soil erosion and surface water runoff may be inadequate (Burrough, 1993). Land management may require the removal of as much soil variation as possible by amelioration through *e.g.* deep ploughing and fertilising (Burrough, 1993). However measures such as amelioration may be inefficient and therefore non-cost effective or may even fail if soil variation is too great (Robert, 1993; Burrough, 1993). It may therefore be necessary in environments exhibiting high variability for land managers to adopt a management approach which is soil specific or spatially sensitive (Robert, 1993). The concept of spatially sensitive management is relatively new and

"*allows for variable management practices within a field according to soil or site conditions*" (Robert, 1993).

The optimisation of benefits from spatially sensitive management largely depends upon the resolution of information which in turn governs how well the management moulds to the variable soil conditions (Robert, 1993). Wilding (1985) has suggested the adoption of class limits whereby the land is divided into blocks on the basis that each block has a range of variation which does not exceed critical limits. These blocks can then be managed according to the degree and nature of the variation (Robert, 1993). The spatially sensitive management concept however, requires newer and higher levels of technology as well as new management skills. Both present difficulties, and are slow in being adopted within the present managerial establishment due largely to the costs involved in implementing this concept (Robert, 1993).

From an ecological point of view, distinct soil variations will support a diversity of ecosystems, increasing the ecological value of a region (Ibanez *et al.*, 1995). Furthermore, such diversity is considered beneficial in that it promotes stability and resilience within the environment (McBratney, 1992). Some processes which are seen as degrading to the environment *e.g.* gully erosion, may be beneficial since they may increase heterogeneity and hence diversity (McBratney, 1992). Cerda (1995) working in Genoves, Spain, has reported a mosaic of runoff producing areas, related to infiltration which is controlled by the spatial variability in shrub patches. Runoff is produced in areas between these patches, but re-infiltrates in the shrub areas.

"*Any disturbance of the mosaic will modify the rainfall - runoff relationships and increase water and sediment losses*" (Cerda, 1995).

Thus the presence of spatial variation in terms of vegetation cover is beneficial in that it creates areas capable of re-absorbing runoff from adjacent areas. There is no continuous hydrological pathway and hence erosion is minimal as runoff and sediment never reaches the bottom of the slope (Cerda, 1995).

1.4 Soil Moisture Variation

Values of soil water content and an understanding of the spatial and temporal variations in surface soil moisture is of great importance to several disciplines (Charpentier and Groffman, 1992; Giacomelli *et al.*, 1995). In agriculture an understanding of the spatial and temporal variations in soil moisture is valuable for optimising irrigation, the timing of fertiliser application and crop yield forecasting; in climatology for estimating net surface radiation; in ecology for assessing plant species stress, plant competition and soil aeration (O'Loughlin, 1986; Charpentier and Groffman, 1992; Giacomelli *et al.*, 1995); in environmental science for determining zones of rapid pollution transport within the soil system (Henninger *et al.*, 1976; Ritsema and Dekker, 1995) and in engineering for the effect that saturated zones have on soil cohesion (Gardner *et al.*, 1991). Perhaps, however, the most important use of the quantification of soil moisture variation is its significant relevance to hydrological studies (Amerman, 1965; Hawley *et al.*, 1983; Burt and Butcher, 1985; Sharma *et al.*, 1987; O'Loughlin, 1986; Ward and Robinson, 1990; Phillips, 1992; Loague, 1992a; Ritsema and Dekker, 1994). An understanding of the spatial and temporal variations in soil water can be used to establish functional relationships between soil water content and various hydrological processes (Zhang and Berndtsson, 1988). O'Loughlin (1986) has reported that the response of catchments to a storm event is closely related to the prevailing wetness state of the landscape. Without information concerning soil moisture variability,

"*prediction and interpretation in catchment hydrology is problematic*" (O'Loughlin, 1986).

Among these various hydrological processes, the identification of zones of runoff and thus consequently zones of potential erosion is of significant importance, particularly in regions vulnerable to flooding and/or erosion. Hence identifying spatial and temporal variations in soil water content is also beneficial in understanding some geomorphic processes, in particular erosion, mass movements and weathering. Identifying the spatial and temporal pattern of zones of surface and subsurface runoff is also critical in improving the performance in prediction of rainfall - runoff models (Loague, 1992b).

1.5 Soil Moisture Variation and Surface Runoff

Several hydrological studies have identified and reported on the relationship existing between soil moisture and surface runoff (Betson, 1964; Kirkby and Chorley, 1967; Hewlett and Hibbert, 1967; Betson and Marius, 1969; Dunne and Black, 1970; Henninger *et al.*, 1976). These studies have reported on how spatial and temporal variations in soil moisture can lead to the development of source areas or partial areas which generate surface runoff (Hewlett and Hibbert, 1967; Dunne and Black, 1970). These partial areas are the result of soil saturation, and have been shown to be both spatially and temporally variable over a catchment reflecting the soil moisture pattern (Amerman, 1965; Hewlett and Hibbert 1967; Betson and Marius, 1969; Henninger *et al.*, 1976). Berndtsson and Larson (1987) have argued that the application of the partial area concept to semi-arid catchments is valid due to the highly variable nature of the soil properties. Spatial and temporal variations in soil moisture also play a significant role in the pattern and development of subsurface throughflow (Hewlett and Hibbert, 1967; Whipkey, 1967; Weyman, 1974, 1975; Mosely, 1979; Jones, 1981). Source areas represent hydrologically active localities within a catchment and depending upon antecedent soil moisture and storm duration, it may only be these localities and not the whole catchment which contribute to surface runoff (Heerdegen and Beran, 1982). Antecedent soil moisture and storm duration will partly determine the nature of these source areas, ie. their size and degree of saturation, and hence the volume of surface runoff produced by and the response time to a precipitation event. Therefore the hydrological response of a catchment can be expected to change given different antecedent moisture and storm type conditions (O'Loughlin, 1981). Although source areas within a catchment may produce surface runoff in response to a precipitation event, this runoff may not contribute to catchment outflow or at least quickflow (Brown, 1965; Amerman, 1965; Burt and Butcher, 1985; Sharma *et al.*, 1987). The contribution of source areas to catchment outflow is dependent upon their location within a catchment and upon their degree of connectivity (connectivity being defined here as a continuous hydrological pathway between two points or more) (Amerman, 1965; Burt and Butcher, 1985; Sharma *et al.*, 1987). When there is no connectivity between runoff producing areas, then only those source areas located adjacent to the channel or catchment outlet will contribute to catchment outflow (Amerman, 1965; O'Loughlin, 1981; Burt and Butcher, 1985; Sharma *et al.*, 1987). Surface runoff from source areas which are isolated and upslope of the channel will be re-absorbed by the surrounding drier areas and hence will not contribute to catchment outflow. This will be particularly the case in dry periods and for short duration storms (Brown, 1965; Burt and Butcher, 1985; Sharma *et al.*, 1987). Amerman (1965) has observed at the North Appalachian Experimental Watershed , Ohio, the re-absorption of surface runoff from saturated zones by surrounding drier zones reporting that

"*water flowing at one point disappeared at another*".

Connectivity between source areas within a catchment is partly dependent upon the spatial distribution of soil hydraulic properties (Sharma *et al.*, 1987). Therefore in the horizontal plane the degree of soil variation will determine whether source areas in a catchment are spatially isolated or spatially interactive (Sharma *et al.*, 1987; Cerda, 1995). Sharma *et al.* (1987) have reported that in spatially correlated (dependent) soil systems, areas which are favourable to surface runoff will be adjacent, and soils not favourable to surface runoff will also tend to be adjacent. Hence soils favourable to surface runoff will interact less with soils not favourable to surface runoff, resulting in a quicker response to and a greater volume of runoff from precipitation events (Sharma *et al.*, 1987). The degree of connectivity within a catchment is also dependent upon the wetness state of that catchment (Burt and Butcher, 1985). Given high levels of antecedent soil moisture and/or long storm duration, dry zones (non-source areas), although having different hydrological properties compared to the wet zones and thus spatially uncorrelated, will also reach saturation, becoming source areas of surface runoff (Amerman, 1965; Burt and Butcher, 1985). Therefore at a certain '*wetness threshold*' (saturation), large areas if not the whole catchment will be contributing to surface runoff, regardless of the spatial distribution in soil hydraulic properties. At this point the spatial variability in soil hydraulic properties becomes irrelevant. It is only at times when the wetness state is below this threshold that spatial variability in soil hydraulic properties becomes important in determining connectivity between source areas and hence the size of the area contributing to effective surface runoff (where effective surface runoff is runoff which directly contributes to catchment outflow). Since differing soil types and soil horizons have different soil water storage capacities, the expansion of saturated areas and hence greater connectivity will increase through time as each storage capacity is exceeded. The rate of expansion to the point of complete catchment saturation given similar antecedent conditions will be quicker for a spatially well correlated catchment than a spatially poorly correlated catchment.

1.6 Soil Moisture Variation and Erosion

Closely related to source areas of surface runoff and subsurface throughflow is soil erosion (Jones, 1981; Moore *et al.*, 1988; Murphy and Flewin, 1993; Morgan, 1995). Moore *et al.* (1988) have reported that in Australia, the location of ephemeral gullies often coincides with the location of zones of saturation. It appeared that variations in soil moisture content was a dominating factor in controlling ephemeral gully erosion (Moore *et al.*, 1988). In a badlands area of central Spain simulated storms have shown a close relationship existing between changes in runoff coefficients and soil moisture content (Ternan *et al.*, 1995). Blackburn (1975) has reported a positive correlation between initial moisture content and sediment loss, arguing that more sediment is produced from soils with high antecedent soil moisture than soils with low antecedent soil moisture. On a structurally degraded soil in New South Wales, Australia, high erosion rates have been linked to high antecedent moisture conditions (Murphy and Flewin, 1993). Erosion was reported as being much higher under high moisture levels than if the same rain had fallen when the soil was dry (Murphy and Flewin, 1993). Due to high soil moisture levels and the development of zones of saturation, low intensity rainfall resulted in higher rates of soil erosion than would be expected from an analysis of rainfall intensity alone (Murphy and Flewin, 1993). Murphy and Flewin (1993) have argued therefore, that when quantifying erosion hazard, not only should the return period for a particular storm be taken into account, but also the return period for having a certain set of soil conditions, especially levels of antecedent soil moisture.

1.7 Point Sampling or Remote Sensing of Soil Moisture

The number of sampling measurements necessary to quantify the spatial and temporal pattern in soil moisture will depend upon how variable the properties which govern soil moisture distribution are, as well as upon the degree of resolution required by the aims of the investigation. The number of samples required will also depend upon seasonal variation in variability and on soil conditions, whether wet or dry (see section 1.9) at the time of sampling (Hills and Reynolds, 1969; Reynolds, 1970). The scale at which sampling is undertaken will depend upon the scale at which the factors governing soil moisture distribution operate. These factors could be single or multiple and operate over different scales, which will probably be unknown to the investigator. In such cases a nested sampling design will be the most appropriate and the most rewarding since this design can reveal variability at several scales. Measurements of soil moisture can either be done at point locations requiring field sampling or by using the thermal wave bands available through remote sensing (Davidson and Watson, 1995). The well correlated relationship between surface soil moisture and natural thermal radiation has been long established, making remote sensing a particularly attractive option for investigating spatial and temporal variations in surface soil moisture (Charpentier and Groffman, 1992; Davidson and Watson, 1995). However several factors may complicate the collection of soil moisture data by remote sensing, through their effects on the ability of remote sensing devices to measure thermal emissions from the soil (Charpentier and Groffman, 1992). These factors include vegetation type, soil texture, surface roughness, soil surface temperature, topographic variability and exposure to the wind (Charpentier and Groffman, 1992; Giacomelli *et al.,* 1995). The spatial resolution of soil moisture variability reflected by remotely sensed data will depend upon the pixel size of the thermal images (Charpentier and Groffman, 1992). Individual pixels will only give information on the average soil moisture conditions since remotely sensed data only provides one value per pixel (Charpentier and Groffman, 1992; Davidson and Watson, 1995). Therefore soil moisture variations within the pixel size will not be given and thus there will be a loss in data resolution. The usefulness of remotely sensed data for measuring soil moisture variation will therefore depend upon the extent of within pixel variability (Charpentier and Groffman, 1992). Furthermore Charpentier and Groffman (1992) have reported that remote sensing will be less reflective of actual soil moisture conditions with increasing topographic variability since soil moisture is more variable under these conditions. Therefore the use of remotely sensed data may be restricted to relatively flat areas (Charpentier and Groffman, 1992). Questions may also be raised concerning the monetary expense of acquiring high temporal resolution using remote sensing techniques (Gardner *et al.,* 1991).

1.8 Extent of Soil Moisture Variation

Significant variations in soil moisture may occur over very small distances (Amerman, 1965; Beckett and Webster, 1971; Hawley *et al.*, 1983; Ritsema and Dekker, 1995; Nyberg, 1996). Nyberg (1996) has reported a wide range in soil moisture from 10-60% for the 0-30cm horizon with adjacent samples (less than 10cm apart) having a difference in volumetric water content of more than 10%. In the surface soil (0-5cm) Ritsema and Dekker (1995) have also reported a 10% difference in moisture content for adjacent samples (less than 5cm apart). In a later paper (Dekker and Ritsema, 1996) fingerlike wetting patterns with soil moisture contents of up to 45% were found immediately adjacent to dry soil with moisture contents less than 25%. Amerman (1965) working in cultivated and pastured watersheds has reported that *"large areas were found to be firm underfoot and were supporting no surface runoff, whereas adjacent areas under seemingly identical storm and physical conditions were soggy and supported surface runoff".*

Van Wesenbeeck and Kachanoski (1988) have reported substantial differences in soil moisture between crop inter-row and row positions. A high variability in soil moisture has also been reported for subsoil's (Wierenga, 1985). Using airborne thematic mapper (ATM) data, Davidson and Watson (1995) have reported for a field with 50% weeds and 50% bare soil, moisture values ranging from 3.7 - 20.4% measured at 20m intervals. Values for a semi-permanent pasture ranged from 1.7 - 41.5% (Davidson and Watson, 1995). McBratney (1992) measured volumetric soil moisture content using Time Domain Reflectometry (TDR) to a depth of 15cm at the nodes of a 5x5m grid. Soil moisture values were found to range from 7 - 27%, with increased variation occurring at less than the measuring interval of 5m (McBratney, 1992). Further evidence suggested that this soil moisture variation was occurring at less than 0.5m (McBratney, 1992). Yates and Warrick (1987) have reported a range in soil moisture values from 2.5 - 13.5% for 71 random locations over a 90 x 90m grid system in Arizona, United States.

1.9 Wetting Up and Drying Out Periods

The extent or range of variation in soil moisture values will change depending on whether measurements are taken during a wet period or during a drying out period. Hawley *et al.* (1983) have reported that soil moisture variability should be lowest after a prolonged dry period and largest immediately after rain. An increase in variance and standard deviation has been associated with an increase in moisture content (Reynolds, 1970). This relationship between soil moisture content and variability may be due to the effects of soil heterogeneity being least during dry periods and greatest during wet periods (Reynolds, 1970; Tricker, 1981). Hawley *et al.* (1983) have argued that at higher tensions, soil moisture content is less variable than when near saturation, explaining the relationship. They have further argued that at saturation, uniform conditions are present and therefore the effect of soil pore size variations will be maximised resulting in variations of soil moisture content (Hawley *et al.*, 1983). They have, however, acknowledged that under extremely dry conditions, variation may increase when compared to wet conditions (Hawley *et al.*, 1983). Theoretically as soil moisture across a catchment nears zero, then spatial variability in soil moisture content will also tend towards zero (Hendrickx *et al*, 1990). Working in the north - west deserts of China, Berndtsson and Chen (1994) reported very low spatial variability in soil moisture (0-40cm) and attributed this to the very low range (1-3%) in soil moisture content. However after a rainfall event and hence an increase in soil moisture, spatial variation in soil moisture increased, with a spatial correlation of 5m before rain, falling to less than 2m after rain (Berndtsson and Chen, 1994). Nash *et al.* (1989) found that after flooding a clay loam soil, the spatial distribution of soil water was completely random. Only after several days of drainage did the spatial correlation between the 1m sampling intervals increase to 8-20m.

In contrast, Reid and Parkinson (1987) and Charpentier and Groffman (1992) have reported that soil moisture variability decreased as soil moisture levels increased. Zhang and Berndtsson (1988) have found that during a dry summer period the spatial variability in soil moisture was larger than during a wet winter period. Furthermore Van Wesenbeeck and Kachanoski (1988) have reported an increase in spatial variance as mean soil water content decreases during drying. Wierenga (1985), Greminger *et al.* (1985), Hendrickx *et al.* (1990) and McBratney (1992) have also reported that total soil moisture variation and local soil moisture variation increased as the soil dries out. McBratney (1992) has argued that the observed increase in soil moisture variation during dry and drying out periods may be caused by soil water redistribution creating patchiness. Wierenga (1985) has argued that during dry period's soil water tension increases, resulting in an increase in variance. It may, however, be that variability is highest when a soil is between the two extremes of absolute wet and dry (Hills and Reynolds, 1969).

"*The intermediate position is probably characterised by small areas of rapid drying, resulting in a very non-uniform pattern*" (Hills and Reynolds, 1969).

1.10 Temporal Persistence of Dry and Wet Zones

Comegna and Basile (1994) have been able to partition the spatial variability of soil moisture into areas or patches known as dry or wet zones. Charpentier and Groffman (1992), Loague (1992a) and Ritsema and Dekker (1994, 1995) have also reported the presence of wet and dry zones creating a mosaic pattern of areas with similar soil moisture contents. Where there are clear and strong deterministic links between the causes of the variation in soil moisture values, with the zones identified, then it is expected that the spatial mosaic (structure) of these zones will persist through time (Comegna and Basile, 1994). This persistence through time is known as time stability and is defined as the temporal persistence of a spatial pattern (Vachaud *et al.*, 1985; Kachanoski and De Jong, 1988). Since the spatial variation of soil moisture is of a deterministic nature, then the application of the time stability concept to soil moisture variability is realistic (Vachaud *et al.*, 1985). This temporal persistence can be determined using correlation analysis of successive measurement dates. Evidence for the existence of temporal persistence in soil moisture has been given by Munoz - Pardo *et al.* (1990) who have reported that

"*the driest and wettest locations at one sampling date tend to remain the driest and the wettest ones at other dates*".

Zhang and Berndtsson (1988) have reported that although soil water content varies in time, the spatial pattern of soil moisture variation remains fairly constant. Hawley *et al.* (1983) have reported the existence of clustering patterns of soil moisture values, which are consistent from date to date, indicating temporal persistence. Tomer and Anderson (1995) have reported spatial patterns of soil water storage remaining unchanged through time. Temporal persistence in spatial soil moisture patterns has also been observed by Berndtsson and Chen (1994) and Nyberg (1996). Temporal persistence may not, however, be completely time independent (Comegna and Basile, 1994). As the time interval between observations is increased, the correlation between dates worsens (Comegna and Basile, 1994). Zhang and Berndtsson (1988) have also reported that temporal persistence may decrease during dry or summer periods.

1.11 Causes of Soil Moisture Variation

The level of soil moisture at any point, and hence the degree of variability between points, will depend partly on the degree of variability of internal soil processes which directly influence moisture holding capacity, and partly on the variability of external processes which influence soil moisture content (Reynolds, 1970). Furthermore, through the numerous interactions and feedback mechanisms occurring between these processes, their influence on soil moisture values may be complex, whereby a single factor may or may not be dominant (Zhang and Berndtsson, 1988). Being directly related to hydrological factors such as hydraulic conductivity, infiltration rate, evaporation and soil water retention characteristics, soil moisture content can be expected to vary wherever these factors vary (Nielsen *et al.*, 1973; Zhang and Berndtsson, 1988). The variability of these hydrological factors is however influenced by the variability of other factors such as bulk density, surface sealing, vegetation and in a feedback loop by soil moisture itself. The variability of these factors is again influenced further still by the variability of other factors such as climatic conditions and landuse management. Thus the controlling factors of soil moisture variation operate on many different levels and over many different spatial and temporal scales (Reynolds, 1970; Hawley *et al.*, 1983; Kachanoski and De Jong, 1988; Ritsema and Dekker, 1994).

1.12 Soil Moisture and Topography

The relationship between topography and soil moisture distribution has been well established (Hewlett and Hibbert, 1967; Dunne and Black, 1970; Ward and Robinson, 1990). Areas of increased soil moisture are expected to occur in topographic hollows, zones of convergence (Ward and Robinson, 1990) and at the base of slopes adjacent to river channels (Hewlett and Hibbert, 1967).

"*Topographic non-uniformity within small catchments is a major factor controlling the spatial variability of soil water*" (Moore *et al.*, 1988).

Hawley *et al.* (1983) and O'Loughlin (1986) have also reported that variations in soil moisture can be explained in terms of local topography. In an attempt to explain spatial variations in soil moisture content for a covered forested catchment on the Swedish west coast, Nyberg (1996) examined topography, soil hydraulic properties, soil depth, water inputs and fine root distribution as possible controlling factors. It was concluded that macro-topography was a major contributor to the variability in soil water content. This was substantiated by spatial correlation of the soil water content data set which displayed a range of spatial correlation of 20m which was

"*interpreted as a characteristic length for the topographically homogeneous sub-areas*" (Nyberg, 1996).

Since topography controls the spatial distribution of soil water, then topographic features can be used to identify source areas, contributing surface and subsurface runoff across a catchment (Moore *et al.*, 1988). Burt and Butcher (1985) used topographic features such as slope, plan curvature and drainage area to formulate topographic indices which were then correlated with the observed soil moisture distributions. However, the correlations were found to be poor suggesting that the topographic features used were inappropriate in explaining the pattern of soil moisture (Burt and Butcher, 1985). It was only at times of high soil wetness that the relationship between topographic indices and soil moisture improved (Burt and Butcher, 1985). Topography encompasses several variables, such as slope, aspect and upslope contributing area, each of which can influence soil moisture content and hence soil moisture variability

(Hawley *et al.*, 1983; Moore *et al.*, 1988). Of these variables, both Burt and Butcher (1985) and Nyberg (1996) have concluded that upslope drainage area was more important in controlling soil moisture content then any of the other variables. Charpentier and Groffman (1992) have reported, however, that although increased topographic heterogeneity resulted in higher variability of soil moisture values, this variability could not be attributed to topography or aspect. No correlation between topography and soil moisture was found (Charpentier and Groffman, 1992). Instead they attributed this variation to factors such as soil texture, structure, landuse management and vegetation cover (Charpentier and Groffman, 1992). Berndtsson and Chen (1994) found no relationship between topography and soil moisture for depths less than 1m. However below 1m depth the soil moisture pattern was related to topography (Berndtsson and Chen, 1994). Although reporting isolated zones of high soil moisture exceeding 70% volumetric in some places, Ritsema and Dekker (1995) found no relationship between these areas and topography.

1.13 Soil Moisture and Vegetation

Both spatial and temporal variations in vegetation cover and species type will influence soil moisture variability (Reynolds, 1970; Hawley *et al.*, 1983). To some extent the vegetative cover and its composition will determine how much rainfall reaches the ground surface (interception rate). Through shading it will influence how much solar energy is available for evaporation and its density will determine how much air movement there is near the soil surface (Reynolds, 1970). Vegetation, through its rooting system and the production of organic material, will influence hydrological, physical and biological variables such as hydraulic conductivity, pore density and stability and water holding capacity, all of which are important factors in determining soil water content and hence soil water variation. Differences in species type may result in differences in the rates of drying out of the soil through evapotranspiration when water demand exceeds rainfall (Reynolds, 1970). Such differences may be most evident when endemic and exotic species are compared in adverse environments, whereby the endemic species have adapted to the adverse environmental conditions and the exotic species are less well adapted *e.g.* in arid regions or climates with a seasonal moisture deficit, endemic species will be better adapted to moisture stress than exotic species which may be less well adapted resulting in differing rates of soil drying. In bare soils, soil moisture variation is much less than in vegetated areas where soil moisture variation is greater (Reynolds, 1970; Hawley *et al.*, 1983; Wierenga, 1985). Furthermore variability in soil moisture is lower with a full canopy cover when compared to a partial vegetation cover (Hawley *et* *al.*, 1983). Variability in soil moisture is higher again where the vegetation occurs in clumps or is clustered into patches (Hawley *et al.*, 1983). The extent of soil moisture variability may also differ between natural vegetation communities containing several species and planted monoculture communities. Higher soil moisture variability would be expected in the natural communities, where different species have different rooting depths and spacing between species will be variable. In a planted monoculture community rooting depth will occur at the same level in the soil profile and equal spacing between plants may apply. The influence exerted by vegetation cover and composition on soil moisture variation may diminish the influence exerted by topographical differences and soil heterogeneity (Hawley *et al.*, 1983; Zhang and Berndtsson, 1988). This effect may be greatest when investigating only the upper soil layers and during dry or drying out periods (Zhang and Berndtsson, 1988). Bouten *et al.* (1992) have reported that for a Douglas fir stand, the trees had a preferential uptake of water from the wetter soil areas. This phenomena along with drainage resulted in an originally spatially varied soil moisture distribution to become a homogeneous distribution. Nyberg (1996) working in a catchment dominated by Norway spruce found no correlation between water content and distance to the nearest tree and attributed this to the randomly distributed nature of the fine roots found in the lateral plane for these trees. Francis *et al.* (1986) have also reported a poor and not significant correlation (r = 0.2) between soil moisture distribution and vegetation cover, for a semi-natural matorral scrub in south east Spain.

1.14 Soil Moisture and Soil Texture

Where significant differences in soil texture and soil structure occur, then it is likely that these factors will be dominant in controlling soil moisture variability (Beckett and Webster, 1971; Greminger *et al.*, 1985). Price and Bauer (1984) have reported that

"lateral variability of soil moisture reflects textural changes over a few metres".

Subsoil variations in soil moisture have also been related to variations in texture (Wierenga, 1985). Nash *et al.* (1989) have reported "*drastic changes*" in soil moisture with distance, the causal factor being changes in soil texture. Wilding (1985) has reported that soil moisture is spatially more variable in fine textured soils with significant cracking than in coarser textured soils. Several studies have reported a close relationship between variations in soil moisture and silt and clay content (Vachaud *et al.*, 1985;

Zhang and Berndtsson, 1988; Munoz – Pardo *et al.*, 1990). Vachaud *et al.* (1985) and Munoz - Pardo *et al.* (1990) and have reported that the temporal persistence of soil moisture spatial patterns is determined by the imposed spatial distribution of silt and clay. Variability in soil structure encompassing crack density, pore density, pore size distribution, pore connectivity and structural stability can result in significant variations in soil water content. Preferential flow paths allowing the rapid movement of water through narrow channels (often macropores) can result in areas of high soil moisture whilst the adjacent bypassed soil matrix is left dry (Beven and Germann, 1982; Dekker and Ritsema, 1996). In some situations, however, soil texture and structure is often related to slope position, making it difficult to distinguish between the effects of these two causes on soil moisture variation (Hawley *et al.*, 1983).

1.15 Other Causes of Soil Moisture Variation

Ritsema and Dekker (1994, 1995) and Dekker and Ritsema (1996) have reported considerable variations in soil water content for soils ranging from fine sands to heavy clays and have attributed this variation to the varying degrees of water repellency exhibited by these soils. Water repellency is partly dependent upon initial soil moisture content with air dry soils being the most repellent and wet soils being the least or not at all repellent (Dekker and Ritsema, 1996). Water repellency can also be induced by organic films, produced by certain varieties of hyphae and plant residues, which coat soil particles and soil aggregates, inhibiting water penetration (Dekker and Ritsema, 1996). Water repellency has been shown by Dekker and Ritsema (1996) to result in a 20% difference in soil moisture content for adjacent areas.

1.16 Introduction to Soil Erosion

Soil erosion can occur as natural erosion, also termed geological erosion, which in many instances may be considered as an acceptable level of erosion since the loss of soil is often balanced by the formation of soil (Morgan, 1995; Hudson, 1995). Soil erosion may also occur however, at rates far in excess of soil formation the cause of which is primarily attributable to human activities (Evans, 1980). The physical degradation, social and economic costs of this 'accelerated' erosion makes it an issue of concern to governments, businesses, individual landowners and academics in both the physical and social sciences, whose research, aims to understand the complex processes and causes of erosion in an attempt to formulate effective prevention and control measures.

Soil erosion occurs through the action of two physical processes (Luk, 1979; Young and Onstad, 1982; Morgan 1995). This involves firstly, the detachment of soil particles, which in the case of erosion by water, occurs through raindrop impact and runoff and secondly, the subsequent transport of his detached soil which occurs by raindrop splash and runoff (Gertis *et al.,* 1990). The effectiveness of raindrop impact, rainsplash and surface runoff as detachment and transporting agents of soil particles is partly dependent upon their simultaneous occurrence (Luk, 1979; Morgan, 1978, 1995). Rainsplash and raindrop impact are therefore dependent to a certain extent on the depth of surface runoff, being more effective up to a critical depth of water (Bryan, 1979; Luk, 1979; Thornes, 1980; Poesen and Savat, 1981). In addition raindrops impacting into surface runoff will increase the turbulence of the runoff and therefore its ability to detach and transport soil (Morgan, 1995). The effectiveness of these detaching and transporting processes is dependent partly upon soil erodibility which may be defined as

"*the vulnerability or susceptibility of the soil to erosion as reflected by its inherent properties*" (Stern *et al.*, 1991),

and in part by rainfall erosivity which may be defined as

"*the potential ability of rain to cause erosion and is a function of the physical characteristics of rainfall*" (Hudson, 1971).

Both soil erodibility and rainfall erosivity are dynamic, changing from season to season and changing even within an individual storm (Govers, 1991; Bajrachaya and Lal, 1992; Le Bissonnais and Singer, 1993; Morgan, 1995).

Severe soil erosion can lead to the development of a highly dissected landscape dominated by rills and gullies (Campbell, 1989). These landscapes, called 'badlands' because of their poor agricultural productivity and aesthetic appearance, can develop in different climatic regions of the world, but are usually associated with unconsolidated or poorly cemented materials (Bryan and Yair, 1982; Campbell, 1989). Badlands often occur in environments with a fragile ecological balance, and hence natural events such as extreme rainfall or climatic change can lead to their development (Bryan and Yair, 1982). Human disturbance however, often in the form of vegetation clearance, can also cause badland development or extend or rejuvenate naturally occurring badlands (Bryan and Yair, 1982; Campbell, 1989; Bocco, 1991).

1.17 Gully Erosion

A gully is a channel that is fluvially incised into unconsolidated earth materials. They are characterised by ephemeral flow, often steep sides and steeply sloping headscarps (Morgan, 1995; Hudson, 1995). Gullies may form as a result of increased erodibility in soil materials, possibly caused by for example a reduction in organic material, and/or more commonly by an acceleration of runoff or concentration of flowing waters often caused by land use changes (Ireland *et al.*, 1939; Bocco, 1991; Morgan, 1995). Gullies are arbitrarily distinguished from rills when their width and depth reach extents that prevent normal tillage (Bocco, 1991; Morgan, 1995; Hudson, 1995). Gully initiation is often the result of surface erosion (Heede, 1970), but can also occur through subsurface erosion and pipe collapse (Gutierrez *et al.*, 1988; Morgan, 1995). The development of gullies can be categorised into several distinct stages (Ireland *et al.*, 1939). At each stage the morphology, complexity and the dominance of erosion processes operating within the gully can change (Ireland *et al.*, 1939; Ternan *et al.*, 1998). For example, in the early stages of gully development, headward erosion and gully deepening by surface runoff is dominant (Ireland *et al.*, 1939; Bocco, 1991). In later stages of gully development headward erosion may become less important as headward retreat reduces the size of the runoff contributing area (Ireland *et al.*, 1939). At this stage, gully sidewall erosion may become an important source of sediment loss, sometimes accounting for more than half of the total volume of eroded sediment within gullies (Blong *et al.*, 1982; Blong, 1985; Crouch, 1990). The erosion processes may also change from erosion caused by surface runoff to erosion caused by soil creep and slumping, related to high soil water content. In this respect antecedent soil moisture becomes a critical variable in gully erosion (Ireland *et al*, 1939; Bocco, 1991). The morphology of gullies, which show a variety of forms (Ireland *et al.*, 1939; Imeson and Kwaad, 1980), is dependent upon the dominant erosion processes and the properties inherent in the eroding materials (Ireland *et al.*, 1939; Ternan *et al.*, 1988). According to Ireland *et al.* (1939) the type and success of conservation measures used to control gully erosion is dependent upon the stage of gully development and upon an understanding of the complex and dynamic erosional processes involved.

1.18 Spatial and Temporal Variability of Erosion

Understanding, monitoring and predicting soil erosion is a complex and at times insurmountable problem due to its enormous variation in both time and space (Thornes, 1980; Scoging, 1989). The unique topography of landforms found in badlands is evidence of the high spatial variability and complexity of soil erosion processes in operation (Campbell and Honsaker, 1982; Bryan and Yair, 1982). Scoging (1989) has argued that high variability in soil erosion over short distances and within apparently homogeneous sites suggests that using a lumped approach methodology to erosion studies is both unreliable and inaccurate. Furthermore using catchment sediment loss records as indicators of erosion is unreliable when source areas are variable (Scoging, 1989). Francis and Thornes (1990) have reported that soil erosion resulting from runoff is strongly related to rainfall, which in semi-arid areas is strongly seasonal. Therefore the temporal variation in erosion will be primarily seasonally controlled. Ireland *et al.* (1939) related the type and rate of erosion in gullies to seasonal differences in rainfall characteristics. During the winter months prolonged drizzling rains were ineffective in producing an erosive runoff, but did saturate gully rims causing slumping (Ireland *et al.*, 1939). Gully activity therefore showed a seasonal variation with distinct erosional processes operating in different seasons, the combination of which caused effective and extensive erosion (Ireland *et al.*, 1939). Variability in erosion may also occur throughout a storm if prolonged or if several concurrent storms occur, as sediment sources will eventually become exhausted (Cammeraat, 1992). Thornes (1980) and Scoging (1982, 1989) have argued that spatial variations in erosion are caused by variations in the resistance of the soil and surface cover (vegetation, stones). Scoging (1989) has further suggested that the variability in erosion may be related to the spatial pattern of runoff. However when the spatial pattern of erosion was compared to the spatial pattern of runoff it was found that areas of maximum erosion did not coincide with the areas of maximum runoff (Scoging, 1989). The variation in erosion was therefore related to detachment and transporting capacity (Scoging, 1989). Luk (1982) believes that much of the variability in erosion found within site studies is due to random variation and hence has no structured pattern which can be related to other variables.

1.19 Runoff Generation in Semi-Arid Environments

A knowledge of the factors which control runoff generation is essential in understanding the hydrological and erosional response of hillslopes and drainage basins (Yair and Lavee, 1985; Gertis *et al.*, 1990; Bocco, 1991). It is often assumed that Hortonian overland flow (runoff generated when rainfall intensities exceed infiltration capacity), is the dominant runoff generating process in semi-arid environments (Bryan and Yair, 1982; Scoging, 1989). However, Bryan and Yair (1982) have reported that

"badland catchments generally conform to partial and variable source area concepts of runoff generation".

The variable source area concept (Hewlett and Hibbert, 1967) and the partial area concept (Betson, 1964; Betson and Marius, 1969), relate to surface runoff generation from localised saturated areas (saturated overland flow) which may expand and contract throughout the duration of a rainfall event. Hodges and Bryan (1982) in a study of runoff generating processes on badland slopes, reported that the occurrence of Hortonian overland flow was uncommon. Instead runoff was primarily generated by a thin saturated layer at the soil surface (Hodges and Bryan, 1982). Scoging (1989) and Bocco (1991) have reported that the partial area concept has been successfully applied to semi-arid areas in identifying both runoff and sediment sources. It is probable that runoff generation in semi-arid environments results from a combination of runoff processes including both Hortonian overland flow and saturation overland flow (Bryan and Yair, 1982; Scoging, 1989; Gertis *et al.*, 1990). The occurrence of subsurface throughflow in the form of matrix or translatory flow is generally uncommon in semi-arid environments (Hodges and Bryan, 1982; Yair and Lavee, 1985; Scoging, 1989). Flow through subsurface pipes however, can be a significant source of runoff and erosion in semi-arid landscapes (Drew, 1982; Harvey, 1982; Jones, 1982; Bryan and Yair, 1982; Bocco, 1991; Morgan, 1995).

1.20 Spatial and Temporal Variation in Runoff Generation

Runoff generation is spatially and temporally highly variable in semi-arid landscapes and may be considered as an inherent characteristic feature of these areas (Bryan and Yair, 1982; Yair and Lavee, 1985; Scoging, 1982, 1989; Campbell, 1989). Spatial and temporal variations in runoff generation can be related to the variability within a single or a combination of controlling factors including, topography, antecedent soil moisture, vegetation cover, lithology, land use, infiltration and rainfall (Ireland *et al.*, 1939; Thornes, 1980; Scoging, 1989).

Rainfall intensity, duration and frequency, even when assuming no spatial variation in these properties (an assumption applicable to small catchment studies), are significant controlling factors in determining the temporal variation in runoff and its spatial extent (Ireland *et al.*, 1939; Campbell and Honsaker, 1982; Scoging, 1982; Yair and Lavee, 1985; Lavee, 1985; Cammeraat, 1992). Ireland *et al.* (1939) have reported that after frequent rains of long duration any further rainfall is likely to result in a high percentage of runoff, whereas rainfall after a relatively dry period is more likely to be absorbed and infiltrate rather than be converted into runoff. Scoging (1989) has reported that runoff is greater and more widespread with increasingly wetter antecedent conditions. Lavee (1985) has argued that a certain rainfall duration threshold value exists above which the size of the runoff contributing area is increased. Therefore two storms with identical characteristics may result in quite different amounts of runoff depending upon antecedent soil moisture and the frequency of rainfall events (Campbell and Honsaker, 1982; Cammeraat, 1992). Hodges and Bryan (1982) and Scoging (1982, 1989) have reported that the spatial variation in runoff generation is predominately controlled by lithological variations, in particular the particle size distribution and its effects on infiltration, soil moisture storage capacity and the structural stability of surface soil properties. Lavee *et al.* (1995) have reported spatially non-uniform runoff on a semi-arid hillslope in southern Spain which could be related to differences in surface roughness and microtopography. Spatial variation in antecedent soil moisture is also considered to be a significant factor in the spatial occurrence of runoff (Luk, 1979; Hodges and Bryan, 1982; Scoging, 1982; Yair and Lavee, 1985). Spatial variability in soil moisture has been related to the spatial variability in lithology (Hodges and Bryan, 1982; Scoging, 1982, 1989). Hodges and Bryan (1982) have reported that the

"moisture regime of a lithologic unit or a complete micro-catchment is the critical factor determining the incidence, timing and magnitude of runoff response to rainfall".

Similarly, Scoging (1982) has also reported that the

"moisture regime is the critical factor determining the timing and magnitudes of runoff".

1.21 Hydrological Response Units, Spatial Arrangement and Thresholds

Morgan (1995) has reported that the spatial pattern of runoff generation over a hillslope is critical in determining the effectiveness of overland flow as an eroding agent. This is supported by Campbell and Honsaker (1982) who argue that knowing the spatial pattern of antecedent moisture for a wide range of conditions is essential in identifying the spatial patterns of runoff and hence those times when runoff and erosion is widespread. Scoging (1989) sees this as an important step for identifying critical conditions or thresholds which are of value in the effective allocation of scarce resources to combat erosion.

Runoff and erosion can be studied at several scales, ranging for example from the individual plant to the drainage basin (Imeson *et al.*, 1995). At every scale it is highly probable that the hydrological response will show variation, even if this variation is very small. The variation in hydrological response becomes more evident with increasing scale as areas become more dissimilar. Contrasting areas of hydrological response, which for example may range in scale from a pore channel adjacent to the soil matrix up to an agricultural field next to a forest may be categorised into distinct units based on their hydrological response. Each unit can be given a threshold value determined by the conditions necessary for widespread runoff and erosion to occur within that unit. Above this threshold value widespread runoff and erosion occurs. These units can be termed *hydrological response units* and it is their spatial arrangement within the scale studied which is critical in determining the extent and severity of runoff and erosion (Imeson *et al.*, 1995; Flugel, 1995). For example, consider the variation in discharge from contrasting spatial units within a hydrological sequence of an agricultural field, next to an agricultural field, next to an agricultural field adjacent a stream channel. Each field represents an individual response unit. However if all fields have a low threshold value, and given their spatial arrangement, they may act as one unit with the potential for widespread runoff and erosion which can exit the drainage basin. A spatial sequence of an agricultural field, next to a forest, next to an agricultural field, next to a forest adjacent a stream channel suggests that runoff and erosion will be localised to the agricultural fields and only occur in the forest when their higher threshold level is surpassed. Assuming that the forests trap sediment and absorb runoff and the threshold is rarely exceeded, little if any sediment will leave the drainage basin. Therefore the extremity of an event required to initiate catchment runoff and erosion is dependent upon the spatial arrangement and threshold values of hydrological response units. Land use management can be a significant controlling factor in determining the spatial arrangement of response units and their threshold values and hence the frequency and severity of runoff and erosion.

It should also be noted that the hydrological response units at one scale form one level of a nested hierarchical scalar system, the complexity of which increases with increasing scale. At large scales *e.g.* catchments, there will be several nested levels (greater complexity). In this example, for a storm to initiate catchment runoff and erosion it must overcome the spatial arrangement and threshold values at all scales. Therefore runoff and erosion at the catchment scale requires larger magnitude storms whereas runoff and erosion at smaller scales *e.g.* within an agricultural field may be initiated by smaller storms.

1.22 Soil Erosion in Spain

Gonzalez Hildalgo *et al.* (1991) have reported that two thirds of Spain is suffering problems of soil erosion, 26.7% of this is considered to be moderate erosion, a further 21.7% of the land surface is undergoing severe erosion (Medio Ambiente en Espana 1985, 1986, 1989). The cause of this erosion is largely attributable to

"*poor land management and an ignorance of soil limitations*" (Navas and Machin, 1991).

It is also partly caused by the predominance of a semi-arid or seasonally arid climate and the natural fragility of Spain's landscapes. The combination of severe erosion and a semi-arid climate can lead to potentially irreversible desertification. Past and present erosion is resulting in the loss of productive land, a reduction in reservoir storage capacity through sedimentation, decreasing biological diversity and is degrading the aesthetic qualities of the landscape (Ternan *et al.*, 1995; Kosmas *et al.*, 1997). In 1991 the Institute for the Conservation of Nature (ICONA) unveiled a Spanish national plan to combat erosion and desertification (Rojo-Serrano, 1995). The plan favoured re-afforestation as the principle means of conservation, proposing that 2 million hectares of land should be re-afforested immediately (Rojo-Serrano, 1995). The plan encourages the use of indigenous species for planting and the

"*reconstruction of the natural vegetation community*" (Rojo-Serrano, 1995).

Furthermore several species should be used in re-afforestation to increase and preserve the natural biological diversity (Rojo-Serrano, 1995). The plan also proposes that re-afforestation should not be undertaken on lands with an existing natural vegetation cover including matorral scrub when this vegetation provides adequate protective cover (Rojo-Serrano, 1995). The plan also proposed that the participation of landowners should be promoted, a suggestion strongly emphasised as being critical to the success of future soil and water conservation projects in Spain by Garcia-Perez *et al.* (1995). In Castilla La Mancha, the Royal Decree (1993) established a reforestation program with the aim of reforesting 132,000 ha in 5 years (1993-1997) (del Cerro-Barja *et al.*, 1996). Between 1993 and 1995 63,343 ha had been reforested with native species in an attempt to restore the natural habitat, promote biodiversity and to combat erosion and desertification (del Cerro-Barja *et al.*, 1996).

1.23 Soil Erosion in Central Spain

Most erosion studies in Spain have been concentrated in the south-east of the country (e.g. Scoging, 1982; Harvey, 1982; Faulkner, 1995; Francis and Thornes, 1990; Imeson *et al.*, 1995) and in the north-east (Ebro basin) (e.g. Gutierrez *et al.*, 1988; Benito *et al.*, 1993). In contrast very little research (Ternan *et al.*, 1994, 1995, 1996a, b, 1997, 1998) has been undertaken on the badlands found in north west Guadalajara province, central Spain. The land surface of Castilla la Mancha region, of which Guadalajara is a province, suffers from 32.3% of moderate erosion, higher than any other region in Spain. A further 30.4% is severely eroded (Medio Ambiente en Espana 1985, 1986, 1989). del Cerro-Barja *et al.* (1996) have reported that 26% of unforested land in Castilla La Mancha is suffering soil losses greater than 12 Tm/(ha $year^{-1}$). In comparison to other badland areas of Spain, the badlands of Guadalajara province may be considered as well vegetated (Ternan *et al.*, 1995). It is perhaps the contrast between severe erosion and the good vegetation cover of these badlands which makes them a unique and fascinating environment. Ternan *et al.* (1995) have also argued that this environment, with its higher annual rainfall and greater frequency of rainfall, is potentially at a greater risk of erosional degradation than the badlands of southern Spain. Land degradation in the area is largely related to poor land management, the susceptibility to disturbance of the natural vegetation and the erodibility of the sediments (Ternan *et al.*, 1994). Gullies are the most actively eroding areas in these badlands, with the inter-gully areas being relatively well vegetated and hence generally stable (Ternan *et al.*, 1994). Erosion studies by Ternan *et al.* (1994, 1995, 1996a, 1996b) have indicated that of the four principal land uses in this area, the agricultural lands are the most susceptible to erosion, followed by recent bench terraced and afforested areas in which erosion is highly localised and from which runoff may contribute to active gullying. Soil properties under *Pinus* forest and matorral shrub are the most resistant to erosion where these areas are undisturbed (Ternan *et al.*, 1995, 1996a). It was concluded that vegetation and soil management through their effects on soil structure are the most important factors controlling erosion in this area (Ternan *et al.*, 1995). The semi-natural matorral scrub, if properly managed, may provide the most effective, natural and sustainable solution to erosion control in this area (Ternan *et al.*, 1995, 1996b).

1.24 Summary and Aims of this Research

Soil moisture is considered to be a key factor in determining hydrological response and its measurement in both time and space is therefore of concern to both hydrologists and geomorphologists. Although the quantification of spatial patterns is widely acknowledged as being necessary for interpreting hydrological and geomorphic processes, it is often neglected due to the complexity encountered and the limited resources available. Semi-arid environments in particular, often display considerable variation in rainfall, topography, vegetation and soils and subsequently hydrological response. Together with the threat of severe erosion and degradation in these environments, quantifying the spatial variation of those factors which are considered to be important in determining hydrological response should be seen as a key aim of hydrological and erosion studies within these areas. Despite this, relatively few studies have examined the spatial generation of runoff within semi-arid environments (e.g. Cerda, 1995) and even fewer have considered the spatial continuity of runoff generating areas and the implications of this variability for runoff and erosion control management (*e.g.* Morin and Kosovsky, 1995). Furthermore, only a small number of studies (Yair and Lavee, 1985; Yair, 1992; Grayson *et al.*, 1997) have quantified spatial patterns in soil moisture with the aim of identifying source areas of runoff. To the best knowledge of the author, no study has ever carried out a detailed investigation into the temporal and spatial variability of soil moisture within gully catchments, with the aim of identifying source areas in an attempt to understand the hydrological functioning of gully catchments. This may be considered as being of particular importance since Vandaele and Poesen, (1995) have argued that gullies are the principal sediment source areas, contributing up to 41% of the total soil loss, in semi-arid environments. In central Spain, Ternan *et al.* (1995) have reported that gullies represent the principal runoff generating and sediment source areas.

Given the general lack of research in this area and its potential significance for furthering the understanding of hydrological and geomorphological processes, fieldwork was undertaken in a badlands environment, located in central Spain, with the following research objectives:

1. To determine temporal and spatial variations in soil moisture at different spatial scales under different land uses.

2. To identify the relationships between these variations in soil moisture and factors known to control soil moisture, particularly soil physical properties, topographic position, vegetation characteristics and land use.

3. To examine whether the primary controlling factors change as the scale of measurement changes *eg.* does the primary factor important in explaining the spatial and temporal variations in soil moisture at the small scale become secondary or redundant at the larger scale? Alternatively are the factor(s) determining soil moisture variability scale-independent?

4. To identify zones of potential surface runoff (source areas) from the spatial patterns of soil moisture.

5. To understand the hydrological functioning of gullied catchments through the determination of the continuity of overland flow pathways and subsequently the potential for the occurrence of widespread runoff based on the spatial sequence of source areas and the existence of critical thresholds

6. To determine whether the spatial extent and severity of erosion is related to the spatial pattern of soil moisture and the development of continuous overland flow pathways.

7. To identify the implications and research needs for the hydrological monitoring and management of areas displaying heterogeneity in hydrological response.

Chapter 2

Study Location and Site Description

2.0 Location

The study area lies approximately 65-70 km north-east of Madrid in the Puebla de Valles - Retiendas region of west Guadalajara province (Castilla La Mancha), central Spain, at an altitude of approximately 1000m (figure 2.1). To the north of this region lies the Guadarrama mountain range and to the south an inland basin. The study site is located within a 'bahada', a Spanish term used to describe the gentle, sloping surface leading down from a mountain front to an inland basin (Espejo-Serrano, 1985). The bahada forms part of the drainage divide between the Rio Sorbe to the east and the Rio Jarama to the west. Within this area a typical badlands terrain has developed, characterised by extensive gullying. Ternan *et al.* (1997) have reported highly variable erosion rates within this area ranging from 1.6 kg m^{-2} yr^{-1} in well vegetated areas to 15.3 kg m^{-2} yr^{-1} in degraded areas.

Previous research into the geology and geomorphology of this area has been undertaken by Espejo-Serrano (1985), Perez-Gonzalez and Gallardo (1987), Gallardo *et al.* (1987) and Ibanez *et al.* (1994). The mineralogical properties of the Rana soils within this region were studied by de Herrera and Quadrado (1970), Espejo-Serrano (1985), Rodriguez-Pascuel *et al.* (1987), Garcia-Gonzalez and Aragoneses (1990) and Aragoneses and Garcia-Gonzalez (1991). A socio-economic perspective of the area was undertaken by Garcia-Perez *et al.* (1995). Studies into runoff and erosion within the area have all been undertaken by Ternan *et al.* (1994, 1995, 1996a, 1996b, 1997, 1998). Their studies have involved the use of rainfall simulation, runoff plots and gauging stations within gully catchments to quantify runoff and erosion from the differing land uses (Ternan *et al.*, 1995). Several other areas of erosion research have also been studied including the stability of soil aggregates in relation to land management (Ternan *et al.*, 1996a), the effectiveness of bench terracing as an erosion control measure (Ternan *et al.*, 1996b) and the spatial occurrence of soil piping and its relation to gully morphology (Ternan *et al.*, 1998). The variability in soil moisture and soil properties across terraces, hillslopes and within runoff plots has also been recorded (Ternan *et al.*, 1995, 1996b, 1997). This research therefore continues the work of Ternan *et al.* and is similar in that it attempts to understand the hydrologic and geomorphic response of the area. This research differs significantly however, in that it places a greater emphasis upon and undertakes a more detailed measurement of the variability in soil moisture and soil properties and the consequences of this variation for runoff and erosion within this area and other heterogeneous environments.

Three first order, valley side, gullies and their watersheds, each located in three different adjacent land uses (*Pinus* afforestation, matorral shrub, bench terracing with afforestation) were selected for study within this badlands environment (figure 2.2). The forest and bench terrace gullies are developed in north-east facing slopes and the matorral gully has developed in a south-east facing slope (figure 2.2).

Figure 2.1. Location map of the study area.

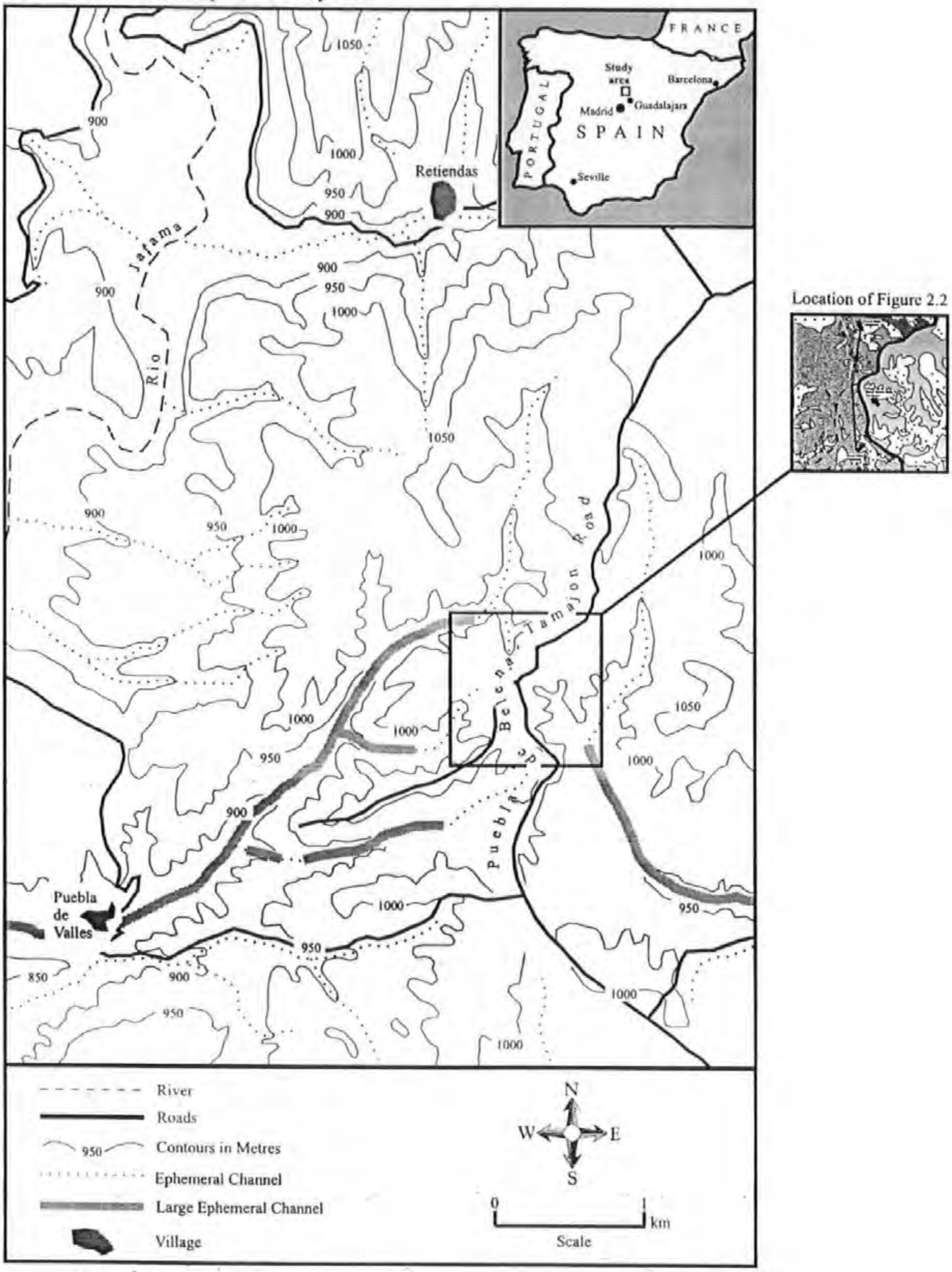
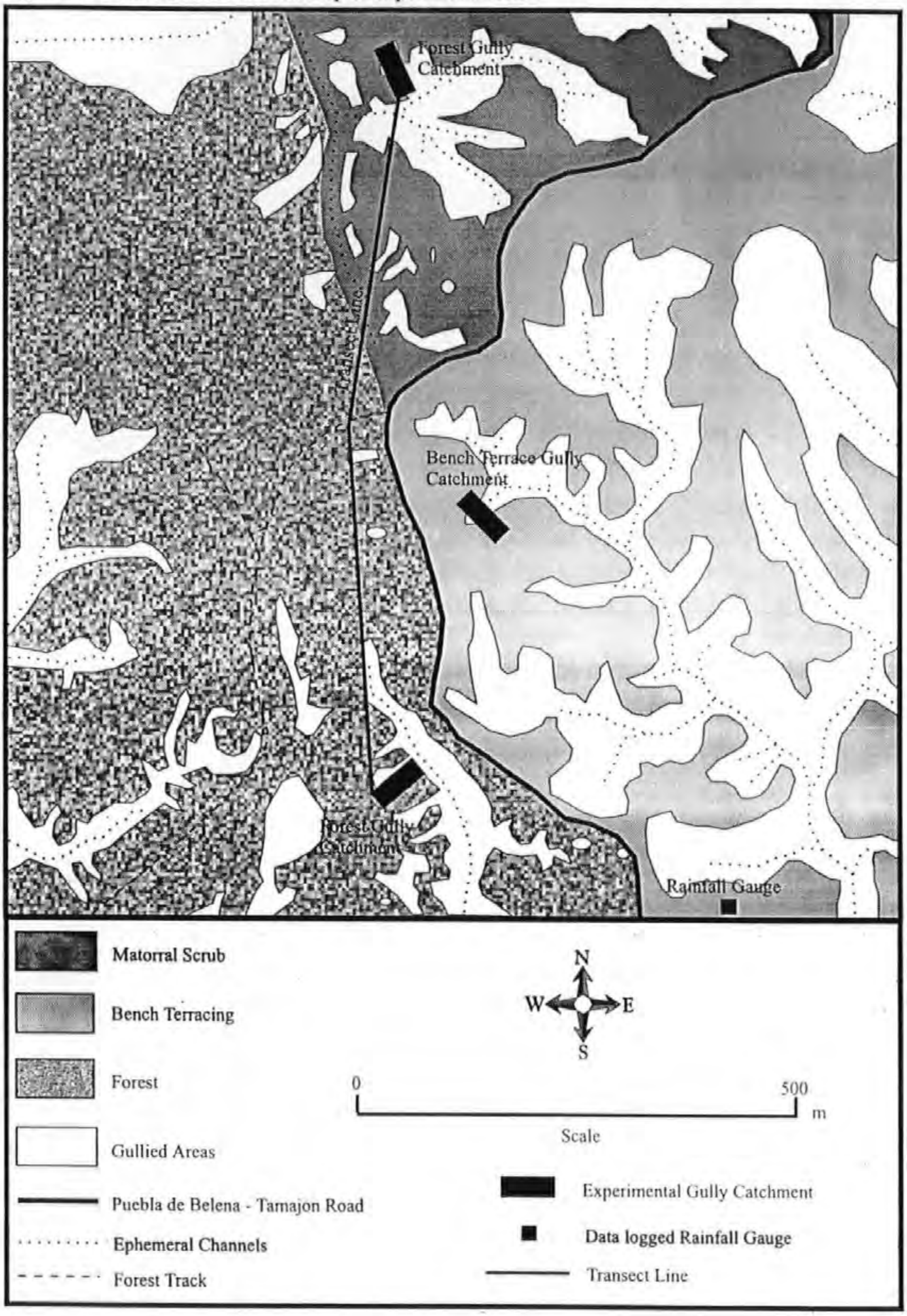


Figure 2.2. Land use and location map of experimental sites.



2.1 Climate

The nearest established meteorological station is at El Vado, located approximately 5 km north of Retiendas at an altitude of 1000m. Long term climatic data (1942-1975) from El Vado is presented in table 2.1 (Elias-Castillo and Ruiz-Beltran, 1981). Average annual rainfall for this period is 770.7 mm with December the wettest month receiving an average of 98.2 mm and July the driest month, receiving 18.2 mm (table 2.1). According to Munoz *et al.* (1989) maximum daily rainfall intensity for the period 1941-1970 recorded at El Vado, averaged 20 mm day^{-1} with a maximum of 65 mm day^{-1} in November 1976. In the period from December 1992 to December 1994 maximum thirty minute rainfall intensities ranged from 13 to 18 mm hr^{-1} (Ternan *et al.*, 1995). Average annual evapotranspiration is 713.1 mm and there is a pronounced moisture deficit from June to September reaching a maximum in July of minus 119 mm. Ternan *et al.* (1995) reported a soil moisture status which remained below field capacity from May until November. The strongly seasonal rainfall and evapotranspiration produces a climate which may be described as semi-arid continental Mediterranean (Ibanez *et al.*, 1994; del Cerro-Barja *et al.*, 1996)

Table 2.1. Meteorological data for the period 1942-1975 recorded at El Vado.

Meteorological Characteristics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall (mm)	86.3	73.8	79.3	64.3	75.3	50.5	18.2	19.0	52.6	67.0	86.2	98.2	770.7
N° of Rainfall Days	8	7	10	9	10	7	3	3	6	7	9	8	87
Evapotranspiration (mm)	10.0	12.4	27.8	46.6	75.0	105.8	137.2	125.0	87.4	51.8	22.1	12.0	713.1
Rainfall - Evapotranspiration (mm)	76.3	61.4	51.5	17.7	0.3	-55.3	-119.0	-106.0	-34.8	15.2	64.1	86.2	372.7
Mean Maximum Temperature (°C)	7.2	8.8	12.0	15.0	19.0	24.0	28.8	28.5	23.8	17.4	11.7	8.4	17.1
Mean Minimum Temperature (°C)	-0.3	0.4	2.8	5.3	8.7	12.2	15.3	15.1	12.4	8.0	3.5	1.0	7.0

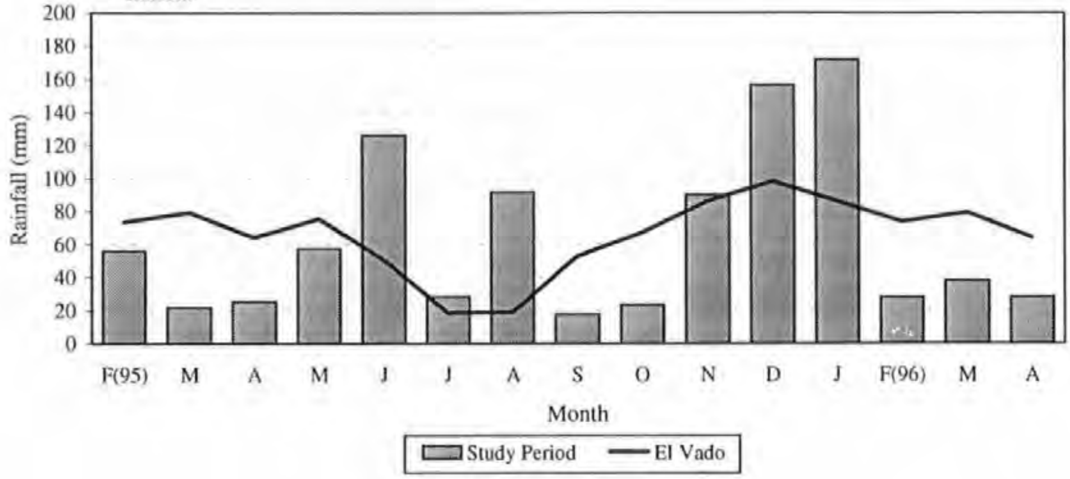
(Source : Elias-Castillo and Ruiz-Beltran 1981).

The maximum monthly temperature is 37.4°C (average 28.8°C) and the minimum monthly temperature is -12.6°C (average -0.3°C) (table 2.1). The occurrence of needle ice up to 6 cm in length was observed in January 1995 and January 1996.

Based on an annual gross precipitation of approximately 500 mm, Ternan *et al.* (1995) calculated an interception loss of 32% for the *Pinus* forest and 28% for the matorral shrub.

In addition to the meteorological data from El Vado, rainfall for the duration of the study period (February 1995 - April 1996) was recorded by an automatic data-logged rainfall gauge located approximately 400m from the forest gully catchment (figure 2.2). Figure 2.3 shows a comparison of the monthly rainfall recorded for the duration of the study period with the long term monthly rainfall recorded at El Vado.

Figure 2.3.Comparison of monthly rainfall recorded during the study period (February 95 - April 96) with average monthly rainfall (1942 - 1975) recorded at El Vado meteorological station.



Monthly rainfall during the study period was notably below average in the months of March, April, September and October compared to the long term average recorded at El Vado. The winter months of December and January were in contrast exceptionally wet (156 mm compared to 98.2 mm in December and 171 mm compared to 86.3 mm in January, figure 2.3). Local news reports suggested that the winter of 1995-1996 had been the wettest for 25 years. The most notable differences in monthly rainfall recorded during the study period when compared to the El Vado rainfall records occurred in June when rainfall was more than double (126 mm compared to 50.5 mm) and in August when rainfall was four times higher (91 mm compared to 19 mm) than the long term average.

A pilot study used to establish whether the recorded spatial patterns in soil moisture within an individual gully were related to spatial variations in rainfall, was undertaken for the period November 1994 - February 1995, using 6 manual raingauges distributed throughout the matorral gully and its watershed. For the period studied, no significant differences in rainfall were measured between gauges. The spatial variability in soil moisture recorded within the gully catchments is therefore not considered to be attributable to spatial variations in rainfall.

2.2 Geology

The study area is characterised by unconsolidated alluvial sediments of the Rana formation. Rana is a general term applied to any

"flat geomorphic surface with a detrital covering and with entrenched valleys at its margins" (Espejo-Serrano, 1985).

In Spain, the Rana formation covers approximately 400,000 ha and is found in large areas of the Iberian peninsula (Aragoneses and Garcia-Gonzalez, 1991). The sediments forming the Rana surface in the study area originated from the Guadarrama shale-quartzite mountain range to the northeast during markedly warmer climatic conditions than those of today (Garcia-Gonzalez and Aragoneses, 1990). The Rana surfaces are of Tertiary age belonging to the middle Pliocene epoch (Espejo-Serrano, 1985). River entrenchment into the Rana surface by the Rio Sorbe and the Rio Jarama and their tributaries occurred in the early Quaternary, creating a sequence of terraces separated by steeper, frequently gullied slopes (Espejo-Serrano, 1985; Ternan *et al.*, 1996a). Perez-Gonzalez and Gallardo (1987) have also suggested that the several platforms into which the Rana surface is divided may be attributed to neotectonic processes. On Mapa Geologica de Espana, Valdepenas de la Sierra (485 20-19 scale 1: 50000) the study area is located within mapping unit 28, which principally consists of fine sands, sands and siliceous conglomerates. Sediment horizons are generally yellow in colour indicating the presence of limonite - iron in an oxidised and hydrated form (Ireland *et al.*, 1939). Some red coloured horizons, which are usually sandy in texture, also occur indicating the presence of haematite - iron in an oxidised and non-hydrated form (Ireland *et al.*, 1939). These sediments are highly variable in terms of their texture ranging from gravel and coarse sediments, horizons of which may be 3-5m thick, to sediments dominated by silt and clay sized materials which may be found to form horizons up to 90m thick (Mapa Geologica de Espana – Valdepenas de la Sierra, 1990). Sands are predominately (65%) quartz and schist. In the Rana sediments of central Spain, Aragoneses and Garcia-Gonzalez (1991) have reported that smectite clay minerals are concentrated in coarse fractions. Beidellite, also a smectite clay mineral, was found in fine silt fractions, whereas montmorillonite was found in clay fractions (Aragoneses and Garcia-Gonzalez, 1991). All of these clay minerals have a 2:1 lattice structure and are therefore expandable clays, swelling upon wetting (Brady, 1990). Kaolinite (a non-expanding clay) however, was found to be the most abundant phyllosilicate within the Rana sediments (Aragoneses and Garcia-Gonzalez, 1991). Illite is also abundant within the Rana sediments and although this clay mineral has a 2:1 lattice structure it is considered to be relatively non-expanding (Mapa Geologica de Espana – Valdepenas de la Sierra, 1990; Brady 1990). Kaolinite is primarily dominant in surface horizons of the Rana sediments, whereas smectites are largely found in abundance in deeper horizons (Aragoneses and Garcia-Gonzalez, 1991). The sediments are generally horizontally interbedded and therefore form clear and distinguishable horizons, although erosional and depositional processes may also produce areas of colluvium. The variability of these sediments and their horizontal interbedding is best seen in the walls of gullies which have dissected hillslopes. In these gullies, the gully wall is often composed of several distinct horizons which may be repeated at different locations along the length of the gully and on both sides of the gully. Furthermore, the sediments may vary in their degree of compactness reflecting changes in past depositional environments and ongoing geomorphic processes. A large variation in the structural and textural composition of sediments may therefore be found within the study region and as a result it is expected that the hydrologic and geomorphic response of these sediments will also be variable.

2.3 Soils

The dominant soil type in the study area is an Alfisol, although Ultisols may also be found (Ibanez *et al.*, 1994). These soils may display hydromorphic characteristics and in particular show evidence of pseudogleying which occurs predominately in the distinctive argillic (clay rich, Btg) horizon of these soils, indicating poor drainage below the surface horizon (de Herrera and Quadrado, 1970; Gallardo *et al.*, 1987). The fine earth fraction (<2.00mm) is generally of silt loam texture although the gravel content (>2.00mm) varies greatly (Aragoneses and Garcia-Gonzalez, 1991; Ternan *et al.*, 1996b). Other soil properties may also vary. For example, Ternan *et al.* (1995) have reported that saturated hydraulic conductivity may vary from 21.2 mm hr^{-1} in bench terracing to 579 mm hr^{-1} under matorral landuse. Furthermore this magnitude of variation may be found within a single landuse (Ternan *et al.*, 1995). The bulk density of the soils has been found to vary from 1.35-2.17 g cm^{-3} (Ternan *et al.*, 1997). Considering the variation in these hydraulic properties it is not surprising that soil moisture was also found to be highly variable (4.7 – 49.5%) (Ternan *et al.*, 1997). The stability of soil aggregates has also been found to be highly variable ranging from 24 to 99% (R.S.S.I) (Ternan *et al.*, 1995). The organic carbon content of the soils is generally less than 2.5% and the organic matter content is less than 5% (Aragoneses and Garcia-Gonzalez, 1991; Ternan *et al.*, 1995). Aragoneses and Garcia-Gonzalez (1991) have reported that a general characteristic of Rana soils is the low content of organic materials. Where the vegetation cover is well developed, little runoff and erosion may be expected to occur from these soils. However, only a minor disturbance to this cover may be necessary to cause severe erosion (Ternan *et al*, 1995). The soils within this region may therefore be considered as vulnerable to runoff and erosion when exposed or disturbed (Ternan *et al.*, 1996a).

2.4 Vegetation and Land Use

During the 1920's and 1930's much of the study area was under cultivation and pastoralism (Garcia-Perez *et al.*, 1995). During this period inhabitants of the nearby village of Puebla de Valles, noticed an increase in surface runoff and that local rivers where responding rapidly, with sometimes dangerous flows, to rainfall events (Garcia-Perez *et al.*, 1995). In 1948 the Spanish government afforested 463 ha of this cultivated land with *Pinus nigra* which has now in many areas developed into a dense and mature forest with a thick covering of pine needle litter (Garcia-Perez *et al.*, 1995) (figure 2.2). Together with the construction of check dams sequentially along the lengths of some gullies the afforestation was principally for flow regulation and soil conservation rather than to crop the timber commercially (Ternan *et al.*, 1994; Garcia-Perez *et al.*, 1995). Social and economical changes in the 1960's and 1970's led to the abandonment of cultivation on steeper slopes, allowing the re-growth of semi-natural matorral scrub dominated by *Cistus spp.*, *Rosmarinus spp.*, *Thymus spp.* and in some places *Juniperus spp.* (Garcia-Perez *et al.*, 1995) (figure 2.2.). Due to the re-growth of matorral and the forest, local rivers were now more regular in their flow and less responsive to rainfall events (Garcia-Perez *et al.*, 1995). Limited grazing of the matorral scrub however, continues and although burning is rare some areas of matorral may be cleared to provide fresh shoots for grazing (Ternan *et al.*, 1995). Where perpetual disturbance to the matorral scrub occurs, irreversible degradation, preventing natural regeneration may result. As a consequence the proportion of matorral cover and its stage of development and thus the protection it offers to the underlying soil may vary from one area to another. Where the matorral cover is disturbed, severe runoff and erosion has been found to occur (Ternan *et al.*, 1996b). In 1980 - 1981 matorral land to the east of the Puebla de Belena - Tamajon road, which from aerial photographs appeared to be severely degraded, was mechanically bench terraced (Ternan *et al.*, 1996b) (figure 2.2). The principal aim of this bench terracing was for erosion control rather than for commercial purposes. The bench terraces were constructed using bulldozers on slopes up to 40^0. In the construction of bench terraces an angledozer is used to plough up the soil and deposit it at the side and a tiltdozer is used to create an inward tilting profile, producing a reverse slope terrace (Braquehais-Garcia *et al.*, 1989). The aim of reverse slope terraces is to retain ponded surface water at the riser-tread boundary of the terrace where it may infiltrate preventing the downslope flow of surface water. In this respect bench terraces act as mechanical barriers which prevent runoff from attaining an erosive velocity (Constantinesco, 1976; Schwab *et al.*, 1981; Das, 1981). Along the treads of the terrace all previously existing vegetation was removed. The treads were then subsoiled (2 lines) and left bare and exposed for up to 1 year before being planted with *Pinus pinaster* (R. Blanco, personal communication). Subsoiling was undertaken to loosen and break up compact subsurface soils to aid infiltration and tree growth. Remnants of the previous matorral cover remained on the risers of the terraces and although partially buried, have in many places since begun to re-colonise the treads. The *Pinus* trees planted along the treads show great variation in their growth and spatial coverage. Many have died or have stunted growth caused by a combination of drought, disease and soil toxicity (Ternan *et al.*, 1996b; A. Perez-Gonzalez, personal communication). It is not uncommon therefore, to find bare areas adjacent to well vegetated areas when walking along the terraces. In many areas the bench terraces have been poorly constructed and maintained and do not display the desired reverse slope. Instead many of the terraces have a forward and/or a lateral sloping tread which can feed erosive runoff into gullies, increasing gully activity (Ternan *et al.*, 1996b). In some instances lateral runoff along treads has led to the development of gullies along the length of the tread (Ternan *et al.*, 1996b). The effectiveness of bench terraces for erosion control in this environment has been questioned by Ternan *et al.* (1996b). Today, matorral scrub, *Pinus* afforestation and afforested bench terraces form the three principal land uses within the study area (figure 2.2).

2.5 Gully Catchment Descriptions

Although a detailed description of the gully catchments dimensions are given in chapter 3, a brief description of their location and morphology is presented here.

A first order, valley side, gully catchment was selected (see chapter 3 for selection criteria) in each of the different land uses. From here on these catchments are termed the matorral gully catchment, the forest gully catchment and the bench terrace gully catchment. The gully catchments within the forest and bench terraced area are developed in northeast facing slopes and the gully catchment within the matorral land use has developed in a southeast facing slope. Based on the classification of gully forms presented by Ireland *et al.* (1939), the lower half of the matorral gully catchment may be described as having a linear morphology which develops into a bulbous morphology in the upper half of the catchment (Plates 2.1 a, b and c). The bulbous morphology may be described as being semicircular or amphitheatre in shape (Ireland *et al.*, 1939), and is believed to result from incision into piping susceptible horizons (Ternan *et al.*, 1998). The forest gully catchment has a dendritic morphology which is both deep (>16m) and wide (>25m) (Plates 2.2 a and b). The forest gully has a large upslope catchment area which has a relatively dense stand of trees (Plate 2.2c). The bench terraced gully catchment may be described as having a linear morphology along its entire length which narrows towards the gully head. The watershed on either side of the gully's drainage channel has been bench terraced along with the walls of the gully which have approximately 2-3 terraces on each wall. The treads of the terraces within this gully catchment therefore follow the contour lines of the landscape and run parallel to the catchment channel. Within the bench terrace catchment several of the terraces are degraded and have forward and/or lateral sloping treads.

Plate 2.1. (a) View of the Matorral Gully Catchment.
(b) View of the Matorral Gully's upper bulbous shaped morphology.
(c) View of the Matorral Gully's lower 'V' shaped morphology.

(a)

(b)

(c)

Plate 2.2. (a and b) View of the Forest Gully.
(c) View of the Forest Gully's Catchment Watershed.

(a)

(b)

(c)

Plate 2.3. (a and b) View of the Bench Terrace Gully.

(a)

(b)

2.6 Conclusions

The landscape in which the badlands of Guadalajara are formed was suitably described by Ternan *et al.* (1995) as a

"*complex mosaic of different materials, vegetation and land management practices*".

This heterogeneity in the materials, vegetation and landforms of this area provides a suitable opportunity in which to study the nature and causes of variation in hydrologic and geomorphic response.

Chapter 3

Experimental Design, Field and Laboratory Methodology

Since all field methodology has to be related to the aims of the research, these are once more stated below:

3.0 Research Aims

1. To determine temporal and spatial variations in soil moisture at different spatial scales under different land uses.

2. To identify the relationships between these variations in soil moisture and factors known to control soil moisture, particularly soil physical properties, topographic position, vegetation characteristics and land use.

3. To examine whether the primary controlling factors change as the scale of measurement changes *eg*. does the primary factor important in explaining the spatial and temporal variations in soil moisture at the small scale become secondary or redundant at the larger scale? Alternatively are the factor(s) determining soil moisture variability scale-independent?

4. To identify zones of potential surface runoff (source areas) from the spatial patterns of soil moisture.

5. To understand the hydrological functioning of gullied catchments through the determination of the continuity of overland flow pathways and subsequently the potential for the occurrence of widespread runoff based on the spatial sequence of source areas and the existence of critical thresholds

6. To determine whether the spatial extent and severity of erosion is related to the spatial pattern of soil moisture and the development of continuous overland flow pathways.

7. To identify the implications and research needs for the hydrological monitoring and management of areas displaying heterogeneity in hydrological response.

3.1 Field Methodology

Spatial variations in soil moisture are most likely to be greatest where the known factors controlling soil moisture are also spatially varied ie. a spatially uneven vegetation cover and uneven topography exposing several varying soil textures is likely to show a greater spatial variation in soil moisture than a uniform slope with a uniform vegetation cover. Gullies as compared to inter-gully zones represent areas where topographical non-uniformity is greatest. They also represent areas where several differing lithologies may be exposed through dissection. Gullies also have a greater spatial variation in vegetation cover compared to the more stable inter-gully areas. Therefore gullies when compared to inter-gully zones have a greater range in variation of the factors known to control soil moisture and hence are expected to be areas showing high spatial and temporal variations in soil moisture. Gullies are also areas of active erosion and pose the greatest threat, through headward extension and lateral expansion to the surrounding and potentially productive inter-gully zones. Gullies therefore, represent areas in need of critical soil conservation management. Hence gullies and their contributing watersheds were chosen as the most appropriate areas in which to fulfil the research aims outlined in section 3.0.

Three gullies and their catchment areas, one in each land use, as described in Chapter 2 (matorral gully, forest gully, bench terrace gully), were selected on the basis of the following criteria, the first three of which are aimed to maximise the variation in those factors believed to be controlling soil moisture distribution :

1. Each gully should have a high degree of lithological variation in terms of its texture, compactness and thickness of sedimentary horizons.

2. Each gully should have a spatially non-uniform vegetation cover so that both bare and vegetated areas are represented.

3. Each gully should show a range of topographical characteristics including, slope gradient, profile and form.

4. The catchment area of each gully should be similar.

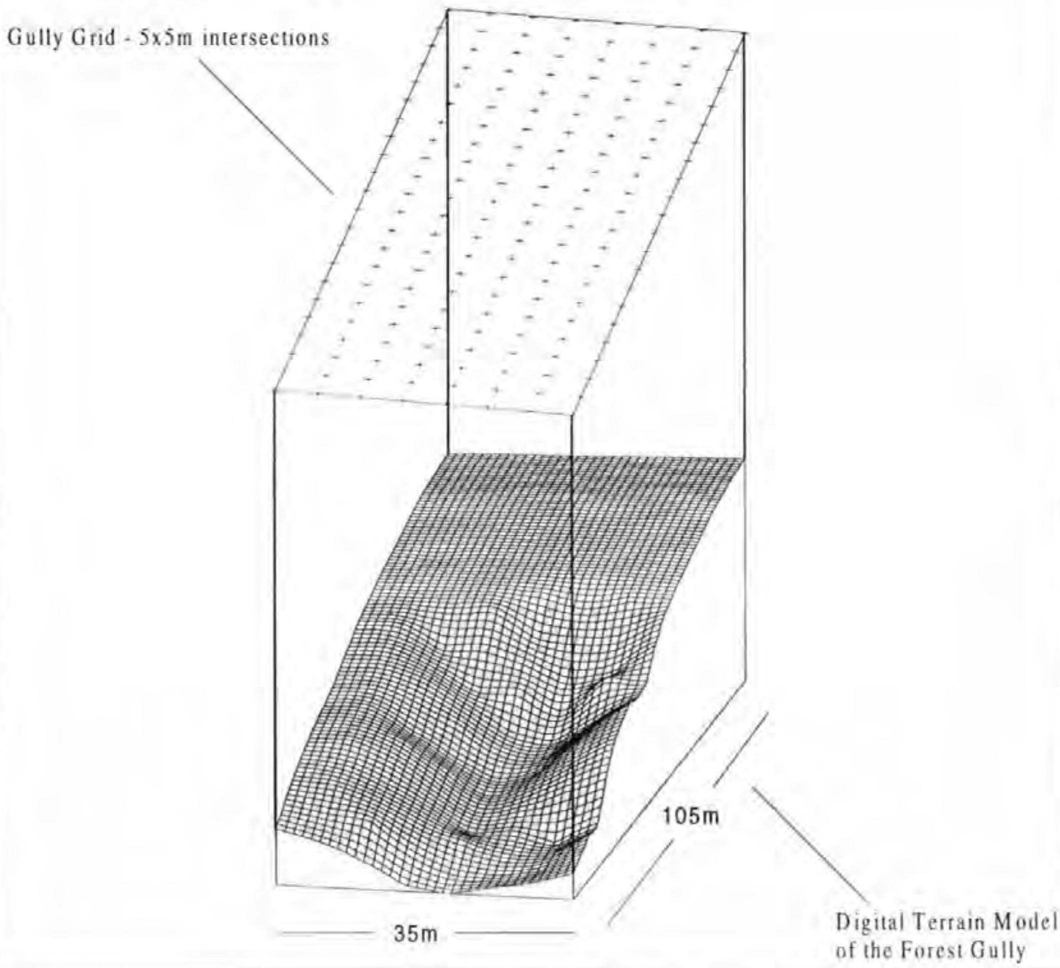
5. Each gully should be located within the same geological unit as represented on the Mapa Geologica de Espana (1:50,000) Valdepenas de la sierra.

6. Taking the above into consideration each gully should as far as possible be representative of other gullies in its land use type.

3.2 Soil Moisture Measuring Network

In order to characterise the spatial variability in soil moisture across a gully catchment, the sampling strategy needed to be one which gave complete spatial coverage of the catchment. Complete and equal spatial coverage of an area is best achieved using a grid sampling strategy. This is also preferable and advantageous in later geostatistical analysis of the data set. According to Trangmar *et al.* (1985) and Webster and Oliver (1990), regular sampling based on an equilateral triangle design is the most efficient for geostatistical analysis. However, regular sampling based on square or on rectangular grids will also give acceptable levels of precision, with the advantage over equilateral triangles in that they are easier to construct (Trangmar *et al.*, 1985; Webster and Oliver, 1990). A grid sampling system also allows easier identification of anisotropy within the data set. The sampling of soil moisture content was therefore based on a rectangular grid constructed over each of the gullies and their watersheds (from here on termed as gully grids), with each point in the grid separated by a distance of 5m (figure 3.1). Although these gully grids were laid down as unit ground lengths in the field, within this thesis they have been displayed as artificial rectangular grids so as to remove distortion of the grids resulting from uneven terrain and so allowing for an easier interpretation of spatial patterns. However, the use of artificial rectangular grids causes displacement of the grid points as compared to their true ground positions. The degree of displacement between the true grids as laid down in the field and the artificial rectangular grids used in this thesis are detailed in appendix 1 (page 264). A location marker (a wooden stake) was inserted at each 5m intersection on the gully grids. The TDR rods were at a sufficient enough distance from the stakes to be unaffected. These markers also acted as erosion pins allowing the spatial measurement of erosion across each gully grid. Therefore both soil moisture and erosion/deposition were recorded at the same sampling location and at the spatial scale of 5m across the gully grids.

Figure 3.1. Construction of a rectangular grid over the forest gully.



To characterise soil moisture variability at different spatial scales a nested sampling strategy was adopted. According to Vieira *et al.* (1981), Wilding (1985), Webster and Oliver (1990), Oliver and Webster (1991) and Burrough (1993) a nested sampling design is the best and most efficient sampling strategy which can be used to identify spatial and temporal structures. It also has the advantage over other sampling designs in that "*several orders of magnitude of scale can be covered in one design to reveal the approximate scale of spatial variation*" (Oliver, 1987; Oliver and Webster, 1991).

Nested sampling strategies designed specifically for measuring variations in soil water content have been used by Tomer and Anderson (1995) and Nyberg (1996). After the first measurement of soil moisture content for all three gully grids it was clear that soil moisture could vary considerably over a distance of less than 5m. To characterise and explain this small scale variability in soil moisture a second grid (from here on termed a minigrid), nested within a 5x5m cell of the gully grid was constructed with sampling intervals of 1m. The 5x5m cells of the gully grids chosen for the location of the minigrids were selected where variability in soil moisture was high between the four 'anchor' points of the gully grid (anchor points are the four sampling locations which make up a 5x5m cell within the gully grid - see figure 3.2 for a visual explanation). The cells selected for the minigrids were therefore areas displaying considerable short range variability in soil moisture, which could not be characterised and explained by a 5x5m sampling strategy. Erosion/deposition was not measured within the minigrids because of the closeness of the sampling points, which would have resulted in too much disturbance when measured. To characterise soil moisture variability at a larger spatial scale, an 800m long transect line was constructed linking the forest gully grid to the matorral gully grid. Soil moisture was sampled at 25m intervals along this transect line (figure 3.2).

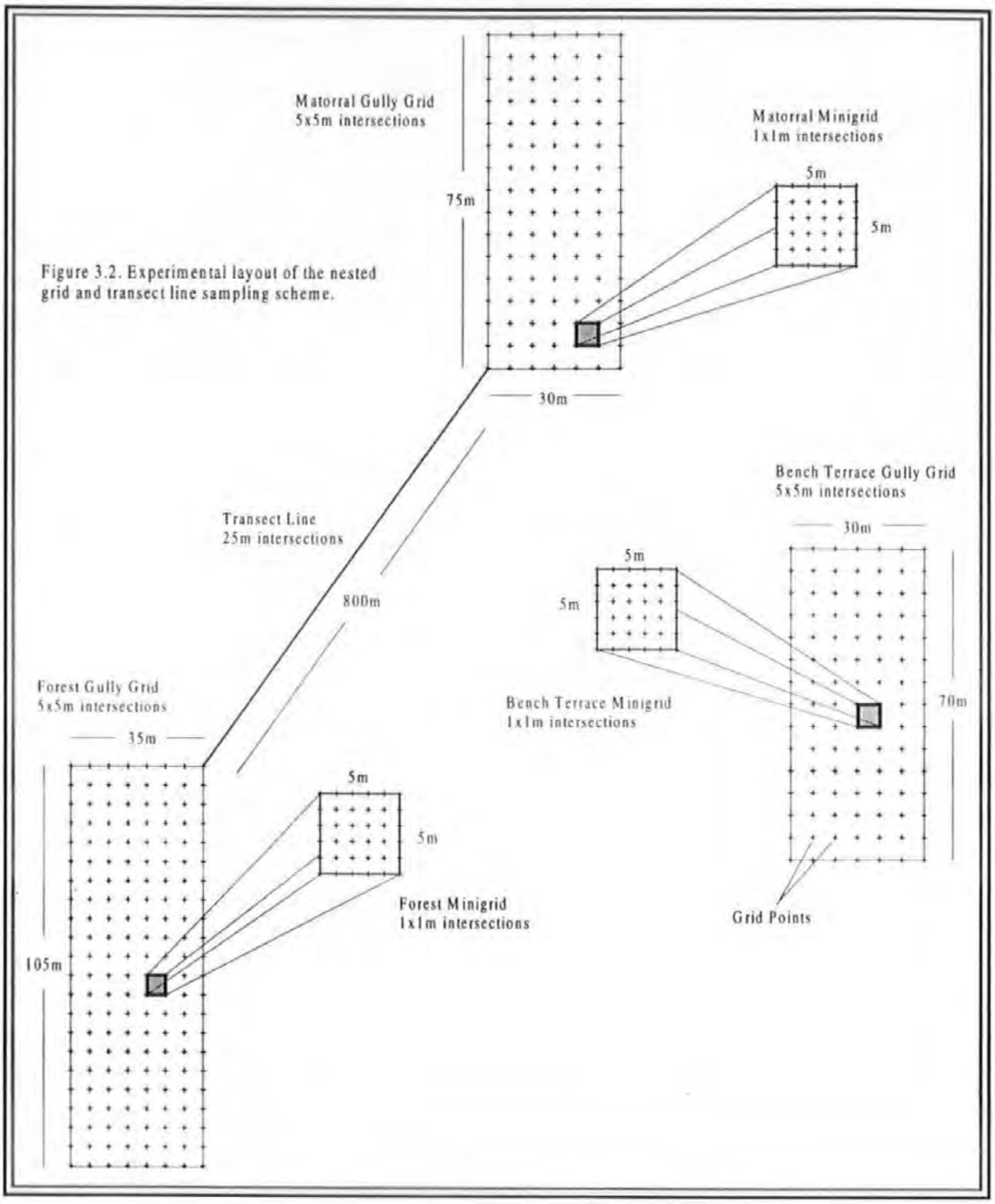


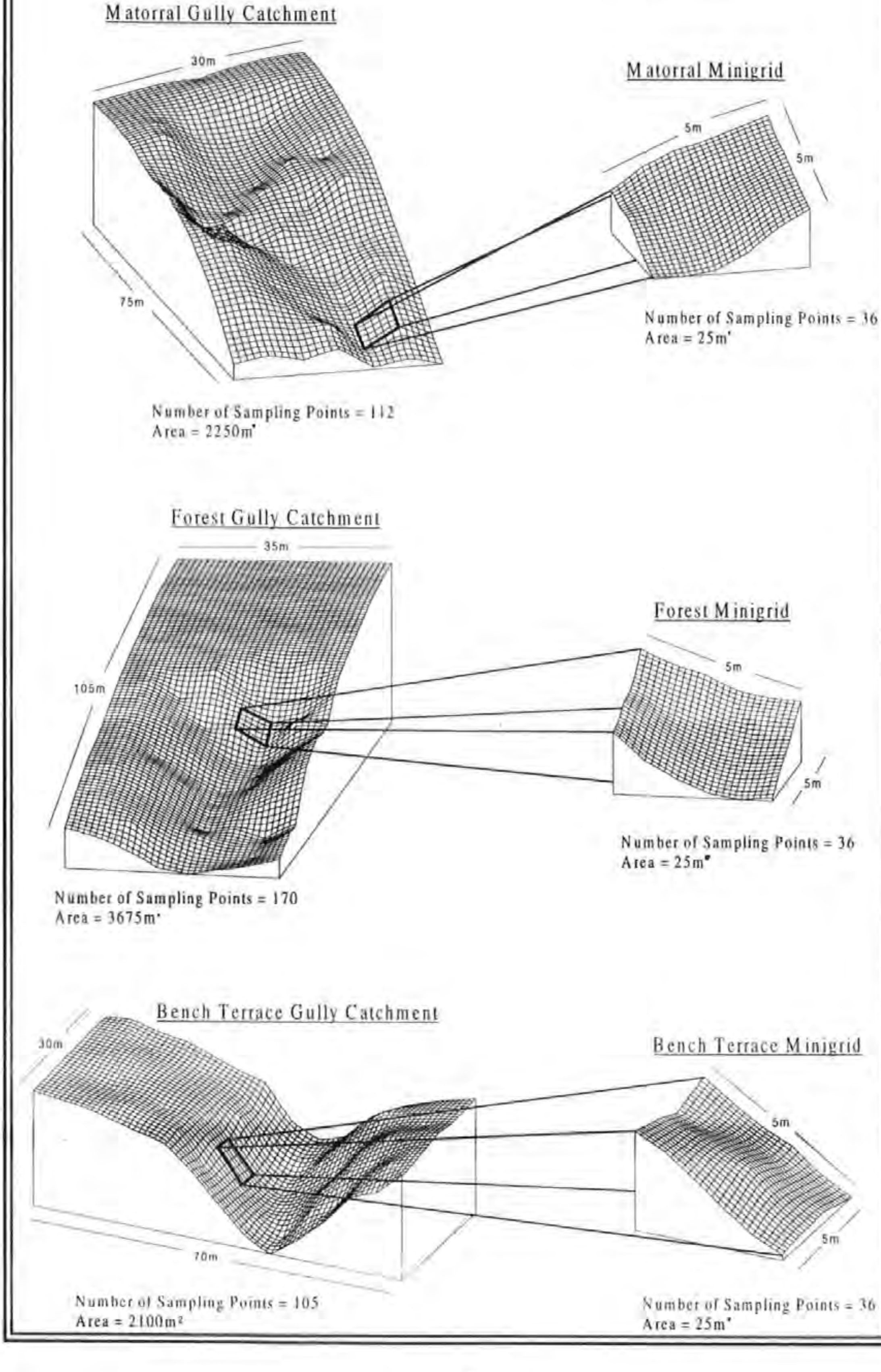
Figure 3.2. Experimental layout of the nested grid and transect line sampling scheme.

Soil moisture content was therefore measured at 528 points covering three spatial scales, these being 25m, 5m and 1m, using a nested grid and transect line sampling strategy. Erosion/deposition was measured at one spatial scale, this being at the gully grid scale, 5x5m. A summary of the grids/transect lines dimensions, the spatial scales studied and the number of sampling points used in the soil moisture measuring network is given in table 3.1 and figure 3.3.

Table 3.1. Summary of the grid/transect dimensions, spatial scales and the number of sampling points used in the soil moisture measuring network.

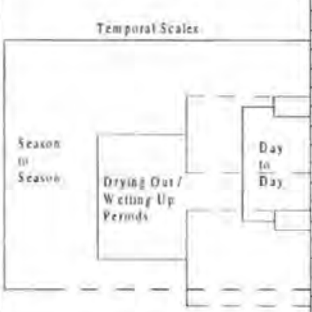
Sample Location	Spatial Scale	Length (m)	Width (m)	Area (m^2)	N° of Sampling Points
Matorral Gully Grid	5x5m	75	30	2250	112
Forest Gully Grid	5x5m	105	35	3675	170
Bench Terrace Gully Grid	5x5m	30	70	2100	105
Minigrids	1x1m	5	5	25	36
Transect Line	25m	800	------	------	33
Total	------	------	------	------	528

Figure 3.3. Digital terrain models of the three gully catchments and the minigrids, showing the location of the minigrids within each gully catchment.



To ensure soil moisture values were comparable between gullies and between scales, all 528 sampling points were measured within the same day with the exception of March 8, May 20, July 11, January 26,27,28 and February 1 (table 3.2), when equipment failure or poor weather conditions inhibited the measurement of all sampling points. Given these exceptions, comparable soil moisture values were recorded on 16 occasions between gully grids and minigrids and on 13 occasions between all sampling points at all scales (table 3.2). This temporal sampling strategy permitted variability at different temporal scales (daily, seasonal, drying out/wetting up) to be evaluated (table 3.2)

Table 3.2. Examples of the temporal scales of measurement and the dates for each site when soil moisture was recorded.



Date	Matorral Gully Grid	Forest Gully Grid	Bench Terrace Gully Grid	Matorral Minigrid	Forest Minigrid	Bench Terrace Minigrid	Transect Line
March 8 1995		✓					
May 20 1995	✓			✓	✓		✓
July 11 1995	✓	✓	✓	✓	✓	✓	
September 8 1995	✓	✓	✓	✓	✓	✓	✓
September 14 1995	✓	✓	✓	✓	✓	✓	✓
October 27 1995	✓	✓	✓	✓	✓	✓	✓
October 28 995	✓	✓	✓	✓	✓	✓	✓
October 30 1995	✓	✓	✓	✓	✓	✓	✓
November 1 1995	✓	✓	✓	✓	✓	✓	✓
November 4 1995	✓	✓	✓	✓	✓	✓	✓
January 26 1996	✓		✓				
January 27 1996	✓	✓	✓	✓	✓	✓	
January 28 1996	✓	✓	✓	✓	✓	✓	
January 30 1996	✓	✓	✓	✓	✓	✓	✓
Febuary 1 1996	✓						
Febuary 2 1996	✓	✓	✓	✓	✓	✓	✓
Febuary 4 1996	✓	✓	✓	✓	✓	✓	✓
March 28 1996	✓	✓	✓	✓	✓	✓	✓
March 30 1996	✓	✓	✓	✓	✓	✓	✓
April 1 1996	✓	✓	✓	✓	✓	✓	✓

✓ = indicates when soil moisture was measured.

3.3 Field Measurements

3.3.1 Soil Moisture Measuring Technique - Time Domain Reflectometry (TDR)

It was essential that the technique used to measure soil moisture content comply with the following criteria:

1. Since soil moisture (and erosion) at the same location were to be recorded through time, a measuring technique which involved non-destructive sampling and minimal disturbance was required.

2. With over 500 measuring points located over a 1 km^2 area to be measured within one day, a rapid, reliable and portable measuring technique is essential.

The sampling technique chosen for soil moisture determination and which met the above criteria was Time Domain Reflectometry (TDR).

Time Domain Reflectometry (TDR) has become a popular and widely used technique for rapid, reliable and routine monitoring of *in situ* volumetric soil water content (Topp and Davis, 1985; Dalton and Van Genuchten, 1986; Zegelin *et al.*, 1989; Topp *et al.*, 1982b; Rajkai and Ryden, 1992; Knight, 1992; Whalley, 1993; Jacobsen and Schjonning, 1993a). Its suitability for making large numbers of field measurements and for monitoring soil water content over long periods of time makes TDR especially attractive for studies detailing spatial and temporal variations in soil water content (Topp *et al.*, 1982b; Dalton and Van Genuchten, 1986; Rajkai and Ryden, 1992). Rajkai and Ryden (1992) have concluded that

"TDR is a technique with which the spatial variation of soil moisture content can be studied with sufficient efficiency on an approximate spatial scale".

The increasingly preferential use of TDR over other techniques such as gravimetric sampling and the neutron probe, for the determination of soil moisture content stems from the overwhelming advantages associated with TDR compared to these other techniques. In comparison to gravimetric sampling the TDR is non-destructive and hence allows the same site to be monitored over time, it is less time consuming, is more suitable to large scale studies, allows continuous measurement throughout a precipitation event providing detailed information on infiltration and water distribution in the soil profile and provides immediate results on soil water content. In comparison to the neutron probe some of the advantages of TDR outlined above apply again in addition to the ability to measure close to the soil surface, having a '*universal*' calibration equation (see below), having no radiation hazard, results in less disturbance to the soil and is more flexible and convenient allowing a wider application to field studies (Topp *et al.*, 1980; Topp and Davis, 1985; Dalton and Van Genuchten, 1986; Zegelin *et al.*, 1989; Nielsen *et al.*, 1995).

The principal of time domain reflectometry is founded upon the unique relationship existing between the dielectric constant of soils and the volumetric moisture content, whereby the dielectric constant of soil is primarily related to water content (Topp *et al.*, 1980, 1982a, 1982b; Rajkai and Ryden, 1992; Knight, 1992; Whalley, 1993; Heimovaara and de Water, 1993). Therefore a

"*simple and reliable measurement of the dielectric constant................ would be a practical and effective measure of soil water content*" (Topp *et al.*, 1982a).

The dielectric constant of soil can be determined by measuring the propagation velocity of electromagnetic waves through the soil surrounding the transmission line probes embedded in the soil (Topp *et al.*, 1980, 1982a; Knight, 1992; Whalley, 1993). When the transmission line probes are of known length, the velocity of an electromagnetic wave can be determined by measuring the time for the wave to travel the known length of the probes (Topp *et al.*, 1982a; Knight, 1992; Rajkai and Ryden, 1992; Whalley, 1993). The dielectric constant can thus be found by:

$$Ka = (ct/L)^2 \quad (1)$$

where Ka is the dielectric constant, c is the speed of light (3×10^8 m sec^{-1}), t is the travel time and L is the length of the transmission probe (Topp *et al.*, 1982a). Once Ka has been determined the volumetric water content θ_v can be found using an empirical polynomial equation proposed by Topp *et al.* (1980):

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} Ka - 5.5 \times 10^{-4} Ka^2 + 4.3 \times 10^{-6} Ka^3 \quad (2)$$

Equation (2) was shown by Topp *et al.* (1980, 1982a) to be valid regardless of soil type (sandy loam - clay), soil density (1.04 - 1.44 g cm^{-3}), soil temperature, soluble salt content and even valid for an organic soil (range in organic matter for mineral soil was 1-6%), when measured at a range of water contents from air dry to saturation. The standard error of the estimate for this equation and all the soils used in the study was only 1.3% (Topp *et al.*, 1980). Because of its apparent validity in a range of soil types and under different conditions of wetness, this equation was considered '*universal*' (Knight, 1992; White *et al.*, 1994). Jacobsen and Schjonning (1993a) have claimed to have improved the equation for θ_v proposed by Topp *et al.* (1980) by including linear terms of dry bulk density, organic matter and clay content. However these improvements were

"*small compared with the uncertainty of the measurement of dielectric constant and of water content determined gravimetrically*" (Jacobsen and Schjonning, 1993a).

When using field data the inclusion of bulk density in the calibration resulted in no improvement of the Topp *et al.* (1980) equation (Jacobsen and Schjonning, 1993b). Dasberg and Hopmans (1992) and White *et al.* (1994) have reported that the equation proposed by Topp *et al.* (1980) is only applicable to coarse textured soils and that fine textured soils have a lower dielectric constant at the same water content compared to coarse textured soils and hence the calibration will be different to that proposed by Topp *et al.* (1980). Robinson *et al.* (1994) have further reported that the presence of iron minerals, in particular magnetite can influence soil dielectric constant significantly as measured by TDR. The dielectric constant is greatly effected in the presence of 15% magnetite and the TDR signal most affected during wet conditions (Robinson *et al.*, 1994).

In uniformly wet soils the TDR technique has been shown to provide accurate determination of the soil water content (Topp *et al.*, 1980). The TDR technique has also been shown to give accurate average water contents over a given depth even when the water is not uniformly distributed over that depth (Topp *et al.*, 1982a). The water content measured by TDR was found to give the same as average water content to within 1% in extremely non-uniform conditions (Topp *et al.*, 1982a). The TDR technique was also found to be useful in detecting and monitoring the progression of wetting front advance through the soil (Topp *et al.*, 1982a). Topp *et al.* (1982a) have reported that large changes in soil moisture with depth along the transmission probes results in a noticeable trace (reflection) on the TDR wave form. Nadler *et al.* (1991) and Dasberg and Hopmans (1992) have however, reported difficulties in wave form interpretation when the transmission probes were inserted in soil with abrupt changes in water content leading to sometimes considerable errors in the estimation of soil water content.

Soil moisture contents determined by the TDR technique can be correlated and thus the TDR calibrated by taking adjacent gravimetric samples and determining the volumetric soil water content for these samples. Topp *et al.* (1982b) found that differences in soil moisture content between the TDR and gravimetric samples were always less than 3%. Dasberg and Dalton (1985) and Nielsen *et al.* (1995) found a correlation of r = 0.84 between TDR and gravimetrically determined soil moisture contents. Nyberg (1996) reported a correlation of 0.5 between TDR and gravimetrically determined soil moisture content and accepted this as a validation of the TDR's accuracy. Rajkai and Ryden (1992) reported a small but still significant correlation of r = 0.32 between TDR and gravimetric soil moisture data. Dasberg and Dalton (1985) and Jacobsen and Schjonning (1993b) have suggested that differences between gravimetrically determined soil water content and the TDR may be due to spatial variability in soil structure and/or texture in the horizontal planes of the measuring volumes. All points in the sample volume of the gravimetric method are given the same weight whereas the measuring sensitivity (see below) of TDR is highest in a small volume around the probes (Jacobsen and Schjonning, 1993b). Therefore small scale variation in soil structure ie. root channels, cracks and texture ie. stones around the TDR probes might result in high variations in TDR measured soil moisture content (Jacobsen and Schjonning, 1993b). Differences between the TDR and gravimetric water contents does not imply that either measurement is in error, but only that each is measuring a different volume (Jacobsen and Schjonning, 1993b).

"A critical question which arises when using the TDR technique is: what is the volume of the surrounding soil over which soil water content is sampled?" (Knight, 1992).

Baker and Lascano (1989) have reported that it is also necessary to know what the spatial distribution of probe sensitivity is within the volume measured. Baker and Lascano (1989) and Knight (1992) have reported that for parallel wire probes, measurement sensitivity is concentrated close to the probes. Baker and Lascano (1989) have reported that the sensitivity of two parallel probes 5 cm apart and 0.3175 cm in diameter, was largely confined to a quasi-rectangular area of approximately 1000 mm^2 surrounding the waveguides. Beyond this area, sensitivity is lower, but does extend to an area of approximately 4000 mm^2 (Baker and Lascano, 1989). Little variation in sensitivity was found along the length of the transmission probes (Baker and

Lascano, 1989). Knight (1992) and White *et al.* (1994) have reported that the spatial sensitivity of TDR probes is a function of the ratio between wire spacing and wire diameter. If the probe diameter is small compared to the spacing of the probes then sensitivity is strongly concentrated around the probe to the point of a '*skin effect*' and large errors can occur if the probes are not in contact with the soil ie. air gaps (Baker and Lascano, 1989; Knight, 1992). Therefore the probe diameter should be as large as possible compared to probe spacing (Knight, 1992). However, thin probes are more desirable because of easier insertion into the soil and minimal soil compaction and disturbance (Knight, 1992; Topp and Davis, 1985). In recognition of this dilemma, Knight (1992) has recommended that the ratio of probe spacing to probe diameter should not be greater than 10. White *et al.* (1994) recommended that probe diameter should be at least 10 times the mean pore size or particle size.

The configuration of TDR probes is commonly in the form of a two wire parallel probe, although Zegelin *et al.* (1989) have presented a three and four wire probe (Topp *et al.*, 1980, 1982a, 1982b; Topp and Davis, 1985; Knight, 1992; Whalley, 1993). The choice of probe configuration will be dependent upon the spatial sensitivity of the probe, its reliability, ease of insertion, simplicity, robustness, degree of soil disturbance and cost of manufacture (Topp and Davis, 1985; Knight, 1992; White *et al.*, 1994). Zegelin *et al.*, (1989) have reported that three and four wire probes are more reliable, more accurate and produce a sharper signal which is easier to interpret than two wire probes. However the four wire probe is disadvantaged in that its insertion causes greater soil disturbance than two wire probes (Zegelin *et al.*, 1989). Knight (1992) has reported that two wire probes are better suited to field use. Nadler *et al.* (1991) and Dasberg and Hopmans (1992) have compared two wire probes with three wire probes and concluded that both give similar results and are equally adequate in determining field soil moisture contents.

3.3.1.1 Procedure used in this Research

At each measuring point for all scales soil moisture was measured using time domain reflectometry (TDR). A Tektronix 1502c TDR cable tester was used to generate and display the TDR waveforms. The point of waveform reflection was determined visually in the field. Two parallel TDR rods (length 15 cm, diameter 0.3

cm, spacing 4-5 cm) (two-wire parallel probe) were inserted vertically, but perpendicular to the soil surface and remained in the soil permanently, allowing consecutive measurements over a period of time for the same location with minimal disturbance. Since the TDR rods are 15cm in length, only the soil moisture of the upper 15cm of the soil was measured. In a environment were surface processes dominate, the measurement of only the near-surface properties is considered appropriate. Soil moisture was calculated using the equation proposed by Topp *et al.* (1980). To validate the use of this equation with the soils found in this environment a sub-sample of TDR derived soil moisture values were correlated with gravimetrically determined soil moisture values (Gardner *et al.*, 1991). The results of this correlation are presented below in table 3.3 and described in section 3.3.1.2. All TDR rods were located between 15 and 25 cm from the sample location marker/erosion pins.

3.3.1.2 TDR Calibration

The cores taken for the determination of saturated hydraulic conductivity and bulk density (section 3.3.8.4) were also used to calculate volumetric soil water content which can be compared to TDR derived volumetric soil water content and thus used to calibrate the TDR (Topp *et al.*, 1982b; Dasberg and Dalton, 1985; Gardner *et al.*, 1991; Rajkai and Ryden, 1992; Nielsen *et al.*, 1995; Nyberg, 1996). Immediately before the insertion of sample cores in the field, volumetric soil water content was measured at the grid points using TDR . After extraction, the cores were weighed in the field using a portable electronic balance. Once the cores were oven dried, volumetric soil water content at the time of sampling could be calculated. The equation below was used to calculate volumetric soil water content for the cores.

$$\theta_V (\%) = \frac{\text{field soil weight (g) - oven dry soil weight (g)}}{\text{soil volume (cm}^3\text{)}} \times 100 \quad (3)$$

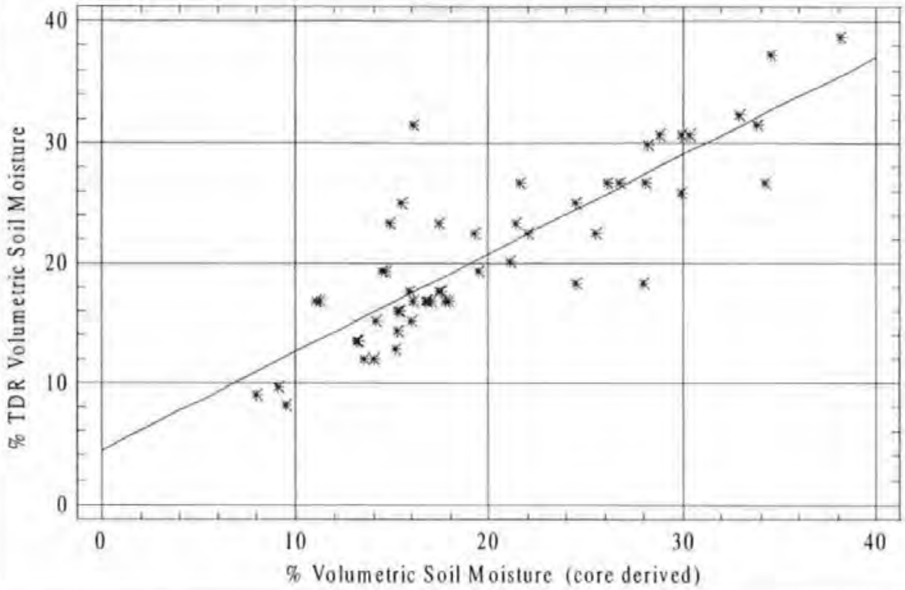
Table 3.3 and figure 3.4 shows a correlation of 0.85 between TDR derived soil moisture using equation 2 (Topp *et al.* 1980) and volumetric soil moisture based on all 53 samples. This result is in accordance with the 0.84 correlation found between TDR and gravimetric determined soil moisture, reported by Dasberg and Dalton (1985) and Nielsen *et al.* (1995). The highest correlation 0.95, between TDR and volumetric soil moisture is found between samples taken from the matorral gully. Soil moisture values from the bench terrace gully samples show the poorest correlation 0.76, although this is still significant at the 95% confidence interval. The small differences in soil moisture which occur between TDR and volumetric values may be caused by the sample location of the cores used for determining volumetric soil moisture. The cores could not be taken in exactly the same location as the TDR rods, but were located within an area $0.3m^2$ centred on the TDR rods. Therefore small differences in the structure and texture of the soil measured by the TDR and that measured by the cores may account for the differences in soil moisture obtained by these techniques. Other possible causes of the differences in soil moisture values between TDR and core derived volumetric soil moisture were outlined in section 3.3.1, page 53.

Table 3.3. Calibration of the TDR using correlation between TDR derived volumetric soil moisture and volumetric soil moisture derived from soil cores.

Gravimetric / TDR Soil Moisture	TDR S.M. Matorral	TDR S.M. Forest	TDR S.M. Bench Terrace	TDR S.M. All Data
Gravimetric S.M. - Matorral (16 samples)	0.95*	------	------	------
Gravimetric S.M. - Forest (21 samples)	------	0.86*	------	------
Gravimetric S.M. - Bench Terrace (16 samples)	------	------	0.76*	------
Gravimetric S.M. - All Data (53 samples)	------	------	------	0.85*

* = significant at $p<0.05$ (95%).
S.M. = soil moisture.

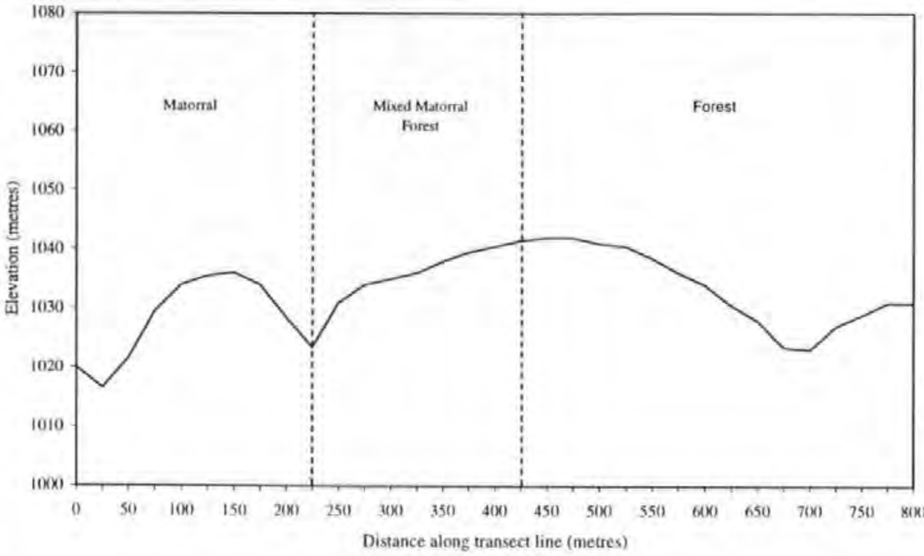
Figure 3.4. Calibration of the TDR using regression analysis between TDR derived volumetric soil moisture and volumetric soil moisture derived from soil cores.



3.3.2 Topographic Characteristics

An Electronic Distance Measurer (EDM) was used to survey each sampling point on both the gully grids and the minigrids. From this data, height, slope angle, slope length and topographic location can be determined. This data was used to derive the digital terrain models (DTM's) for each gully grid and minigrid, shown in figure 3.3. The altitude of sampling points along the transect line was recorded using an electronic altimeter (accurate to 50 cm). The resulting topographical profile of this transect line is shown in figure 3.4.

Figure 3.5. Topographic profile of the transect line.



3.3.3 Vegetation Cover

Percentage vegetation cover and litter cover was estimated for an area $0.5m^2$ centred on the sample location marker/erosion pins, for all sampling points in the gully grid.

3.3.4 Rainfall Characteristics

Rainfall characteristics (volume, intensity, duration) for the study period were recorded by a single data logged rainfall gauge located within 400m of the study sites (figure 2.2, section 2.0, Chapter 2).

3.3.5 Erosion/Deposition

Erosion/deposition was recorded using erosion pins located at every sampling point on the gully grids on four occasions throughout the study period:

July 11 1995
November 2 1995
February 3 1996
March 29 1996

3.3.6 Soil Physical Properties

Due to the inevitable disturbance caused by sampling for soil physical properties, no samples of this nature were taken until the end of the study period (April 1996) after all soil moisture and erosion pin measurements were completed. As it was clearly impractical to analyse samples from all 528 soil moisture monitoring points a sub-sampling strategy had to be devised.

3.3.6.1 Sub-sampling Strategy

3.3.6.2 Particle Size Distribution - Soil Texture

Due to practical constraints, only 124 sample points were analysed for soil texture using a combination of dry sieving and laser diffraction. These sample points are located either within the gully grid or the minigrid (figure 3.6). None of these 124 points are taken from the transect line. All samples collected for soil textural analysis were located within a $0.1m^2$ area centred on the TDR rods ie. the soil volume between and immediately surrounding the TDR rods.

3.3.6.3 Organic Carbon and Aggregate Stability

Organic carbon and aggregate stability determination were carried out for subsamples of the 124 samples used in the determination of soil texture (figure 3.6). These samples were therefore also located within a $0.1m^2$ area centred on the TDR rods.

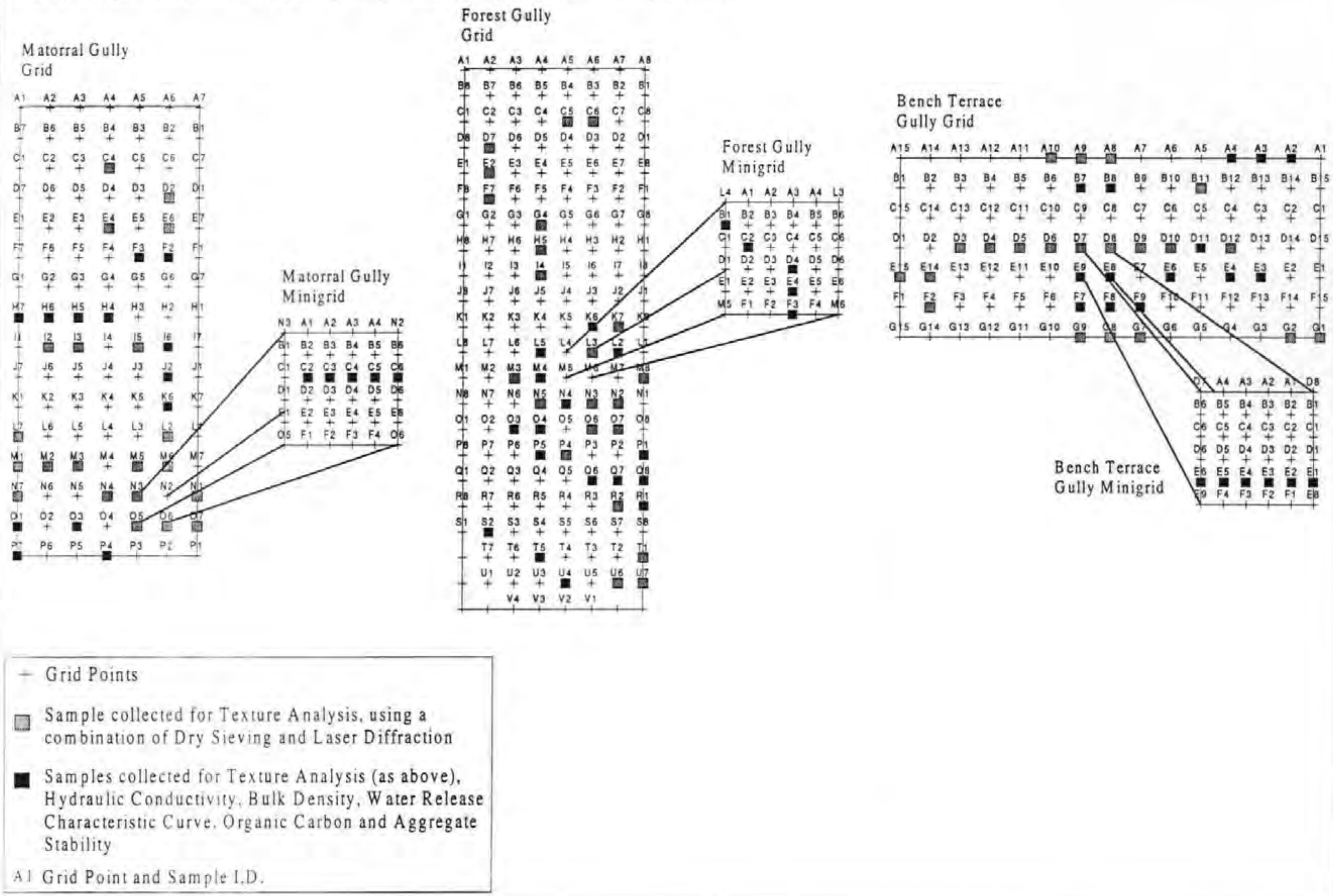
3.3.6.4 Soil Water Release Characteristic Curve, Saturated Hydraulic Conductivity and Dry Bulk Density

The soil water release characteristic curve was determined from undisturbed 54 mm diameter x 30 mm (68 cm^3) deep cores collected using an American Pitman corer. Due to practical constraints only 60 measuring points were sampled. These 60 measuring points were in the same location as 60 of the 124 points sampled for texture, organic carbon and aggregate stability (figure 3.6). At each measuring point a surface (0-3 cm) and a sub-surface (4-7 cm) sample core was taken, resulting in a total of 120 individual cores.

Saturated hydraulic conductivity (K_{sat}) and bulk density were determined from undisturbed 9.9 cm diameter x 12.7 cm (977 cm^3) deep cores extracted at the same location as the 60 points sampled for the soil water release characteristic curve (figure 3.6).

All sample cores were located as close to the TDR rods as possible. In some cases however sub-surface stones and roots made sampling adjacent the TDR rods impossible. However, all sample cores were located within a 0.3m^2 area centred on the TDR rods.

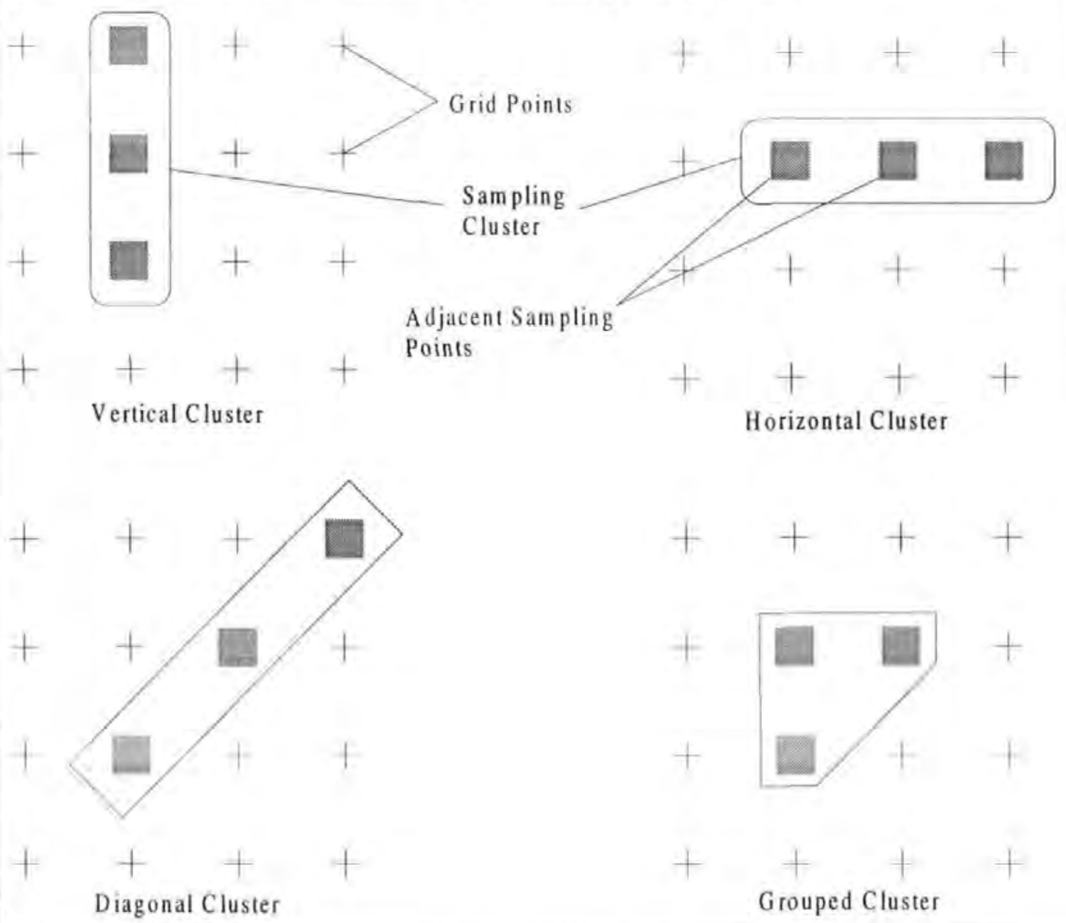
Figure 3.6. The location of samples taken for the determination of the soils physical and hydrological properties within the gully grids and minigrids (sub-sampling strategy)



3.3.6.5 Criteria for the Location of the Field Samples

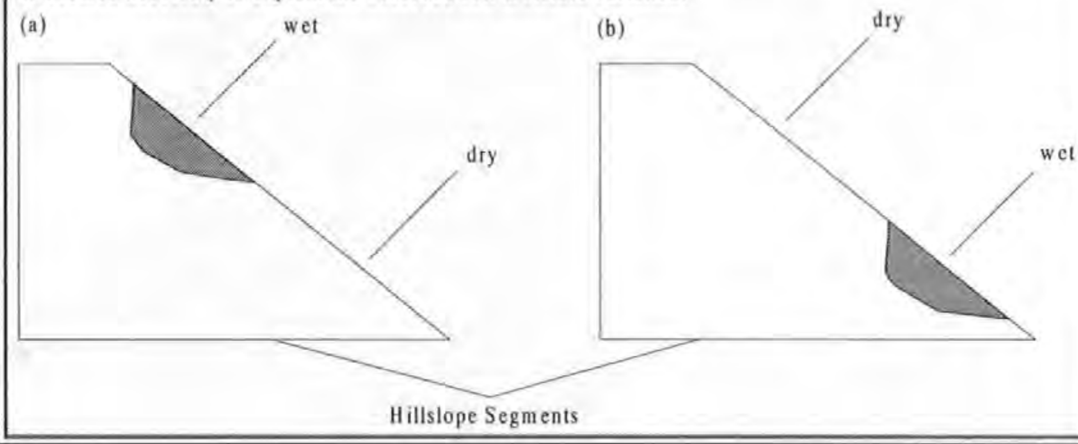
The location of a measuring point for the sampling of the soil's physical properties was not in isolation compared to the location of other measuring points. A sample taken in isolation from its surrounding points would give no information as to why its soil moisture content differs from the surrounding points. At the gully grid scale, excluding those samples which form the borders of the grid, every grid point is immediately surrounded by a further eight grid points (figure 3.7). If the central grid point is to be sampled for the soil's physical properties, then at least one other grid point either in the vertical, horizontal or diagonal plane, should also be sampled so as to determine whether the differences in soil moisture between the two point's is attributable to differences in the point's soil physical properties (figure 3.7).

Figure 3.7. Field samples were taken in small clusters from adjacent grid points to determine whether the differences in soil moisture between two points is attributable to differences in the points soil physical properties.



An example of two field situations is given in figure 3.8 where adjacent sampling is deemed necessary to explain the observed soil moisture variation.

Figure 3.8. Two hypothetical field situations where adjacent sampling is deemed necessary to explain the observed soil moisture variation.



In situation (a) it is clear that topography is unlikely to be the controlling factor in soil moisture distribution. Both points therefore need to be sampled to determine whether differences in soil physical properties are the controlling factor. In situation (b) it appears that topography may be the controlling factor in soil moisture distribution, however both points still need to be sampled to ensure that similar physical properties do exist between the points.

The sampling of soil physical properties was therefore predominately undertaken in small clusters of adjacent grid points (figure 3.7). In an attempt to sample different areas and different features within a gully grid, sampling locations were spread throughout the grid.

The location of the clusters was determined by the soil moisture content of the grid points forming the clusters during a wet period (February 2nd 1996). Soil moisture contents during a wet period were chosen because differences in moisture content for adjacent grid points are greater under wet conditions than during dry conditions. Thus during a wet period it is easier to pick out contrasting areas which may help elucidate the factors controlling soil moisture. The areas selected for sampling were based on the following criteria:

1. Adjacent grid points where there was a large difference in soil moisture.

2. Adjacent grid points with similar moisture contents, but contrasting topographical features.

3. Adjacent grid points with different moisture contents and different catenal positions ie. a wet grid point upslope and a dry grid point downslope or a dry grid point upslope and a wet grid point downslope.

Wet and dry grid points were determined by arbitrarily dividing the soil moisture content for the wet period using four categories of wetness:

Category 1 = points with less than 20% soil moisture

Category 2 = points with 21-29% soil moisture

Category 3 = points with 30-38% soil moisture

Category 4 = points with 39% or more soil moisture

Adjacent grid points, one of which was in category 1, the other in category 4 were deemed to be the most important sites to sample, although adjacent grid points falling into categories 3 and 4, for example, were also sampled.

The minigrids were originally selected in areas of high soil moisture variation and therefore were automatically sites requiring analysis of the soils physical properties.

3.4 Soil Analyses : Laboratory Analytical Procedures

3.4.1 Particle Size Distribution - Soil Texture

Soil texture is an important variable in understanding soil hydrology and for providing a first insight into a soil's physical and chemical properties (Landon, 1993; Rowell, 1994). Soil texture (together with structure and biota) largely determines the pore size distribution of a soil and hence soil water storage capacity, water movement (hydraulic conductivity), soil drainage and soil aeration. The water holding capacity and water content of a soil can be greatly affected by its stoniness and clay content (Kadmon *et al.*, 1989). Soil texture is also important in determining soil structure and soil stability, in particular the stability of pore channels and soil aggregates. The determination of soil texture is therefore essential in understanding the hydrological response and the susceptibility to erosion of a soil during precipitation events.

The 124 samples taken for texture analysis were dry sieved to less than 1.7 mm through a stack of four sieves; 16 mm, 8 mm, 2 mm and 1.7 mm. A subsample from the less than 1.7 mm fraction was treated with 6% hydrogen peroxide (H_2O_2) to remove binding organic material. The sample was then oven dried at 105°C for 24 hrs. To determine the particle size distribution for the less than 1.7 mm subsample a Malvern longbed Mastersizer X was used. This method uses laser diffraction or more correctly Low Angle Laser Light Scattering (LALLS) to measure particle sizes from 0.1μm to 1700μm. The method is based upon the inverse proportional relationship between diffraction angle and particle size. This method can provide high resolutions with up to 100 size classes in the range of 0.1μm to 80μm. The analysis used a polydisperse model and the presentation used was 2OHD (secondary scatter) with a refractive index of 1.54 and absorption of 0.1. The less than 1.7 mm treated subsample was subsampled again, this part being added to the mastersizer's sampling/dispersing bath containing 1 litre of water. 50 ml of 8% calgon was added to disperse the sample. The sample was further ultrasonically dispersed for 30 seconds. The sample was then analysed by the Mastersizer. Particle size distribution was calculated for each sample as gravel (>2000μm), sand (<2000μm - >63μm), silt (<63μm - >2μm) and clay (<2μm). In the following chapters these particle size classes have been expressed as a percentage of the whole sample.

3.4.2 Soil Water Release Characteristic Curve

The soil water release characteristic curve shows the relationship between water content and matric potential in a drying soil (Hillel, 1982; Jury *et al.*, 1991; Reeve and Carter, 1991; Rowell, 1994). The shape or form of the water release characteristic curve is strongly affected by soil texture, soil structure and bulk density, particularly at low suctions (Hillel, 1982; Reeve and Carter, 1991). A clay soil will have a higher total porosity and a more uniform pore size distribution than a sandy soil, which is normally dominated by large size pores (Hillel, 1982; Jury *et al.*, 1991). The water release characteristic curve of a clay soil will therefore have a greater water retention at a given suction and the slope of its curve will be less steep than that of a sandy soil, particularly at low suctions (Hillel, 1982; Reeve and Carter, 1991). A known relationship between pore size and pore drainage under different suctions enables the calculation of the pore size distribution from the water release characteristic curve (Hillel, 1982; Reeve and Carter, 1991; Jury *et al.*, 1991; Rowell, 1994). The quantity of pores in a soil and their size distribution (classification into transmission pores, storage pores and residual pores) provides a general indication of the soil's physical and hydrological condition enabling statements to be made concerning soil water movement and susceptibility to saturation and hence surface runoff (Landon, 1993; Reeve and Carter, 1991; Williams *et al.*, 1992; Rowell, 1994).

Cores taken for the determination of the soil moisture characteristic curve and subsequently the pore size distribution were allowed to saturate for seven days before being placed on sand tables following the procedure outlined by Soil Survey (1982). The cores volumetric water content was determined at 5cm, 10cm, 15cm, 20cm, 50cm and 100cm of suction. Cores were equilibrated at each suction when the change in core weight from day to day was no greater than 0.05g. For the determination of volumetric water content at higher suctions, the soil cores were placed on pressure plates (Soil Moisture Corporation) where a pressure of 200cm and 1500cm was applied to the cores. Cores were considered to be equilibrated at each pressure when the day to day change in drainage water weight was no greater than 0.05g. The cores were then oven dried at 105°C for 72 hrs, allowing volumetric water content to be calculated at saturation and at each suction. The equation used to give an approximation of pore diameter is given below:

$$\text{Pore Diameter (mm)} = \frac{3}{d} \quad (4)$$

d = pressure (bar / KPa)

3.4.3 Saturated Hydraulic Conductivity

Soil saturation represents a condition where the conductivity of water through soil pores is at a maximum and is known as saturated hydraulic conductivity (K_{sat}) (Selby, 1982; Jabro, 1992; Rowell, 1994). It is dependent upon pore size, pore number, pore orientation and pore connectivity, all of which are largely controlled by soil texture and structure. Hence coarse textured soils generally have a higher K_{sat} than fine textured soils (Jabro, 1992; Rowell, 1994). It has also been related to bulk density (Sharma and Bhandari, 1989; Jabro, 1992; Shafiq *et al.*, 1994), organic material content (Ohu *et al.*, 1994) and soil stability. Below saturation, the conductivity of a soil is also dependent upon the soil water content, being greater the higher the water content (Hillel, 1982; Brady, 1990; Jury *et al.*, 1991). Values of K_{sat} may be used as a measure of soil structure (Hartge, 1991) and can also give an indication of how quickly infiltrated water is redistributed away from the soil surface and thus the time to ponding and surface runoff (Jabro, 1992).

Cores taken for the determination of saturated hydraulic conductivity (K_{sat}) were allowed to saturate for 72 hrs before being tested using a falling head permeameter. Each core was run 5 times and the average of the 5 runs was calculated for saturated hydraulic conductivity. Saturated hydraulic conductivity was calculated using the equation below:

$$K_{sat}\ (\text{cm s}^{-1}) = \frac{(2.302 \times a \times 12.7)}{A} \times \frac{(\log H_0 - \log H_1)}{t} \quad (5)$$

a = area of manometer tube (cm^2)

A = area of sample (cm^2)

H_0 = initial head (cm)

H_t = final head (cm)

t = time of test (sec)

3.4.4 Dry Bulk Density

Measurements of dry bulk density can be used as a guide to soil compaction and porosity, both of which will control the amount and rate of water moving through the soil (Landon, 1984; Brady, 1990; Campbell and Henshall, 1991; Rowell, 1994). Bulk density is dependent upon soil texture, structure, biological activity and most significantly land use management (Ekwue, 1990; Brady, 1990; Kuznetsova, 1991; Rowell, 1994; Tamminen and Starr, 1994).

After measuring saturated hydraulic conductivity the cores were oven dried at 105°C for 72 hrs for the calculation of dry bulk density. Dry bulk density was calculated using the equation below:

$$\text{Bulk Density}\ (\text{g cm}^{-3}) = \frac{\text{soil mass (g)}}{\text{soil volume (cm}^3\text{)}} \quad (6)$$

3.4.5 Organic Carbon

"*Organic materials are responsible perhaps, more than any other single factor, for the stability of soil aggregates*" (Brady, 1990).

Organic material therefore supplies the major soil aggregate forming cements, improving and maintaining soil structure and therefore important to the hydrological functioning and erodibility of a soil (Ekwue, 1990; Rowell, 1994; Miller and Donahue, 1995). The organic material content of a soil is dependent upon the plant density and the plant species type as well as the biological activity, the climatic conditions and the land use management (Brady, 1990).

The organic carbon content of the fine earth fraction (<2.00mm) was measured by high temperature catalytic oxidation with non-dispersive infra red detection using a Shimadzu 5000 total organic carbon analyser.

3.4.6 Aggregate Stability

"*The erodibility of soil is essentially related to the stability of soil aggregates*" (Thornes, 1980).

The stability of soil aggregates is to a large extent dependent upon soil organic material (Panabokke and Quirk, 1957; Grieve, 1979a; Guerra, 1994), and in particular the source and type of organic material (Albrecht *et al.*, 1992; Graham *et al.*, 1995; Ternan *et al.*, 1996a). Gertis *et al.* (1990), Perfect and Kay (1990), Albrecht *et al.* (1992) and Ternan *et al.* (1996a) have argued that it is the finer, colloidal organic materials which are more important in stabilising soil aggregates rather than coarser organic material. The soils textural composition may also affect the stability of soil aggregates (Buschiazzo *et al.*, 1995). In general clay has a cementing effect, forming complexes with organic materials and binding other soil particles together increasing aggregate stability (Brady, 1990; Lee and Foster, 1991). However if the clay fraction is dominated by smectite clays (swelling clays), then aggregates may be vulnerable to rapid dispersion and breakdown upon wetting (Ternan *et al.*, 1996a). The stability of soil aggregates is also dependent on biological activity (Lee and Foster, 1991; Rampazzo *et al.*, 1995), freeze-thaw processes (Staricka and Benoit, 1995), landscape position (Pierson and Mulla, 1990), sesquioxides (Gertis *et al.*, 1990; Igwe *et al.*, 1995), soil and soil water chemistry (Ternan *et al.*, 1996a) and the aggregates initial moisture content and the rate of wetting (Panabokke and Quirk, 1957; Grieve, 1979a, b; Utomo and

Dexter, 1982). Ternan *et al.* (1996a) have also stressed the importance of past and present land use management in controlling the amount and type of aggregate forming cements and therefore the stability of soil aggregates. Aggregate stability provides a quantitative indication of the soils susceptibility to erosion (Grieve, 1979a, b; Ternan *et al.*, 1996a). Stable aggregates are critical for maintaining the surface soils structure and hence its permeability during a precipitation event, permitting infiltration and reducing the potential for surface runoff and erosion (Grieve, 1979a; Guerra, 1994; Rasiah and Kay, 1995; Ternan *et al.*, 1996a).

Aggregate stability was tested using laboratory rainfall simulation (Ternan *et al.*, 1994, 1996a). Samples were sieved to derive 25 4.0-5.6mm air dried aggregates. These aggregates were placed on a 2.8mm sieve and subjected to 40 runs of simulated rainfall with an intensity of c 45mm hr^{-1} with a mean drop size of 583µm (S.D. 251µm). Each run lasted 30 seconds, separated by a 10 second interval used to count the surviving aggregates. At the end of each rainfall simulation, surviving aggregates were destroyed to check for stones. A mean Rainfall Simulation Survival Index (R.S.S.I) was calculated for each sample using equation 8 (Ternan *et al.*, 1996a).

$$\text{R.S.S.I}\,(\%) = \frac{(A + B + C + D) \times 100}{4} \qquad (8)$$

$$A = \frac{\text{N}^{\circ}\text{ of aggregates surviving after 3.8 mm of rainfall}}{\text{Total N}^{\circ}\text{ of aggregates}}$$

$$B = \frac{\text{N}^{\circ}\text{ of aggregates surviving after 7.5 mm of rainfall}}{\text{Total N}^{\circ}\text{ of aggregates}}$$

$$C = \frac{\text{N}^{\circ}\text{ of aggregates surviving after 11.3 mm of rainfall}}{\text{Total N}^{\circ}\text{ of aggregates}}$$

$$D = \frac{\text{N}^{\circ}\text{ of aggregates surviving after 15 mm of rainfall}}{\text{Total N}^{\circ}\text{ of aggregates}}$$

3.5 Geostatistical Methods

Geostatistics is a relatively new and to many an unfamiliar analysis tool for characterising and interpreting spatial data in the physical sciences. The theory and concepts behind geostatistics may at first seem complicated and the usefulness and interpretation of the results it provides not obvious. Therefore a lengthy but necessary detailed and informative discussion of geostatistical methods and its significant relevance to this research is presented below.

3.5.1 Classical Statistics

Classical statistical tools are not applicable in the analysis of spatial and temporal structures because they assume that variation is randomly distributed and hence spatially uncorrelated (Trangmar *et al.*, 1985; Di *et al.*, 1989; Munoz - Pardo *et al.*, 1990; Oliver and Webster, 1991; Cambardella *et al.*, 1994). Using classical statistics, variability about the sampling mean is considered random and therefore samples are independent of each other regardless of their separation distance and geographic location (Trangmar *et al.*, 1985; Cambardella *et al.*, 1994). Furthermore classical statistics assumes that for interpolation, the sample mean will be the expected value everywhere within the sampling unit (Trangmar *et al.*, 1985; Oliver and Webster, 1991). Therefore classical statistics is inadequate for the interpolation of spatially dependent variables (Trangmar *et al.*, 1985; Munoz - Pardo *et al.*, 1990). Wilding (1985) has also argued that classical statistics cannot further our knowledge and understanding of the causal factors responsible for the observed soil property variations. Geostatistical techniques are now considered to be far superior than classical statistical techniques for describing, interpolating and understanding the causal factors, of spatially and temporally structured soil variables (Vieira *et al.*, 1981; Trangmar *et al.*, 1985; Oliver and Webster, 1991; McBratney, 1992; Burrough, 1993).

3.5.2 Geostatistics

Measurements taken at different locations are usually not completely independent, but are correlated up to a certain distance (Addiscott, 1993; Comegna and Basile, 1994). Thus it is generally accepted that samples collected close to one another are more similar than samples collected further apart (Oliver and Webster, 1991; Cambardella *et al.*, 1994).

"*Soil properties are continuous variables whose values at any location can be expected to vary according to direction and distance of separation from neighbouring samples. By so varying, soil properties exhibit spatial dependence within some localised region*" (Trangmar *et al.*, 1985).

Geostatistical techniques are proven to be ideally applicable to the description of this spatial dependence (Oliver and Webster, 1991). The application of geostatistical techniques to a wide range of environmental data to quantify spatial and temporal structures is becoming increasingly more common (Davidson and Watson, 1995). Geostatistics comprises a set of statistical tools (see below) which can be used to describe both the structured and the random characteristics of spatially distributed variables (Trangmar *et al.*, 1985; Oliver, 1987; Webster and Oliver, 1990; Oliver and Webster, 1991). Geostatistics also allows for optimal and unbiased estimation as well as proving valuable for designing efficient sampling schemes (Trangmar *et al.*, 1985; Webster and Oliver, 1990; Oliver and Webster, 1991). Through geostatistical analysis, identification of the underlying structure of soil properties can be used to understand or begin to explore the underlying processes responsible for the variation (Trangmar *et al.*, 1985; Oliver, 1987). Geostatistics is applicable to all scales of investigation and even if the soil is believed to be homogeneous, greater information on spatial variability can be sought through geostatistical analysis (Greminger *et al.*, 1985; Oliver, 1987). Geostatistics is based on the theory of regionalised variables (Journel and Huijbregts, 1978). A random variable becomes a regionalised variable z (x) when it takes different values z according to its location x within some region (Trangmar *et al.*, 1985). A regionalised variable z (x) may therefore be considered as a realisation of a random variable Z for a fixed location x within the region (Trangmar *et al.*, 1985). If the values of z (x) at all locations within the region are taken into account, then each regionalised variable z (x) becomes a member of an infinite set of random variables Z (x) for all locations within the region (Trangmar *et al.*, 1985). This set of random variables is called a random function because it relates a random variable Z with any location x (Trangmar *et al.*, 1985). The theory of regionalised variables provides the theoretical foundations for the analysis of spatial dependence using variograms (Trangmar *et al.*, 1985)

3.5.2.1 Stationarity

An often problematic assumption required for geostatistical analysis is that of stationarity (Trangmar *et al.*, 1985; Webster and Oliver, 1990; Oliver and Webster, 1991; Pohlmann, 1993). Both stationarity and the weaker assumptions of stationarity known as the intrinsic hypothesis "*requires that the expected value of the difference (variance) between any two samples depends on the distance between them, but not on their location in the sampled region*" (Trangmar *et al.*, 1985).

Thus the structure of variation can be regarded as constant within a given region, regardless of geographic location (Oliver, 1987). The occurrence of non-stationarity in data increases as the sampling distance increases due to the decay in spatial covariance (Trangmar *et al.*, 1985; Pohlmann, 1993). Therefore the assumption of stationarity becomes increasingly valid over shorter distances (Trangmar *et al.*, 1985; Pohlmann, 1993). Stationarity over relatively short distances or restricted areas is known as quasi-stationarity and may be used to validate stationarity in geostatistical analysis when non-stationarity over larger distances occurs or can be used when trends, hence non-stationarity in the data are present (Trangmar *et al.*, 1985; Pohlmann, 1993).

3.5.2.2 The Variogram

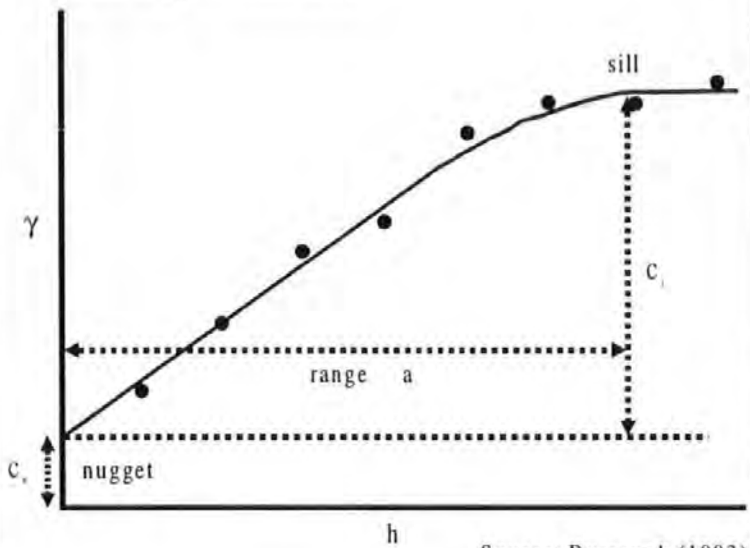
A fundamental statistical tool necessary for geostatistical analysis is the variogram (Journel and Huijbregts, 1978; Webster and Oliver, 1990; Oliver and Webster, 1991). The variogram summarises the variation of a property within a region by mathematically expressing the change in variance of the property as the distance and direction separating any two points varies (Oliver and Webster, 1991; Webster and Oliver, 1992). Thus the variability between two values z (x) and z (x+h), at two locations x and x+h separated by the distance h, can be characterised by the variogram function γ (x,h), which is defined as half the expected squared difference between values (Journel and Huijbregts, 1978; Oliver and Webster, 1991).

$$\gamma(x,h) = \tfrac{1}{2}E\,[\,(\,z\,(x) - z\,(x+h)^2\,] \quad (9)$$

Given the intrinsic hypothesis, the variogram is only a function of separation distance h and not of location x. Thus $\gamma(x,h) = \gamma(h)$ (Pohlmann, 1993). In the variogram, h represents both distance (h) and direction (¥) (Journel and Huijbregts, 1978). For each distance or lag (h) the semi-variance can be computed by comparing all neighbouring pairs of observations at that lag (Webster and Oliver, 1990). By varying the distance or lag in discrete steps an ordered set of semi-variances can be obtained (Webster and Oliver, 1990). The variogram is thus constructed by plotting the semi-variance for each lag against increasing lag distance (figure 3.9) (Trangmar *et al.*, 1985; Webster and Oliver, 1990; McBratney, 1992).

Thus pairs of measurements (z(xi), z(xj)) are grouped into classes according to their separation distance (h(xi, xj)) (Pohlmann, 1993). The more alike the pairs are then the smaller the semi-variance and the smaller the variability and vice versa (Burgess and Webster, 1980; Cambardella *et al.*, 1994). The variogram will become more erratic with increasing lag distance since the distance between pairs of points is greater and fewer data points are available for computing the semi-variance (Burgess and Webster, 1980).

Figure 3.9. Variogram of a regionalized variable showing the sill ($C=C_0+C_1$), the range (a), the spatially related variance (C_1) and the nugget variance (C_0).



Source: Burrough (1993)

If samples are collected at regular intervals as with a grid system, then the lag distance is generally the distance between the shortest sampling interval (Uehara *et al.*, 1985). At lag distances less than the shortest sampling interval the shape of the variogram and hence the form of the spatial structure is not known (Webster and Oliver, 1990). Webster and Oliver (1992) have argued that a minimum of 150 to 200 sampling points are needed to accurately estimate the variogram. Variograms calculated from too few samples will appear erratic (Webster and Oliver, 1992). Furthermore, greater sampling at shorter lags will give the variogram greater accuracy (Webster and Oliver, 1992).

The variogram can be interpreted as representing the average rate of change of a property with distance (Oliver, 1987). The variograms shape "*describes the pattern of spatial variation in terms of its magnitude, scale and general form*" (Oliver, 1987).

At short lags the semi-variance is small but increases steadily with increasing distance (Webster and Oliver, 1990). The steepness of the variograms initial slope gives an indication of the rate of change in a property with increasing separation distance and the rate of decrease in spatial dependence (Oliver, 1987). A steep slope indicates a high rate of change with separation distance and a high rate of falling spatial dependence (Webster and Oliver, 1990). An ideal variogram, would be one where semi-variance increases with distance, rising to a constant value (Sill (C) - see below) at a given separation distance (Range (a) - see below) (Trangmar *et al.,* 1985). Such a variogram may be interpreted as representing variation that is transitional such as different soil types or lithology (Oliver, 1987). However variograms can and do take several forms and the semi-variance can increase indefinitely (Journel and Huijbregts, 1978; Trangmar *et al.,* 1985; Webster and Oliver, 1990).

3.5.2.3 Sill Value

If the semi-variance rises to a constant value, then the variogram is said to have a sill (C) (figure 3.9) (Burgess and Webster, 1980; Trangmar *et al.,* 1985; Webster and Oliver, 1990). The sill value is equal to the constant value of semi-variance. The sill value ($C = C_1+C_0$) therefore includes random variance (Nugget variance (C_0) - see below) and systematic variance (C_1) due to spatial dependence in the data (Burgess and Webster, 1980). Variograms with sills represent data which is stationary at the scale of investigation (Oliver, 1987; Webster and Oliver, 1990).

3.5.2.4 Range

The separation distance (lag) at which the semi-variance becomes constant *ie.* the sill, is called the range (a) (figure 3.9) (Journel and Huijbregts, 1978; Burgess and Webster, 1980; Webster and Oliver, 1990). The range represents the maximum distance of spatial dependence unless there is periodicity (Journel and Huijbregts, 1978; Trangmar *et al.,* 1985; Webster and Oliver, 1990; Davidson and Watson, 1995). Samples separated by distances closer than the range are spatially related. Samples separated by distances greater than the range are not spatially related, implying random variation (Journel and Huijbregts, 1978; Trangmar *et al.,* 1985; Webster and Oliver, 1990). The size of the variogram range depends upon the scale of observation and the spatial interaction of soil processes affecting each property at the sampling scale (Trangmar *et al.*, 1985). The maximum radius from which samples are drawn for interpolation using kriging (see below) is defined by the range (Trangmar *et al.*, 1985). The range value can be used as a guide to indicate the size of spatial classes (Oliver, 1987; Davidson and Watson, 1995). Davidson and Watson (1995) used the size of the range value to indicate the size of areas of low moisture content. They further argued that the range could be used to indicate distances over which soil is interrelated (Davidson and Watson, 1995). Therefore the range may be used to express the spatial frequency of soil moisture changes (Davidson and Watson, 1995). Wierenga (1985) and Nash *et al.* (1989) have reported a range of maximum spatial dependence for soil water content of between 8 and 22m. Munoz-Pardo *et al.* (1990) found a range of 79m for gravimetric soil water content in a agricultural field. Hawley *et al.* (1983) found a range of influence for soil moisture of 6m for topographically variable land. On fairly topographically uniform land the range of influence increased to 30-40m (Hawley *et al.*, 1983). Nyberg (1996) has reported for the 0-15cm layer that the variogram for soil moisture followed a spherical model with a range of approximately 20m. Trangmar *et al.* (1985) have reported variogram ranges varying from 0.6m to 58km for a wide variety of soil properties and sampling scales.

3.5.2.5 The Nugget Effect

Theoretically the semi-variance should be zero when the lag distance is zero and hence the variogram should pass through the origin when the distance of sample separation is zero (Journel and Huijbregts, 1978; Trangmar *et al.*, 1985). However many soil properties display non-zero semi-variance as h approaches zero (Trangmar *et al.*, 1985; Oliver and Webster, 1991). This non-zero variance is known as nugget variance or the nugget effect (figure 3.9) (Journel and Huijbregts, 1978; Trangmar *et al.*, 1985; Oliver, 1987; Webster and Oliver, 1990; Burrough, 1993). The nugget variance (C_0) represents the unexplained or random variance which may be caused by measurement error and/or variability within the soil property which cannot be detected at the sampling scale (Journel and Huijbregts, 1978; Trangmar *et al.*, 1985; Oliver, 1987). The nugget variance however usually represents spatially dependent variation which occurs over distances much smaller than the shortest sampling interval (Webster and Oliver, 1990). The size of the nugget variance will generally increase as sampling scale increases due to variance incurred by short range processes (Trangmar *et al.*, 1985). A pure nugget effect occurs when the semi-variance $\gamma(h)$ equals the sill value at all values of h (figure 3.10b) (Webster and Oliver, 1990).

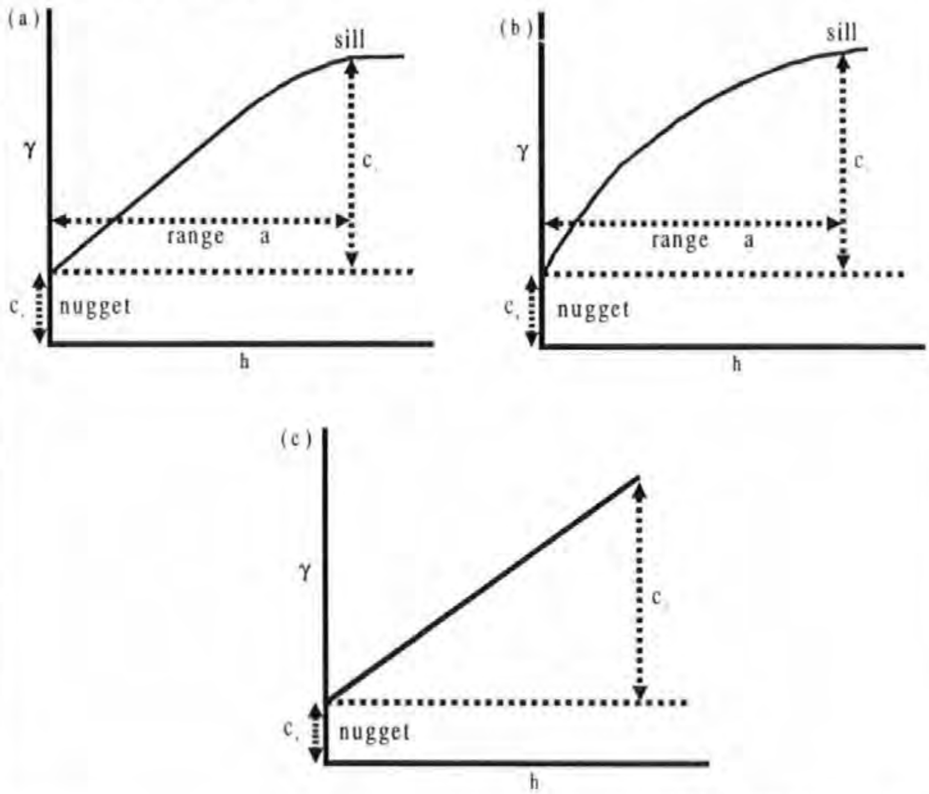
"*Pure nugget effect arises from very large point variation at short distances of separation and indicates a total absence of spatial correlation at the sampling scale used*" (Trangmar *et al.*, 1985).

If a pure nugget effect occurs at all scales of sampling then the best estimate is the sample mean computed from all sampling points in the region (Trangmar *et al.*, 1985; Burrough, 1993). Oliver and Webster (1991) argue however that because the soil is a continuum, a pure nugget effect should not occur. Spatial dependence of soil variables must be present at some scale (Oliver and Webster, 1991). The nugget effect may be expressed as a percentage of the total variance (sill) allowing comparisons to be made between the relative size of the nugget effect among soil properties (Trangmar *et al.*, 1985; Cambardella *et al.*, 1994). A nugget effect of 0% of the sill implies zero short range variation and a nugget effect of 100 % of the sill implies pure nugget effect *ie.* random variation (Trangmar *et al.*, 1985). Cambardella *et al.* (1994) have used this ratio to define distinct classes of spatial dependence for soil variables. Since the nugget variance cannot be predicted, the size of this unexplained variance has important implications for kriging (see section 3.5.2.9), because it sets a lower limit to the size of the estimation variance and therefore to the precision of the interpolation (Trangmar *et al.*, 1985; Oliver, 1987).

3.5.2.6 Variogram Interpretation

The variogram can be a useful tool for understanding the relationship between and the causal factors of spatial patterns for different soil properties at the same site (Burrough, 1993). If the variograms of two different soil variables are similar in terms of their sill and range, then it may be that the same causal factor is responsible for the spatial pattern of both variables. Both variables will also have the same spatial frequency and therefore the spatial pattern of one variable may be dependent on the spatial pattern of the other variable (Davidson and Watson, 1995). The variogram has also been shown to be useful for indicating the occurrence of greater soil moisture variation as the soil dries out through the development of an increasing nugget variance (Wierenga, 1985). Temporal persistence of soil moisture patterns may be identified by variogram analysis (Hawley *et al.*, 1983; Munoz-Pardo *et al.*, 1990; Comegna and Basile, 1994). If the variograms of soil moisture from one date to the next show a similar structure and a similar range then soil moisture patterns may be considered as being temporally persistent (Hawley *et al.*, 1983; Munoz-Pardo *et al.*, 1990; Comegna and Basile, 1994). The variogram can also be used to check the data for stationarity (Trangmar *et al.*, 1985). Non-stationarity of data may be assumed if the variogram exponential model reaches a sill asymptotically and the unbounded linear model does not have a sill because semi-variance increases indefinitely (Journel and Huijbregts, 1978; Oliver, 1987; Webster and Oliver, 1990). The exponential model has been shown to represent transitional structures such as changes in soil type or patches of different soil which recur, these being the main causes of the soil variation (Webster and Oliver, 1990, 1992). Since many variograms are approximately linear over short lag distances and the variogram used for kriging is usually only that part covered by the short lag distances, then a linear model may be fitted to the variogram (Webster and Oliver, 1990).

Figure 3.11. The three most common models fitted to variograms of soil properties.
(a) Spherical model.
(b) Exponential model.
(c) Unbounded linear model.



Source: Burrough (1993)

3.5.2.9 Interpolation Using Kriging

"Kriging is a means of local estimation in which each estimate is a weighted average of the observed values in its neighbourhood" (Trangmar *et al.*, 1995).

Interpolation using kriging differs from interpolation using classical statistics, because the data used for interpolation in kriging carry different weights based on their position both in relation to the estimated point and to one and other (Oliver, 1987; Oliver and Webster, 1991; Pohlmann, 1993). When interpolating, kriging uses only those samples which are spatially related to the kriged location *ie.* those samples within the range of spatial dependence as defined by the variogram (Hawley *et al.*, 1983; Trangmar *et al.*, 1985). The interpolated value of a soil property Z at any point xo is a weighted average of the observed values in that neighbourhood (Burgess and Webster, 1980).

$$Z(xo) = \S 1\ Z(x1) + \S 2\ Z(x2) + \ldots\ldots\ldots\ldots \S n\ Z(xn) \quad (10)$$

$$\S = \text{weights}$$

Sample points occurring in clusters will carry less weight than lone points and sample points lying between the kriged point and more distant samples will screen the distant samples so that they have less weight in the kriging equation (Trangmar *et al.*, 1985; Oliver and Webster, 1991). Sample points nearest the kriged point will be the most heavily weighted, explaining why the variogram needs to be accurate only over the first few lags (Burgess and Webster, 1980; Trangmar *et al.*, 1985). For reliable estimation, the number of nearest neighbouring samples required for kriging is 16 to 25 points (Trangmar *et al.*, 1985; Oliver, 1987; Webster and Oliver, 1990). The kriged estimates are equal in terms of volume, size and shape as the physical dimensions of the original samples from which they are estimated (Burgess and Webster, 1980).

Kriging is an optimal interpolation technique (Trangmar *et al.*, 1985; Burgess and Webster, 1980; Oliver, 1987; Webster and Oliver, 1990; Oliver and Webster, 1991). It is optimal because it provides unbiased estimates with minimum and known variance (Burgess and Webster, 1980; Oliver and Webster, 1991; Pohlmann, 1993). The interpolation estimate is unbiased because the weights assigned to sampling points used in kriging sum to 1 (Burgess and Webster, 1980). Kriging assigns weights to the data that minimise the estimation variance (Burgess and Webster, 1980; Pohlmann, 1993). By calculating the estimation variance (error variance) for each estimated value, kriging provides a measure of the reliability of the interpolation (Trangmar *et al.*, 1985). This estimation variance is dependent upon the variogram which expresses the degree of spatial dependence and on the configuration of observation points in relation to the area to be estimated (Vieira *et al.*, 1981; Trangmar *et al.*, 1985; Di *et al.*, 1989; Oliver and Webster, 1991; Pohlmann, 1993). The estimation variance does not depend upon the actual measured values themselves (Oliver and Webster, 1991; Pohlmann, 1993). The estimation variance will be reduced if sampling is evenly spread throughout the kriged region, highlighting the benefits of using a grid sampling system (Trangmar *et al.*, 1985; Di *et al.*, 1989). Estimation variances will always increase along the margins of the study region, due to fewer observation points from which the kriged estimate can be interpolated (Trangmar *et al.*, 1985). Due to its optimality, kriging provides the most precise interpolation values possible from the available data, which can be used with known confidence (Trangmar *et al.*, 1985).

Although kriging is mainly used for local estimation it can be used to provide regional estimates by averaging the local kriged estimates weighted by the area they represent (Oliver, 1987). Dividing a region into distinct classes based on soil type, geology etc. prior to kriging can make values more meaningful, since estimates could be made for each class type separately (Webster and Oliver, 1990). These estimates based on values within a certain class type would also be more precise, since variation within each class would be less than in the region as a whole (Webster and Oliver, 1990).

3.5.2.10 Other Interpolation Techniques

There are several other interpolation techniques, apart from kriging which can be used with spatially dependent data (Burrough, 1993). These other interpolation techniques include trend surface analysis, inverse distance averaging, the fitting of exact or smoothing spline functions, regular tessellation and even triangulation (Burrough, 1993). Kriging however has the advantage over these other interpolation techniques in that it is optimal *ie.* it provides unbiased estimates with minimum and known variance (Oliver and Webster, 1991; Burrough, 1993; Pohlmann, 1993). Kriging also has the advantage over other interpolation techniques in that the estimation variance can be calculated before the actual sampling is made (Vieira *et al.*, 1981). Kriging can be less successful compared to other interpolation techniques only when soil changes are abrupt (Burrough, 1993). However kriging within the distinct boundaries caused by the abrupt changes in soil will restore the advantages and estimation precision of kriging (Webster and Oliver, 1990; Burrough, 1993).

3.5.2.11 Types of Kriging

There are several forms of kriging available for interpolation, these include point kriging, block kriging, co-kriging, universal kriging and disjunctive kriging (Trangmar *et al.*, 1985; Webster and Oliver, 1990). Each one of these forms of kriging has a specific interpolation purpose and all of them retain the optimality of kriging (Trangmar *et al.*, 1985).

3.5.2.12 Point Kriging

Point kriging (sometimes referred to as punctual kriging) is the most common kriging procedure used in soil science (Trangmar *et al.*, 1985). Point kriging provides estimates for single point locations within the interpolated study region (Burgess and Webster, 1980; Trangmar *et al.*, 1985; Webster and Oliver, 1990). A disadvantage of point kriging is that because it is an exact interpolator, it may produce local discontinuities where interpolated points coincide with sample locations (Trangmar *et al.*, 1985). Point kriging is also particularly sensitive to the size of the nugget variance (Burgess and Webster, 1980; Trangmar *et al.*, 1985). If the nugget variance is large then the estimation variances produced by point kriging will also be undesirably large (Burgess and Webster, 1980; Trangmar *et al.*, 1985).

3.5.2.13 Block Kriging

Local discontinuities and large estimation variances produced by point kriging may be overcome by using block kriging which results in smoother maps and smaller estimation variances (Burgess and Webster, 1980; Trangmar *et al.*, 1985; Oliver, 1987). Smoother maps resulting from block kriging may be more desirable when regional patterns of variation are of more interest than local detail (Trangmar *et al.*, 1985). Block kriging produces an estimated value for an area or block with its centre at xo, rather than values at points as in point kriging (Burgess and Webster, 1980; Trangmar *et al.*, 1985). Thus in block kriging

"*the semi-variances between the data points and the interpolated points are replaced by the average semi-variance between the data points and all the points in the region*" (Burgess and Webster, 1980).

Therefore the kriged value of a soil property Z for a block V is a weighted average of the observed values xn in the neighbourhood of the block (Trangmar *et al.*, 1985). If the size of the block to be kriged is smaller than the shortest sampling interval of the variogram, then estimates will be less reliable (Webster and Oliver, 1990). Kriging variances decrease substantially with increasing size of block (Webster and Oliver, 1990; Oliver and Webster, 1991).

3.5.2.14 Co-Kriging

Co-kriging is a multivariate technique (McBratney, 1992). Where kriged estimates are based on a few or sparsely distributed soil property values, then estimation variances are likely to be large (McBratney and Webster, 1983). However if the soil property is spatially correlated with one or several other soil properties (co-variables) that have been measured more frequently, then estimates of the undersampled property can be improved by using the additional information provided by the co-variables (McBratney and Webster, 1983; Trangmar *et al.*, 1985; Oliver, 1987; Yates and Warrick, 1987). The spatial distribution of a soil property may often be closely related to the spatial distribution of other soil properties (Trangmar *et al.*, 1986). Where two or more soil properties are spatially correlated, then they are said to be co-regionalized and are spatially dependent on one and other (Trangmar *et al.*, 1985; Oliver, 1987). In co-kriging the variables used must be spatially correlated and have well structured variograms before a well structured cross-variogram can be obtained (Trangmar *et al.*, 1986; Stein *et al.*, 1988). The cross-variogram is calculated using only the locations where both properties have been sampled (Trangmar *et al.*, 1986). The range of spatial dependence of the undersampled variable as defined by its variogram is used to define the search radius for the co-kriging system (Trangmar *et al.*, 1986). At least one sample point of both the undersampled and the co-variable must be within the neighbourhood for co-kriging (Trangmar *et al.*, 1986). Co-kriging should produce superior results through improved estimation when the size of the sample correlation between the undersampled and the co-variable is greater than 0.5 and the co-variable is over-sampled with respect to the variable being estimated (Yates and Warrick, 1987). The greater the correlation between two variables then the greater the reduction in the average kriging variance (Yates and Warrick, 1987). Stein *et al.* (1988) have reported that co-kriging resulted in more precise estimates (0-25% increase in accuracy) than did point kriging. Maximum benefits will be gained from co-kriging when using a geometric sampling scheme whereby the undersampled variable is regularly interspersed with the co-variables (Trangmar *et al.*, 1986). Co-kriging is best employed and most efficient when a variable is difficult or costly to sample and hence is undersampled, producing estimates of unacceptable precision (Trangmar *et al.*, 1986; Yates and Warrick, 1987).

3.5.2.15 Disjunctive and Universal Kriging

Disjunctive kriging provides estimates of the probability of a soil property being above or below given limits (McBratney, 1992). Thus disjunctive kriging can be used to determine the probability that a soil property exceeds critical thresholds (Oliver and Webster, 1991). In this respect disjunctive kriging may be an essential tool in pollution and other environmental studies (McBratney, 1992). Oliver and Webster (1991) provide an excellent example of the application of disjunctive kriging to agricultural management. Universal kriging has been developed to allow kriging in the presence of strong trends *ie.* universal kriging can be used for non-stationary data (Trangmar *et al.*, 1985).

3.5.3 Application of Geostatistics to this Research

Geostatistics will be an important tool in analysing and interpreting the data collected for several variables used in this research. In particular the variogram will be used to analyse the soil moisture data recorded within each gully catchment. The shape of these variograms together with the parameters which describe the fitted models, will provide information on the spatial pattern of soil moisture and the distance over which soil moisture is spatially correlated. The variograms will therefore provide an indication of the spatial continuity of soil moisture from which assumptions on the hydrological functioning of the gully catchments may be inferred. In addition to the spatial variation in soil moisture, changes in the shape of the variograms for different measurement dates may be used to describe the temporal variation in the spatial pattern of soil moisture. The spatial pattern of soil moisture for different seasons (climatic conditions) can therefore be described and compared. Identifying the spatial pattern of soil moisture and any changes through time may also provide information on the factor(s) controlling the pattern. For example, if the spatial pattern of soil moisture is found to be persistent through time, then this may indicate that the factor(s) determining the pattern are also spatially fixed. In such a case the variability in rainfall may be eliminated as a controlling factor of the soil moisture patterns.

By constructing variograms of other soil properties which are known to control soil moisture, similarities between the shape and model parameters of these variograms and the variograms of soil moisture can be compared. When the variograms of two properties display a similar shape then the spatial variation of these properties is comparable which may infer that the properties are inter-dependent. Geostatistical analysis can therefore be used to indicate possible linkages between the spatial and temporal behaviour of the variables.

Geostatistical analysis has been undertaken using the computer program GEO-EAS version 1.2.1 (Geostatistical Environmental Assessment Software, U.S. Environmental Protection Agency, 1990). Variograms were constructed with a minimum lag spacing equal to the minimum sampling distance between two points. Exceptions to this were made when it was necessary to remove 'noise' from the variograms, in which case the lag distance was greater than the minimum sampling distance. At each lag distance a minimum of 200 sampling pairs was used to calculate the semi-variance. The presence of anisotropy within the data sets was checked by calculating the variograms in three directions in increments of 45° with a directional tolerance of +/- 22.5° (Oliver and Webster, 1991). Anisotropy was judged to be present when the slope and range of the three variograms was significantly different. Models of the variograms were fitted by eye, on the basis that the model passed through or was as close as possible to the first three points on the variogram. Models were fitted on this condition since the calculation of semi-variance at shorter lag distances is more reliable than at larger lag distances due to the shorter separation distance between samples and the greater number of samples used to calculate the semi-variance.

Chapter 4

Soil Properties: Description, Comparisons and Inter-Relationships

4.0 Introduction

Variability in soil moisture may be closely related to variations in soil hydrological properties, which reflect its physical structure. The physical characteristics of a soil are principally determined by properties such as texture, bulk density, aggregate stability, organic material content, chemical composition and vegetation characteristics (Blackburn, 1975; Hillel, 1982; Brady, 1990; Landon, 1993). In addition, the erodibility of a soil is also a function of these properties and the severity of erosion can be expected to vary as these properties change (Gertis *et al.*, 1990; Martz, 1992). An analysis of the soils physical and hydrological properties is therefore necessary for understanding and interpreting soil moisture and erosion patterns within the studied areas. Deterministic relationships between the soil's physical and hydrological properties can also be established.

This chapter aims to describe the physical and hydrological properties of the soils in the studied area and examines the inter-relationships between these properties. Comparisons are made between each of the three gully catchments using samples derived from the gully catchment and minigrid scales. However, distinguishing between samples taken at the gully grid scale and samples taken at the minigrid scale is unproductive, since samples derived from the minigrid alone, are too few to perform a reliable statistical analysis. Samples from both scales are therefore combined and no distinction between scales is made. Since all of the samples are derived from within the gully catchments, the samples may be considered to represent soil conditions at the individual gully catchment scale.

4.1 Soil Properties

Only those soil physical properties considered to be important in determining the hydrological and erosional response of soils are described below. These include, soil texture, pore size characteristics, saturated hydraulic conductivity, bulk density, organic carbon and aggregate stability (Blackburn, 1975; Lind, 1989; Truman and Bradford, 1990; Edwards *et al.*, 1994; Schjonning, 1994; Oyarzun, 1995). In addition, vegetation cover, litter cover and the volume of roots are also considered to be important determinants of the hydrological and erosional response of soils and are therefore also described below

(Dunne *et al.*, 1991; Nyberg, 1992; Snelder and Bryan, 1995; Nicolau *et al.*, 1996; Bergkamp *et al.*, 1996; Kosmas *et al.*, 1997).

4.1.1 Soil Texture

Tables 4.1-4.4 provide summary statistics of the percentage clay, silt, sand and gravel content within each of the three gully catchments.

Clay content

Within each of the three gully catchments the average percentage clay is low (less than 5%) and is significantly lower within the forest gully catchment compared to the matorral and bench terrace catchments ($p<0.05$) (table 4.1). Although the percentage clay content of the sediments within the gully catchments is generally less than 5%, some areas within the bench terrace gully catchment may have up to 10% clay, which may reflect the nature in which the terraces are constructed. On the treads of the terraces the surface soil horizon is often removed, exposing sub-surface illuvial horizons in which clay may be concentrated.

Table 4.1. Summary statistics of the percentage clay recorded within each gully catchment

Summary Statistics	Matorral Clay	Forest Clay	Bench Terrace Clay
Mean (%)	3.55	2.67	4.34
Minimum (%)	1.04	0.68	1.10
Maximum (%)	8.12	6.44	10.72
Standard Deviation	1.74	1.31	2.09
Variance	3.02	1.71	4.35
Coefficient of Variation (%)	48.93	49.10	48.06

Silt content

Within each of the gully catchments the average percentage silt content is high, greater than 40% and is significantly higher in the matorral gully catchment compared to the forest and bench terrace catchments ($p<0.05$, table 4.2). Within all three gully catchments the silt content of some samples may be over 70% and is always above 10%. Furthermore, the average percentage silt content is higher than any other particle size fraction implying that silt is the predominant particle size within each of the gully catchments.

Table 4.2. Summary statistics of the percentage silt recorded within each gully catchment

Summary Statistics	Matorral Silt	Forest Silt	Bench Terrace Silt
Mean (%)	53.58	43.33	42.41
Minimum (%)	13.79	12.49	19.38
Maximum (%)	79.78	78.95	73.68
Standard Deviation	18.37	18.83	13.39
Variance	337.29	354.41	179.18
Coefficient of Variation (%)	34.27	43.45	31.56

Sand content

The average percentage sand content within the three gully catchments is similar and not significantly different (approximately 25%) (table 4.3). In some sediment horizons within each of the gully catchments sand can be the dominant particle size (up to 57% in the forest catchment).

Table 4.3. Summary statistics of the percentage sand recorded within each gully catchment

Summary Statistics	Matorral Sand	Forest Sand	Bench Terrace Sand
Mean (%)	24.41	25.97	26.77
Minimum (%)	8.97	11.63	12.93
Maximum (%)	48.57	57.48	48.71
Standard Deviation	9.17	11.64	8.89
Variance	84.01	135.55	79.01
Coefficient of Variation (%)	37.55	44.84	33.20

Gravel content

Within each of the three gully catchments the gravel content of the sediments can be highly variable ranging from almost none to over 75% (table 4.4). Within each of the gully catchments some sediment horizons are dominated by gravel. The forest and bench terrace gully catchments have similar average gravel contents whereas the matorral gully catchment has a significantly lower gravel content ($p<0.05$).

Table 4.4. Summary statistics of the percentage gravel recorded within each gully catchment

Summary Statistics	Matorral Gravel	Forest Gravel	Bench Terrace Gravel
Mean (%)	18.70	28.35	26.79
Minimum (%)	0.03	0.15	0.13
Maximum (%)	76.23	74.94	65.75
Standard Deviation	20.55	23.82	19.74
Variance	422.39	567.16	389.67
Coefficient of Variation (%)	109.90	83.99	73.68

Summary

The matorral gully catchment has a significantly higher percentage of silt sized particles and fewer coarse sized particles than either the forest or bench terrace gully catchments. Within the matorral gully catchment therefore, more of the sediment horizons may be expected to be of a fine texture compared to the forest or bench terrace gullies. The extent of variation in soil texture may be related to gully dissection and gully morphology. Active gullying, resulting in deep dissections, exposes several sediment horizons which may have contrasting textures. In areas where no dissection has occurred or where gullying is shallow, such as in the forest gully's watershed and in the upper half of the matorral catchment, soil texture is relatively uniform over large areas. Within the bench terrace gully, the construction of the terraces resulted in the partial mixing of sediment horizons and the exposure of sub-surface horizons creating considerable variability in soil texture over relatively short distances. The disturbance caused by bench terracing may therefore have consequently increased the variability within an area which may have previously already been considered as heterogeneous. The alluvial nature in which the sediments were deposited within this area has given rise to sediment bands which are principally dominated by a single size fraction. It is unusual to find a sediment band which has an approximate equal mix of more than one size fraction. This has important implications for the hydrology and erosion of these gully catchments since the nature of the deposition of the sediment bands has created distinct and contrasting textural horizons which can vary over relatively short distances from horizons dominated by silt to horizons dominated by gravel. It may therefore be expected that due to the distinct and contrasting nature of textural horizons within this area, that soil texture will be an important factor in determining the hydrological and erosion response of this region. The low percentage of clay within these sediments suggests however, that clay, unlike silt, sand and gravel, will play a relatively insignificant role in determining the hydrological and erosional response of the gully catchments.

4.1.2 Pore Size Distribution

The water release characteristic is a fundamental soil property, providing information on soil structure and pore size characteristics which are important factors in determining runoff (O'Sullivan and Ball, 1993; Schjonning, 1994; Edwards *et al.*, 1994). The total porosity (which is also the percentage volumetric soil moisture at saturation) has been divided into transmission pores, storage pores and residual pores based on the pore size classification system used by Thomasson (1978) and Rowell (1994).

Transmission pores (pores >60μm in diameter) are those pores which will freely drain under gravity and which can allow rapid water movement through the soil. Storage pores (pores 0.2-60μm in diameter) retain water under gravity and provide a valuable source of water to plants. Residual pores (pores <0.2μm in diameter) hold water which is retained as thin films in the lattices of soil aggregates and which is unavailable to plants.

Transmission Pores

Table 4.5 shows within each gully catchment the summary statistics for transmission porosity in the surface (0-3cm) and sub-surface (4-7cm) soil. The average percentage of transmission pores in the surface horizon is similar within each gully catchment (13-14%) and is generally higher than in the sub-surface horizon. Within each gully catchment transmission porosity may exceed 20% within some areas and may be as high as 27% within the matorral gully. The variability in transmission porosity is lowest within the bench terrace gully with a coefficient of variation of 28% in the surface horizon and is highest within the matorral gully (C.V. of 46% in the surface horizon). No significant differences in transmission porosity however occur between the gully catchments in either the surface or sub-surface horizons (Kruskal-Wallace analysis of variance). Transmission porosity is therefore similar within each of the gully catchments.

Table 4.5. Summary statistics of the transmission porosity recorded within each gully catchment.

	← Surface Horizon →			← Sub-surface Horizon →		
Summary Statistics	Matorral Transmission Pores	Forest Transmission Pores	Bench Terrace Transmission Pores	Matorral Transmission Pores	Forest Transmission Pores	Bench Terrace Transmission Pores
Mean (%)	13.74	13.84	13.23	9.91	13.50	10.26
Minimum (%)	6.83	4.63	7.96	2.58	4.10	2.75
Maximum (%)	27.50	26.22	23.76	19.33	22.93	15.28
Standard Deviation	6.37	4.61	3.76	4.34	5.97	3.94
Variance	40.61	21.24	14.14	18.83	35.64	15.50
Coefficient of Variation (%)	46.38	33.28	28.42	43.80	44.22	38.39

Storage Pores

Table 4.6 shows summary statistics for storage porosity in the surface and sub-surface soil within each gully catchment. The average percentage of storage pores within each gully catchment is slightly higher in the surface and sub-surface horizons than the transmission porosity. The average percentage storage porosity is also similar between the surface and sub-surface horizons within each gully catchment.

Storage porosity within the matorral gully in the surface horizon may in some areas be over 30% which compares to a maximum of 20% in the forest gully and 23% in the bench terrace gully. Similar to the transmission porosity, the storage porosity is most variable within the matorral gully catchment. No significant differences in storage porosity however, occur between the gully catchments (Kruskal-Wallace analysis of variance).

Table 4.6. Summary statistics of the storage porosity recorded within each gully catchment.

	← Surface Horizon →			← Sub-surface Horizon →		
Summary Statistics	Matorral Storage Pores	Forest Storage Pores	Bench Terrace Storage Pores	Matorral Storage Pores	Forest Storage Pores	Bench Terrace Storage Pores
Mean (%)	15.59	14.24	15.28	14.63	14.37	14.46
Minimum (%)	9.90	10.58	8.84	10.23	9.33	9.37
Maximum (%)	31.02	20.77	23.14	23.03	23.17	23.54
Standard Deviation	5.27	2.82	3.82	3.81	3.57	3.55
Variance	27.73	7.98	14.61	14.55	12.74	12.60
Coefficient of Variation (%)	33.77	19.83	25.02	26.07	24.84	24.55

Residual Pores

Table 4.7 shows summary statistics for residual porosity in the surface and sub-surface soil within each gully catchment. Within each gully catchment the average percentage residual porosity is higher in the sub-surface horizon compared to the surface horizon. Within both horizons the residual porosity is highest within the matorral gully catchment (19-20%), although no significant differences in the residual porosity occurs between the catchments (Kruskal-Wallace analysis of variance). Residual pores are the dominant pore size within each gully catchment in the sub-surface horizon and are the dominant pore size in the surface horizon within the matorral gully catchment where the residual porosity in some areas may be over 40%. This is much higher than the maximum residual porosity which can be found in the surface horizon within the forest (27%) and bench terrace (23%) gullies. The average and maximum percentage of residual pores is therefore higher, although not significantly in the matorral gully catchment compared to the forest and bench terrace catchments.

Table 4.7. Summary statistics of the residual porosity recorded within each gully catchment.

	◄— Surface Horizon —►			◄— Sub-surface Horizon —►		
Summary Statistics	Matorral Residual Pores	Forest Residual Pores	Bench Terrace Residual Pores	Matorral Residual Pores	Forest Residual Pores	Bench Terrace Residual Pores
Mean (%)	19.80	14.69	14.88	20.30	16.27	16.70
Minimum (%)	8.56	7.44	8.45	8.66	7.67	9.40
Maximum (%)	41.48	27.67	23.36	39.27	32.45	25.15
Standard Deviation	4.28	5.93	3.93	9.30	7.51	4.98
Variance	90.52	35.20	15.47	86.58	56.43	24.85
Coefficient of Variation (%)	48.04	40.40	26.42	45.84	46.18	29.85

Total Porosity

Table 4.8 shows summary statistics for total porosity in the surface and sub-surface soil within each gully catchment. Within each of the gully catchments the average total porosity of the surface and sub-surface horizon exceeds 40% and is slightly higher in the matorral gully catchment than in the forest or bench terrace catchments. Total porosity within the surface horizons can exceed 50% within each of the gully catchments. No significant difference in total porosity occurs between the gully catchments in either the surface or sub-surface horizon (Kruskal-Wallace analysis of variance).

Table 4.8. Summary statistics of the total porosity recorded within each gully catchment.

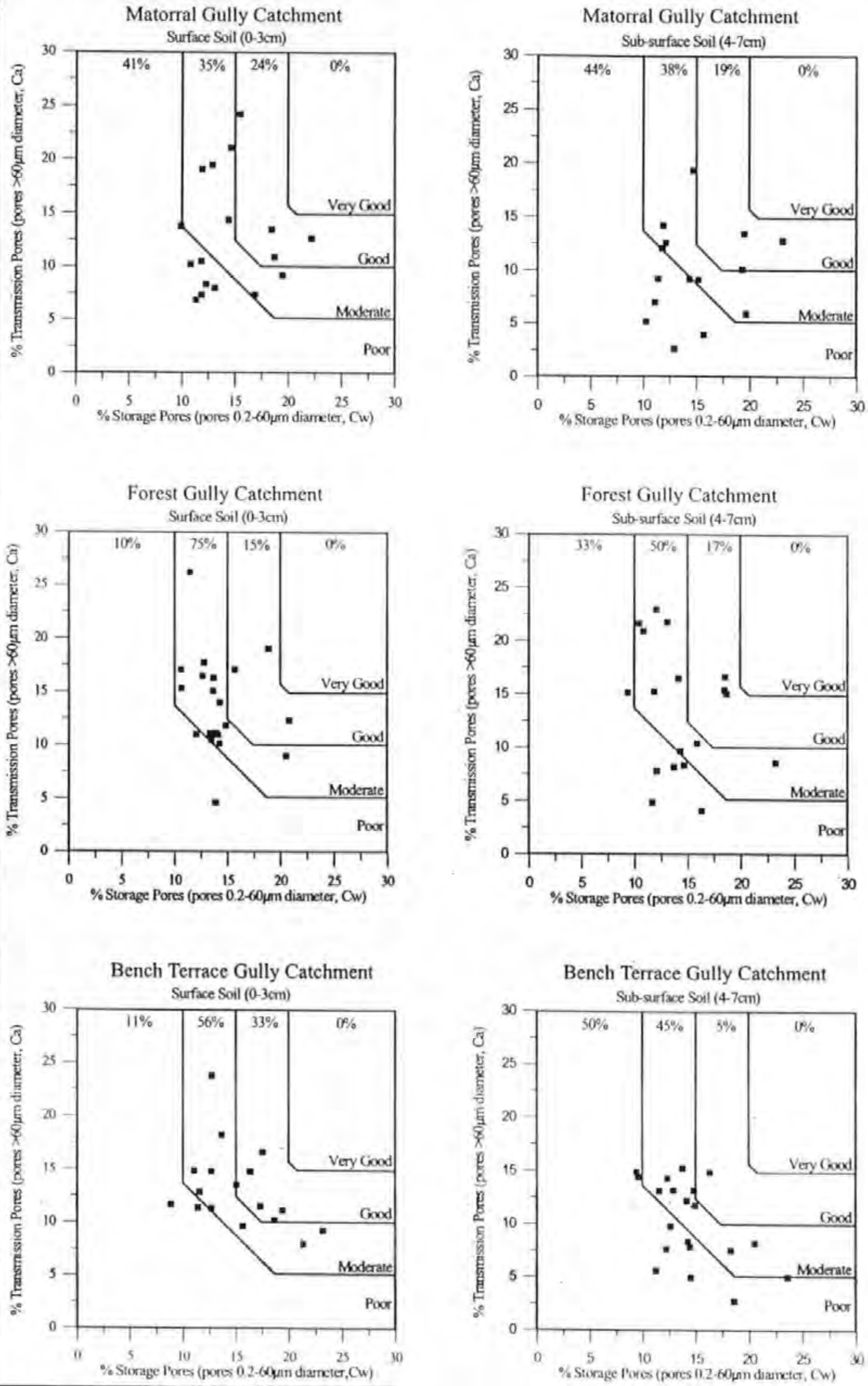
	◄— Surface Horizon —►			◄— Sub-surface Horizon —►		
Summary Statistics	Matorral Total Porosity	Forest Total Porosity	Bench Terrace Total Porosity	Matorral Total Porosity	Forest Total Porosity	Bench Terrace Total Porosity
Mean (%)	45.50	42.78	43.39	44.84	44.13	41.41
Minimum (%)	38.11	33.04	31.51	34.31	32.13	34.08
Maximum (%)	52.29	56.38	53.36	55.28	52.31	47.42
Standard Deviation	4.28	6.42	6.13	5.32	4.97	3.82
Variance	18.29	41.25	15.47	28.29	24.67	14.59
Coefficient of Variation (%)	9.40	15.01	26.42	11.86	11.25	9.22

Soil Structure

Based on Thomasson's (1978) classification of soil structure using the percentage transmission and storage pores, 41% of the samples from the surface horizon within the matorral gully may be classified as having poor soil structure (figure 4.1). In comparison only 10% of the samples in the surface horizon from the forest gully and 11% from the bench terrace gully may be classified as having poor soil structure. Instead the majority of the samples within the forest (75%) and bench terrace (56%) gully catchments may be described as having moderate soil structure (figure 4.1). Furthermore, the bench terrace gully has the highest percentage of samples (33%) with good soil structure in the surface horizon. Within each gully catchment none of the samples from the surface and sub-surface horizon may be classified as having very good soil structure. In the sub-surface soil the percentage of samples with poor soil structure increases within each gully catchment which may be expected, due to compaction from the weight of overlying soil and the lower flora and fauna activity within these horizons. In the bench terrace and forest gully catchments the number of samples with poor soil structure in the sub-surface horizon increases dramatically by 40% and 30% respectively compared to just a 3% increase within the matorral gully catchment (figure 4.1). In the sub-surface horizon each of the gully catchments have samples with less than 5% transmission porosity which Thomasson (1978) considers are likely to be impermeable.

To provide a general indication of the potential continuity in transmission pores and hence the hydrological continuity between the surface and sub-surface soil, the percentage of transmission pores within the surface soil were correlated with those in the sub-surface soil for each gully catchment. Within the matorral and forest gully catchments the correlations are significantly positive (0.70 and 0.66 respectively, ($p<0.05$), indicating potentially very good hydrological continuity between these two horizons. The correlation in the bench terrace gully is in contrast very low and not significant (0.27), indicating potentially very poor hydrological continuity between horizons within this catchment. This may be a reflection of the dramatic increase in the number of samples within the bench terrace catchment which have poor soil structure in the sub-surface horizon.

Figure 4.1. Classification of soil structure based on the percentage transmission pores and storage pores within each gully catchment.



Summary

Following Thomasson's (1978) classification, the majority of the samples within the matorral gully catchment may be classified as having a poor soil structure. In comparison the majority of the samples from the forest and bench terrace catchments have a moderate soil structure. The forest and bench terrace catchments however, show a dramatic increase in the number of samples with poor soil structure in the sub-surface horizon which in the case of the bench terrace gully may account for the potentially very poor hydrological continuity between the surface and sub-surface horizons. Within the matorral gully catchment total and residual porosity is higher than in either the forest and bench terrace catchments and may be a reflection of the predominance of sediment horizons with fine particle sizes in this catchment. Although significant differences in soil texture occur between the catchments, these differences are not enough to cause statistically significant contrasts in the pore size characteristics between the catchments. The variability in pore size characteristics is therefore similar between the catchments, although the small differences that do occur can make the difference between whether a catchments soils are classified as either poorly or moderately well structured. Significant differences in pore size characteristics do however occur within each of the gully catchments. The variability in pore size characteristics is therefore high within each of the catchments resulting in areas within each catchment which have soil structure ranging from poor to good.

4.1.3 Saturated Hydraulic Conductivity (K_{sat})

Table 4.9 shows within each gully catchment the summary statistics for saturated hydraulic conductivity. The K_{sat} of the soils within this region is highly variable and ranges from almost impermeable (0.03 mm hr^{-1}) in the matorral gully to very rapid (1080 mm hr^{-1}) in the bench terrace gully. These large differences in K_{sat} are not unexpected for such a complex environment which has a diverse range of sediments and vegetation cover. Both the matorral and bench terrace gully catchments show a much wider range in k_{sat} values than the forest gully. The average K_{sat} in the matorral and forest gullies is similar (54 and 43 mm hr^{-1} respectively) and may be considered as moderate (Landon, 1993). Average K_{sat} in the bench terrace gully is however significantly higher ($p<0.05$) at 91.32 mm hr^{-1} and may be considered as moderately rapid (Landon, 1993). Figures 4.2 show that within the forest and bench terrace gully catchments 48% and 50% of the samples respectively may be described as having slow permeability with K_{sat} values of less than 20 mm hr^{-1}. In comparison 76% of the samples within the matorral gully catchment have K_{sat}

values of less than 20 mm hr^{-1}. Furthermore, 88% of the samples from the matorral gully catchment have K_{sat} values below 60 mm hr^{-1} and may therefore be described as having moderate to poor permeability (Landon, 1993) (figures 4.2). In the forest and bench terrace gullies 76% and 80% of the samples respectively have a moderate to poor hydraulic conductivity (figures 4.2). Within each of the gully catchments K_{sat} may vary dramatically over distances as short as 5m and 1m. Figures 4.3 show that K_{sat} may vary from 0.2 to 720 mm hr^{-1} in the matorral gully, from 0.2 to 173.5 mm hr^{-1} in the forest gully and from 11.8 to 222 mm hr^{-1} in the bench terrace gully over a distance of 5m. Over a distance of just 1m K_{sat} may vary by as much as 30 mm hr^{-1} within each gully catchment.

Table 4.9. Summary statistics of saturated hydraulic conductivity (K_{sat}) recorded within each gully catchment.

Summary Statistics	Matorral Gully K_{sat} (mm hr^{-1})	Forest Gully K_{sat} (mm hr^{-1})	Bench Terrace Gully K_{sat} (mm hr^{-1})
Mean	54.19	43.00	91.32
Minimum	0.03	0.18	0.41
Maximum	720.00	208.44	1080.00
Standard Deviation	172.81	59.82	238.65
Coefficient of Variation (%)	318.91	139.11	261.33
Number of Samples	17	21	20

Figure 4.2. Saturated Hydraulic Conductivity.

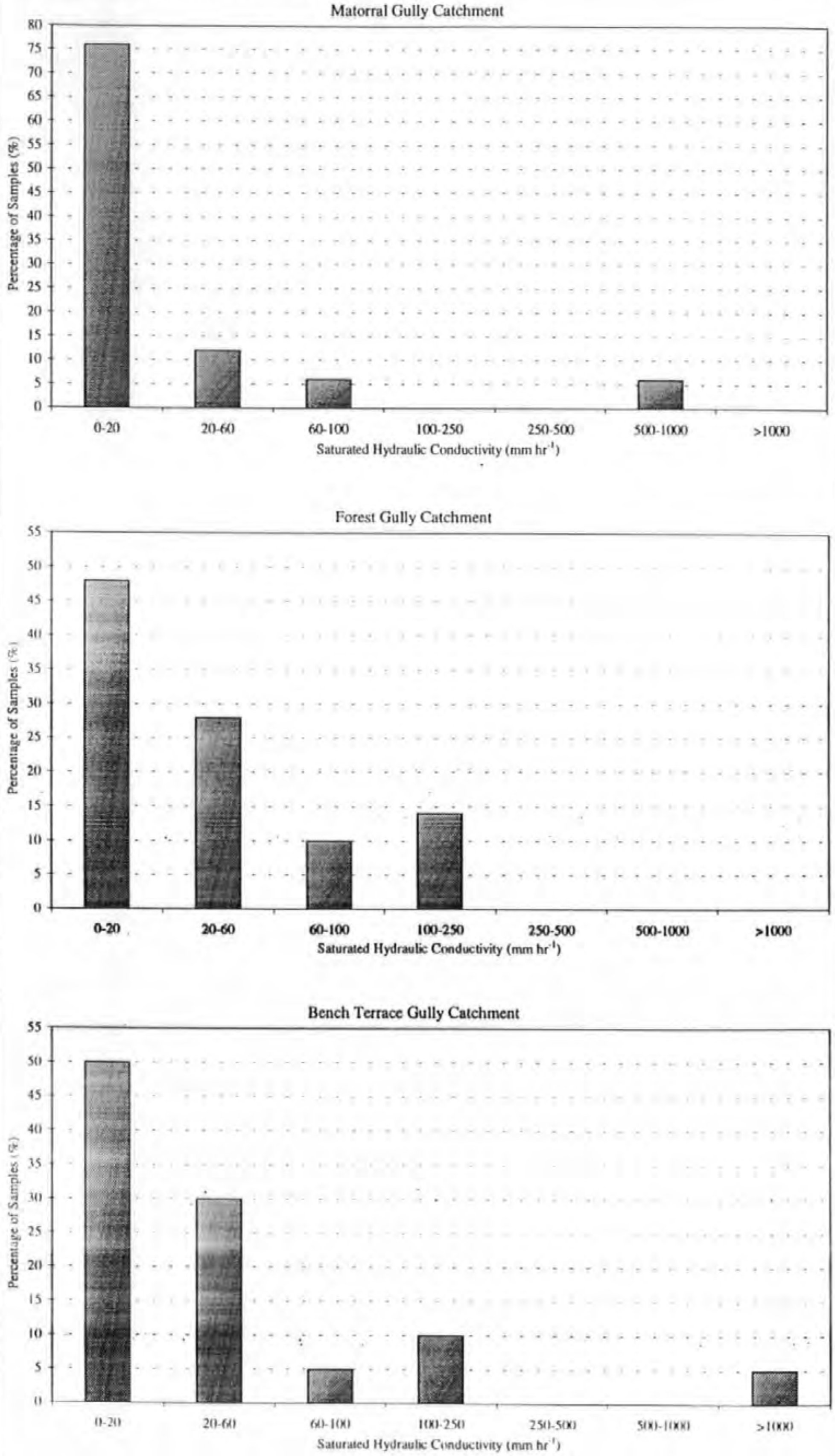
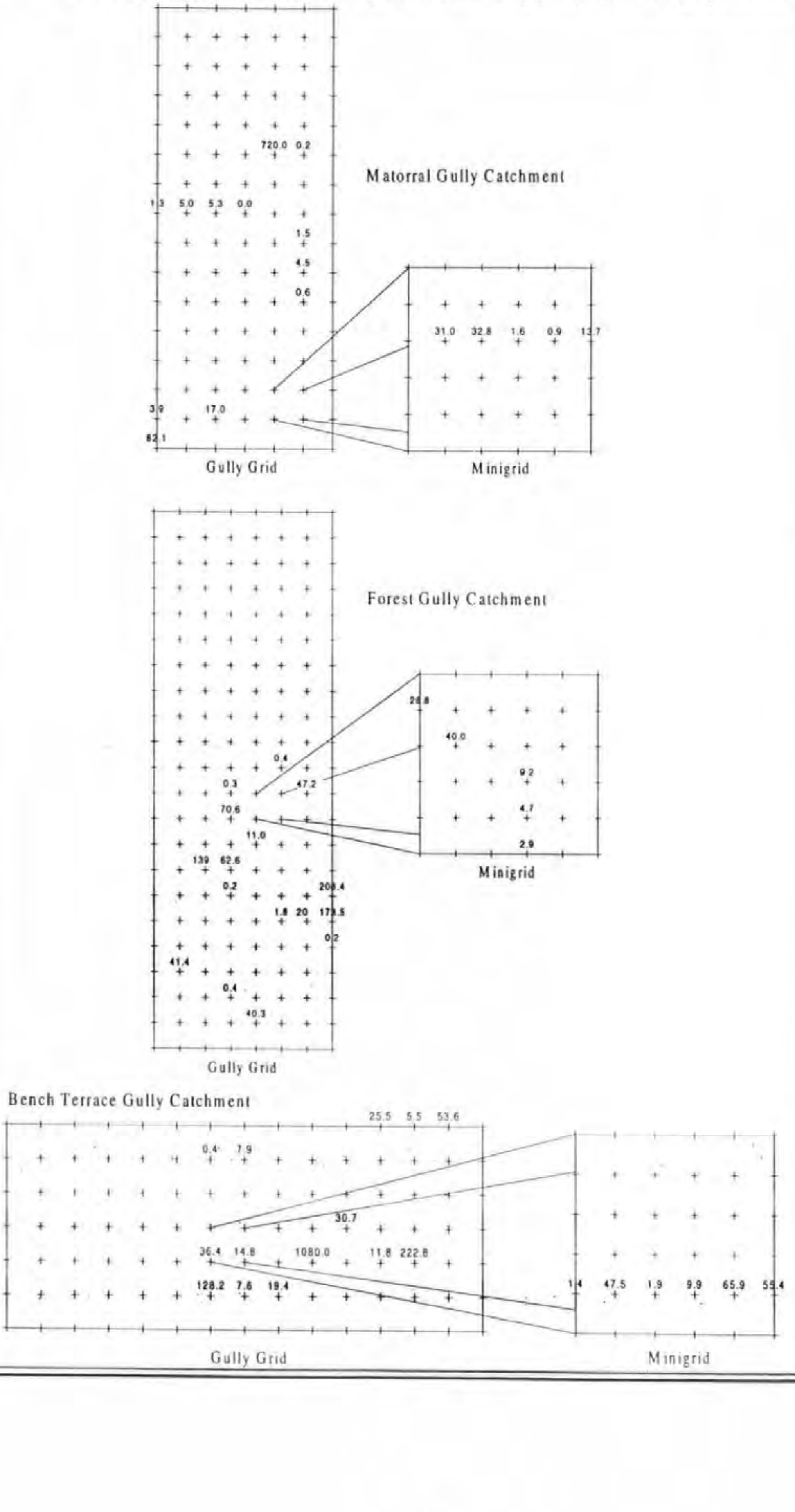


Figure 4.3. Spatial variability in saturated hydraulic conductivity (Ksat) within each gully catchment.



Summary

Within each of the gully catchments k_{sat} may vary dramatically over distances as short as 5m and 1m. O'Loughlin (1986) has reported that k_{sat} values can be notoriously variable and commonly range over 3 orders of magnitude even within the same soil type. Although the average k_{sat} is significantly higher in the bench terrace gully compared to the matorral or forest gullies, within each of the catchments over 75% of the samples may be described as having moderate to low permeability (less than 60 mm hr^{-1}). The low permeability of the majority of the samples reflects the generally poor soil structure of the soils within this region and suggests that many areas within the catchments may be susceptible to saturation and surface runoff as a result of poor drainage.

4.1.4 Bulk Density

Bulk density is a soil property which reflects porosity and compaction with high soil bulk densities being related to runoff production and erosion (Martz, 1992; Edwards *et al.*, 1994; Oyarzun, 1995). Table 4.10 shows summary statistics for bulk density within each gully catchment. Average bulk density values are similar within each of the gully catchments and are not significantly different between the catchments. Within each gully catchment however, bulk density may vary considerably and figures 4.4 show that bulk density may vary by a maximum of 0.3 g cm^{-3} over 5m and 1m distance within each of the gully catchments. In the matorral gully catchment 39% of the samples have bulk density values greater than 1.6 g cm^{-3} which may be considered as very compact (Landon, 1993) (figures 4.5). In comparison 33% and 30% of the samples from the forest and bench terrace gully catchments respectively may be described as very compact. Furthermore, none of the samples from the matorral gully have bulk density values below 1.4 g cm^{-3} whereas 10% and 20% of the samples from the forest and bench terrace gullies respectively have bulk density values below 1.4 g cm^{-3} (figures 4.5)

Table 4.10. Summary statistics of bulk density recorded within each gully catchment.

Summary Statistics	Matorral Gully Bulk Density (g cm^{-3})	Forest Gully Bulk Density (g cm^{-3})	Bench Terrace Gully Bulk Density (g cm^{-3})
Mean	1.58	1.54	1.54
Minimum	1.43	1.34	1.25
Maximum	1.77	1.70	1.79
Standard Deviation	0.10	0.10	0.14
Coefficient of Variation (%)	6.60	6.42	9.26
Number of Samples	18	21	20

Figure 4.4. Spatial variability in bulk density within each gully catchment.

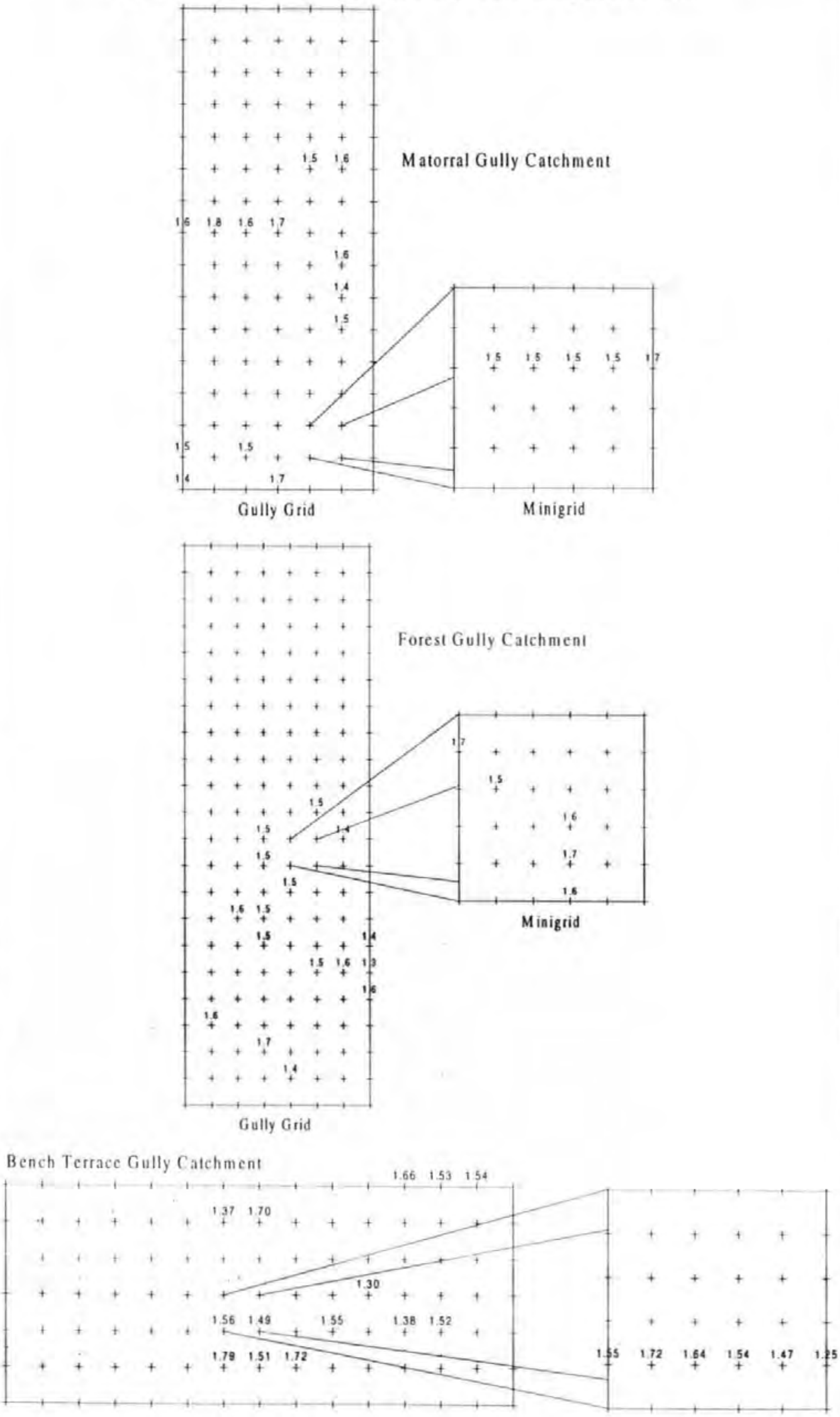
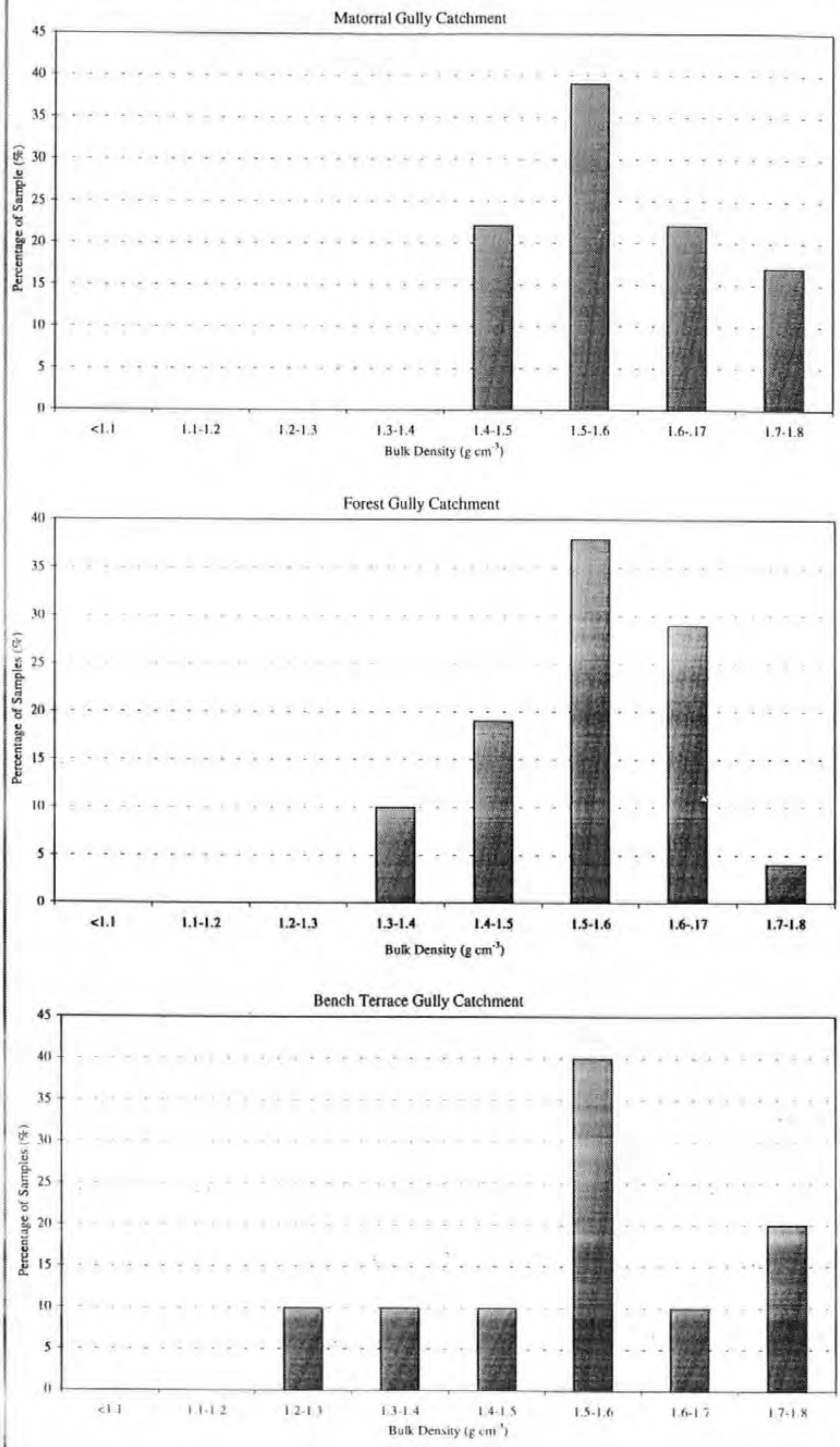


Figure 4.5. Bulk Density.



Summary

Average bulk density is similar between the catchments (1.54 to 1.58 g cm^{-3}) and is in agreement with the bulk density value of 1.54 g cm^{-3} reported for Rana soils by Ingelmo *et al.* (1994). Bulk density values may however range from as low as 1.25 g cm^{-3} to 1.77 g cm^{-3} within the gully catchments. Within each of the gully catchments over 80% of the samples have a bulk density greater than 1.4 g cm^{-3} indicating soils with a moderate to high degree of compaction. Furthermore, in the matorral catchment 40% of the samples may be considered as very compact. The moderate to high bulk density of the majority of the samples supports the generally low hydraulic conductivity and poor structure of these soils reported in previous sections.

4.1.5 Organic Carbon

Organic carbon was determined from samples collected in April prior to the onset of high summer temperatures which can encourage the oxidation of organic materials. Sample values therefore reflect a period in the annual fluctuation of this property when organic carbon content may be expected to be high.

Organic Carbon

Table 4.11 shows summary statistics for organic carbon within each gully catchment. Within each of the gully catchments the average organic carbon content is less than 1% and is less than 0.5% in the matorral and bench terrace catchments. No significant differences in organic carbon content however, may be found between the catchments. Organic carbon may however, be highly variable within the catchments ranging from 0.03% to 2.5%. Figures 4.6 show that organic carbon may vary from between 1-2% over 5m distance within each of the catchments although little variation occurs over smaller distances of 1m. Greenland (1977) and Morgan (1996) have suggested that soils may also be vulnerable to erosion if the organic carbon content is less than 2%. Figures 4.7 show that all of the samples within the bench terrace gully have an organic carbon content below 2% and that 97% and 93% of the samples within the matorral and forest catchments respectively have organic carbon contents below the 2% threshold. Furthermore, 98% of the samples within the bench terrace gully have an organic carbon content below 1% which compares to 79% and 70% of the samples in the matorral and forest catchments respectively (figures 4.7).

Table 4.11. Summary statistics of the percentage organic carbon recorded within each gully catchment.

Summary Statistics	Matorral Gully Organic Carbon (%)	Forest Gully Organic Carbon (%)	Bench Terrace Gully Organic Carbon (%)
Mean	0.48	0.71	0.45
Minimum	0.03	0.03	0.04
Maximum	2.07	2.50	1.11
Standard Deviation	0.51	0.70	0.26
Coefficient of Variation (%)	105.45	99.08	58.34

Figure 4.6. Spatial varibility in organic carbon within each gully catchment.

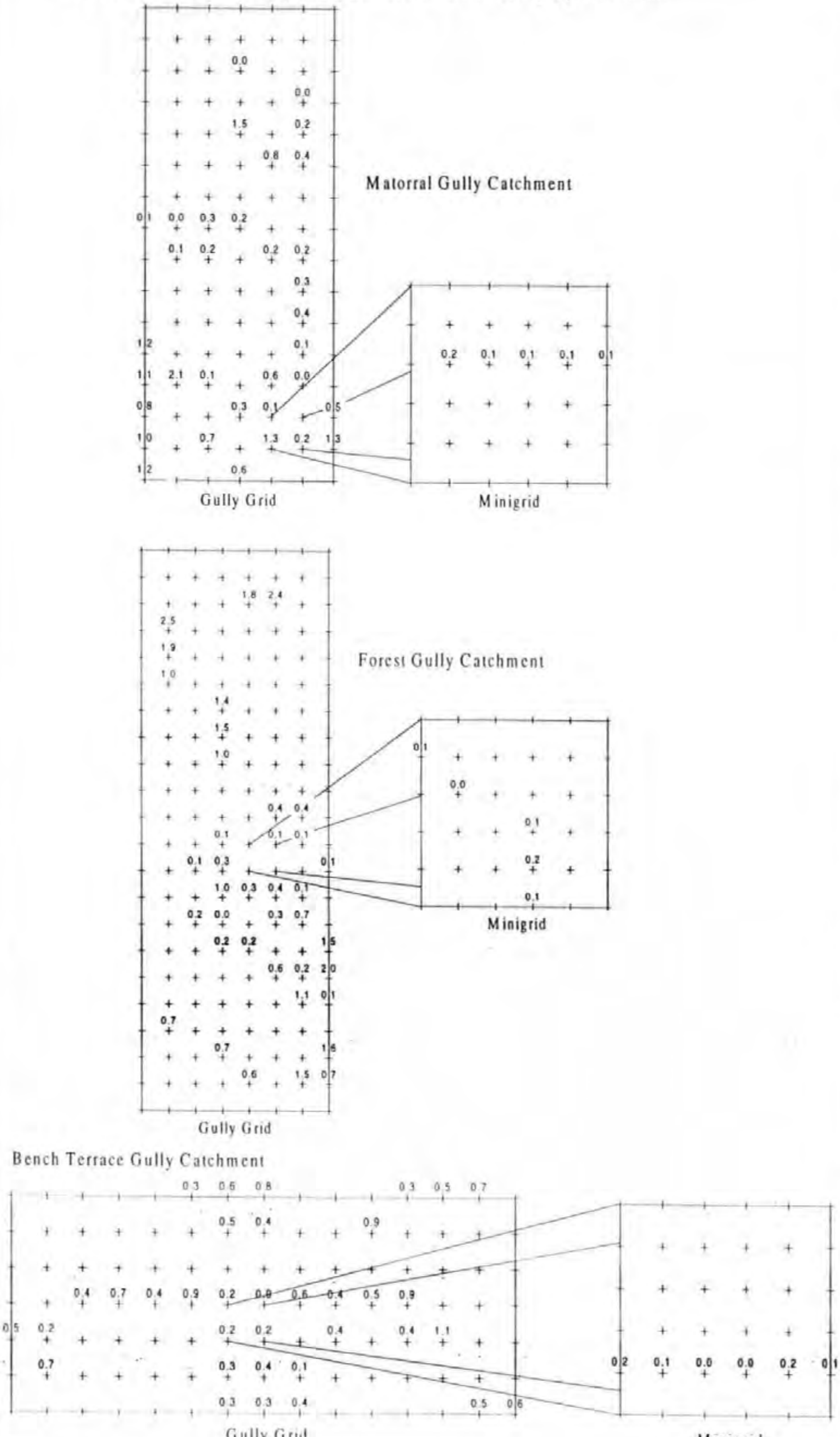
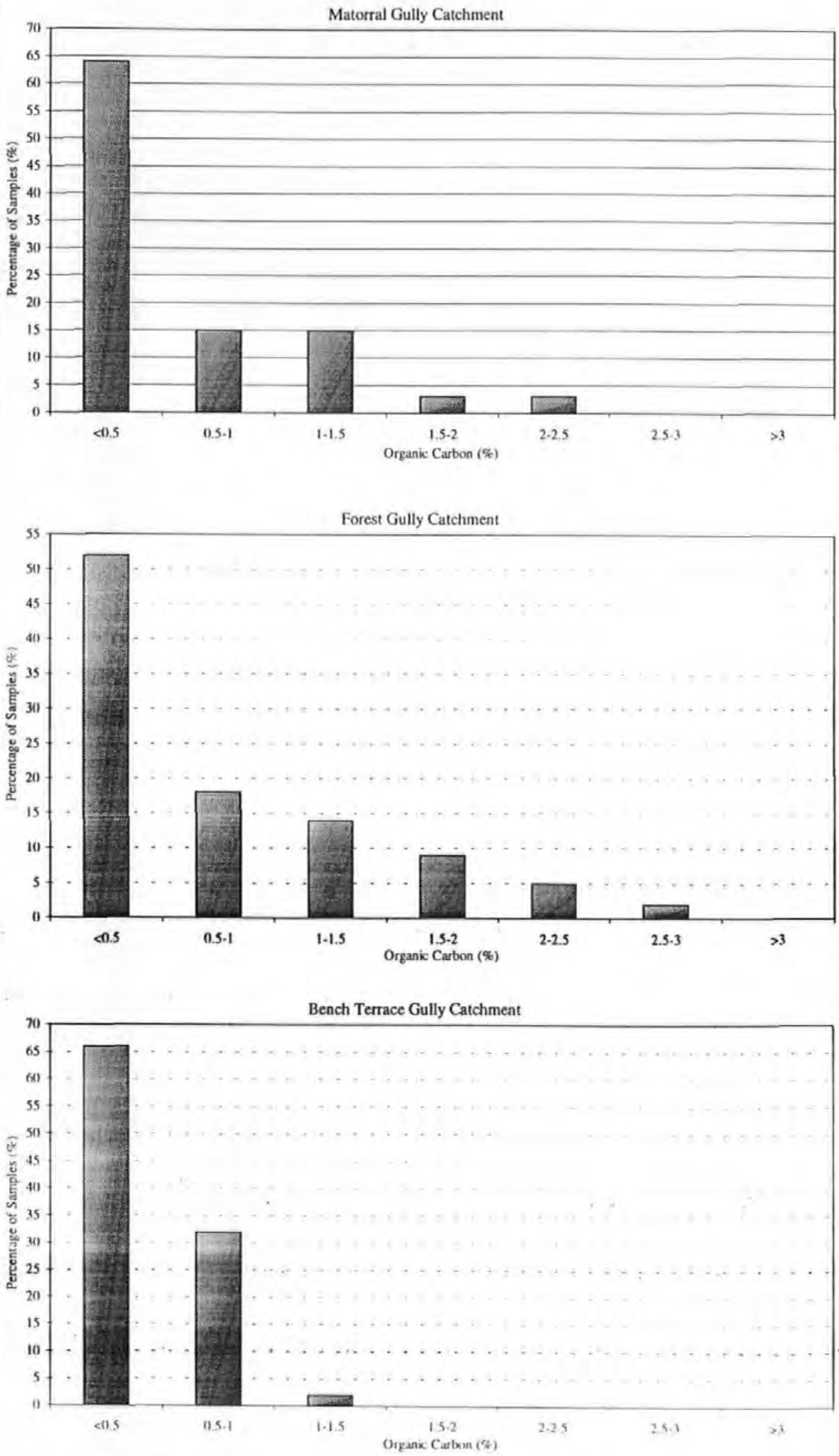


Figure 4.7. Percentage Organic Carbon.



Summary

Although there are no significant differences in organic carbon content between the catchments, considerable variability in this property may occur within the catchments, particularly over 5m distance. In the bench terrace gully catchment the percentage of samples with organic carbon contents below the critical thresholds identified for soils vulnerable to erosion is higher than in either the matorral or forest gully catchments. In all three catchments however, the majority of the samples have organic carbon contents below the critical thresholds identified by Greenland (1977) and Morgan (1996). The majority of the soils within the catchments may therefore be considered as vulnerable to erosion.

4.1.6 Aggregate Stability (R.S.S.I)

The breakdown of relatively weak surface aggregates may result in soil surface sealing which can lead to the rapid onset of surface runoff regardless of the underlying soils structure or permeability (Truman and Bradford, 1990; Moore and Singer, 1990). The stability of surface aggregates can therefore play a key role in determining the soils hydrological and erosional response to rainfall (Truman *et al.*, 1990; Rasiah *et al.*, 1990). Table 4.12 shows summary statistics for aggregate stability within each gully catchment. No significant differences in aggregate stability occur between the gully catchments although the average percentage stable aggregates is 10% higher in the bench terrace gully catchment than in the matorral catchment. Within each of the gully catchments aggregate stability is highly variable and ranges from 11% to 95% in the matorral gully, 10% to 99% in the forest gully and 32% to 93% in the bench terrace gully over distances as short as 5m (figures 4.8). Within each of the gully catchments approximately half of the samples have aggregate stability values greater than 75% (figures 4.9). Furthermore, only 20% of the samples in the bench terrace gully have an aggregate stability value below 50% which compares with 36% and 30% of the samples within the matorral and forest gullies respectively (figures 4.9).

Table 4.12. Summary statistics of the percentage aggregate stability recorded within each gully catchment.

Summary Statistics	Matorral Gully R.S.S.I (%)	Forest Gully R.S.S.I (%)	Bench Terrace Gully R.S.S.I (%)
Mean	61.87	67.44	71.69
Minimum	1.00	10.00	9.00
Maximum	100.00	100.00	100.00
Standard Deviation	34.31	29.03	25.12
Coefficient of Variation (%)	55.45	43.04	35.04

Figure 4.8. Spatial variability in aggregate stability within each gully catchment.

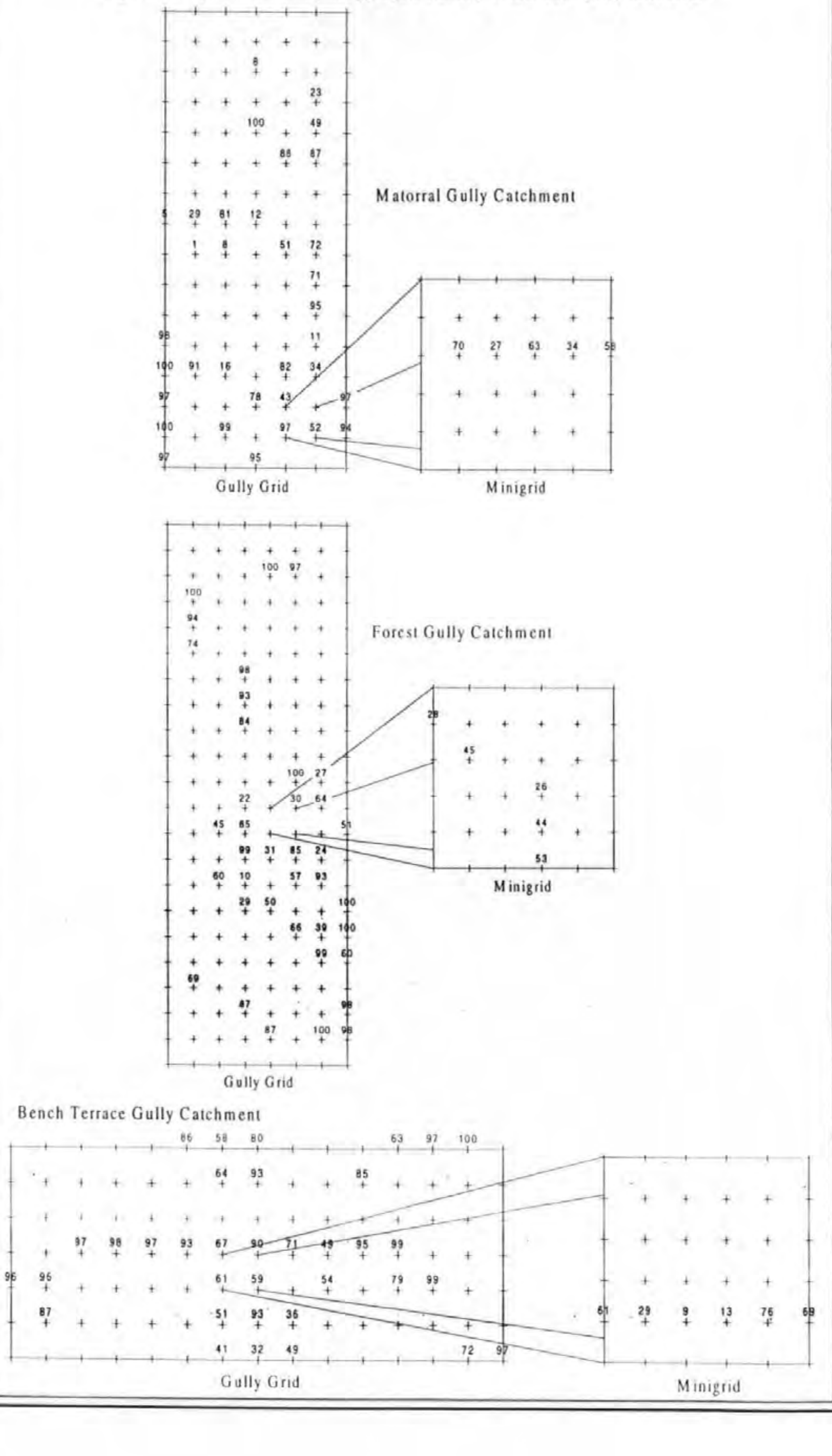
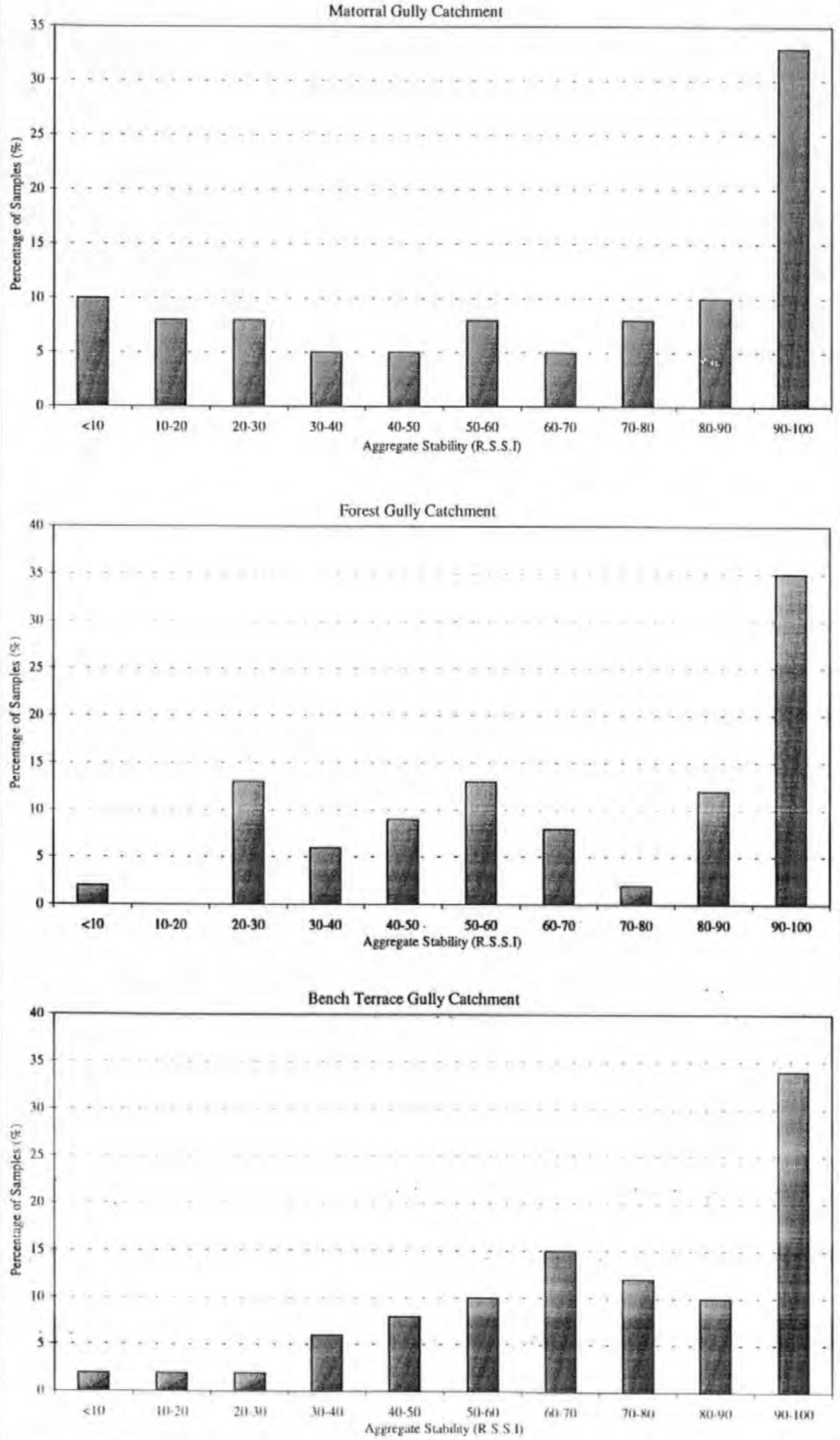


Figure 4.9. Aggregate Stability (R.S.S.I).



Summary

Similar to other properties, the stability of soil aggregates may vary considerably over distances as short as 5m. Although the majority of the samples within each of the gully catchments have organic carbon contents below the critical threshold, implying that these soils are vulnerable to erosion, approximately 50% of the samples within the gully catchments have aggregate stability values above 75% which in contrast suggests relatively stable soils. However, the implied stability of these soils may be a reflection of the rainfall simulation technique used in this study to test the stability of soil aggregates. Other measurement techniques of aggregate stability such as the WSA test used by Ternan *et al.* (1996a) have shown that aggregates from this area have a very low stability. Using this technique nearly all of the aggregates dispersed (J.L. Ternan, personal communication). The rainfall simulation technique is more sensitive to variations in aggregate stability in low stability soils. Therefore the rainfall simulation technique, although it may wrongly suggest relatively stable soils, allows comparisons to be made between aggregates from soils of low stability.

Although in general samples within the bench terrace gully have a lower organic carbon content than in the matorral and forest catchments, aggregate stability is generally higher in the bench terrace gully. This suggests that either factors other or as well as organic carbon are important in determining aggregate stability or that the critical threshold of organic carbon, above which soils are considered stable, are much lower in this environment than those identified by Greenland (1977) and Morgan (1996).

4.1.7 Vegetation and Litter Cover

Areas with high vegetation and/or litter cover are often areas with good soil physical and hydrological properties (Dunne *et al.*, 1991; Bohm and Gerold, 1995). Runoff and erosion is often reported to be considerably higher in areas bare of vegetation (Johnson and Gordon, 1988; Nicolau *et al.*, 1996).

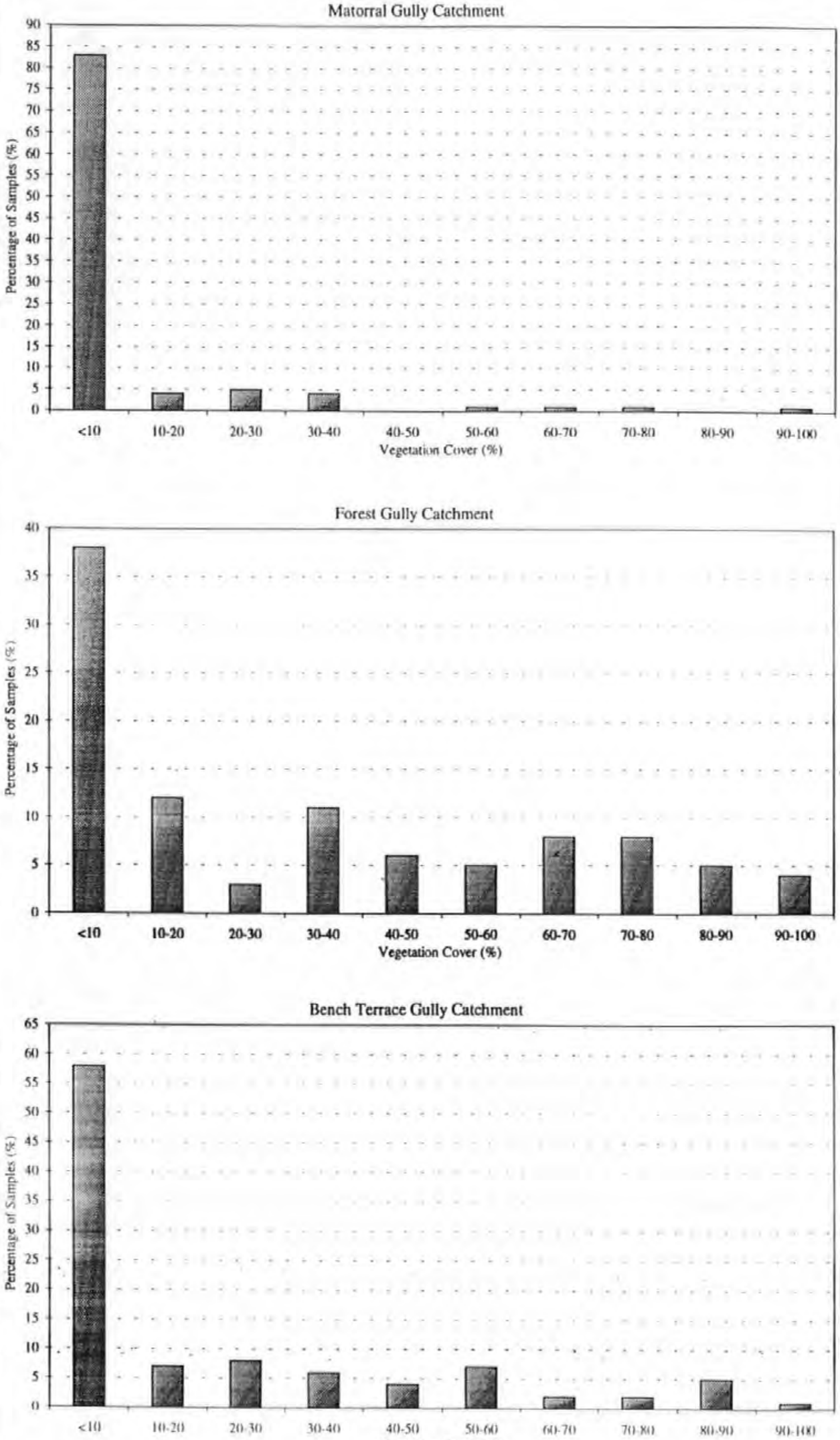
Vegetation Cover

Table 4.13 shows summary statistics for vegetation cover within each gully catchment. The average percentage vegetation cover is low in all three catchments, but is significantly higher in the forest gully than the matorral or bench terrace gullies. The average percentage vegetation cover in the matorral gully is very low at just 7.82%. The percentage vegetation cover is however highly variable within each of the catchments ranging from 0% cover to 97% cover (table 4.13). Snelder and Bryan (1995) have identified a critical threshold vegetation cover of 55% below which erosion rates increased rapidly. Figures 4.10 show 96% of the soil moisture sampling sites within the matorral gully have a vegetation cover below 55%. In comparison 71% and 84% of the sample sites within the forest and bench terrace gullies respectively have a vegetation cover below 55% (figures 4.10).

Table 4.13. Summary statistics of the percentage vegetation cover recorded within each gully catchment.

Summary Statistics	Matorral Gully Vegetation Cover (%)	Forest Gully Vegetation Cover (%)	Bench Terrace Gully Vegetation Cover (%)
Mean	7.82	33.21	20.26
Minimum	0.00	0.00	0.00
Maximum	97.00	97.00	97.00
Standard Deviation	16.32	31.75	27.28
Coefficient of Variation (%)	208.62	95.60	134.66

Figure 4.10. Percentage Vegetation Cover.



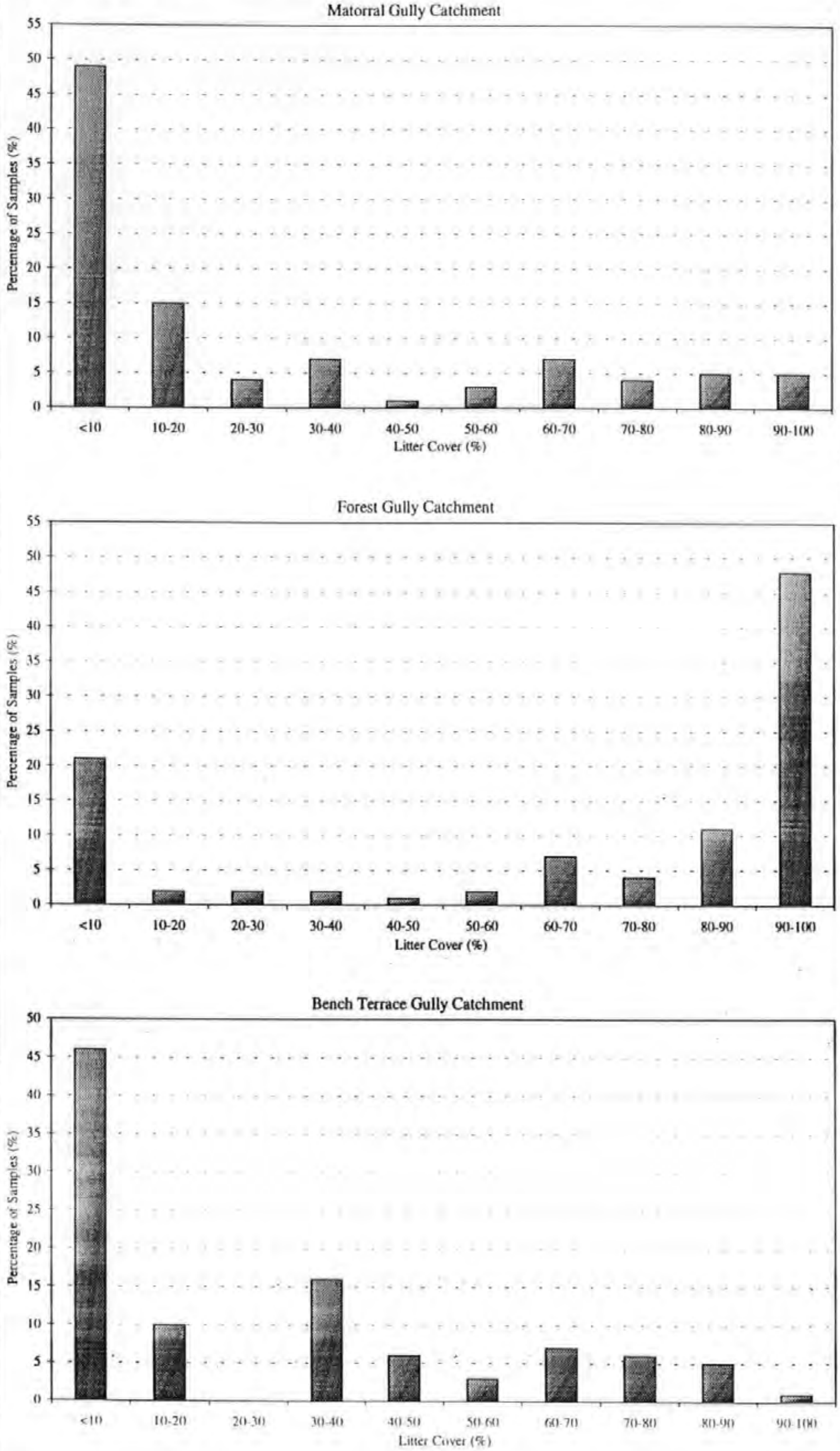
Litter Cover

Table 4.14 shows summary statistics for litter cover within each gully catchment. Within each of the gully catchments the percentage litter cover is higher than the percentage vegetation cover, although litter cover remains low in the matorral and bench terrace gullies (25-30%). The average percentage litter cover in the forest catchment is significantly higher, more than double (71%), than the litter cover in the matorral and bench terrace gullies. Figures 4.11 show that in the matorral and bench terrace gullies 76% and 78% of the sample sites respectively have a litter cover below 55%. In contrast only 38% of the sample sites in the forest gully catchment have a litter cover below 55% (figures 4.11).

Table 4.14. Summary statistics of the percentage litter cover recorded within each gully catchment.

Summary Statistics	Matorral Gully Litter Cover (%)	Forest Gully Litter Cover (%)	Bench Terrace Gully Litter Cover (%)
Mean	27.14	71.07	30.03
Minimum	0.00	0.00	0.00
Maximum	100.00	100.00	95.00
Standard Deviation	31.90	38.18	28.09
Coefficient of Variation (%)	117.53	53.72	93.54

Figure 4.11. Percentage Litter Cover.



Summary

The percentage vegetation and litter cover is significantly higher in the forest gully catchment than in the matorral and bench terrace gullies. This however may not be unexpected since more than a third of the forest gully catchments sample points are located within its watershed areas which are relatively undisturbed and have a mature covering of *Pinus* trees. In comparison most of the sample sites within the matorral gully, which has the lowest vegetation and litter cover, are located within the gully itself, where steeply sloping sidewalls and active erosion prevent the development of widespread vegetation cover. Taking this into account however, the percentage of litter cover still remains higher in the forest gully compared to the matorral gully and may be attributed to the greater canopy cover of *Pinus* trees and hence the greater dispersion of litter within the forest gully. A low percentage of litter cover may be less critical than a low percentage of aerial vegetation cover due to its effects on surface roughness. Litter is in direct contact with the soil surface and therefore a relatively low coverage of litter may still significantly increase surface roughness, which only needs to increase slightly, to have a dramatic effect in retarding runoff and erosion (Edwards *et al.*, 1994; Sardo *et al.*, 1994; Morin and Kosovsky, 1995).

4.1.8 Root Weight

Root weight is the weight of roots greater than 1mm in diameter within a 977 cm^3 soil core. Roots have positive effects on soil structure and can be important in determining hydrological pathways and the depth of water penetration within soils (Dunne *et al.*, 1991; Morin and Kosovsky, 1995). Table 4.15 shows summary statistics for root weight within each gully catchment. Average root weight is significantly higher in the forest gully catchment compared to the matorral and bench terrace catchments ($p<0.05$). Furthermore the root weight within the forest gully catchment may be up to 15g in some areas. Figures 4.12 show that 35% of the samples within the forest gully catchment have a root weight below 1g. In comparison 72% and 68% of the samples within the matorral and bench terrace catchments have root weights below 1g. Within each gully catchment and in particular within the forest gully root weight may vary considerably over relatively short distances. Figures 4.13 show that within the forest catchment root weight can vary by as much as 8g over 5m distance and by just over 1g in the matorral and bench terrace catchments.

Table 4.15. Summary statistics of the root weight recorded within each gully catchment.

Summary Statistics	Matorral Gully Root Weight (g)	Forest Gully Root Weight (g)	Bench Terrace Gully Root Weight (g)
Mean	0.75	2.51	0.78
Minimum	0.00	0.03	0.01
Maximum	2.44	15.85	2.51
Standard Deviation	0.73	3.71	0.64
Coefficient of Variation (%)	97.90	147.74	82.07

Figure 4.12. Root Weight.

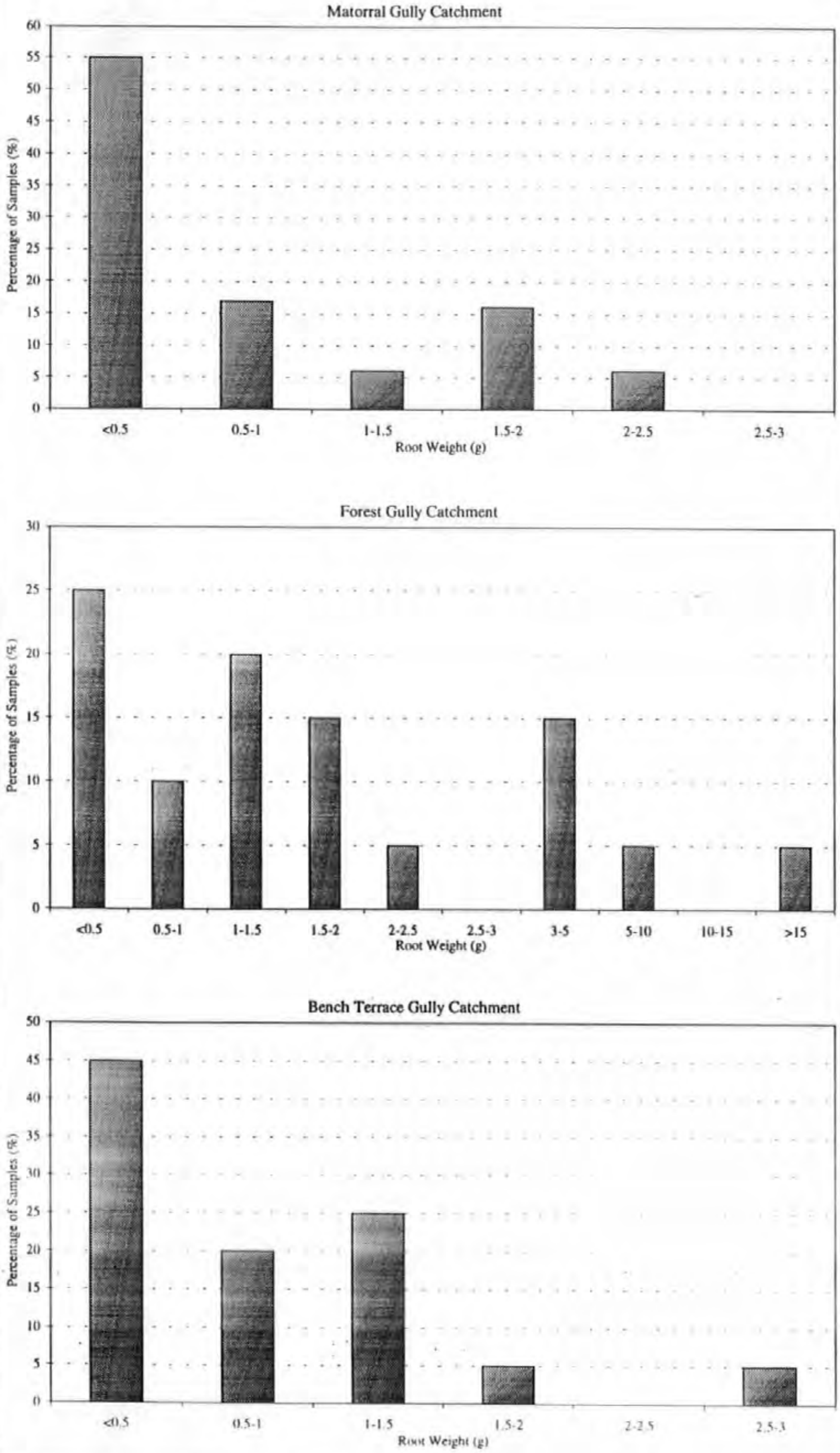
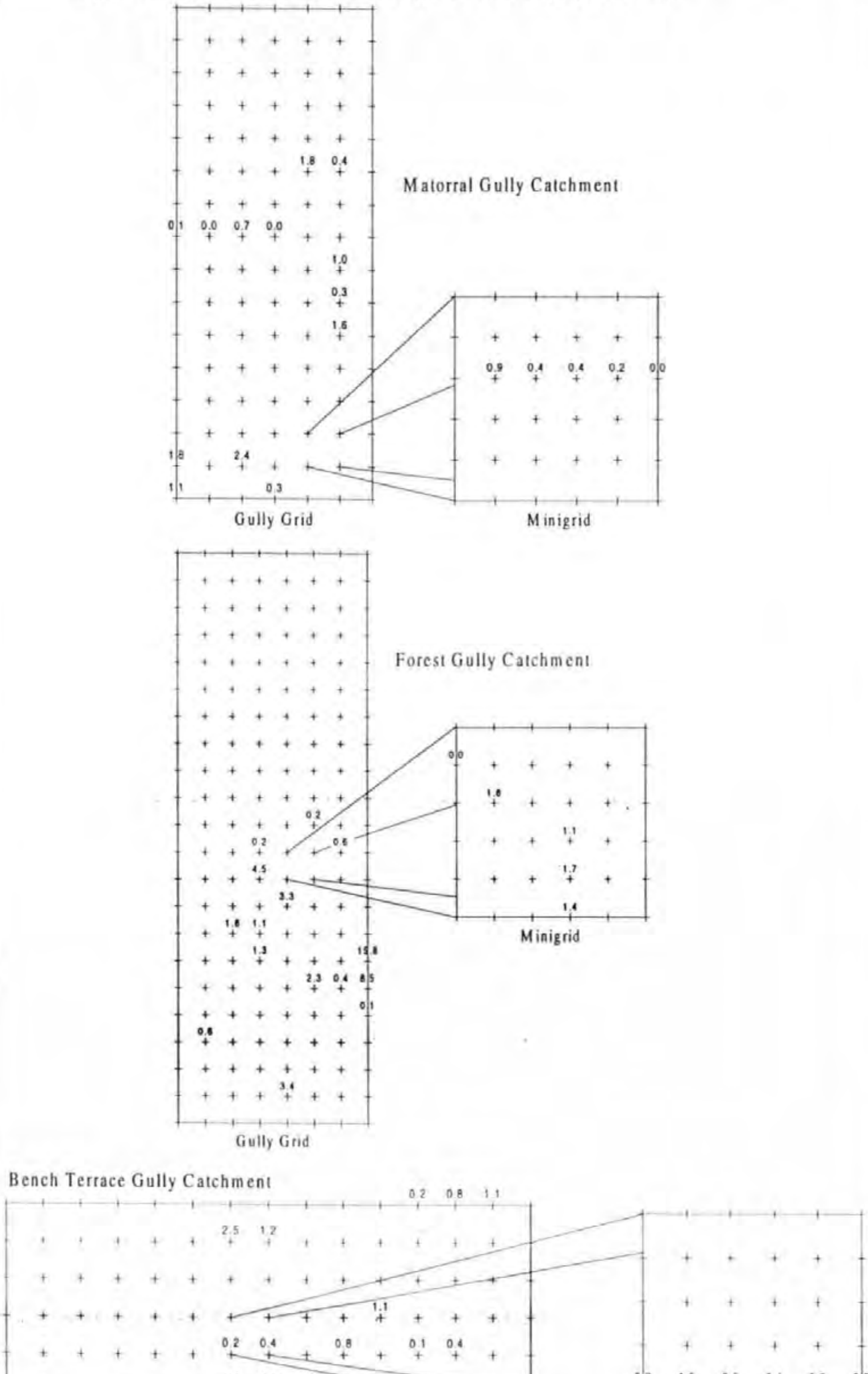


Figure 4.13. Spatial variability in root weight within each gully catchment.



Summary

The significantly higher root weight within the forest gully catchment compared to the matorral and bench terrace gullies reflects the significantly higher percentage vegetation cover within this catchment. The role of roots in determining hydrological response and soil moisture patterns is therefore likely to be more significant within the forest gully catchment and in particular within this catchments watershed where the density of trees is highest. Within each of the gully catchments the role of roots in determining soil moisture patterns is expected to be highly localised and restricted to the area of soil immediately surrounding the roots. Due to the considerable variability in root weight over short distances the continuity of channels created by roots is expected to be short. The role of roots in determining sub-surface flow is therefore also expected to be small.

4.2 Inter-Relationships between Properties

Within each of the three gully catchments the pore size distribution of the soils appears to be largely dependent upon soil texture (tables 4.16 and 4.17). Significant positive correlations occur between the residual porosity and the percentage of finer particle sizes (clay and silt) in both the surface and sub-surface horizons. In contrast, transmission pores are generally positively correlated with the proportion of coarser materials such as sand and gravel. Storage pores in the matorral and bench terrace gullies are significantly positively correlated with sand content although negatively correlated with gravel content (tables 4.16 and 4.17). The total porosity shows a similar relationship with soil texture to that shown by residual pores ie. total porosity is higher in sediments dominated by a finer particle size. Within each of the gully catchments therefore, sediment horizons characterised by a fine particle size may be expected to have a higher residual and total porosity than sediments of coarser texture which in contrast will generally have a higher transmission porosity. Storage pores will be highest in those sediments dominated by sand sized particles.

k_{sat} is not significantly correlated with soil texture in any of the gully catchments and is only significantly positively correlated with transmission pores in the forest catchment (tables 4.16 and 4.17). K_{sat} is not significantly related to any of the other pore size distributions in both the surface and sub-surface soil. Lind (1989) has also reported a random pattern in the relationship between porosity and hydraulic conductivity. K_{sat} is however significantly positively correlated with the volume of roots and organic carbon in the forest gully. Roots may play a significant role in creating channels within the soil and maintaining soil structure which can therefore promote a higher conductivity (Nicolau *et al.*, 1996; Bergkamp *et al.*, 1996). Organic carbon may also promote soil stability and therefore maintain a permeable soil structure. The correlations may only be significant within the forest gully since both organic carbon and in particular, the volume of roots are higher in this catchment when compared to the matorral and bench terrace gullies.

Table 4.17. Correlation matrix between those variables considered to be important in determining runoff and erosion (pore size characteristics are from the surface horizon).

	Ksat			*Transmission Pores*			*Storage Pores*			*Residual Pores*			*Total Porosity*			*R.S.S.I*		
	Matorral	*Forest*	*Bench*	*Matorral*	*Forest*	*Bench*	*Matorral*	*Forest*	*Bench*	*Matorral*	*Forest*	*Bench*	*Matorral*	*Forest*	*Bench*	*Matorral*	*Forest*	*Bench*
Texture																		
Clay	0.11	0.11	-0.26	-0.15	0.10	0.16	-0.25	-0.05	-0.10	0.62**	0.48*	0.30	0.36	0.49*	0.23	-0.14	-0.17	0.24
Silt	0.14	-0.17	-0.27	-0.52*	-0.33	-0.11	-0.27	0.24	0.23	0.59**	0.68**	0.71**	0.47*	0.49*	0.53*	-0.29*	-0.19	0.13
Sand	-0.05	0.13	-0.10	0.26	0.34	-0.24	0.57*	-0.16	0.64**	-0.38	-0.76**	-0.06	-0.55*	-0.53*	0.21	0.01	-0.39**	-0.11
Gravels	-0.13	0.04	0.27	0.40	0.02	0.21	-0.02	-0.07	-0.54*	-0.43*	-0.04	-0.52*	-0.20	-0.06	-0.54*	0.27*	0.35*	-0.07
Org. Props																		
Org. Carbon	0.38	0.69**	0.18	0.46*	0.04	0.81**	-0.18	0.14	-0.20	-0.52	0.08	-0.08	0.31	0.16	0.32	0.73**	0.76**	0.63**
Root Vol.	0.41	0.82**	0.00	0.26	0.28	0.20	-0.01	0.20	-0.22	-0.38	-0.03	-0.30	0.45*	0.26	-0.20	0.70**	0.56**	0.02
Veg. Cover	-0.06	0.37	0.00	-0.26	-0.20	0.17	-0.18	0.31	0.08	-0.05	0.08	0.09	-0.23	0.07	0.20	-0.04	0.39**	0.20
Litt. Cover	0.65**	0.43*	0.04	----	----	----	----	----	----	----	----	----	----	----	----	0.61**	0.53**	0.42**
Ksat	----	----	----	-0.19	0.42*	0.03	0.05	0.04	0.10	0.02	-0.30	-0.20	0.12	0.05	0.07	0.22	0.45*	-0.04
Bulk Density	-0.11	-0.58**	0.04	0.08	-0.20	-0.20	0.18	0.21	-0.20	0.30	0.05	-0.18	-0.71**	-0.01	-0.36	-0.36	-0.57**	-0.39*
R.S.S.I	0.22	0.45*	-0.04	0.27*	-0.31*	0.58**	-0.07	-0.11	-0.16	-0.48**	0.19	-0.15	0.29*	-0.09	0.15	----	----	----
Net Erosion	0.23	0.32	0.12	0.30	-0.32	-0.15	0.45*	0.17	0.22	-0.57**	0.26	-0.05	-0.02	-0.13	0.16	0.61**	0.47**	0.35*

* = significant at p<0.05 (95%)
** = significant at p<0.05 (99%)

Table 4.18. Correlation matrix between those variables considered to be important in determining runoff and erosion (pore size characteristics are from the sub-surface horizon).

	Transmission Pores			*Storage Pores*			*Residual Pores*			*Total Porosity*		
	Matorral	*Forest*	*Bench*	*Matorral*	*Forest*	*Bench*	*Matorral*	*Forest*	*Bench*	*Matorral*	*Forest*	*Bench*
Texture												
Clay	-0.43*	-0.13	-0.03	-0.36	-0.17	-0.02	0.62**	0.47*	0.41*	0.47*	0.43*	0.48*
Silt	-0.77**	-0.45*	-0.52*	-0.21	0.01	0.36	0.87**	0.65**	0.62**	0.74**	0.45*	0.61**
Sand	0.52*	0.47*	-0.29	0.63**	0.02	0.75**	-0.62**	-0.63**	-0.10	-0.23	-0.36	0.26
Gravels	0.53*	0.06	0.53*	-0.14	-0.01	-0.66**	-0.59**	-0.14	-0.43*	-0.69**	-0.15	-0.63**
Organic Properties												
Organic Carbon	0.44*	0.01	0.14	-0.09	0.07	-0.20	-0.35	-0.02	0.15	-0.32	0.04	0.61**
Root Volume	0.11	0.16	0.04	-0.04	0.07	-0.33	-0.03	-0.13	-0.07	0.01	0.04	-0.35
Vegetation Cover	-0.42	-0.04	-0.17	-0.28	0.30	0.35	0.46*	-0.05	0.12	0.14	0.04	0.25
Ksat	-0.16	0.29	0.22	0.37	0.12	-0.17	-0.15	-0.29	-0.16	-0.14	-0.01	-0.14
Bulk Density	-0.04	-0.20	-0.06	-0.41*	0.24	-0.28	-0.11	0.25	-0.06	-0.52*	0.32	-0.40*
R.S.S.I	0.35*	-0.14	0.43	-0.07	-0.06	-0.21	-0.28*	0.02	-0.13	-0.26	-0.18	0.08
Net Erosion	0.40*	-0.30	-0.02	0.58**	0.41*	0.61**	-0.62**	0.18	-0.34	-0.25	-0.04	0.10

* = significant at p<0.05 (95%)
** = significant at p<0.05 (99%)

The correlations in tables 4.16 and 4.17 suggest that in addition to soil texture, organic carbon may also affect the pore size distribution. Within the matorral and bench terrace gullies organic carbon is significantly positively correlated with the number of transmission pores. Similarly, Nyberg (1995) has also reported strong correlations between porosity and organic content. Organic material is known to increase the water holding capacity of the soil by increasing porosity (Brady, 1990; Landon 1993). An increase in the number of transmission pores related to organic carbon content may reflect the strong and significant positive correlations that this property has with R.S.S.I (table 4.16). A greater aggregate stability and a more stable soil structure resulting from the presence of organic carbon may promote and maintain the number of transmission pores.

Although organic carbon is related to soil porosity, the organic properties in general appear to be most significant in determining aggregate stability within each of the gully catchments. Organic carbon is significantly positively correlated with aggregate stability within each of the gully catchments. Ternan *et al.* (1996a) reported similar findings and suggested that

"coarse organic material may have a less beneficial effect on aggregate stability than finer material".

Fine roots may also encourage inter-particle bonding and this is reflected in the strong positive correlations between the volume of roots and aggregate stability in the matorral and forest gullies. The positive correlations between litter cover and aggregate stability may indirectly reflect the significant positive correlations between litter cover and organic carbon. Vegetation cover shows few direct significant correlations with the other soil properties. Its role however, may be indirect since the principal effects that vegetation has on the soil's physical and hydrological properties is through its rooting characteristics and input of organic material (Bohm and Gerold, 1995). Vegetation cover is therefore only an indirect measure of these characteristics which may explain its generally weak correlation with all of the soil properties examined. Dunne *et al.* (1991) have found similar weak relationships with vegetation cover, reporting that the removal of above ground surface vegetation had no significant effects on infiltration or runoff, because the below ground surface vegetation structure ie. roots and organic material remained intact. Aggregate stability displays a negative trend with bulk density within each of the gully catchments which suggests that areas of low aggregate stability have a higher bulk density. Blackburn (1975) has also reported that in areas where bulk density is high, sediment production may also be high.

Net erosion ie. the erosion/deposition which occurred in the period from July 1995 to April 1996, has also been included within the correlation matrix, since soil erosion may be an important variable reflecting and determining the values of soil properties (Lowery *et al.*, 1995). Net erosion is significantly positively correlated with aggregate stability within each of the gully catchments (table 4.16). These correlations are positive since erosion is recorded as a negative number. The correlations therefore, suggest that areas of high aggregate stability are susceptible to less erosion than areas of lower aggregate stability. Net erosion is also significantly positively correlated with litter cover in each of the gully catchments which reflects the importance of litter cover in protecting the soil surface and retarding surface runoff.

4.3. Conclusions

The alluvial nature in which sediments have been deposited within this region has resulted in the near horizontal interbedding of clearly distinct and contrasting textural horizons. Within each gully catchment these sediments may be dominated (with the exception of clay) by a single particle size. Sediments dominated by gravel may therefore be found adjacent to sediments dominated by silt. This variability in soil texture together with a spatially non-uniform vegetation cover and a typical badlands topography has created a heterogeneous environment where soil properties may be highly variable over relatively short distances. It may therefore be expected that the hydrological and erosional response of the gully catchments will also be highly variable reflecting the spatial distribution of those properties determining hydrological response. Within each gully catchment runoff and erosion may therefore be spatially non-uniform. Furthermore, gullying itself may increase the variability in soil properties by exposing several contrasting sediment horizons through gully dissection. Heterogeneity in hydrological and erosional response may therefore be expected to be higher within gullies compared to adjacent inter-gully areas where only one or two sediment horizons are exposed. Since significant differences in soil texture may be found within gullies, the hydrological response of gullies may reflect the spatial pattern of soil texture. In contrast, variation in hydrological response within inter-gully areas may be better related to the spatial pattern of vegetation cover which may be more variable than soil texture in these areas. Gully morphology may also determine the variability of hydrological response. Gullies characterised by deep dissections may have a variable hydrological response due to the exposure of several varying sediment horizons. In contrast, a shallow bulbous shaped morphology may have a uniform hydrological response due to the exposure of only one or two sediment horizons.

Gully morphology may explain the higher silt content found within the matorral gully compared to the forest or bench terrace gullies. The upper half of the matorral gully is shallow and dissects only one or two sediment horizons which are dominated by silt. Silt content will therefore be highest within the matorral gully since a significant proportion of the gully has developed within a silt dominated horizon. Similarly, the forest gully has a higher sand content compared to the matorral gully which may be related to the extensive watershed of the forest gully which is developed in a sediment horizon dominated by sand. Furthermore, the significant correlations between soil texture and the pore size distribution suggests that although the differences are not significant, transmission porosity and storage porosity may be higher in the forest gully catchment compared to the matorral gully catchment where residual porosity will be higher. Since residual pores retain water at high suctions, the average soil moisture content of the soils within the matorral gully may be higher than in the forest gully particularly during dry weather periods. The available soil water storage capacity may therefore be higher within the forest gully catchment compared to the matorral gully since fewer pores are filled with water. Soil moisture storage is considered to be a key factor in determining times to runoff and total runoff volume (Scoging, 1982).

Within the bench terrace catchment, disturbances to the soils and vegetation cover together with a more variable although structured terrain, appears to have increased the spatial variability in soil properties compared to the matorral and forest catchments. The increased variability may be attributed to the mixing of sediment horizons, the exposure of sub-surface horizons and the establishment of a patchy and mixed vegetation cover consisting of *Pinus* trees and matorral scrub, which has begun to re-colonise the terraces after being cleared. Furthermore, a greater percentage of samples within the bench terrace gully have a better soil structure, a higher K_{sat} and a lower bulk density than the soils in the matorral gully and is similar to the forest gully. The improved soil properties within the bench terrace catchment compared to the matorral catchment mat be attributed to several factors. Firstly, the terraces were subsoiled during their construction which loosened the soil with the aim of improving soil structure and reducing soil compaction. Secondly, a similarity between the bench terrace gully and forest gully, but difference with the matorral catchment is the presence of *Pinus* trees within the vegetation assemblage. The rooting characteristics of *Pinus* trees may promote a better soil structure than the rooting characteristics of matorral scrub and the presence of both vegetation types may further improve the soil structure. Thirdly, the difference in soil properties between the bench terrace and matorral catchments may be simply attributed to the extensive occurrence of one sediment horizon within the matorral gully catchment which is dominated by silt sized particles. The small particle size and associated higher residual porosity of this sediment horizon may account for the generally lower K_{sat} and higher bulk density of the soils within the matorral gully compared to the bench terrace catchment. The differences in soil properties may therefore be related to gully morphology which may change as different sediment horizons are encountered (Ternan *et al.*, 1998).

The occurrence of erosion within the three gully catchments is significantly correlated with the stability of soil aggregates and the percentage litter cover. Areas with high aggregate stability and/or a high litter cover are less susceptible to erosion than areas of low aggregate stability and a low litter cover. The stability of soil aggregates is primarily determined by organic carbon content and although the majority of the samples within each gully catchment have an organic carbon content below 1%, aggregate stability in the majority of samples is high, over 75% (using the rainfall simulation technique). This suggests that within this environment only a small amount of organic carbon can have a significant effect on aggregate stability and therefore that the threshold of organic carbon below which soils are vulnerable to erosion is lower than the 2% threshold stated by Greenland (1977) and Morgan (1996). In a semi-arid region in the south of Spain, M-Mena *et al.* (1998) have also reported that very small increments of organic carbon (less than 0.5%) can result in a significant difference in the stability of soil aggregates.

Considerable variation in those properties considered to be important in determining hydrological and erosional response occurs within each of the gully catchments. Within each gully catchment therefore, well structured, permeable and stable soils may be found adjacent (less than 5m distance) to poorly structured and unstable soils. The hydrological and erosional response of the gully catchments may therefore be expected to be spatially non-uniform. Similarly the spatial pattern of soil moisture within each gully catchment may also be expected to be highly variable and within the gullies themselves to reflect the spatial pattern of soil texture which is more variable within gullies compared to inter-gully zones. An exception to this however, occurs within the upper half of the matorral gully catchment where the shallow morphology exposes only one or two sediment horizons and therefore the spatial pattern of soil moisture may be expected to be uniform over relatively large areas within in this part of the catchment. Within inter-gully areas such as the forest catchments watershed, soil texture is again relatively uniform over large areas and the spatial pattern of soil moisture may therefore better reflect the variability in rooting characteristics and canopy cover within these areas. The generally greater variation in soil properties and better soil structure within the bench terrace gully catchment suggests that the hydrological response will be most variable within this catchment and source areas of runoff will be fewer, particularly when compared to the matorral catchment.

Within the following chapters, the spatial patterns of soil moisture and their relation to topographical, vegetation and soil properties, together with the variability in hydrological and erosional response from within each of the gully catchments are described and discussed.

Chapter 5

Temporal and Spatial Variability in Soil Moisture at the Macroscale (Transect Line)

5.0 Introduction

Transect lines have been used to quantify the spatial variability of soil moisture in a range of environments from temperate agricultural fields (e.g. van Wesenbeeck and Kachanoski, 1988) to desert sand dunes (e.g. Berndtsson and Chen, 1994). Their easy construction allows variables to be measured over relatively large distances. For example, Nash *et al.* (1991) measured soil water content over a 2.7 km long transect line in New Mexico. Transect lines may therefore be used to examine large scale variability in soil properties. The transect line used in this research was constructed with the aim of quantifying the temporal and spatial variability in soil moisture at the macroscale, using 25m sampling intervals. A second aim of the transect line was to determine the factors which predominately control the temporal and spatial variability in soil moisture at the macroscale. At this scale two possible controlling factors of soil moisture variability are considered:

1. *Topographic Characteristics:* The transect line crosses catchment divides, drainage channels and entire hillslopes. Topographical characteristics such as upslope drainage length, slope angle and elevation may therefore be important controlling factors.

2. *Vegetation Characteristics:* Since the transect line traverses three different vegetation assemblages, a change in the spatial and temporal variability in soil moisture may occur related to vegetation.

5.1 Temporal and Spatial Variability in Soil Moisture at the Macroscale

The soil moisture values recorded along the transect line on 13 measuring dates during the period from May 20 1995 to April 1 1996 are shown in figure 5.1. Summary statistics of the transect line soil moisture data set are presented in table 5.1. The soil moisture appears to cluster into two distinct groups which can be related to dry and wet weather conditions. Grayson *et al.* (1997) have reported that the transition period for soil moisture between dry and wet states may be relatively short. From March 8 1995 to

October 4 1995 average monthly rainfall was 57mm and on the measuring dates during this period soil moisture along the transect line is relatively low at all sampling points (average = 9.98%) and is similar for each measuring date. In contrast, average monthly rainfall between November 1995 and April 1996 was 81 mm, and represents an approximate 20% increase in monthly rainfall during this period. Soil moisture values recorded during this period are significantly higher ($p<0.05$) than the soil moisture values recorded during March 1995 to October 1995, confirming the division of the soil moisture data set into two distinct groups representing measurements recorded during dry and wet periods. Based on this division an average wet and dry soil moisture value for each sampling point along the transect line has been calculated and is shown in figure 5.2. Zhang and Berndtsson (1988) have also reported a clear seasonal change in the spatial variability of soil moisture allowing the data to be divided into dry and wet periods. Average minimum wet period soil moisture is nearly treble the average minimum dry and the maximum wet values are more than double the dry period soil moisture values (table 5.1). Furthermore the average mean soil moisture value increased by nearly 17% during wet weather conditions from 9.98% in dry weather conditions (table 5.1). During wet weather conditions the transect line is characterised by large fluctuations in soil moisture which are dampened during dry weather. A similar rainfall induced effect has been reported by Berndtsson and Chen (1994) along a transect line in a sand dune area in north-western China. The percentage of difference in soil moisture values between points during wet conditions is higher than the percentage of difference in soil moisture between points under dry conditions. For example, during wet conditions soil moisture can vary by a maximum of 22% over a distance of 25m compared to a maximum of 10% for the same distance under dry conditions. Furthermore during wet conditions soil moisture can vary by 22.4% at the same point compared to an 11.6% change in soil moisture for the same point during dry conditions. Therefore under wet conditions soil moisture appears to be more variable between points and at the same point than under dry conditions. The magnitude of difference in soil moisture values between points during dry and wet conditions is however similar and may even be slightly higher during dry periods ie. soil moisture may be more than 3 times higher at some points in both dry and wet conditions. The magnitude of variation is therefore similar in both dry and wet periods. Furthermore, the coefficient of variation (table 5.1), which provides a measure of the variability in soil moisture, is marginally higher during dry conditions compared to wet conditions, implying more variability in soil moisture values during dry periods.

Figure 5.1. Soil moisture recorded along the transect line on the 13 measuring dates during the period May 20 1995 - April 1 1996.

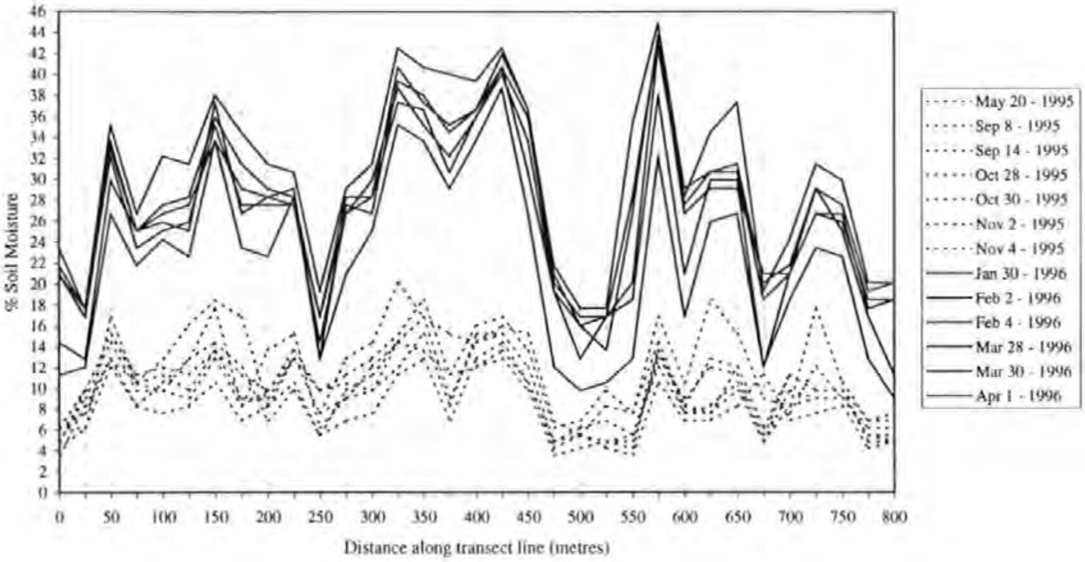
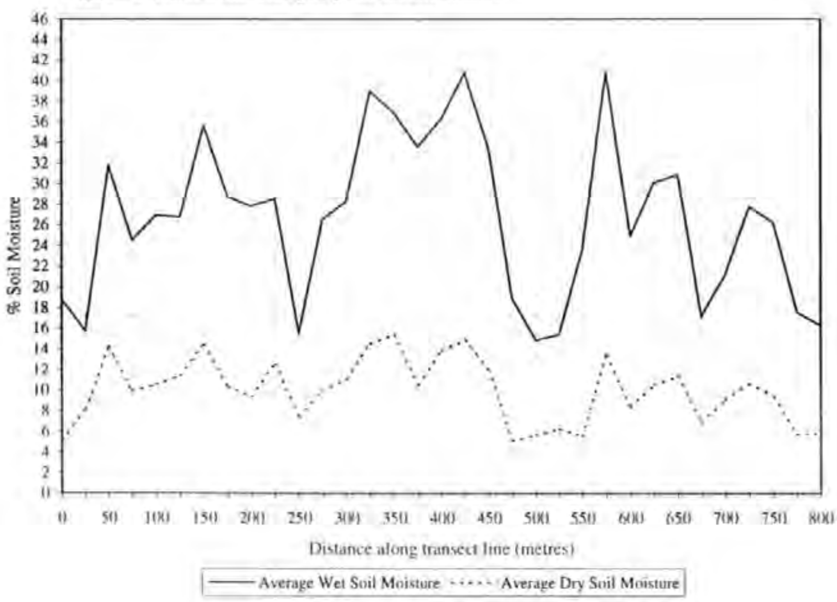


Table 5.1. Summary statistics of the soil moisture data recorded along the Transect Line

Soil Moisture Sampling Dates	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Variance	Coefficient of Variation (%)
May 20 1995	10.05	4.87	17.65	3.73	13.93	37.11
September 8 1995	12.24	5.53	20.12	4.32	18.64	35.29
September 14 1995	9.30	3.60	14.42	3.46	11.97	37.20
October 28 1995	11.03	6.20	18.47	3.27	10.72	29.64
October 30 1995	9.90	4.87	16.84	3.29	10.83	33.23
November 1 1995	9.25	4.87	15.22	3.20	10.24	34.59
November 4 1995	8.10	3.60	14.42	2.91	8.45	35.92
January 30 1996	27.34	14.42	43.15	7.44	55.35	27.21
February 2 1996	28.70	16.84	44.89	7.64	58.36	26.62
February 4 1996	26.79	13.62	43.74	7.36	54.19	27.47
March 28 1996	22.06	9.04	38.72	8.51	72.34	28.57
March 30 1996	25.55	11.29	40.69	8.79	77.35	34.40
April 1 1996	29.84	16.03	42.55	8.36	69.86	28.01
Mean Dry S.M.	9.98	5.07	15.35	3.14	9.83	31.46
Mean Wet S.M.	26.71	14.86	40.77	7.81	61.06	29.23

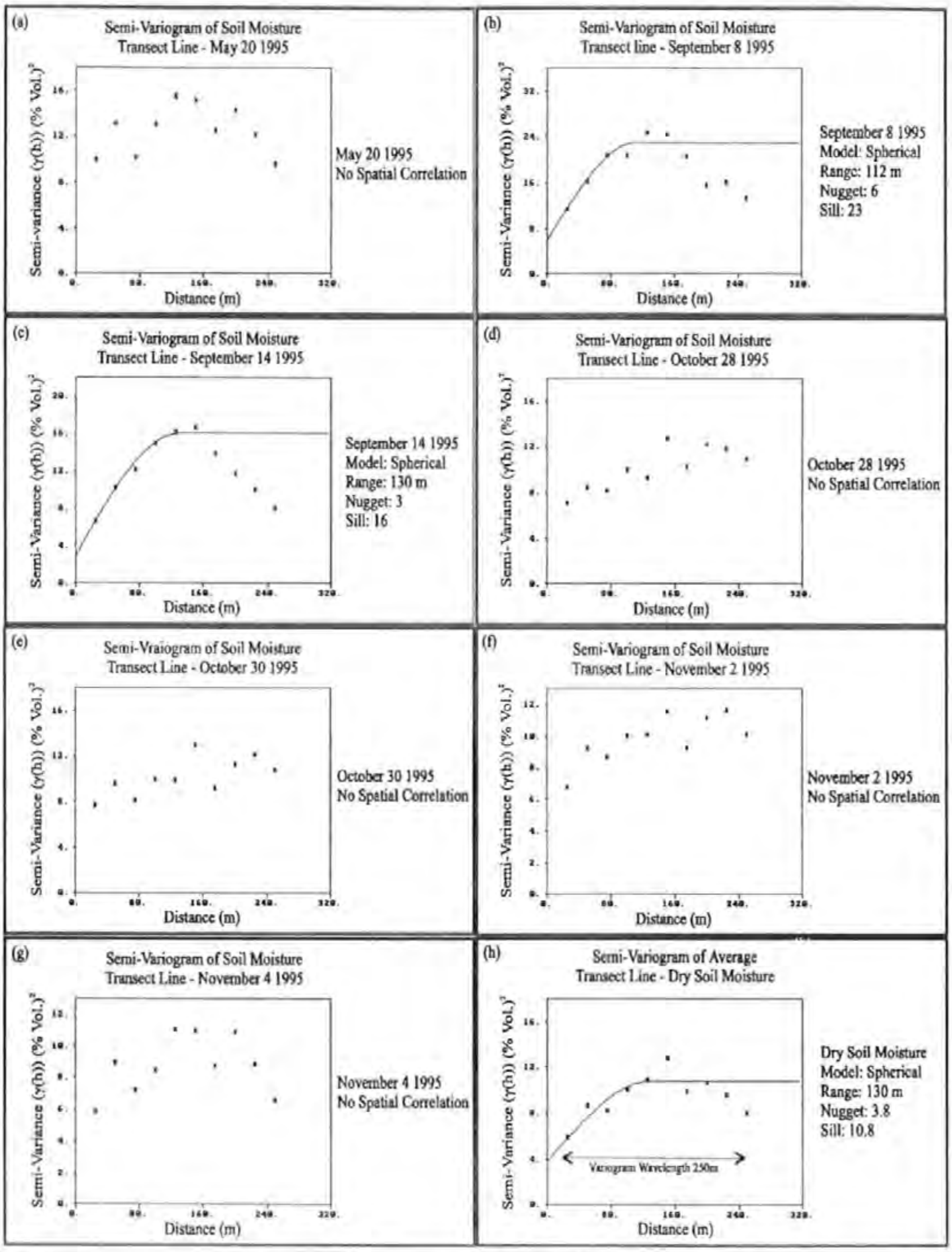
The largest differences in soil moisture between dry and wet conditions occur at the wettest points along the transect line (figure 5.2). For example, the point located at 425m distance along the transect line is relatively high in soil moisture in both dry and wet conditions and increases in soil moisture from 16% to 42% during wet conditions. In contrast the smallest differences in soil moisture between wet and dry conditions occurs at the driest points along the transect line. For example, the point at 250m distance along the transect line is relatively low in soil moisture in both wet and dry conditions with an increase in soil moisture from 8% to 16% under wet conditions. The large increase in soil moisture from dry to wet conditions at the relatively wet locations, suggests that these point have a larger water holding capacity compared to the relatively dry points along the transect line. Under this assumption, during wet conditions saturated overland flow would be expected to occur first from the relatively dry points since their smaller water holding capacity would be exceeded sooner. Alternatively these dry points may have rapid drainage effectively transmitting water to deeper soil horizons and therefore maintaining a relatively low surface soil moisture content even under wet conditions. Under this assumption, these dry points may not contribute to saturated overland flow, but may instead act as sinks for overland flow produced from surrounding wet areas. The relatively dry points along the transect line, with the exception of the point at 700m, may be characterised as having a dry weather soil moisture value of less than 8% and a wet weather soil moisture value of less than 20%. These points represent only 9 of the 33 points along the transect line and show an increase in soil moisture of less than 14% from dry to wet conditions. The remaining points all increase in soil moisture by more than 14% from dry to wet conditions and may be characterised as having a dry weather soil moisture value greater than 8% and a wet weather soil moisture value greater than 20%, with the exception of the point at 550m.

Figure 5.2 Transect Line average dry and wet soil moisture



Variograms of soil moisture during dry weather conditions are shown in figures 5.3a-g. These variograms have different shapes, indicating that under dry weather conditions the spatial structure of soil moisture is variable. The variograms for September 8 and 14 are similar in shape and have a rising semi-variance to a sill value, indicating increasing dissimilarity in soil moisture values with increasing lag distance (Journal and Huijbregts, 1978). Beyond this sill value the semi-variance begins to fall with increasing lag distance which indicates that at these larger lag distances soil moisture values are becoming increasingly similar to the values recorded within the first few lags. Nyberg (1996) described a similar variogram pattern for soil moisture in the Gardsjon covered catchment, Sweden, which was attributed to similar topographic controls on both sides of a 'U' shaped catchment. Oliver *et al.* (1989) described a similar shaped variogram for slope angle and interpreted this variogram shape as a 'hole effect', which indicates repetition in the variable measured. The distance over which the variable is repeated is equal to the wavelength of the variogram (Oliver *et al.*, 1989). The September variograms therefore display a repetition in soil moisture values approximately every 250m along the transect line. In contrast, the variograms for May 20, October 30 and November 4 are pure nugget and the variograms for October 28 and November 2 are slightly linear with a high nugget variance. The spatial variation in soil moisture is therefore high on these sampling dates, with soil moisture values spatially uncorrelated over a sampling distance of 25m. The variogram of the average soil moisture for dry weather conditions is shown in figure 5.3h. Although this variogram shows some fluctuations in semi-variance, it is in general a hole effect variogram with a wavelength of approximately 250m. In addition the variogram reaches a sill value at approximately 130m, indicating that soil moisture values are spatially correlated over this distance.

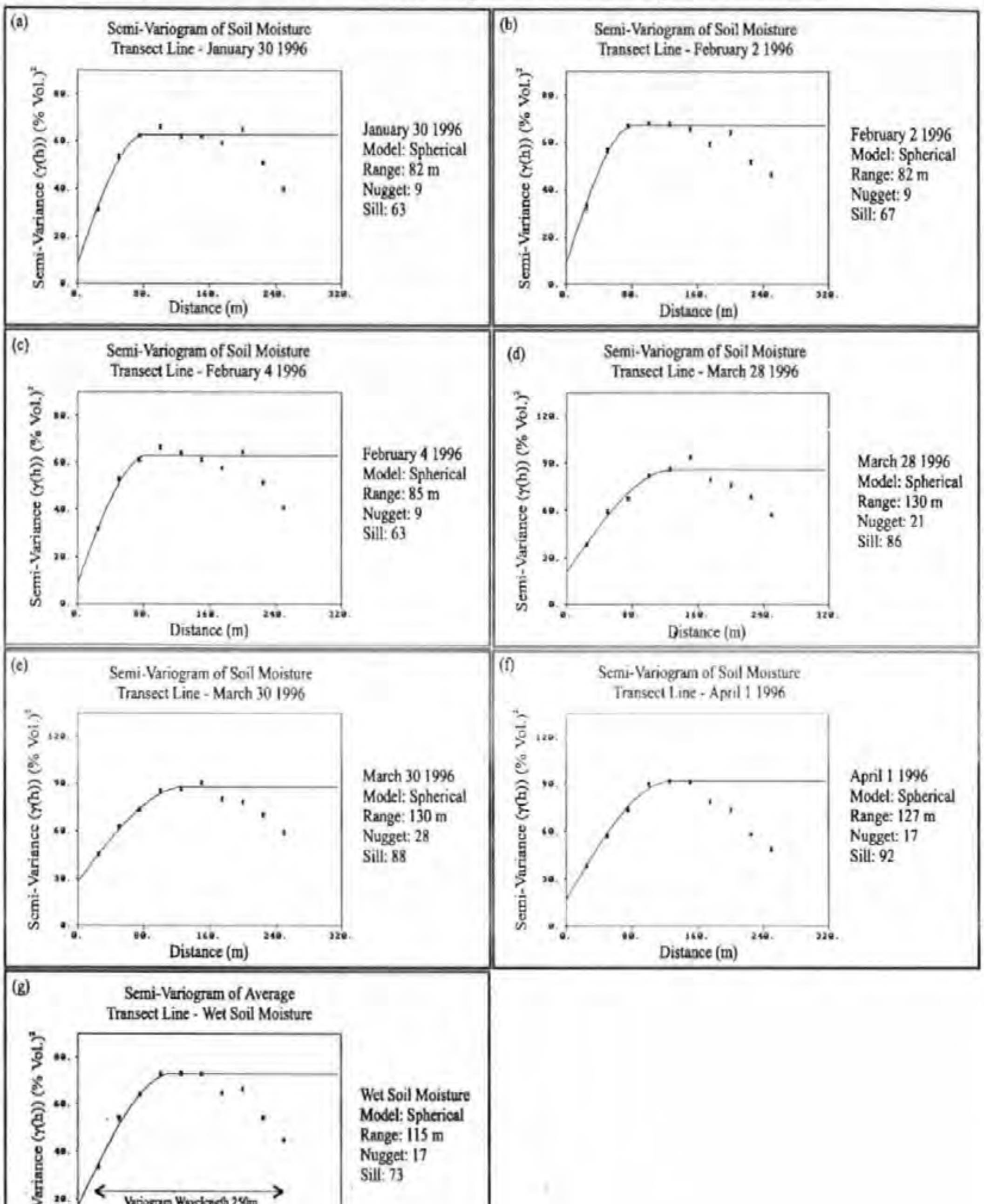
Figure 5.3. Variograms of the soil moisture recorded along the transect line during dry weather conditions.



Figures 5.4a-f show variograms of soil moisture for each measuring date during wet weather conditions and figure 5.4g is the variogram of the average soil moisture for wet weather conditions. In contrast, to the variograms of soil moisture during dry conditions all of the variograms during wet conditions have a similar shape indicating a similar spatial structure in soil moisture between sampling dates. The variograms of soil moisture during wet weather conditions all have a similar wavelength which is

approximately 250m and is similar to the September variograms recorded during dry conditions. The comparable range in wavelength indicates that similar soil moisture values are repeated approximately every 250m along the transect line. In figure 5.2 the average wet soil moisture from 0-25m is approximately 16%. This value is repeated again at 250m and at 500m distance along the transect line, a repetition distance which is equal to the wavelength of the variogram for soil moisture in wet weather conditions. The sill value for semi-variograms of soil moisture during wet weather conditions varies from between approximately 80m to 130m. The distance over which soil moisture during wet weather conditions is spatially correlated is therefore approximately 80m to 130m and is similar to the range of spatial correlation found in the variogram of average soil moisture during dry conditions.

Figure 5.4. Variograms of the soil moisture recorded along the transect line during wet weather conditions.



5.2 Temporal Persistence of the Soil Moisture Patterns

Soil moisture values between consecutive measuring dates are strongly correlated (table 5.2), indicating temporal persistence in the spatial pattern of soil moisture ie. the high and low points of soil moisture generally occur at the same location along the transect line (Kachanoski and De Jong, 1988). The temporal persistence of soil moisture suggests that the factor(s) controlling soil moisture are also temporally persistent ie. that the controlling factor(s) are both space and time invariant (Hawley *et al.*, 1983; Comegna and Basile, 1994). The correlation between the soil moisture measured on November 4 1995 and January 30 1996 is relatively low in comparison to other consecutive soil moisture dates and coincides with the change from dry to wet conditions. This lower correlation reflects a change in the spatial pattern of soil moisture as conditions change from dry to wet. Furthermore, the temporal persistence of the spatial pattern is stronger under wet weather conditions where the correlation is always above 0.90, with the exception of the correlation between February 3 1996 and March 28 1996 (table 5.2). During dry weather conditions however, the strength of the correlation in soil moisture values between consecutive dates, shows greater fluctuation and is in general lower than the correlations during wet weather conditions. Zhang and Berndtsson (1988) have also reported greater fluctuations in the temporal persistence of soil moisture during summer periods. The greater fluctuations and lower correlations in dry weather may indicate the 'fading' in and out of the importance of factors which control soil moisture, causing small changes in the spatial pattern of soil moisture. This fading in and out may take the form of a 'switching' in the effect that a controlling factor has on soil moisture. For example, two points, A and B, may be located in different textures. Point A may have a sandy texture whereas point B has a clay texture. At the beginning of a dry period point B, because of its larger water holding capacity, will have a higher soil moisture content than point A. However, point A because of its sandy texture, may have a surface crust which reduces evaporation to a rate where it is much less than that occurring from point B which shrinks and cracks as it losses moisture. Therefore with continuing evaporation point A will eventually be higher in soil moisture than point B and the spatial pattern will have switched. The patchiness of vegetation cover within this area suggests that the rate of water uptake and hence the rate of evapotranspiration will be variable, resulting in fluctuations in the soil moisture pattern. This effect may in particular be more noticeable during dry periods when the water demands of plants are highest, and may therefore explain the fluctuations in soil moisture patterns observed during this period.

Table 5.2. Correlations of the soil moisture data between consecutive measurement dates showing the temporal persistence of soil moisture patterns along the transect line.

Soil Moisture Sampling Dates	Transect Line
May 20 1995 - Sept 8 1995	0.73**
Sept 8 1995 - Sept 14 1995	0.96**
Sept 14 1995 - Oct 28 1995	0.77**
Oct 28 1995 - Oct 30 1995	0.97**
Oct 30 1995 - Nov 1 1995	0.97**
Nov 1 1995 - Nov 4 1995	0.88**
Nov 4 1995 - Jan 30 1996	0.70**
Jan 30 1996 - Feb 2 1996	0.98**
Feb 2 1996 - Feb 4 1996	0.98**
Feb 4 1996 - Mar 28 1996	0.92**
Mar 28 1996 - Mar 30 1996	0.98**
Mar 30 1996 - April 1 1996	0.96**

** = significant at $p<0.01$ (99%).

Summary

The soil moisture data recorded along the transect may be distinguished into measurements recorded during dry and wet periods, reflecting seasonal differences in rainfall and evapotranspiration. During both periods soil moisture can be highly variable and may differ by a maximum of 22% over 25m distance. A pattern of dry and wet areas which may be immediately adjacent to each other therefore occurs along the transect line. During dry conditions, although the percentage difference in soil moisture between points may be lower, the magnitude of difference may be higher than under wet conditions. Soil moisture along the transect line during dry periods is therefore more variable than during wet periods. The variograms of soil moisture during these two periods also suggest a greater variation in the spatial structure of soil moisture during dry conditions, although the range of spatial correlation for average soil moisture may be similar in dry periods to that recorded during wet periods. The greater variability in soil moisture during dry periods may be caused by the fading in and out of the importance of factors which control soil moisture. Dry points along the transect line may be characterised by relatively good drainage and may therefore act as sinks for overland flow although their number is relatively few in comparison to wet areas. The pattern of soil moisture along the transect line is temporally persistent which suggests that the factor(s) controlling the variation in soil moisture are also stationary in both space and time.

5.3 Factors Controlling the Spatial and Temporal Variations in Soil Moisture

5.3.1 Soil Moisture and Topography

The topographical profile of the transect line, together with the average wet period and dry period soil moisture is shown in figure 5.5. Although the transect line traverses three ephemeral channels its profile is regular and continuous. The largest change in elevation is 8m over a horizontal distance of 25m. However, the erratic nature of the soil moisture pattern during dry and wet conditions was not accounted for by an equally erratic topographic profile. Furthermore, soil moisture may be expected to be highest around the ephemeral channels due to topographic convergence and lowest in upslope locations due to drainage by gravity (Hawley *et al.,* 1983). However, soil moisture within two of the ephemeral channels, located at 25m and 700m, is very low in both dry and wet weather conditions (less than 22%) and is only slightly higher in the third ephemeral channel (225m) (28%) (figure 5.5). The relatively low soil moisture in these convergence zones may be due to the relatively coarse texture of the ephemeral channels which are dominated by gravel. Higher soil moisture may occur at greater depths within these channels, but is beyond the measuring depth of the TDR probes. Soil moisture is only significantly correlated with elevation during wet periods (table 5.3). These correlations are however, positive and may therefore indirectly reflect the location of fine textured horizons which may be expected to be found at higher elevations within a sedimentary sequence. Large changes in soil moisture can occur when there is only a relatively minor change in topography. For example, the soil moisture at 450m distance is 14.5% higher during wet conditions and 7% higher during dry conditions than the soil moisture at 475m, even though both points are characterised by almost identical topographical features (eg. slope, profile, form) (figure 5.5). No significant correlations could be found between soil moisture on any of the measuring dates and slope angle or the length of the upslope drainage length (table 5.3). The generally poor correlations between soil moisture and topographic parameters suggests that topography is not a significant factor in determining the macroscale temporal and spatial pattern of soil moisture.

Figure 5.5. Topographic profile of the transect line together with the average dry and wet soil moisture.

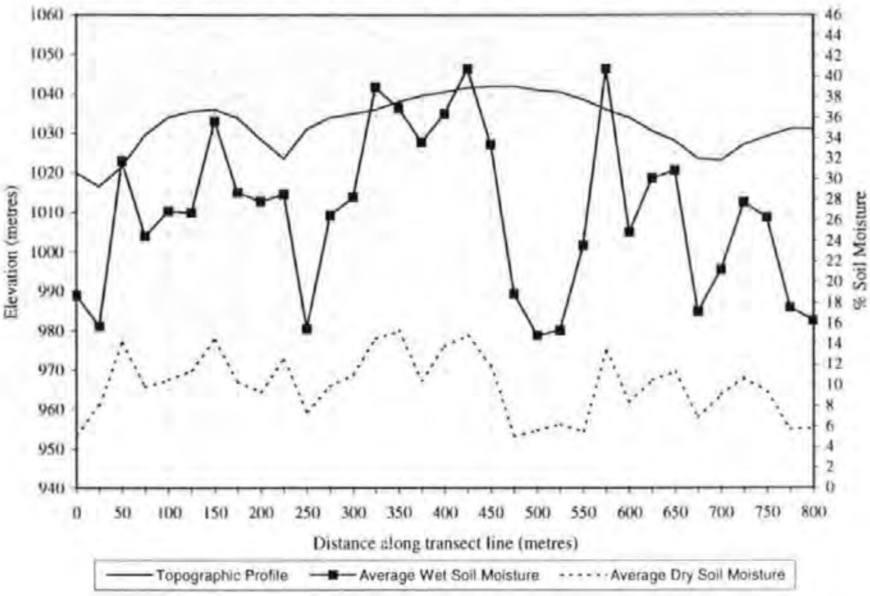


Table 5.3. Correlations between soil moisture, elevation, slope angle and upslope drainage length for the transect line.			
Soil Moisture Sampling Dates	Transect Line Elevation	Transect Line Slope Angle	Transect Line Upslope Drainage Length
May 20 1995	-0.01	0.06	0.18
September 8 1995	0.26	-0.13	0.02
September 14 1995	0.16	-0.08	0.07
October 28 1995	0.24	-0.07	0.12
October 30 1995	0.13	0.05	0.15
November 1 1995	0.12	0.04	0.10
November 4 1995	0.03	0.06	0.15
January 30 1996	0.36*	-0.19	-0.09
February 2 1996	0.39*	-0.20	-0.11
February 4 1996	0.31*	-0.15	-0.05
March 28 1996	0.27	-0.08	0.04
March 30 1996	0.35*	-0.14	-0.04
April 1 1996	0.28	-0.12	-0.05
Mean Dry S.M.	0.15	-0.12	0.18
Mean Wet S.M.	0.33*	-0.15	-0.05

* = significant at p<0.05 (95%).
** = significant at p<0.01 (99%).

5.3.2 Soil Moisture and Vegetation

The first 10 points along the transect line from 0m to 225m are located within a matorral dominated landuse, the predominant species being *Cistus spp* (figure 5.6). The matorral cover is not uniform, ranging from dense to patchy. The next 8 points along the transect line from 225m to 425m are located within a landuse which has a sparse to moderate covering of mature *Pinus nigra* trees with a dense understorey of matorral. The remaining 15 points from 425m to 800m, are located within a landuse dominated by *Pinus nigra* forest. Figure 5.6 shows the average wet and dry soil moisture recorded within each vegetation type along the transect line and table 5.4 provides descriptive statistics of the soil moisture data within each vegetation type. Average soil moisture during dry and wet weather conditions is lowest in the forest where the density of trees is highest. These trees are also exotic to this area and may consume more moisture than the indigenous matorral which is better adapted to moisture stress. Interception and evapotranspiration losses may therefore be expected to be higher within the forest vegetation community. Furthermore, the coefficient of variation is highest in the forest during both dry and wet weather conditions and reflects the large differences in soil moisture which can be observed between points within this vegetation type (figure 5.6). The matorral has the lowest coefficient of variation during wet conditions.

Figure 5.6. Average dry and wet soil moisture recorded within each vegetation assemblage along the transect line.

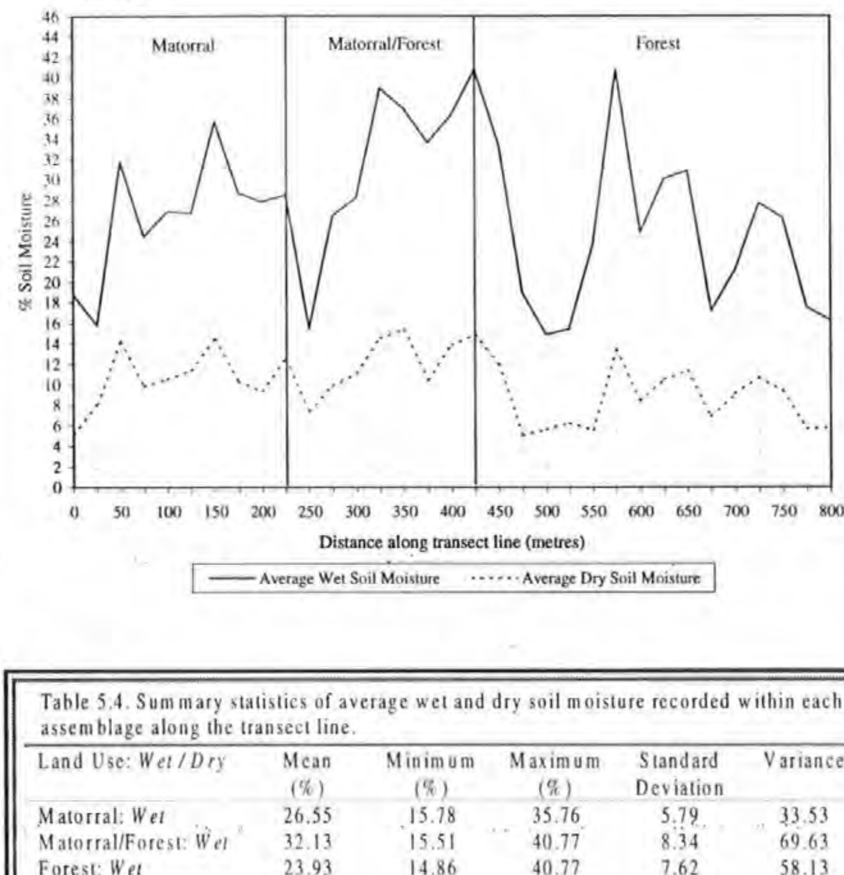


Table 5.4. Summary statistics of average wet and dry soil moisture recorded within each vegetation assemblage along the transect line.

Land Use: *Wet / Dry*	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Variance	Coefficient of Variation (%)
Matorral: *Wet*	26.55	15.78	35.76	5.79	33.53	21.80
Matorral/Forest: *Wet*	32.13	15.51	40.77	8.34	69.63	25.95
Forest: *Wet*	23.93	14.86	40.77	7.62	58.13	31.84
Matorral: *Dry*	10.61	5.17	14.45	2.79	7.76	26.29
Matorral/Forest: *Dry*	**12.20**	**7.43**	**15.35**	**2.87**	**8.24**	**23.52**
Forest: *Dry*	8.38	5.07	13.42	2.74	7.51	32.69

The variance in soil moisture within vegetation types was compared to the variance between vegetation types to test if soil moisture during dry and wet weather conditions was significantly different between the land uses (Kruskal-Wallace analysis of variance). During wet conditions there is no significant difference between vegetation types. During dry conditions however, soil moisture values between the land uses were significantly different ($p<0.05$). Therefore at the landuse scale, vegetation type only becomes important in controlling soil moisture variability during dry weather conditions, when soil moisture is moderate to low and evapotranspiration is highest.

Summary

Elevation, slope angle and upslope drainage length have little, if any, effect in determining spatial patterns of soil moisture recorded at the macroscale in either dry or wet conditions. Berndtsson and Chen (1994) have suggested that at the large scale topography may only be significant in determining soil moisture variability at depths greater than 1m. Differences in soil moisture may however be found between different vegetation assemblages during dry conditions when soil moisture is moderate to low and interception and evapotranspiration is highest. Vegetation may therefore play a significant role in determining soil moisture variability during dry conditions.

5.4 Conclusions

At the macroscale two distinct groups of soil moisture emerged, related to dry (relatively low soil moisture) and wet (relatively high soil moisture) weather conditions. Although the percentage difference in soil moisture between points and at the same point may be higher in wet conditions compared to dry conditions, the magnitude of difference in soil moisture is slightly higher during dry periods. The degree of variation in soil moisture during dry conditions may therefore be higher than the variation in soil moisture recorded during wet conditions. Although the average dry and wet soil moisture variograms display a similar range of spatial correlation in soil moisture (approximately 130m), variograms of soil moisture on individual sampling dates during dry conditions show a greater fluctuation in the spatial pattern than can be observed during wet conditions. These variograms, together with measurements of temporal persistence, indicate that the spatial pattern of soil moisture may be more variable during dry conditions compared to wet conditions suggesting high variability in soil moisture during dry periods. The more variable spatial pattern during dry weather conditions may be related to the fading in and out of the importance of the factors which control soil moisture and in particular to the patchiness of vegetation cover resulting in a non-uniform uptake and evapotranspiration of moisture.

The variability in soil moisture at the macroscale during both dry and wet conditions may be characterised as a pattern of areas of relatively dry and wet soil which can be immediately adjacent to each other. Differences in the type of vegetation assemblage may be an important causal factor of this spatial pattern during dry periods. At the macroscale topography appears to have no influence on the spatial distribution of surface soil moisture.

It is hypothesised that the area of relatively wet and dry soil moisture in the spatial pattern will have a contrasting hydrological response due to differences in infiltration, hydraulic conductivity, water storage capacity and soil strength related to differences in soil moisture and soil texture. The dry areas may therefore be capable of absorbing runoff and act as sinks for overland flow generated from the wet areas, which particularly during wet periods when soil moisture values are high, may act as source areas of saturated overland flow. Runoff at the macroscale may therefore be expected to be spatially non-uniform with implications for both hydrological monitoring and management. The diverse morphology of badland environments may for example, in part be related to the generation of spatially non-uniform runoff.

Chapter 6

Temporal and Spatial Variability in Soil Moisture at the Meso (Catchment) and Micro (Minigrid) Scales

6.0 Introduction

In order to fully understand a catchment's hydrological and erosional response to a precipitation event, measurements made at the catchment scale are essential (Loague, 1992; Seyfried and Wilcox, 1995). Soil moisture is known to be a key factor in determining a catchment's surface runoff response to rainfall (Phillips, 1992). Hawley *et al.* (1983) have argued that variability in initial soil moisture can result in large differences in hydrologic response. In particular, spatial variability in soil moisture plays an important role in determining hydrological pathways within catchments and thus the effectiveness of overland flow as an eroding agent (Morgan, 1995). Quantifying soil moisture and its variability is therefore of great importance in identifying source areas of overland flow and subsequently zones of erosion, allowing for accurate prediction and interpretation in catchment hydrology and geomorphic processes (Ireland *et al.*, 1939; O'Loughlin, 1981; Loague, 1992). Within this chapter spatial patterns in soil moisture recorded within each of the gully catchments (mesoscale) are described and compared.

Strongly seasonal climates may often lead to significant temporal changes in the spatial pattern of soil moisture resulting in a seasonal variation in the severity and spatial extent of runoff and erosion (Ireland *et al.*, 1939; Moore *et al.*, 1988; Grayson *et al.*, 1997). The temporal measurement of soil moisture may therefore be as important as its spatial measurement for interpreting catchment hydrology and may be used to identify those times when a catchments hydrological pathways are most continuous and hence the times at which overland flow and erosion from the catchment is most extensive (Grayson *et al.*, 1997). Furthermore, the temporal measurement of soil moisture patterns may provide an insight into the factors controlling the variability in soil moisture. If the spatial pattern of soil moisture is for example, temporally persistent, then the factors determining this pattern must therefore also be spatially stationary through time (Comegna and Basile, 1994). This chapter therefore also describes the temporal changes in soil moisture observed within each of the gully catchments.

At smaller scales (hillslope and plot) several authors have reported the occurrence of spatially non-uniform runoff (Yair, 1992; Imeson *et al.*, 1992; Cerda, 1995; Bergkamp *et al.*, 1996). Although variations in small scale hydrological response can be important determinants of catchment hydrology (Cerda, 1995), this information may often be overlooked when working at the larger scale (Amerman, 1965). Measurements of spatial patterns at the microscale may therefore also be essential in interpreting catchment hydrology. High spatial variability in soil moisture over short distances may play a key role in determining hydrological response at both the micro and meso scales, particularly if the spatial patterns at the microscale differ from those observed at the mesoscale (Bergkamp, 1995). Quantifying the spatial variability in soil moisture at the microscale may therefore further elucidate not only the hydrological response of gully catchments but also the principal factors controlling the variability in soil moisture within this region.

Measurements of spatial patterns in soil moisture at the microscale were recorded within a minigrid located within a 5x5m cell in each of the three main gully catchment grids (see Chapter 3 for further details regarding the location and set-up of the minigrids). Within these minigrids soil moisture was measured at a sampling interval of 1m. These minigrids therefore represent a 5x magnification of a small section of the soil moisture pattern observed at the gully catchment scale. In addition, similar to the gully catchment scale, the soil moisture within the minigrids was measured through time providing a record of the temporal changes in soil moisture patterns at the small scale.

In chapter 1, temporal and spatial variability in soil moisture was attributed to a number of factors including:

1) a non-uniform distribution of vegetation

2) highly irregular terrain

3) complex geological, pedological and management histories

combinations of which may frequently give rise to considerable variability in the soils physical and hydrological properties. Spatially non-uniform runoff and erosion may therefore be closely related to spatial patterns in topography, vegetation and soil properties (Zhang and Berndtsson, 1988). The spatial pattern of soil moisture will therefore reflect the spatial distribution of these controlling variables (Campbell and Honsaker, 1982). This chapter therefore describes the relationships between soil moisture patterns and these variables (ie. topography, vegetation and the soils physical and hydrological properties) to enable the principal controlling factors of the spatial and temporal variability in soil moisture to be determined. Identifying the spatial and temporal patterns of soil moisture together with their controlling factors enables an understanding of the hydrological and geomorphological functioning of individual gully catchments - a principal aim of this thesis.

6.1 Temporal and Spatial Variability in Soil Moisture at the Mesoscale

Within this section the spatial patterns in soil moisture recorded within the three gully catchments are examined. Since these spatial patterns change in time however, temporal variations in the soil moisture data are first examined. Tables 6.1, 6.2 and 6.3 provide summary statistics of the soil moisture data collected within the three gully catchments during the study period (March 1995 – April 1996). Similar to the division made in the soil moisture data set at the macroscale the soil moisture values recorded during the period from March 8 1995 to November 4 1995 at the meso and micro scales may be classified as measurements taken during a dry condition period. In contrast the soil moisture values recorded between January 26 1996 and April 1 1996 may be classified as measurements taken during a wet condition period when average monthly rainfalls were approximately 20% higher. This separation of the soil moisture data set into dry and wet condition periods is verified by the significantly higher mean soil moisture values recorded within each gully catchment on measurement dates during wet conditions ($p<0.05$). The coefficient of variation provides a measure of the variability of soil moisture values within the gully catchments (Charpentier and Groffman, 1992; Burrough, 1993). In tables 6.1, 6.2 and 6.3, values of the coefficient of variation during dry conditions are significantly higher in all three gullies than the coefficient of variation values for soil moisture during wet conditions ($p<0.05$). This indicates that the variability in soil moisture values during dry conditions is greater than during wet conditions within each of the gully catchments. Zhang and Berndtsson (1988) have also reported a higher variability in soil water content during summer periods. Similarly, Greminger *et al.* (1985), Charpentier and Groffman (1992) and Burrough (1993) have all reported a higher coefficient of variation in soil moisture during dry periods compared to wet conditions. Charpentier and Groffman (1992) have argued that the lower coefficient of variation during wet conditions occurs because there are fewer factors (eg. transpiration, evaporation) affecting soil moisture contents and therefore variability will be lower. Further indicators of the variability in soil moisture values within the gully catchments are shown by the minimum and maximum summary statistics of soil moisture in tables 6.1, 6.2 and 6.3. Sample points within the gullies may differ in soil moisture by as much as 20 to 30% on the same day, showing a high variability in soil moisture at the catchment scale. Furthermore this high variability in soil moisture can also be found over a sampling distance of 5m, where values can change by as much as 24%. McBratney (1992) has also recorded soil moisture values at 5m intervals and reported differences in soil moisture as high as 20% between adjacent sampling points. Beckett and Webster (1971) have argued that considerable variations in soil moisture over short distances may occur particularly in strongly structured soils. This extreme variation in soil moisture over 5m distance is present within all three gully catchments and the magnitude of this variation persists in both dry and wet conditions, although the percentage difference in soil moisture during wet conditions may be greater. In contrast similar soil moisture values can be found to extend over distances of greater than 20m in all three gully catchments and in particular within the upper reaches of the forest gully's watershed. Within the three gully catchments soil moisture may therefore be both highly variable and uniform over relatively short distances, having a complex distribution which may persist in dry and wet conditions.

Table 6.1. Summary statistics of the soil moisture data recorded within the Matorral Gully Catchment.

Soil Moisture Sampling Dates	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Variance	Coefficient of Variation (%)
May 20 1995	13.66	5.53	26.69	4.73	22.41	34.65
July 11 1995	11.96	4.22	21.77	3.79	14.34	31.66
September 8 1995	13.14	2.40	29.89	4.54	20.59	34.53
September 14 1995	9.65	2.99	23.42	3.69	13.59	38.21
October 27 1995	13.86	6.20	24.24	3.92	15.38	28.29
October 28 1995	13.61	6.20	25.06	4.08	16.61	29.94
October 30 1995	12.84	5.53	23.42	3.95	15.64	30.79
November 1 1995	12.08	4.87	23.42	3.91	15.26	32.34
November 4 1995	11.08	4.22	24.24	3.88	15.08	35.05
January 26 1996	30.70	14.42	40.04	5.60	31.31	18.22
January 27 1996	32.20	14.42	40.69	5.40	29.18	16.78
January 28 1996	33.05	16.03	41.94	5.48	30.03	16.58
January 30 1996	32.12	14.42	41.94	5.77	33.31	17.97
February 1 1996	33.35	12.06	44.89	6.13	37.58	18.38
February 2 1996	33.31	15.22	44.89	6.19	38.38	18.60
February 4 1996	31.25	13.62	41.94	6.30	39.70	20.16
March 28 1996	23.18	7.59	36.65	6.18	38.16	26.64
March 30 1996	27.51	10.53	40.04	6.19	38.35	22.51
April 1 1996	31.38	11.29	42.55	6.26	39.15	19.94
Mean Dry S.M.	12.43	4.68	24.68	4.05	16.54	32.83
Mean Wet S.M.	30.81	12.96	41.56	5.95	35.12	19.58

Table 6.2. Summary statistics of the soil moisture data recorded within the Forest Gully Catchment.

Soil Moisture Sampling Dates	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Variance	Coefficient of Variation (%)
March 8 1995	17.92	3.60	35.21	7.86	61.82	43.87
July 11 1995	8.75	3.60	20.94	3.29	10.08	37.56
September 8 1995	12.31	2.40	23.42	4.74	22.43	38.48
September 14 1995	7.70	1.82	20.94	3.74	13.98	48.56
October 27 1995	10.77	4.22	23.42	3.60	12.94	33.41
October 28 1995	11.68	4.87	24.24	3.78	14.27	32.34
October 30 1995	10.54	3.60	23.42	3.87	14.98	36.72
November 1 1995	9.64	3.60	23.42	3.72	13.82	38.56
November 4 1995	8.45	2.99	21.77	3.58	12.82	42.39
January 27 1996	28.96	12.06	46.53	6.97	48.53	24.05
January 28 1996	29.58	10.53	41.32	7.02	49.27	23.73
January 30 1996	28.60	10.53	41.32	7.17	51.36	25.06
February 2 1996	31.10	12.06	46.53	7.45	55.49	23.85
February 4 1996	27.84	8.31	40.69	7.73	59.77	27.77
March 28 1996	19.77	6.20	38.04	7.55	57.01	38.19
March 30 1996	23.48	6.89	40.04	7.63	58.25	32.51
April 1 1996	18.10	9.78	46.53	8.11	65.75	28.86
Mean Dry S.M.	9.98	3.39	22.7	3.79	14.42	38.5
Mean Wet S.M.	25.04	8.88	41.8	7.5	56.36	29.77

Table 6.3. Summary statistics of the soil moisture data recorded within the Bench Terrace Gully Catchment.

Soil Moisture Sampling Dates	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Variance	Coefficient of Variation (%)
July 12 1995	7.97	3.60	21.77	3.27	10.71	41.07
September 8 1995	11.21	2.40	32.22	5.40	29.14	48.14
September 14 1995	6.83	2.40	25.06	3.84	14.77	56.28
October 27 1995	11.44	4.87	28.30	4.11	16.93	35.95
October 28 1995	12.08	6.20	29.10	4.24	17.94	35.05
October 30 1995	10.62	4.22	27.50	4.16	17.27	39.14
November 1 1995	9.59	4.22	25.06	3.78	14.29	39.41
November 4 1995	8.54	3.60	22.59	3.43	11.78	40.18
January 26 1996	23.22	9.04	39.39	6.03	36.38	25.98
January 27 1996	24.42	11.29	40.04	5.84	34.14	23.93
January 28 1996	25.03	10.53	40.69	6.25	39.04	24.97
January 30 1996	24.40	10.53	41.94	6.10	37.21	25.01
February 2 1996	25.73	11.29	41.94	6.60	43.50	25.63
February 4 1996	23.71	10.53	41.32	6.01	36.09	25.34
March 28 1996	18.00	5.53	36.65	6.32	39.94	35.10
March 30 1996	21.62	6.89	39.39	7.02	49.30	32.48
April 1996	24.14	7.59	41.94	7.22	52.13	29.91
Mean Dry S.M.	9.79	3.94	26.45	4.03	16.6	41.9
Mean Wet S.M.	23.36	9.25	40.37	6.38	40.86	27.59

Mean soil moisture values are generally lower in the bench terrace gully than those recorded in the forest gully, particularly during wet conditions and are significantly lower than those in the matorral gully ($p<0.05$). The lower mean soil moisture values in the bench terrace gully may in part be due to the subsoiling of the terrace treads which occurred during their construction to promote infiltration (Ternan *et al.*, 1996b). The steep risers may also drain rapidly resulting in a low soil moisture content on these parts of the terraces. The bench terrace gully also has a higher percentage (>10%) vegetation cover than the matorral gully. Interception and evapotranspiration losses are therefore probably higher in the bench terrace gully. Furthermore due to the discontinuous topographic morphology imposed by the bench terraces, individual sampling points within the bench terrace gully may have a lower catchment area than sampling points within the matorral gully where the topography is more continuous. Maximum soil moisture values within the bench terrace gully are however similar to those recorded within the matorral gully (tables 6.1 and 6.3). Hydrological conditions within some areas of the bench terrace gully may therefore be similar to those in the matorral and forest gullies.

6.1.1 Temporal Persistence of the Soil Moisture Patterns

Table 6.4 shows correlations of the soil moisture data between successive measurement dates for each gully catchment. These correlations are measurements of the similarity in the soil moisture pattern between dates and therefore are a measure of the temporal persistence in soil moisture (Vachaud *et al.*, 1985; Kachanoski and De Jong, 1988). A high correlation indicates that the soil moisture pattern between dates is similar and therefore the spatial pattern of soil moisture has persisted through time. The temporal persistence of soil moisture patterns may also be inferred when variograms of soil moisture from different sampling dates are similar in shape and display a similar range of spatial correlation (Comegna and Basile, 1994). Furthermore the presence of temporal persistence within soil moisture patterns is indicative of strong deterministic links with the causes of the variation in soil moisture (Comegna and Basile, 1994). In table 6.4 the correlations of soil moisture between dates within each of the gullies are high, indicating temporal persistence in the soil moisture pattern. Temporal persistence in spatial soil moisture patterns has also been observed by Zhang and Berndtsson (1988), Berndtsson and Chen (1994) and Nyberg (1996). The correlation between dates of soil moisture measurement may however worsen as the time interval between observations is increased and the soil moisture conditions become increasingly dissimilar (Comegna and Basile, 1994). In table 6.4, within each of the gully catchments, the correlations between the soil moisture patterns from November 4 1995 to January 27 1996 are relatively low in comparison to other consecutive soil moisture dates and reflects the change during this period from dry to wet conditions. Therefore, although the spatial patterns in soil moisture during dry conditions are similar and the spatial patterns in soil moisture during wet conditions are similar, the spatial pattern of soil moisture between these two dates is relatively dissimilar. This change in the spatial pattern of soil moisture from dry to wet conditions within each of the gully catchments is further explored within the following sections.

Table 6.4. Correlations of the soil moisture data between consecutive measurement dates showing the temporal persistence of the soil moisture patterns within the three gully catchments.

Soil Moisture Sampling Dates	Matorral Gully Temporal Persistence	Forest Temporal Persistence	Bench Terrace Temporal Persistence
Mar 8 1995 - May 20 1995	----	----	----
May 20 1995 - July 12 1995	0.92**	----	----
July 12 1995 - Sept 8 1995	0.60**	0.70**	0.72**
Sept 8 1995 - Sept 14 1995	0.84**	0.90**	0.92**
Sept 14 1995 - Oct 27 1995	0.85**	0.87**	0.81**
Oct 27 1995 - Oct 28 1995	0.97**	0.97**	0.95**
Oct 28 1995 - Oct 30 1995	0.97**	0.96**	0.95**
Oct 30 1995 - Nov 1 1995	0.98**	0.98**	0.97**
Nov 1 1995 - Nov 4 1995	0.98**	0.98**	0.98**
Nov 4 1995 - Jan 27 1996	0.71**	0.64**	0.78**
Jan 27 1996 - Jan 28 1996	0.98**	0.98**	0.97**
Jan 28 1996 - Jan 30 1996	0.98**	0.98**	0.97**
Jan 30 1996 - Feb 2 1996	0.98**	0.97**	0.95**
Feb 2 1996 - Feb 4 1996	0.95**	0.96**	0.94**
Feb 4 1996 - Mar 28 1996	0.88**	0.83**	0.87**
Mar 28 1996 - Mar 30 1996	0.96**	0.97**	0.92**
Mar 30 1996 - April 1 1996	0.93**	0.94**	0.96**

** = significant at $p<0.01$ (99%).

6.1.2 Variogram Analysis and Interpretation

The variogram summarises the variation of a property within a region by describing the average rate of change in the property with distance (Oliver, 1987; Oliver and Webster, 1991). The variogram may therefore provide information on the magnitude and scale of variation (Oliver, 1987). Several authors have used the variogram to describe the spatial variability of soil water content and have reported ranges of spatial correlation in soil water varying from 6m to 79m (Hawley *et al.*, 1983; Wierenga, 1985; Nash *et al.*, 1989; Munoz-Pardo *et al.*, 1990; Nyberg, 1996). The variogram range may also be used to indicate the size of areas of different moisture contents and thus the spatial frequency of soil moisture changes (Davidson and Watson, 1995). Variogram analysis is used here to describe the spatial patterns of soil moisture and to determine the range of spatial correlation in soil moisture for each measurement date. In addition contour plots of the soil moisture patterns within each of the gully catchments are used to support the variogram analysis and interpretation.

6.1.3 Matorral Gully Catchment

Figures 6.1a-s show the variograms and contour plots of soil moisture for each measurement date within the matorral gully catchment.

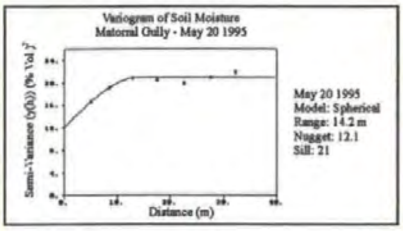
Figures 6.1. Contour plots and semi-variograms of soil moisture for each measurement date within the Matorral Gully Catchment.

(a)

Matorral Gully
May 20 1995

Minimum: 5.5%
Maximum: 26.6%
Mean: 13.6%
Variance: 22.4
Standard Deviation: 4.73
Coefficient of Variation: 34.7%

Temporal Persistence: ----

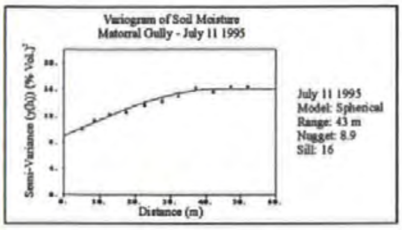


(b)

Matorral Gully
July 11 1995

Minimum: 4.2%
Maximum: 21.7%
Mean: 11.9%
Variance: 14.33
Standard Deviation: 3.78
Coefficient of Variation: 31.7%

Temporal Persistence: 0.92

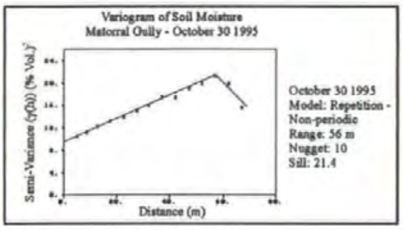


(g)

Matorral Gully
October 30 1995

Minimum: 5.5%
Maximum: 23.4%
Mean: 12.8%
Variance: 15.63
Standard Deviation: 3.95
Coefficient of Variation: 30.8%

Temporal Persistence: 0.97

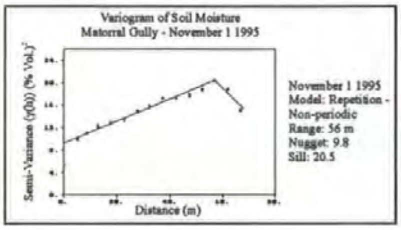


(h)

Matorral Gully
November 1 1995

Minimum: 4.8%
Maximum: 23.4%
Mean: 12%
Variance: 15.26
Standard Deviation: 3.9
Coefficient of Variation: 32.5%

Temporal Persistence: 0.98

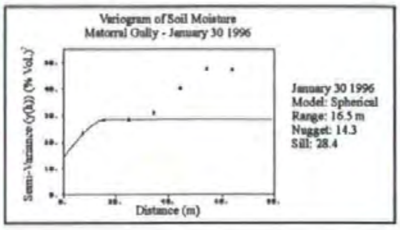


(m)

Matorral Gully
January 30 1996

Minimum: 14.4%
Maximum: 41.9%
Mean: 32.1%
Variance: 33.31
Standard Deviation: 5.77
Coefficient of Variation: 17.9%

Temporal Persistence: 0.98

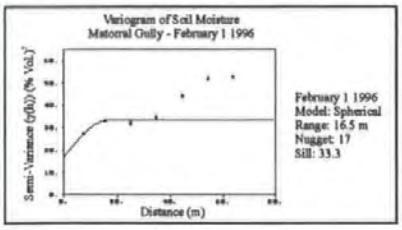


(n)

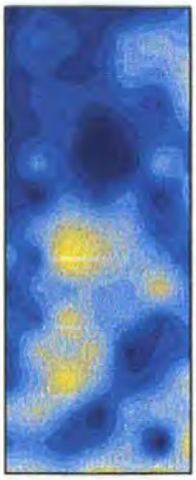
Matorral Gully
February 1 1996

Minimum: 12%
Maximum: 44.8%
Mean: 33.3%
Variance: 37.58
Standard Deviation: 6.13
Coefficient of Variation: 18.4%

Temporal Persistence: 0.97



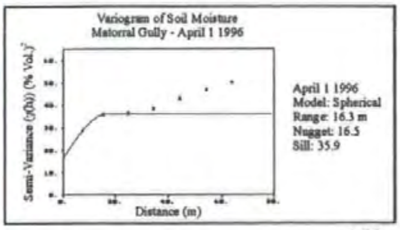
(s)

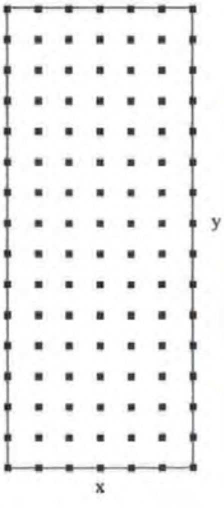


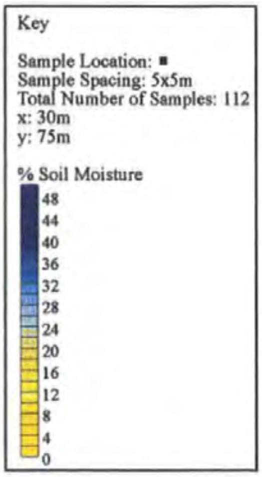
Matorral Gully
April 1 1996

Minimum: 11.2%
Maximum: 42.5%
Mean: 31.3%
Variance: 39.15
Standard Deviation: 6.25
Coefficient of Variation: 19.9%

Temporal Persistence:0.93





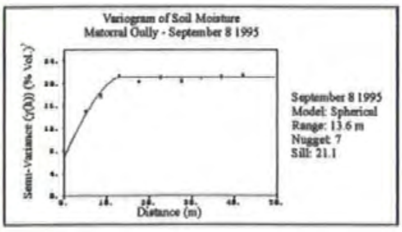


(c)

Matorral Gully
September 8 1995

Minimum: 2.4%
Maximum: 29.8%
Mean: 13.1%
Variance: 20.58
Standard Deviation: 4.53
Coefficient of Variation: 34.4%

Temporal Persistence: 0.60

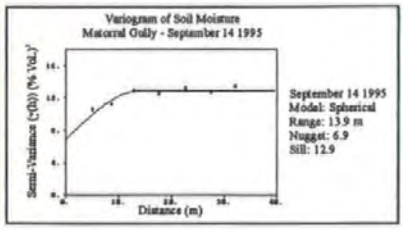


(d)

Matorral Gully
September 14 1995

Minimum: 2.9%
Maximum: 23.4%
Mean: 9.6%
Variance: 13.59
Standard Deviation: 3.68
Coefficient of Variation: 38.3%

Temporal Persistence: 0.84

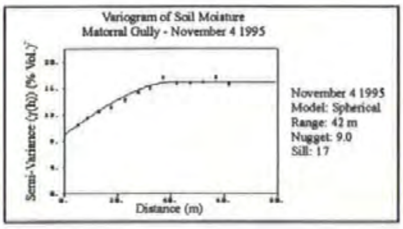


(i)

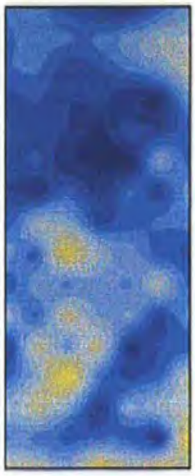
Matorral Gully
November 4 1995

Minimum: 4.2%
Maximum: 24.2%
Mean: 11%
Variance: 15.07
Standard Deviation: 3.88
Coefficient of Variation: 35.2%

Temporal Persistence: 0.98



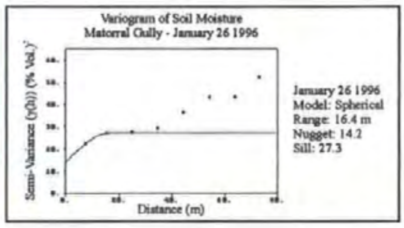
(j)



Matorral Gully
January 26 1996

Minimum: 14.4%
Maximum: 40%
Mean: 30.7%
Variance: 31.31
Standard Deviation: 5.59
Coefficient of Variation: 18.2%

Temporal Persistence: 0.74

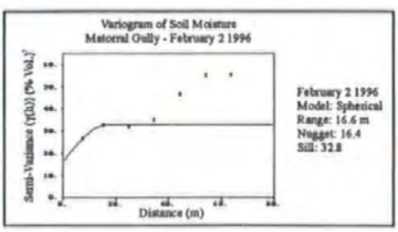


(o)

Matorral Gully
February 2 1996

Minimum: 15.2%
Maximum: 44.8%
Mean: 33.3%
Variance: 38.37
Standard Deviation: 6.19
Coefficient of Variation: 18.5%

Temporal Persistence: 0.98

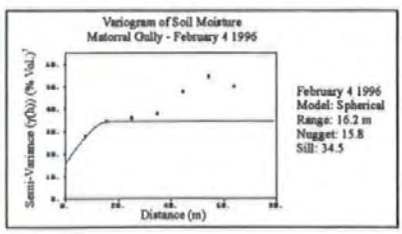


(p)

Matorral Gully
February 4 1996

Minimum: 13.6%
Maximum: 41.9%
Mean: 31.5%
Variance: 39.71
Standard Deviation: 6.3
Coefficient of Variation: 20%

Temporal Persistence: 0.95

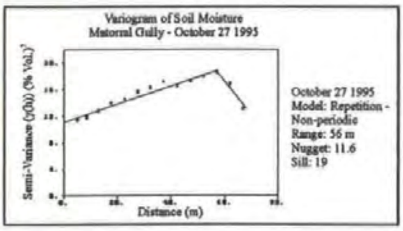


(e)

Matorral Gully
October 27 1995

Minimum: 6.2%
Maximum: 24.2%
Mean: 13.8%
Variance: 15.37
Standard Deviation: 3.92
Coefficient of Variation: 28.4%

Temporal Persistence: 0.85

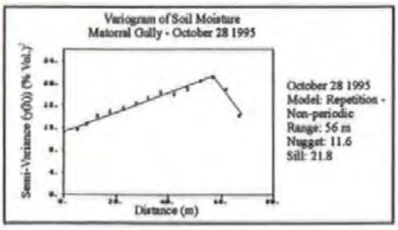


(f)

Matorral Gully
October 28 1995

Minimum: 6.2%
Maximum: 25%
Mean: 13.6%
Variance: 16.59
Standard Deviation: 4.07
Coefficient of Variation: 29.9%

Temporal Persistence: 0.97

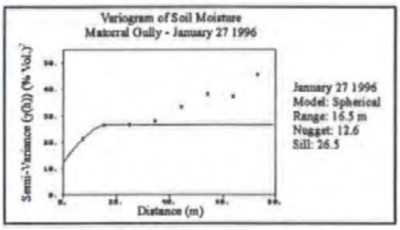


(k)

Matorral Gully
January 27 1996

Minimum: 14.4%
Maximum: 40.6%
Mean: 32.1%
Variance: 29.18
Standard Deviation: 5.40
Coefficient of Variation: 16.8%

Temporal Persistence: 0.98

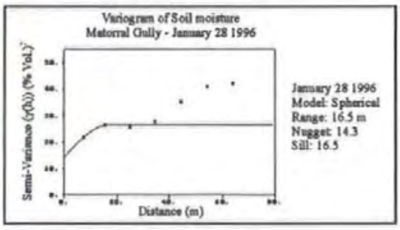


(l)

Matorral Gully
January 28 1996

Minimum: 16%
Maximum: 41.9%
Mean: 33%
Variance: 30.03
Standard Deviation: 5.48
Coefficient of Variation: 16.6%

Temporal Persistence: 0.98

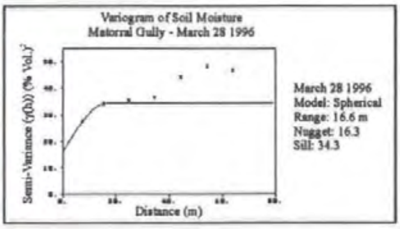


(q)

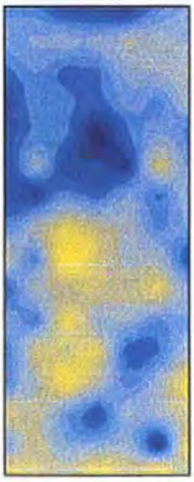
Matorral Gully
March 28 1996

Minimum: 7.5%
Maximum: 36.6%
Mean: 23.1%
Variance: 38.15
Standard Deviation: 6.17
Coefficient of Variation: 26.7%

Temporal Persistence: 0.88



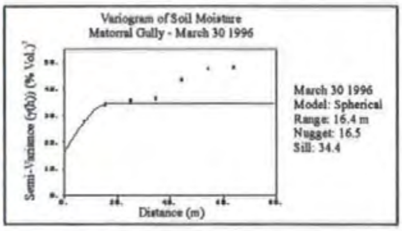
(r)



Matorral Gully
March 30 1996

Minimum: 10.5%
Maximum: 40%
Mean: 27.5%
Variance: 38.35
Standard Deviation: 6.19
Coefficient of Variation: 22.5%

Temporal Persistence: 0.96



Dry Conditions – May 20 1995 to November 4 1995

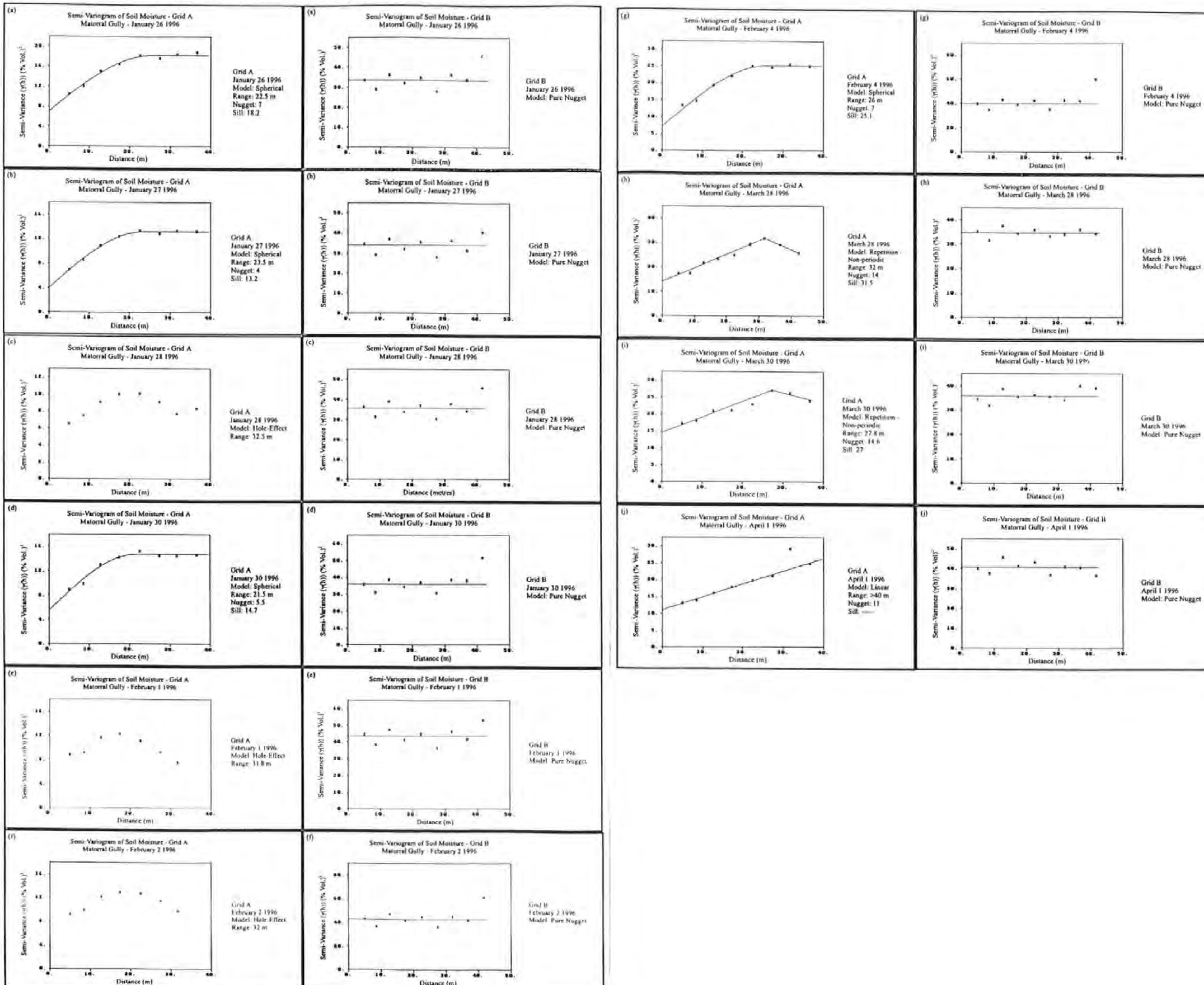
Within the matorral gully catchment the contour plots of soil moisture during dry conditions display a soil moisture pattern which is fragmented into relatively dry and wet areas (figures 6.1a-i). This soil moisture pattern may be described as mosaic in its nature, with the wet areas inter-dispersed amongst the dry areas. The variograms of soil moisture during this period show a range of spatial correlation which is highly variable between dates changing from 13m to 56m. Furthermore the variograms which display a long range of spatial correlation in soil moisture have a shallow slope which indicates a very slow rate of change in soil moisture with increasing separation distance (Oliver, 1987). The varying range of spatial correlation in soil moisture indicates that the soil moisture pattern can change from variable and fragmented (short range) to relatively uniform (long range) during this period. Uniformity in soil moisture values may occur during this period as conditions become increasingly dry (Hawley *et al.*, 1983; Hendrickx *et al.*, 1990), with the effect that the spatial pattern of soil moisture is similar over large areas (McBratney, 1992; Berndtsson and Chen, 1994). Therefore, although the mean soil moisture content within the gully during this period is similar on each measurement date (table 6.1), small changes in the soil moisture values appears to result in a large change in the spatial correlation of soil moisture. The small changes in soil moisture during this period may be attributed to evapotranspiration and/or the redistribution of soil moisture within the gully.

Wet Conditions – January 26 1996 to April 1 1996

The mosaic pattern of soil moisture persists in wet conditions, although a clear contrast in the spatial pattern between the upper and lower halves of the gully catchment can be observed. In the lower half of the catchment the mosaic pattern becomes increasingly more fragmented whilst the moisture values in the upper half of the gully become increasingly similar (figures 6.1j-s). Variograms of soil moisture during this period show a range in spatial correlation of approximately 16m-17m, which implies a variable and fragmented soil moisture pattern. This is true of the lower half of the gully, but in the upper half of the gully soil moisture values appear to be more uniform (figures 6.1j-s). The shape and form displayed by the variograms of soil moisture during this period may explain the different soil moisture pattern observed within the upper half of the gully catchment compared to the lower half. All of the variograms during this period display a second increasing semi-variance after a constant sill value has been reached. This second rising semi-variance also reaches what appears to be a second constant sill value. This 'staircase' shaped variogram indicates that two different spatial structures are present within the gully and that the range of spatial correlation shown by these variograms is an average of these two structures (M.A. Oliver, personal communication). The two different spatial structures refer to the two different soil moisture patterns observed within the gully catchment during wet conditions. To clarify the two spatial structures, the grid of soil moisture has been divided into two separate grids, grid A and B, the boundary of which coincides with the change in the soil moisture pattern. Grid A therefore covers the upper part of the catchment where the soil moisture pattern is relatively uniform and grid B covers the lower part of the catchment where the moisture pattern is more fragmented. The variograms of soil moisture for grid A and B during wet conditions are shown in figures 6.2a-j. In grid A the variogram models are changeable, including spherical, hole-effect, repetition non-periodic and linear (Oliver, 1987). However for all measurement dates the range of spatial correlation in soil moisture has increased to 22-32m, which is more consistent with the spatial pattern of soil moisture observed in this part of the gully. Soil moisture values in the upper part of the gully are therefore more uniform and the spatial pattern is less fragmented. The variograms of soil moisture in grid B all display a pure nugget effect, which indicates a random pattern in soil moisture at the sampling scale used. This supports the fragmented soil moisture pattern observed within this part of the gully catchment during wet conditions.

rising semi-variance also reaches what appears to be a second constant sill value. This 'staircase' shaped variogram indicates that two different spatial structures are present within the gully and that the range of spatial correlation shown by these variograms is an average of these two structures (M.A. Oliver, personal communication). The two different spatial structures refer to the two different soil moisture patterns observed within the gully catchment during wet conditions. To clarify the two spatial structures, the grid of soil moisture has been divided into two separate grids, grid A and B, the boundary of which coincides with the change in the soil moisture pattern. Grid A therefore covers the upper part of the catchment where the soil moisture pattern is relatively uniform and grid B covers the lower part of the catchment where the moisture pattern is more fragmented. The variograms of soil moisture for grid A and B during wet conditions are shown in figures 6.2a-j. In grid A the variogram models are changeable, including spherical, hole-effect, repetition non-periodic and linear (Oliver, 1987). However for all measurement dates the range of spatial correlation in soil moisture has increased to 22-32m, which is more consistent with the spatial pattern of soil moisture observed in this part of the gully. Soil moisture values in the upper part of the gully are therefore more uniform and the spatial pattern is less fragmented. The variograms of soil moisture in grid B all display a pure nugget effect, which indicates a random pattern in soil moisture at the sampling scale used. This supports the fragmented soil moisture pattern observed within this part of the gully catchment during wet conditions.

Figures 6.2. Semi-variograms of soil moisture for Grid A and Grid B within the Matorral Gully Catchment.



6.1.4 Forest Gully Catchment

Figures 6.3a-q show contour plots and variograms of soil moisture for each measurement date within the forest gully catchment.

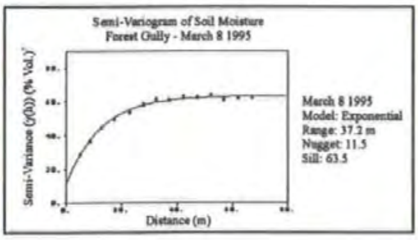
Figures 6.3. Contour plots and semi-variograms of soil moisture for each measurement date within the Forest Gully Catchment.

(a)

Forest Gully
March 8 1995

Minimum: 3.6%
Maximum: 33.7%
Mean: 18.7%
Variance: 56.8
Standard Deviation: 7.53
Coefficient of Variation: 40.2%

Temporal Persistence: ----

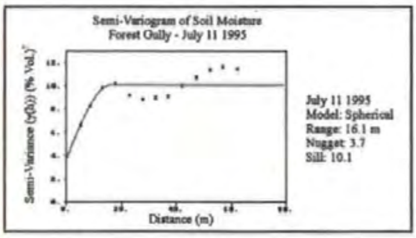


(b)

Forest Gully
July 11 1995

Minimum: 3.6%
Maximum: 18.4%
Mean : 9.4%
Variance: 13.3
Standard Deviation: 3.66
Coefficient of Variation: 38.9%

Temporal Persistence: 0.83

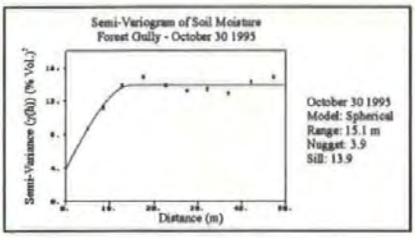


(g)

Forest Gully
October 30 1995

Minimum: 5.5%
Maximum: 20.9%
Mean: 11.4%
Variance: 14.19
Standard Deviation: 3.77
Coefficient of Variation: 33%

Temporal Persistence: 0.96

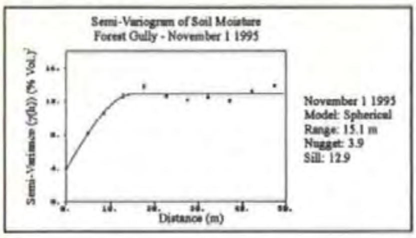


(h)

Forest Gully
November 1 1995

Minimum: 4.8%
Maximum: 20.9%
Mean: 10.6%
Variance: 15.3
Standard Deviation: 3.91
Coefficient of Variation: 36.8%

Temporal Persistence: 0.98

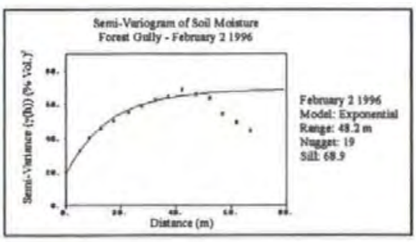


(m)

Forest Gully
February 2 1996

Minimum: 12%
Maximum: 42.5%
Mean: 30.9%
Variance: 67.75
Standard Deviation: 8.23
Coefficient of Variation: 26.6%

Temporal Persistence: 0.97

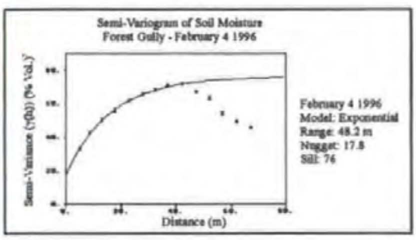


(n)

Forest Gully
February 4 1996

Minimum: 8.3%
Maximum: 40.6%
Mean: 28.2%
Variance: 64.22
Standard Deviation: 8.01
Coefficient of Variation: 28.4%

Temporal Persistence: 0.96

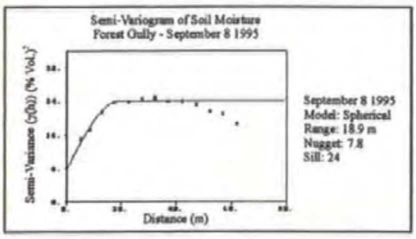


(c)

Forest Gully
September 8 1995

Minimum: 3.6%
Maximum: 21.7%
Mean: 11.1%
Variance: 23.46
Standard Deviation: 4.84
Coefficient of Variation: 43.6%

Temporal Persistence: 0.70

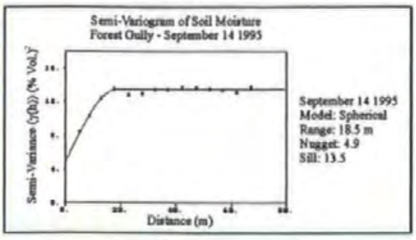


(d)

Forest Gully
September 14 1995

Minimum: 2.9%
Maximum: 16.8%
Mean: 7.6%
Variance: 14.84
Standard Deviation: 3.85
Coefficient of Variation: 50.6%

Temporal Persistence: 0.90

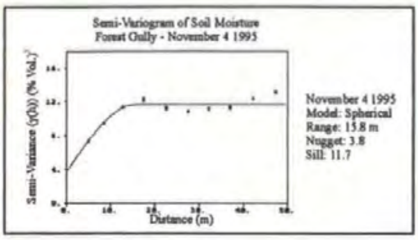


(i)

Forest Gully
November 4 1995

Minimum: 4.2%
Maximum: 18.4%
Mean: 9.5%
Variance: 13.2
Standard Deviation: 3.63
Coefficient of Variation: 38.2%

Temporal Persistence: 0.98

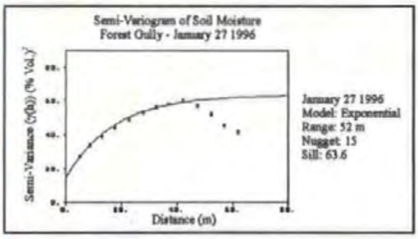


(j)

Forest Gully
January 27 1996

Minimum: 12%
Maximum: 38.7%
Mean: 29%
Variance: 52.29
Standard Deviation: 7.23
Coefficient of Variation: 24.9%

Temporal Persistence: 0.64

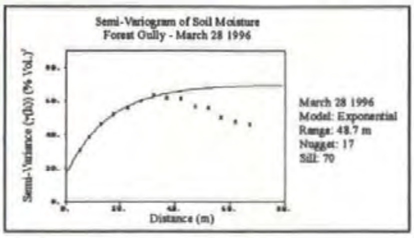


(o)

Forest Gully
March 28 1996

Minimum: 6.2%
Maximum: 36.6%
Mean: 19.5%
Variance: 56.82
Standard Deviation: 7.54
Coefficient of Variation: 38.6%

Temporal Persistence: 0.83

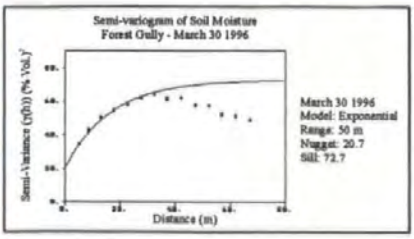


(p)

Forest Gully
March 30 1996

Minimum: 9%
Maximum: 39.3%
Mean: 23%
Variance: 66.79
Standard Deviation: 8.17
Coefficient of Variation: 35.5%

Temporal Persistence: 0.97

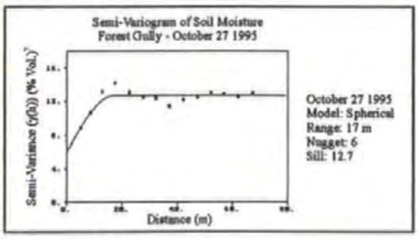


(e)

Forest Gully
October 27 1995

Minimum: 5.5%
Minimum: 19.3%
Mean: 10.8%
Variance: 12.09
Standard Deviation: 3.48
Coefficient of Variation: 32.2%

Temporal Persistence: 0.87

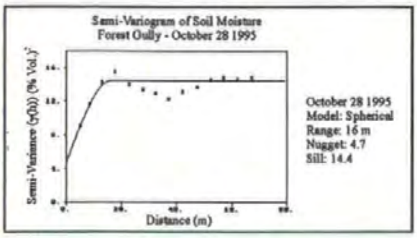


(f)

Forest Gully
October 28 1995

Minimum: 6.2%
Maximum: 20.9%
Mean: 12.2%
Variance: 14.4
Standard Deviation: 3.79
Coefficient of Variation: 31%

Temporal Persistence: 0.97

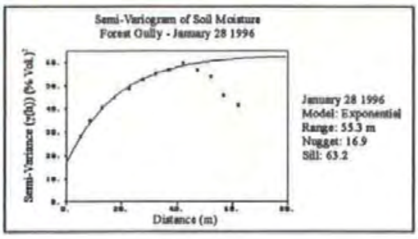


(k)

Forest Gully
January 28 1996

Minimum: 10.5%
Maximum: 40.6%
Mean: 29.9%
Variance: 52.3
Standard Deviation: 7.23
Coefficient of Variation: 24.1%

Temporal Persistence: 0.98

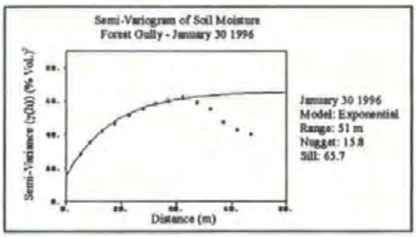


(l)

Forest Gully
January 30 1996

Minimum: 10.5%
Maximum: 40%
Mean: 28.6%
Variance: 59.02
Standard Deviation: 7.68
Coefficient of Variation: 26.8%

Temporal Persistence: 0.98

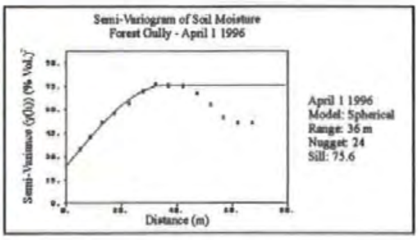


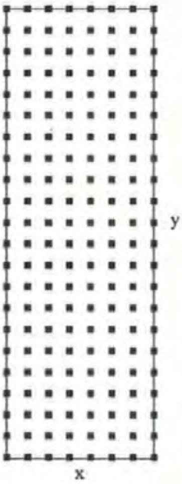
(q)

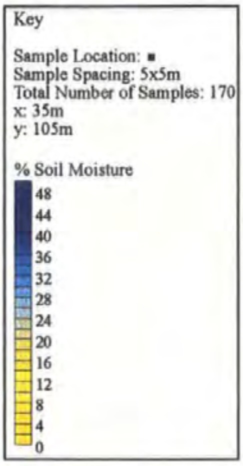
Forest Gully
April 1 1996

Minimum: 11.2%
Maximum: 41.3%
Mean: 27.2%
Variance: 71.4
Standard Deviation: 8.45
Coefficient of Variation: 31%

Temporal Persistence: 0.94







Dry Conditions – March 8 1995 to November 4 1995

Similar to the matorral gully soil moisture in the forest gully displays a mosaic pattern of wet and dry areas which is particularly fragmented during this period. The distinctive fragmentation of the soil moisture pattern during this period is supported by the variograms of soil moisture which are all similar in their shape and form and have a range in spatial correlation of soil moisture which is relatively short, varying from 15m-19m (figures 6.3b-i). The similar shape and range of these variograms provides further evidence of the temporal persistence within the spatial patterns of soil moisture. Furthermore, the rising limb of these models is generally steep indicating increasing dissimilarity in soil moisture values over relatively short distances (Oliver, 1987). During dry conditions the soil moisture pattern within the forest gully is therefore highly variable and fragmented.

Wet Conditions – January 27 1996 to April 1 1996

In contrast to dry conditions, the mosaic pattern in soil moisture during wet conditions is less fragmented due to the development of extensive wet areas over large parts of the gully (figures 6.3(a)j-q). The variograms of soil moisture during this period have all been fitted with an exponential model, with the exception of April 1, which has been described with a spherical model. These variograms show a range of spatial correlation in soil moisture which varies from 37m-55m and which is more than double the range in dry conditions. Vauclin *et al.* (1983) have also reported a greater range in spatial correlation of soil moisture during wet conditions than under dry conditions. The greater range of spatial correlation in soil moisture during wet conditions compared to dry conditions is consistent with the less fragmented soil moisture pattern shown in the contour plots during this period. During wet conditions the development of extensive wet areas results in a greater spatial correlation of soil moisture values.

6.1.5 Bench Terrace Gully Catchment

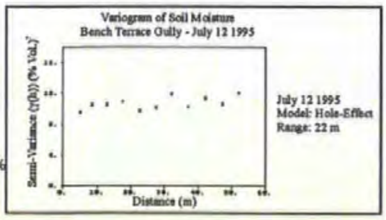
Figures 6.4a-q show contour plots and variograms of soil moisture for each measurement date within the bench terrace gully catchment.

Figures 6.4. Contour plots and semi-variograms of soil moisture for each measurement date within the Bench Terrace Gully Catchment.

(a)
Bench Terrace Gully
July 12 1995

Minimum: 3.6%
Maximum: 21.7%
Mean: 7.9%
Variance: 10.71
Standard Deviation: 3.27
Coefficient of Variation: 41.3%

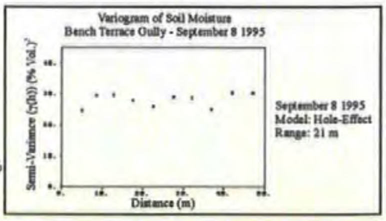
Temporal Persistence: ----



(b)
Bench Terrace Gully
September 8 1995

Minimum: 2.4%
Maximum: 32.2%
Mean: 11.2%
Variance: 29.13
Standard Deviation: 5.39
Coefficient of Variation: 48.1%

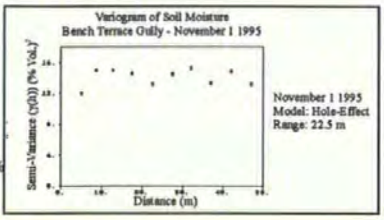
Temporal Persistence: 0.72

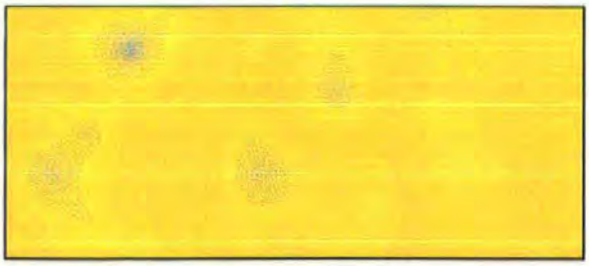


(g)
Bench Terrace Gully
November 1 1995

Minimum: 4.2%
Maximum: 25%
Mean: 9.5%
Variance: 14.28
Standard Deviation: 3.78
Coefficient of Variation: 39.7%

Temporal Persistence: 0.97

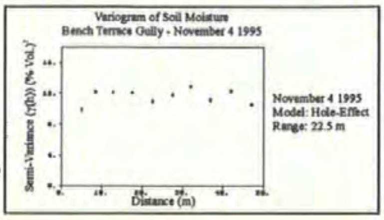




(h)
Bench Terrace Gully
November 4 1995

Minimum: 3.6%
Maximum: 22.5%
Mean: 8.5%
Variance: 11.78
Standard Deviation: 3.43
Coefficient of Variation: 40.3%

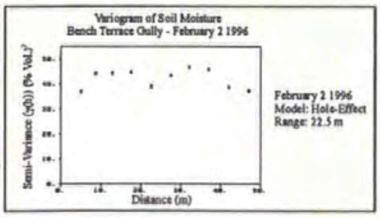
Temporal Persistence: 0.98

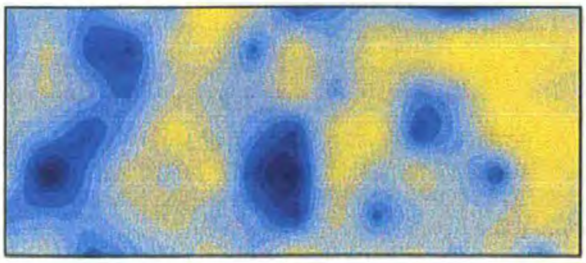


(m)
Bench Terrace Gully
February 2 1996

Minimum: 11.2%
Maximum: 41.9%
Mean: 25.7%
Variance: 43.50
Standard Deviation: 6.59
Coefficient of Variation: 25.6%

Temporal Persistence: 0.95

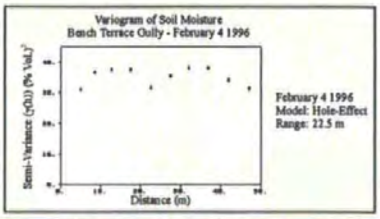


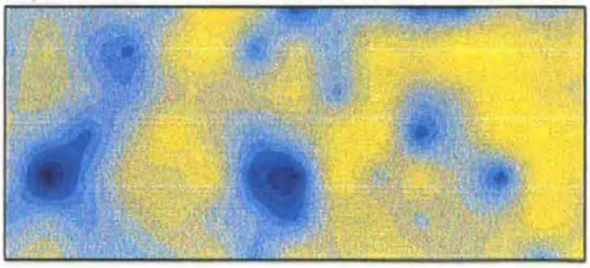


(n)
Bench Terrace Gully
February 4 1996

Minimum: 10.5%
Maximum: 41.3%
Mean: 23.7%
Variance: 36.08
Standard Deviation: 6.0
Coefficient of Variation: 25.3%

Temporal Persistence: 0.94

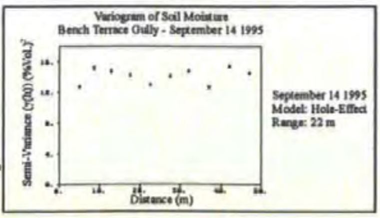


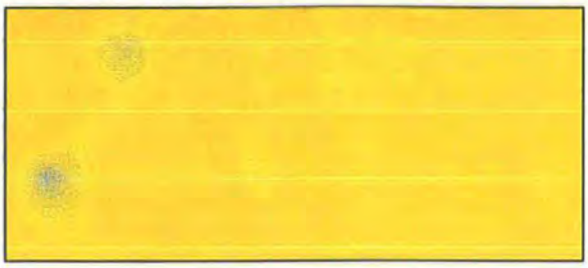


(c)
Bench Terrace Gully
September 14 1995

Minimum: 2.4%
Maximum: 25%
Mean: 6.8%
Variance: 14.77
Standard Deviation: 3.84
Coefficient of Variation: 56.4%

Temporal Persistence: 0.92

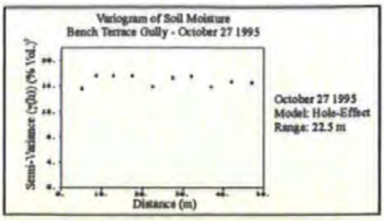


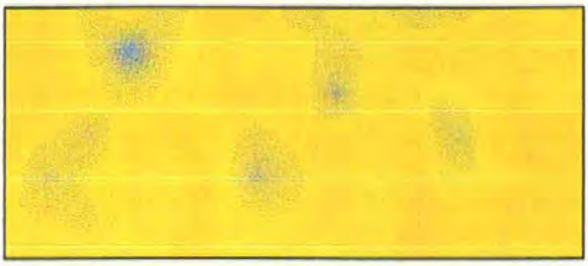


(d)
Bench Terrace Gully
October 27 1995

Minimum: 4.8%
Maximum: 28.3%
Mean: 11.4%
Variance: 16.92
Standard Deviation: 4.11
Coefficient of Variation: 36%

Temporal Persistence: 0.81

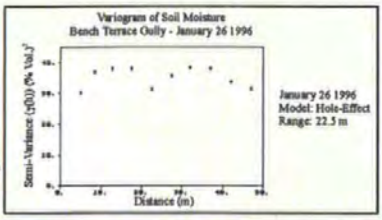


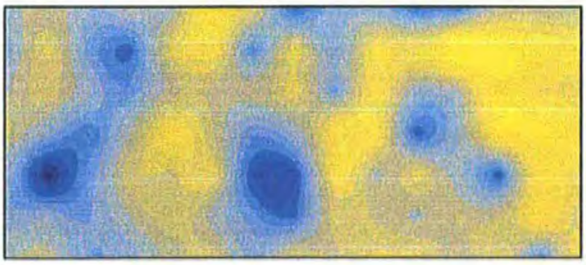


(i)
Bench Terrace Gully
January 26 1996

Minimum: 9%
Maximum: 39.3%
Mean: 23.2%
Variance: 36.37
Standard Deviation: 6.03
Coefficient of Variation: 25.9%

Temporal Persistence: 0.78

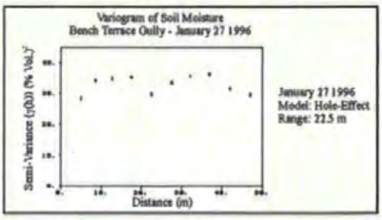


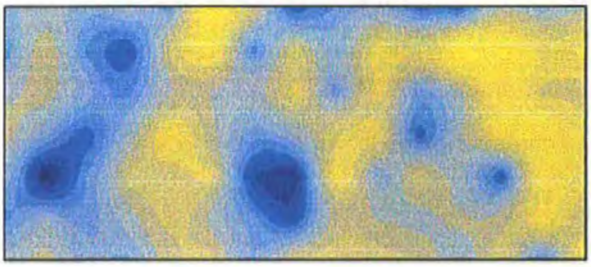


(j)
Bech Terrace Gully
January 27 1996

Minimum: 11.2%
Maximum: 40%
Mean: 24.4%
Variance: 34.14
Standard Deviation: 5.84
Coefficient of Variation: 23.9%

Temporal Persistence: 0.98

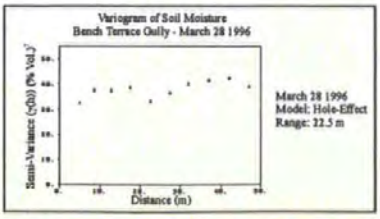


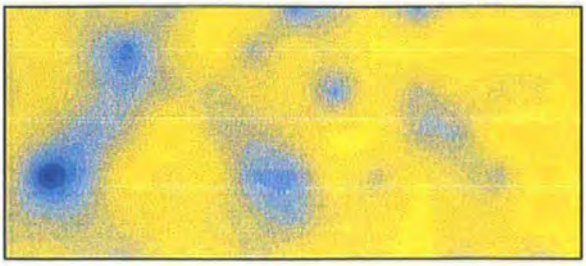


(o)
Bench Terrace Gully
March 28 1996

Minimum: 5.5%
Maximum: 36.6%
Mean: 18%
Variance: 39.92
Standard Deviation: 6.31
Coefficient of Variation: 35%

Temporal Persistence: 0.87

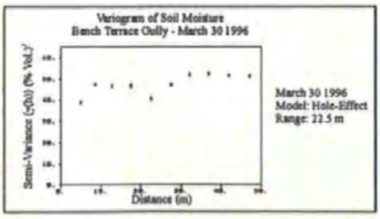


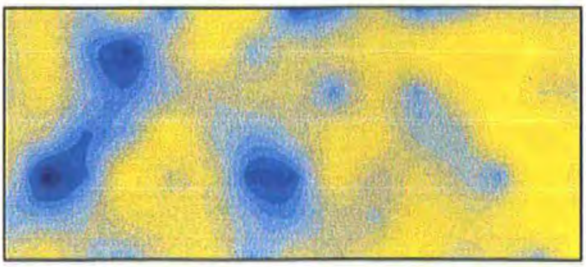


(p)
Bench Terrace Gully
March 30 1996

Minimum: 6.8%
Maximum: 39.3%
Mean: 21.6%
Variance: 49.28
Standard Deviation: 7.02
Coefficient of Variation: 32.5%

Temporal Persistence: 0.92

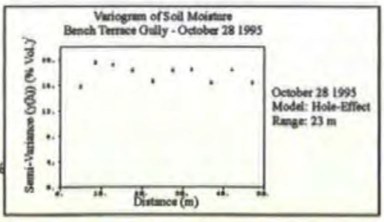


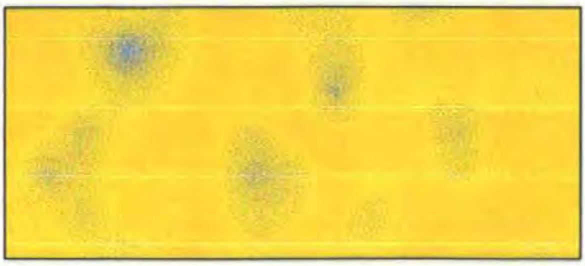


(e)
Bench Terrace Gully
October 28 1995

Minimum: 6.2%
Maximum: 29.1%
Mean: 12%
Variance: 17.93
Standard Deviation: 4.23
Coefficient of Variation: 35.2%

Temporal Persistence: 0.95

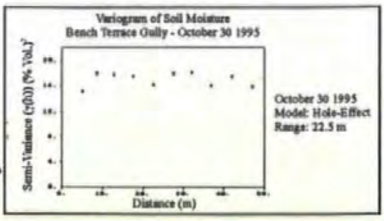


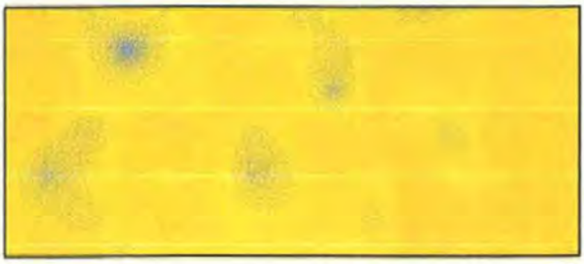


(f)
Bench Terrace Gully
October 30 1995

Minimum: 4.2%
Maximum: 27.5%
Mean: 10.6%
Variance: 17.27
Standard Deviation: 4.15
Coefficient of Variation: 39.1%

Temporal Persistence: 0.95

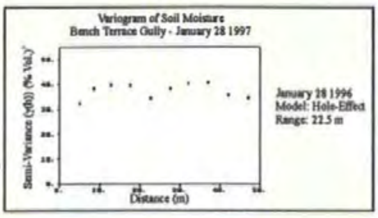


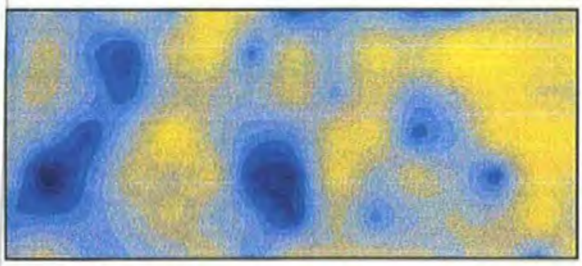


(k)
Bench Terrace Gully
January 28 1996

Minimum: 10.5%
Maximum: 40.6%
Mean: 25%
Variance: 39.03
Standard Deviation: 6.24
Coefficient of Variation: 24.9%

Temporal Persistence: 0.97

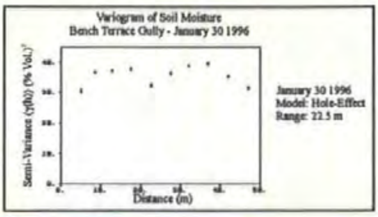


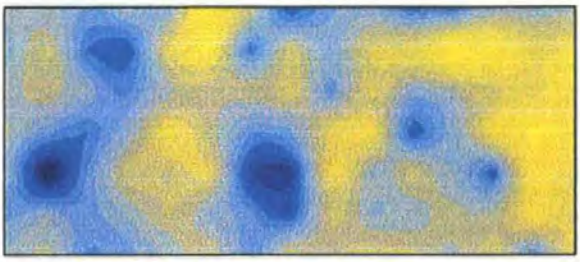


(l)
Bench Terrace Gully
January 30 1996

Minimum: 10.5%
Maximum: 41.9%
Mean: 24.3%
Variance: 37.20
Standard Deviation: 6.10
Coefficient of Variation: 25.1%

Temporal Persistence: 0.97

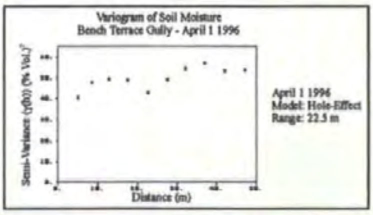


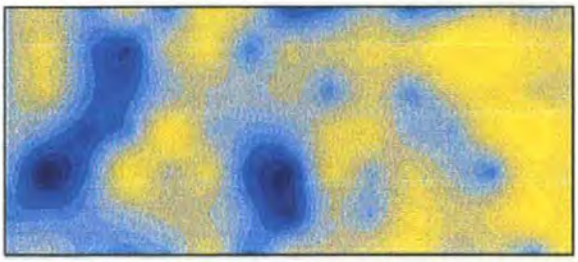


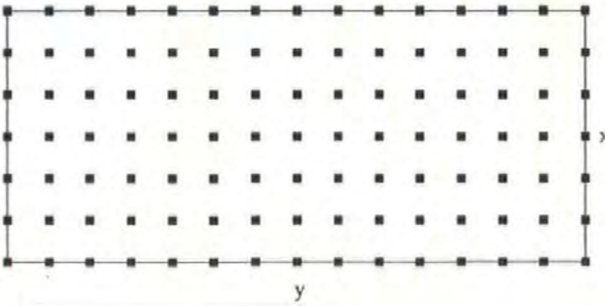
(q)
Bench Terrace Gully
April 1 1996

Minimum: 7.5%
Maximum: 41.9%
Mean: 24.1%
Variance: 52.12
Standard Deviation: 7.22
Coefficient of Variation: 29.9%

Temporal Persistence: 0.96



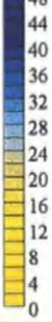




Key

Sample Location: ■
Sample Spacing: 5x5m
Total Number of Samples: 105
x: 30m
y: 70m

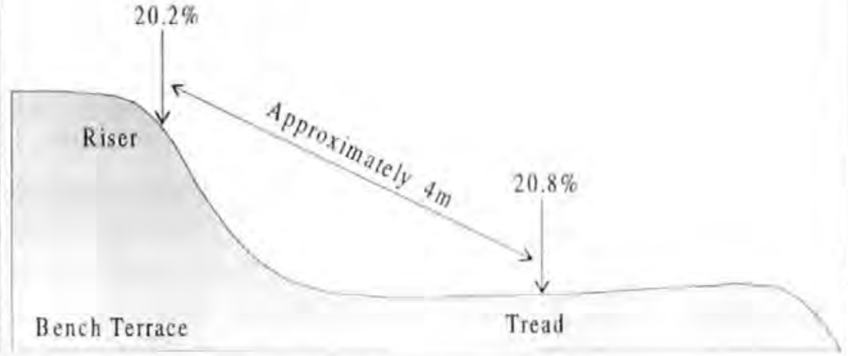
% Soil Moisture



Dry Conditions – July 12 1995 to November 4 1995

Similar to the matorral and forest gully catchments, the soil moisture pattern within the bench terrace gully catchment is fragmented into a mosaic pattern of relatively wet and dry areas. The variograms of soil moisture during this period all display a similar shape and form which is consistent with the contour plots of soil moisture which are also similar between dates (figures 6.4a-h). These variograms may at first appear to be pure nugget (ie. horizontal) which would imply a random variation in soil moisture at the sampling scale of 5m (Trangmar *et al.*, 1985). However, a small sinuosity is present within the variograms, which is consistent with a hole-effect model variogram. This type of variogram is indicative of periodic repetition within the property being examined (Trangmar *et al.*, 1985; Oliver, 1987). Ternan *et al.* (1996b) have reported that bench terraces within this region tend to impose a structured soil moisture pattern in which the treads of the terrace generally have a higher soil moisture content than the riser. Therefore, moving downslope, soil moisture values can be expected to alternate between high and low, being repeated at a separation distance which is approximately equal to the terrace width. The expected repetition in soil moisture across bench terraces is consistent with the hole-effect variograms observed for this gully. However the range of spatial correlation in soil moisture for these hole-effect variograms is between 21-23m (although the wavelength shortens with increasing distance) which is not consistent with the width of bench terraces which is generally 5-6m (Ternan *et al.*, 1996b). The range in spatial correlation in soil moisture for the bench terraces is therefore greater than would have been predicted based on the terrace width. Several factors may explain this apparent discrepancy. Firstly and most significantly, the bench terraces within this gully are not aligned parallel to the columns of the grid over which soil moisture was measured. Instead the bench terraces are at an angle to the grid and thus several sampling points, which run down and over the terraces, may be located in the same position on each separate terrace. These points may therefore be expected to have the same soil moisture, resulting in a greater range of spatial correlation than predicted by the width of the terraces. Secondly, the bench terraces within this region are generally of poor construction, which can vary markedly, particularly when moving down from the top of the hillslope to the bottom as is the case in the bench terrace gully. Therefore the width of the terraces is variable, although none are greater than 10m. Thirdly, figure 6.5 shows an example from the bench terrace gully where the soil moisture content on the riser of the terrace is similar to the soil moisture content on the tread and therefore the expected alternating pattern in soil moisture does not occur everywhere within the gully grid. The range of spatial correlation in soil moisture can therefore be greater than a single terrace width. Finally, if a variogram was constructed using only those points that run along the length of a single terraces tread or riser then the range of spatial correlation may be expected to be high since soil moisture values along the tread or riser would be similar, ie. either all high along the tread or all low along the riser. The variograms constructed for the bench terrace gully are omni-directional and therefore the spatial correlation in soil moisture found across the terraces are averaged with those along the terraces which may produce a range greater than the terraces width.

Figure 6.5. A single terrace where the soil moisture content on the riser is similar to that on the tread. The alternating high/low soil moisture pattern expected on terraces may therefore not always occur.



Wet Conditions – January 26 1996 to April 1 1996

The fragmented and mosaic pattern of soil moisture observed during dry conditions persists during wet conditions but to a lesser extent as the wet areas expand and become more continuous (figures 6.4i-q). In table 6.4 the bench terrace gully catchment displays a stronger temporal persistence within the soil moisture pattern as conditions change from dry to wet than either the matorral or forest gully catchments. The fragmented mosaic pattern is therefore more similar between dry and wet periods within the bench terrace gully than in the matorral or forest gully. During wet conditions the variograms of soil moisture continue to display a hole-effect. However the hole-effect is much more defined in wet compared to dry conditions which reflects the more distinctive contour plots of soil moisture during wet conditions. The range of spatial correlation in soil moisture during wet conditions is 22m-23m and is similar to that in dry conditions. The alternating pattern of high and low soil moisture values expected on bench terraces may be expected to persist through time due to the imposed topographic structure of the terraces. The range of spatial correlation in soil moisture on bench terraces may therefore also be expected to remain approximately constant through time. The variograms of soil moisture in the bench terrace gully in both dry and wet conditions have a high nugget variance which together with the near horizontal structure of these variograms implies high spatial variability in soil moisture irrespective of the spatial range of correlation. Soil moisture is therefore highly variable within the bench terrace gully particularly during dry conditions becoming less variable in wet conditions.

6.1.6 Summary

Comegna and Basile (1994) have been able to partition the spatial pattern of soil moisture into areas or patches known as dry and wet zones. Within the three gully catchments the contour plots of soil moisture also display a soil moisture pattern which is fragmented into relatively wet and dry areas. This soil moisture pattern may be described as mosaic in its nature, with wet areas inter-dispersed amongst the dry areas. Charpentier and Groffman (1992), Loague (1992a) and Ritsema and Dekker (1994, 1995) have also reported the presence of wet and dry zones creating a mosaic pattern of areas of similar soil moisture content. The degree of variation in soil moisture may change depending upon whether measurements are taken during a wet period or during a drying out period (Hawley *et al.*, 1983). With the exception of the matorral gully the fragmentation within the mosaic pattern is greatest during dry conditions. During wet conditions extensive wet areas cover large parts of the gully catchments and the range of spatial correlation in the forest gully is double the range of spatial correlation in soil moisture during dry conditions. Although in the bench terrace gully the range of spatial correlation in soil moisture during wet conditions is similar to dry conditions, the contour plots show the expansion of wet areas during wet conditions within this gully. The variability in soil moisture within these two gullies is therefore highest during dry conditions. Wierenga (1985), Greminger *et al.* (1985), Hendrickx *et al.* (1990) and McBratney (1992) have also reported a decrease in soil moisture variability as soil moisture levels increased. (see Chapter 1, Section 1.9 for a review of wetting up and drying out periods).

In the matorral gully the soil moisture pattern and its changes through time are more complex. During dry conditions soil moisture within the matorral gully can be highly variable with a low range of spatial correlation. However, this gully differs from the forest and bench terrace gully in that soil moisture values during dry conditions may also be relatively uniform and the range in spatial correlation of soil moisture high. Only a small change in the soil moisture pattern during these periods is needed to cause a large change in the spatial correlation of soil moisture. The mosaic pattern of soil moisture in the matorral gully is the least fragmented during dry conditions compared to the forest or bench terrace gullies. The difference in soil moisture patterns between the matorral gully and the forest and bench terrace gullies during dry periods may be due to the significantly lower vegetation cover (7.8%) within the matorral gully compared to the forest (33.2%) and bench terrace (20.2%) catchments. In chapter 5 it was suggested that the non-uniform uptake of moisture by vegetation can lead to a more variable soil moisture pattern during dry periods. The sparse cover of vegetation within the matorral catchment may therefore result in a less variable and more uniform soil moisture pattern during dry periods. In wet conditions the range of spatial correlation in soil moisture in the upper part of the matorral gully is relatively high as indicated by the extensive wet area observed in this part of the gully. Conditions in this part of the matorral gully are therefore similar to the forest and bench terrace gullies during wet periods. In the lower part of the matorral gully however, fragmentation in the soil moisture pattern increases although relatively large wet areas may still persist.

Within the three gully catchments the extent of spatial variation in soil moisture displays a temporal dependence on whether conditions are dry or wet. During dry conditions the spatial variation in soil moisture may be high and becomes less variable during wet periods as extensive wet areas cover large parts of the gully catchments and the spatial continuity in soil moisture increases.

6.2 Temporal and Spatial Variability in Soil Moisture at the Microscale

In the previous sections soil moisture was found to be spatially highly variable at the gully catchment scale, particularly during dry conditions when a fragmented mosaic pattern of soil moisture consisting of adjacent wet and dry areas could be observed. Soil moisture was also found to be highly variable over relatively short distances within the gully catchments and could for example vary by 24% over 5m distance. In addition, all of the variograms of soil moisture within the gully catchments, particularly those from the bench terrace gully, displayed a nugget variance which indicated variability in soil moisture at a sampling scale of less than 5m. Within the following sections the variability in soil moisture at distances shorter than 5m recorded within the minigrids is described. It should be noted that the minigrids were selected in areas within the catchments were considerable short range variability in soil moisture occurs in order to further identify the factors controlling soil moisture patterns.

Tables 6.5, 6.6 and 6.7 provide summary statistics of the soil moisture data collected at the microscale within the matorral minigrid, forest minigrid and bench terrace minigrid, during the study period. Similar to the meso and macro scales the sampling dates of soil moisture for the minigrids may be divided into measurements taken during a dry condition period (May 20 1995 - November 4 1995) and a wet condition period (January 27 1996 - April 1 1996). Similar to the other scales the separation of the soil moisture data set at the microscale is verified by the significantly higher mean soil moisture values recorded within each minigrid on measurement dates during wet conditions ($p<0.05$). Values of the coefficient of variation during dry conditions within the matorral and bench terrace minigrids are significantly higher than the coefficient of variation values for soil moisture during wet conditions ($p<0.05$) (tables 6.5 and 6.7). Soil moisture within these two minigrids is therefore more variable during dry conditions compared to wet conditions reflecting a similar pattern to that found at the gully catchment scale. By contrast the degree of variability in soil moisture within the forest minigrid persists through time and the coefficient of variation is not significantly different between dry and wet conditions (table 6.6). Within the forest minigrid therefore, the degree of fragmentation within the soil moisture pattern during wet conditions may be expected to be similar to that observed during dry conditions. In both the matorral and forest minigrids the coefficient of variation in soil moisture is significantly higher than in the bench terrace minigrid ($p<0.05$). Soil moisture values within the bench terrace minigrid are therefore the least variable. The high variability in soil moisture within the matorral and forest minigrids indicated by the coefficient of variation is further reflected by the minimum and maximum soil moisture values in tables 6.5 and 6.6. Within the matorral minigrid points may vary in soil moisture from 9% to 41% on the same day, a difference in soil moisture of 32% between points within a 5x5m area. Similar differences, particularly during dry conditions can also be found within the forest and bench terrace minigrids where on the same day the soil moisture at some points may be 5 times higher than at other points. During wet conditions however, the magnitude of difference in soil moisture values between points within the bench terrace minigrid is less than in the matorral or forest minigrids.

Table 6.5. Summary statistics of the soil moisture data recorded within the Matorral Minigrid.

Soil Moisture Sampling Dates	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Variance	Coefficient of Variation (%)
May 20 1995	14.02	5.53	32.22	7.97	63.56	56.88
July 12 1995	14.43	6.89	31.45	7.01	49.09	48.54
September 8 1995	13.46	4.87	27.50	6.16	37.93	45.76
September 14 1995	11.61	3.60	23.42	5.62	31.62	48.45
October 28 1995	15.00	6.89	28.30	6.09	37.10	40.61
October 30 1995	13.18	6.20	26.69	5.88	34.61	44.63
November 1 1995	12.88	6.20	25.88	5.87	34.41	45.55
November 4 1995	11.33	4.87	25.06	5.81	33.81	51.32
January 27 1996	28.49	15.22	40.69	7.46	55.67	26.19
January 30 1996	27.83	13.62	41.32	7.51	56.33	26.97
February 2 1996	28.61	11.29	43.15	7.94	63.00	27.74
February 4 1996	26.68	12.06	41.32	7.70	59.30	28.86
March 28 1996	20.18	6.20	38.04	9.10	82.88	45.11
March 30 1996	24.82	9.04	41.32	8.92	79.56	35.94
April 1 1996	28.94	14.42	43.15	8.20	67.28	28.34
Mean Dry S.M.	13.24	5.63	27.57	6.30	40.26	47.72
Mean Wet S.M.	26.51	11.69	41.28	8.11	66.28	31.31

S.M. = Soil Moisture.

Table 6.6. Summary statistics of the soil moisture data recorded within the Forest Minigrid.

Soil Moisture Sampling Dates	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Variance	Coefficient of Variation (%)
May 20 1995	8.81	3.60	20.94	3.71	13.77	42.10
July 12 1995	7.52	3.60	16.84	3.11	9.67	41.36
September 8 1995	8.06	2.99	15.22	3.19	10.19	39.61
September 14 1995	6.15	2.99	15.22	2.77	7.68	45.05
October 28 1995	10.83	5.53	19.30	3.04	9.22	28.04
October 30 1995	10.04	5.53	20.12	3.08	9.49	30.67
November 1 1995	9.84	5.53	19.30	3.15	9.92	31.99
November 4 1995	8.58	3.60	18.47	3.22	10.35	37.51
January 27 1996	23.73	9.04	36.65	7.43	55.20	31.31
January 30 1996	22.76	10.53	35.94	7.21	51.93	31.66
February 2 1996	23.41	10.53	37.35	7.42	55.06	31.69
February 4 1996	21.49	8.31	35.94	7.55	57.05	35.14
March 28 1996	16.72	6.20	32.22	7.21	51.93	43.11
March 30 1996	21.98	9.04	38.04	7.49	56.09	34.07
April 1 1996	24.88	10.53	38.04	7.73	59.81	31.08
Mean Dry S.M.	8.73	4.17	18.18	3.16	10.03	37.04
Mean Wet S.M.	22.14	9.17	36.31	7.43	55.29	34.01

S.M. = Soil Moisture.

Table 6.7. Summary statistics of the soil moisture data recorded within the Bench Terrace Minigrid.

Soil Moisture Sampling Dates	Mean (%)	Minimum (%)	Maximum (%)	Standard Deviation	Variance	Coefficient of Variation (%)
July 12 1995	9.10	4.87	18.47	3.27	10.71	35.97
September 8 1995	14.44	4.22	22.59	4.45	19.85	30.85
September 14 1995	9.64	3.60	18.47	3.71	13.74	38.46
October 28 1995	13.14	6.89	21.77	3.77	14.18	28.66
October 30 1995	12.04	6.89	20.12	3.55	12.58	29.46
November 1 1995	11.34	5.53	19.30	3.50	12.23	30.84
November 4 1995	9.48	4.22	17.65	3.22	10.40	34.01
January 27 1996	26.24	16.84	38.04	5.89	34.70	22.45
January 30 1996	25.81	15.22	36.65	5.71	32.62	22.13
February 2 1996	26.93	16.84	39.39	6.02	36.29	22.37
February 4 1996	25.14	16.03	37.35	5.63	31.70	22.40
March 28 1996	18.58	9.78	29.10	5.76	33.15	30.99
March 30 1996	22.84	11.29	33.74	5.77	33.33	25.27
April 1 1996	26.81	16.84	40.04	5.75	33.09	21.45
Mean Dry S.M.	11.31	5.17	19.77	3.64	13.38	32.61
Mean Wet S.M.	24.62	14.69	36.33	5.79	33.55	23.87

S.M. = Soil Moisture.

The spatial variability in soil moisture at the microscale may therefore be high. In addition the high variability in soil moisture observed within these 5x5m minigrids can be found to occur between adjacent points, ie. over a sampling distance of 1m. For example, in the matorral minigrid adjacent sampling points may have a difference in soil moisture as high as 26%. Adjacent sampling points in the forest and bench terrace minigrids may also have more than a 20% difference in soil moisture. Large differences in soil moisture have also been found by Dekker and Ritsema (1996) who reported up to a 20% difference in soil moisture between immediately adjacent sampling points caused by variations in soil water repellency. Wilding (1985) and McBratney (1992) have further reported considerable variability in soil moisture over distances as short as 0.5m. Burrough (1993) has noted that much of the variation observed over longer distances may be present within the first few metres. The differences in soil moisture at the 1m scale may therefore account for the similar magnitude of variation in soil moisture recorded at the mesoscale (5m) and the macroscale (25m).

6.2.1 Temporal Persistence of the Soil Moisture Patterns

Similar to the macro and meso scales, correlations of the soil moisture data between successive measurement dates for each minigrid are all significantly positive ($p<0.01$), indicating temporal persistence within the soil moisture pattern (table 6.8). Therefore, as at the macro and meso scales the factor(s) determining the spatial pattern of soil moisture at the microscale are stationary through time. The correlations for the soil moisture patterns in the change from dry to wet conditions, ie. from November 4 1995 to January 27 1996, are however relatively low with the exception of the forest minigrid which remains high. The lower correlations in the matorral and bench terrace minigrids indicate that although the soil moisture pattern in dry conditions is similar and the pattern in wet conditions is similar, the spatial pattern between these two periods is different. A similar trend was observed within the gully catchment soil moisture data set and was attributed to the expansion of wet areas, resulting in a less fragmented pattern during wet conditions. In contrast the higher correlation in the forest minigrid suggests that the spatial pattern of soil moisture recorded during wet conditions remains similar to the patterns observed during dry conditions.

Table 6.8. Correlations of the soil moisture data between consecutive measurement dates showing the temporal persistence of soil moisture patterns within the three gully catchments minigrids.

Soil Moisture Sampling Dates	Matorral Temporal Persistence	Forest Temporal Persistence	Bench Terrace Temporal Persistence
Mar 8 1995 - July 12 1995	----	0.94**	----
May 20 1995 - July 12 1995	0.97**	----	----
July 12 1995 - Sep 8 1995	0.90**	0.86**	0.77**
Sep 8 1995 - Sep 14 1995	0.96**	0.93**	0.93**
Sep 14 1995 - Oct 28 1995	0.96**	0.83**	0.83**
Oct 28 1995 - Oct 30 1995	0.99**	0.97**	0.98**
Oct 30 1995 - Nov 1 1995	0.99**	0.98**	0.98**
Nov 1 1995 - Nov 4 1995	0.99**	0.96**	0.97**
Nov 4 1995 - Jan 27 1996	0.73**	0.85**	0.78**
Jan 27 1996 - Jan 30 1996	0.99**	0.98**	0.94**
Jan 30 1996 - Feb 2 1996	0.99**	0.99**	0.95**
Feb 2 1996 - Feb 4 1996	0.99**	0.99**	0.96**
Feb 4 1996 - Mar 28 1996	0.95**	0.92**	0.94**
Mar 28 1996 - Mar 30 1996	0.97**	0.97**	0.97**
Mar 30 1996 - Apr 1 1996	0.97**	0.96**	0.96**

** = significant at $p<0.01$ (99%).

6.2.2 Analysis of Soil Moisture Spatial Patterns

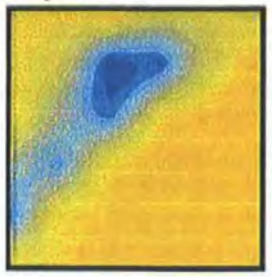
Variogram analysis of the soil moisture patterns at the microscale is not possible due to the small number of sampling points within each minigrid (36) which are too few to accurately calculate semi-variograms (Oliver and Webster, 1990). Instead contour plots of soil moisture are used in the analysis and interpretation of spatial patterns.

6.2.3 Matorral Minigrid

Figures 6.6 show contour plots of soil moisture for each measurement date within the matorral minigrid.

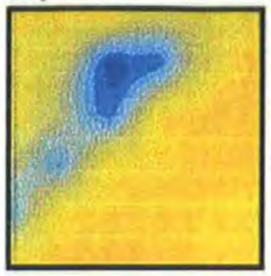
Figure 6.6: Contour plots showing the spatial pattern of soil moisture for each measurement date within the Matorral Minigrid

Matorral Minigrid
May 20 1995



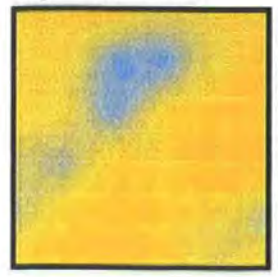
Mean: 14.02%
Minimum: 5.53%
Maximum: 32.22%
Variance: 63.56
Standard Deviation: 7.97
Coefficient of Var: 56.8%
Temporal Persistence: ----

Matorral Minigrid
July 12 1995



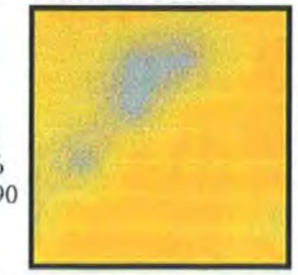
Mean: 14.43%
Minimum: 6.89%
Maximum: 31.45%
Variance: 49.09
Standard Deviation: 7.01
Coefficient of Var: 48.5%
Temporal Persistence: 0.97

Matorral Minigrid
September 8 1995



Mean: 13.46%
Minimum: 4.87%
Maximum: 27.5%
Variance: 37.93
Standard Deviation: 6.16
Coefficient of Var: 45.7%
Temporal Persistence: 0.90

Matorral Minigrid
September 14 1995



Mean: 11.61%
Minimum: 3.6%
Maximum: 23.42%
Variance: 31.62
Standard Deviation: 5.62
Coefficient of Var: 48.4%
Temporal Persistence: 0.96

Matorral Minigrid
October 28 1995

Mean: 15%
Minimum: 6.89%
Maximum: 28.3%
Variance: 37.1
Standard Deviation: 6.09
Coefficient of Var: 40.6%
Temporal Persistence: 0.96

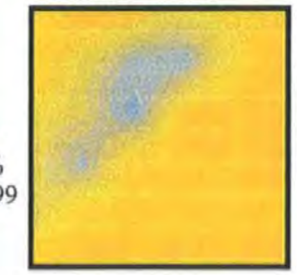
Matorral Minigrid
October 30 1995

Mean: 13.18%
Minimum: 6.2%
Maximum: 26.69%
Variance: 34.61
Standard Deviation: 5.88
Coefficient of Var: 44.6%
Temporal Persistence: 0.99

Matorral Minigrid
November 1 1995

Mean: 12.88%
Minimum: 6.2%
Maximum: 25.88%
Variance: 34.41
Standard Deviation: 5.87
Coefficient of Var: 45.5%
Temporal Persistence: 0.99

Matorral Minigrid
November 4 1995



Mean: 11.33%
Minimum: 4.87%
Maximum: 25.06%
Variance: 33.81
Standard Deviation: 5.81
Coefficient of Var: 51.3%
Temporal Persistence: 0.99

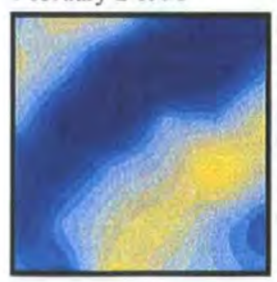
Matorral Minigrid
January 27 1996

Mean: 28.49%
Minimum: 15.22%
Maximum: 40.69%
Variance: 55.67
Standard Deviation: 7.46
Coefficient of Var: 26.1%
Temporal Persistence: 0.73

Matorral Minigrid
January 30 1996

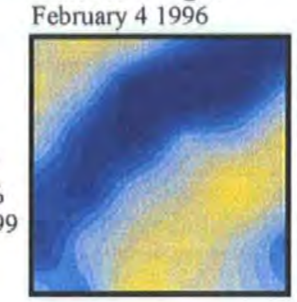
Mean: 27.83%
Minimum: 13.62%
Maximum: 41.32%
Variance: 56.33
Standard Deviation: 7.51
Coefficient of Var: 26.9%
Temporal Persistence: 0.99

Matorral Minigrid
February 2 1996



Mean: 28.61%
Minimum: 11.29%
Maximum: 43.15%
Variance: 63
Standard Deviation: 7.94
Coefficient of Var: 27.7%
Temporal Persistence: 0.99

Matorral Minigrid
February 4 1996



Mean: 26.68%
Minimum: 12.06%
Maximum: 41.32%
Variance: 59.3
Standard Deviation: 7.7
Coefficient of Var: 28.8%
Temporal Persistence: 0.99

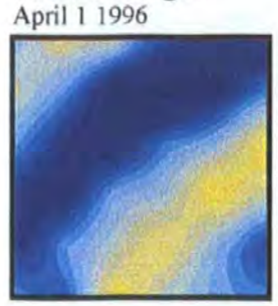
Matorral Minigrid
March 28 1996

Mean: 20.18%
Minimum: 6.2%
Maximum: 38.04%
Variance: 82.88
Standard Deviation: 9.1
Coefficient of Var: 45.1%
Temporal Persistence: 0.95

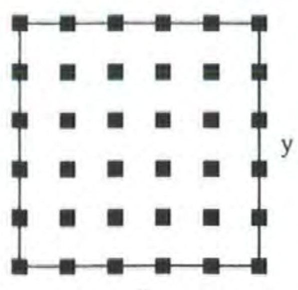
Matorral Minigrid
March 30 1996

Mean: 24.82%
Minimum: 9.04%
Maximum: 41.32%
Variance: 79.56
Standard Deviation: 8.92
Coefficient of Var: 35.9%
Temporal Persistence:0.97

Matorral Minigrid
April 1 1996



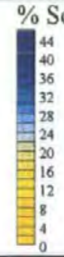
Mean: 28.94%
Minimum: 14.42%
Maximum: 43.15%
Variance: 67.28
Standard Deviation: 8.2
Coefficient of Var: 28.3%
Temporal Persistence: 0.97



Key

Sample Location: ■
Sample Spacing: 1x1m
Total Number of Samples: 36
x: 5m
y: 5m

% Soil Moisture



Dry Conditions - May 20 1995 to November 4 1995

The pattern of soil moisture within the minigrids displays similar characteristics to those shown at the catchment scale, being fragmented into a mosaic of relatively wet and dry areas. A distinct wet zone runs diagonally across the matorral minigrid from the bottom left to the top right. Running parallel and downslope of the wet zone is a clearly diagonal dry zone. In the bottom right hand corner of the minigrid another wet zone can be observed and in the opposite corner (top left) a dry zone can be found. The soil moisture pattern within this minigrid is therefore fragmented and appears to run in parallel lines diagonally across the grid. The moisture pattern therefore proceeds from the top left corner as relatively dry>relatively wet>relatively dry>relatively wet in the bottom right corner. During dry conditions in particular, maximum soil moisture values within the matorral minigrid are generally higher than those in the forest and bench terrace minigrids. During these conditions some points within the matorral minigrid may still retain over 30% soil moisture compared to a maximum of approximately 20% within the forest and bench terrace minigrids. The matorral minigrid is therefore generally wetter than the forest or bench terrace minigrids particularly during dry conditions. Furthermore within the matorral minigrid the wet areas may be considerably higher in soil moisture than adjacent dry areas during these conditions. For example, on July 12, 1995, soil moisture in the wet areas is approximately 25% higher than in the adjacent dry areas.

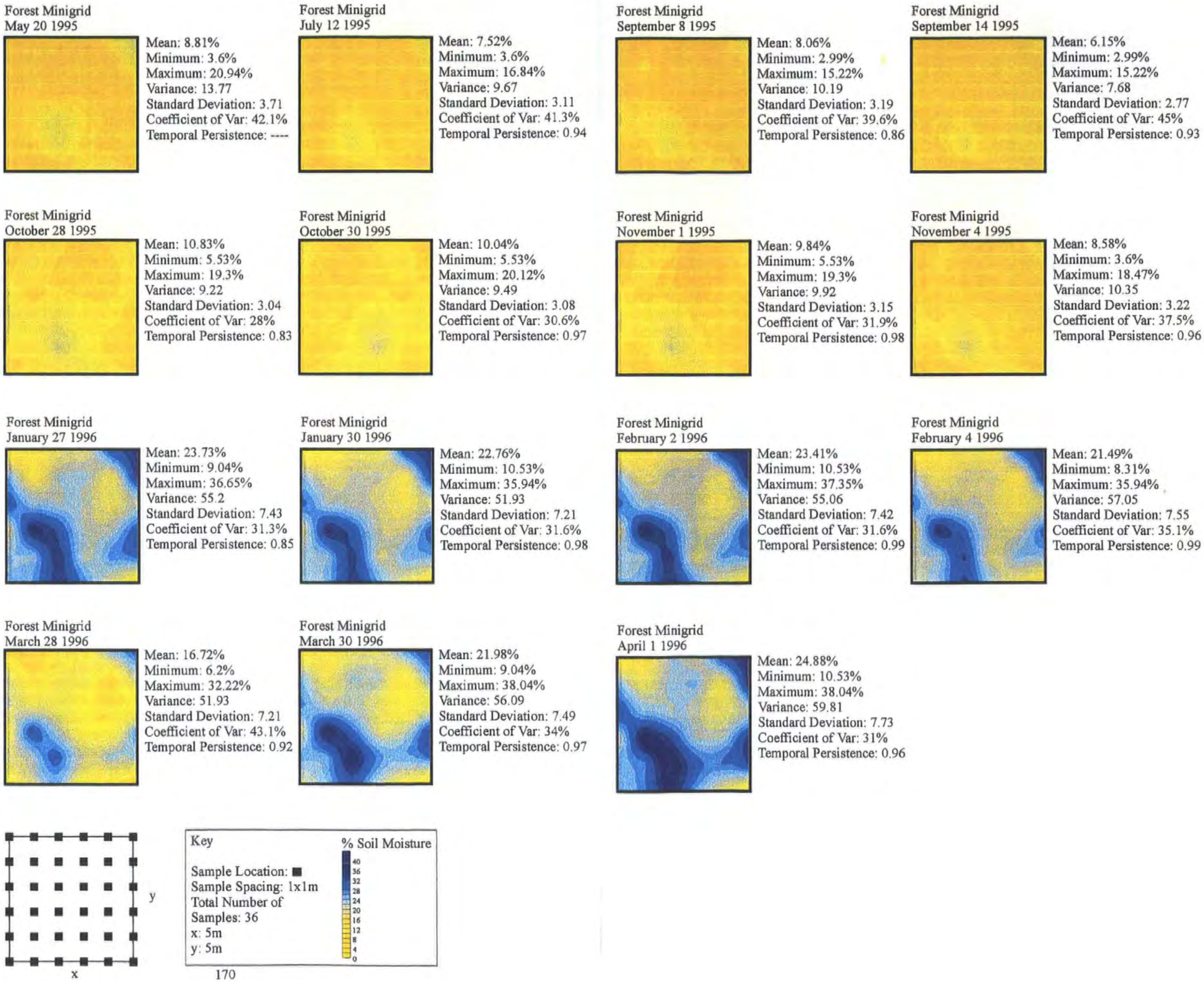
Wet Conditions - January 27 1996 to April 1 1996

The diagonal pattern of soil moisture generally persists during wet conditions although the wet areas are now broader and continuous across the grid. The expansion of the wet areas has resulted in a less variable soil moisture pattern which is reflected by the lower coefficient of variation during these conditions. In the change from dry to wet conditions, maximum soil moisture values in the matorral minigrid may increase at some points by only 10%. Some areas within the matorral minigrid can therefore maintain a persistently high soil moisture content throughout the study period.

6.2.4 Forest Minigrid

Figures 6.7 show contour plots of soil moisture for each measurement date within the forest minigrid.

Figure 6.7: Contour plots showing the spatial pattern of soil moisture for each measurement date within the Forest Minigrid.



Dry Conditions - May 20 1995 to November 4 1995

Similar to the matorral minigrid a fragmented mosaic pattern of soil moisture may also be observed within the forest minigrid. Distinct wet and dry areas may be observed within this 5x5m area. The soil moisture patterns during these conditions are therefore spatially discontinuous with large changes in soil moisture occurring over relatively short distances.

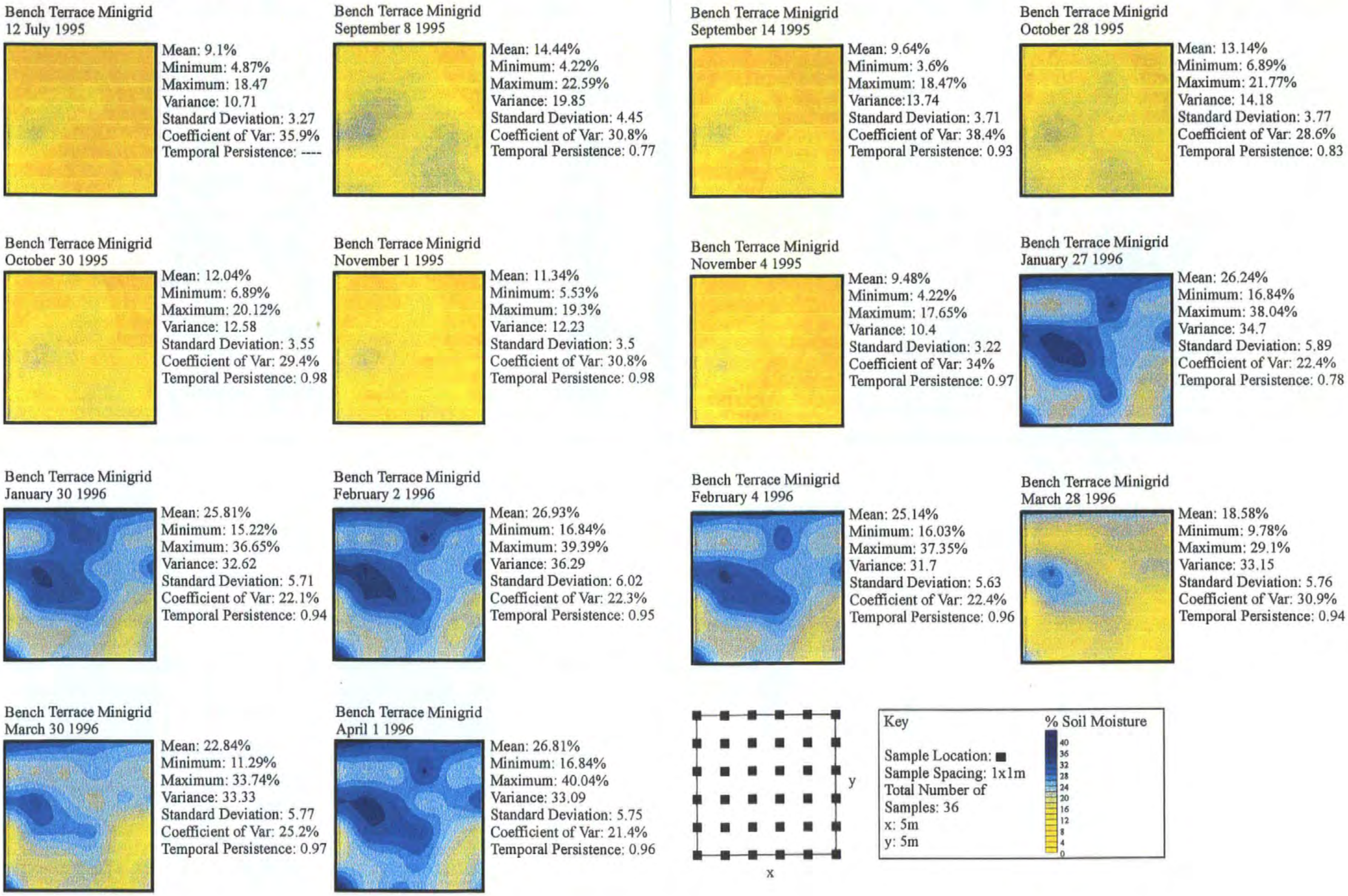
Wet Conditions - January 27 1996 to April 1 1996

During wet conditions the fragmentation in the mosaic pattern tends to persist, although the wet areas have expanded. This persistence of the fragmentation in the mosaic pattern during wet conditions is reflected in the high coefficient of variation of soil moisture during this period within the forest minigrid (table 6.6).

6.2.5 Bench Terrace Minigrid

Figures 6.8 show contour plots of soil moisture for each measurement date within the bench terrace minigrid.

Figure 6.8: Contour plots showing the spatial pattern of soil moisture for each measurement date within the Bench Terrace Minigrid



Dry Conditions - July 12 1995 to November 4 1995

The bench terrace minigrid, similar to the matorral and forest minigrids, also displays a fragmented mosaic soil moisture pattern during dry conditions. Distinct and spatially isolated wet zones may be clearly identified and are surrounded by areas of drier soil.

Wet Conditions - January 27 1996 to April 1 1996

During wet conditions a mosaic pattern of soil moisture may also be observed within the bench terrace minigrid, although the wet zones have expanded and are now connected. The spatial continuity in the soil moisture pattern has therefore increased during wet conditions.

Within all three minigrids the dry zones in the contour plots of soil moisture during wet conditions are only relatively dry in comparison to the wet zones. In many instances the soil moisture content at these dry zones has trebled in wet conditions. The dry zones may therefore show a comparable increase in the magnitude of soil moisture to the wet zones.

6.2.6 Summary

Although the minigrids are a 5x reduction in the scale of soil moisture measurement, the temporal and spatial variability in soil moisture at this microscale may be equal to the variability in soil moisture recorded at the meso and macro scales. The contour plots of soil moisture at the microscale display a pattern of soil moisture which has similar characteristics to those shown at the catchment scale being fragmented into a mosaic of relatively wet and dry areas. During dry conditions the soil moisture pattern is more fragmented within the matorral and bench terrace minigrids than during wet conditions when the expansion of wet areas results in a more uniform soil moisture distribution. In the forest minigrid however, the soil moisture pattern in wet conditions remains variable and fragmented. Specific only to the matorral minigrid, soil moisture at some points may remain persistently high, above 30%, even during dry conditions, whilst adjacent points downslope may have less than 10% soil moisture.

6.3 Factors Controlling the Spatial and Temporal Variations in Soil Moisture

The spatial pattern in soil moisture within the three gully catchments may be highly variable with large differences in soil moisture between points occurring over short distances. The temporal variability in soil moisture at individual points and between points may also be high, although the spatial pattern of soil moisture is generally persistent through time. The spatial and temporal pattern of soil moisture within the gully catchments is therefore complex and may be attributed to the dynamic and diverse nature of badland environments. In order to understand and predict the hydrological functioning of gully catchments however, the principal factors controlling the spatial and temporal patterns in soil moisture need to be identified (Henninger *et al.*, 1976; Loague, 1992).

Due to practical considerations, measurements of the soil's physical properties and vegetation characteristics at the microscale were constrained to a maximum of six sampling points per minigrid (see figure 3.3, Chapter 3 for the location of these sampling points within the minigrids). This small number of samples severely limits the meaningfulness and significance of correlations between soil moisture and these properties at this scale. The samples from the microscale have therefore been combined with samples from the mesoscale when correlating these properties with soil moisture. Although the samples from the microscale represent a small percentage of the total number of samples, the results from the correlations are assumed to be applicable to the soil moisture patterns observed at both the meso and micro scale. This assumption may be justified by the near identical temporal and spatial characteristics in the soil moisture patterns displayed at the micro and meso scales, which suggests that the factors controlling soil moisture patterns at these two scales will also be similar. When analysing and interpreting the correlations therefore, no distinction is made between the meso and micro scale. Topographical parameters were however measured at all 36 sampling points within each minigrid and in the following sections the correlations for these variables at the microscale have been distinguished from those found at the mesoscale.

6.3.1 Soil Moisture and Topography

Mesoscale - Gully Catchments

Moore *et al.* (1988) have reported that

"topographic non-uniformity within small catchments is a major factor controlling the spatial variability of soil water".

Furthermore, Tomer and Anderson (1995) have reported that 51 to 77% of the variation in soil moisture across a hillslope could be attributed to elevation, slope angle and slope curvature. Hawley *et al.* (1983), Wood *et al.* (1990) and Grayson *et al.* (1997) have also reported that topography was a significant controlling factor in determining the distribution of soil moisture. In this section, three topographical characteristics; elevation, slope angle and upslope contributing area, identified by Hawley *et al.* (1983) as being significant in determining soil moisture, will be correlated with soil moisture from each sampling date to determine if these variables are significant controlling factors of the observed soil moisture patterns within the gully catchments.

6.3.1.1 Soil Moisture and Elevation

Table 6.9 shows correlations between soil moisture and the elevation of the sampling points for each of the gully catchments. The relationships between soil moisture and elevation are significantly different between the gully catchments ($p<0.05$). This suggests that elevation is not a universal controlling factor of soil moisture distribution between gully catchments, but that the relationship between soil moisture and elevation is site specific to each individual catchment. In the matorral gully all correlations between elevation and soil moisture are significant and positive (although the percentage variance explained is low) indicating that points at higher elevation are generally wetter than low lying areas. This unusual relationship may be explained by the morphology of this gully catchment. In its upper reaches this gully has a distinctive shallow bulbous shaped morphology (Ireland *et al.*, 1939; Ternan *et al.*, 1997), whilst in it lower reaches the morphology is a deep 'V' shape. The bulbous morphology is a characteristic of a particular fine textured sedimentary horizon found within this region in which piping and slumping are the principal geomorphic processes (Ternan *et al.*, 1997). Due to its formation and related shallowness this bulbous part of the gully generally has a uniformly fine texture which retains more moisture than the downslope 'V' shaped part of the gully which exposes sediments of varying texture some of which retain less moisture. In addition a bulbous shaped feature, because of its morphology will tend to retain more moisture than a 'V' shaped feature. Within the matorral gully the contour plots of soil moisture (figs 6.1) show a more uniform and generally higher soil moisture in its upper reaches, particularly during wet conditions which may explain the higher correlations between soil moisture and elevation during this period (table 6.9).

Table 6.9. Correlations between soil moisture and elevation for each gully catchment.

Soil Moisture Sampling Dates	Matorral Altitude	Forest Altitude	Bench Terrace Altitude
March 8 1995	----	-0.40**	----
May 20 1995	0.29**	----	----
July 12 1995	0.32**	-0.45**	-0.04
September 8 1995	0.27**	-0.13	-0.02
September 14 1995	0.32**	-0.32**	-0.01
October 27 1995	0.29**	-0.26**	-0.07
October 28 1995	0.32**	-0.32**	-0.12
October 30 1995	0.34**	-0.40**	-0.13
November 1 1995	0.35**	-0.39**	-0.14
November 4 1995	0.31**	-0.42**	-0.15
January 26 1996	0.38**	----	-0.03
January 27 1996	0.39**	0.01	-0.03
January 28 1996	0.44**	-0.05	-0.05
January 30 1996	0.43**	-0.04	-0.03
February 1 1996	0.47**	----	----
February 2 1996	0.47**	0.04	-0.06
February 4 1996	0.39**	-0.05	0.00
March 28 1996	0.34**	-0.24**	-0.06
March 30 1996	0.38**	-0.21*	-0.07
April 1 1996	0.37**	-0.24**	-0.03

* = significant at p<0.05 (95%)
** = significant at p<0.01 (99%)

Within the forest gully catchment the correlations between elevation and soil moisture are generally negative and are higher in dry conditions compared to wet conditions ($p<0.05$). In dry conditions therefore low lying areas within the forest gully are generally wetter than higher areas. The correlations are weaker during wet conditions as extensive wet areas cover large parts of the gully over a range of elevations. In the bench terrace gully none of the correlations between elevation and soil moisture are significant. The lack of significant correlations within this gully may be due to the bench terraces being constructed over a range of elevations ie. from the top of the slope to the bottom. Therefore the treads and risers of the terraces, which are generally high and low in soil moisture respectively, can be found over a range of elevations.

6.3.1.2 Soil Moisture and Slope Angle

In the matorral gully soil moisture is negatively related to slope angle with 80% of the significant correlations occurring during the wet period, although the percentage variance explained is low (table 6.10). Gently sloping areas therefore tend to be higher in soil moisture than steeply sloping areas. Steep slopes are likely to be drier than flat areas due to lower infiltration and higher runoff rates (Hawley *et al.*, 1983). Nyberg (1996) has also reported a significant negative correlation between soil moisture and slope angle for the Gardsjon catchment, in Sweden. In contrast to the matorral gully the distribution of soil moisture within the forest gully is positively correlated with slope angle particularly during dry conditions. Steeply sloping areas may therefore be wetter than gently sloping areas. Within the gully catchments the gully sidewall profile follows the general form of convex>linear>concave from the top to the base of the slope. The steepest part of the slope is therefore often the convex and linear segments, which are upslope of the concave segment. The significant positive relationship between soil moisture and slope angle in the forest gully suggests that in some areas of the catchment soil water is being retained in upslope locations (Plate 6.1). Since these correlations are strongest in dry conditions minimal drainage appears to occur between these upslope areas of the gully and downslope locations. Yair and Lavee (1985) have also reported a lack of significant subsurface flow in semi-arid areas which was demonstrated by the occurrence of wet areas located upslope of drier areas. The retention of soil moisture in upslope locations is further discussed in section 6.3.1.3. In the bench terrace gully soil moisture is not significantly related to slope angle on any sampling date. In all three gullies the generally poor correlations with soil moisture indicates that slope angle has only a minor influence in determining soil moisture distribution within the gully catchments.

Table 6.10. Correlations between soil moisture and slope angle for each gully catchment.

Soil Moisture Sampling Dates	Matorral Slope Angle	Forest Slope Angle	Bench Terrace Slope Angle
March 8 1995	----	0.24**	----
May 20 1995	-0.08	----	----
July 12 1995	-0.05	0.34**	0.02
September 8 1995	-0.31**	-0.09	-0.06
September 14 1995	-0.17*	0.16	-0.03
October 27 1995	-0.08	0.14	0.00
October 28 1995	-0.06	0.18*	0.05
October 30 1995	-0.10	0.28**	0.03
November 1 1995	-0.07	0.29**	0.05
November 4 1995	-0.05	0.32**	0.09
January 26 1996	-0.15	----	0.04
January 27 1996	-0.17*	-0.06	0.02
January 28 1996	-0.22*	0.00	0.03
January 30 1996	-0.19*	-0.01	0.03
February 1 1996	-0.26**	----	----
February 2 1996	-0.26**	-0.07	0.03
February 4 1996	-0.15	0.00	0.02
March 28 1996	-0.25**	0.07	0.03
March 30 1996	-0.28**	0.05	0.04
April 1 1996	-0.27**	0.10	0.00

* = significant at p<0.05 (95%)
** = significant at p<0.01 (99%)

Plate 6.1. An example of soil which is wet to the touch (dark areas) occurring above and upslope of soil which is dry to the touch (light areas).

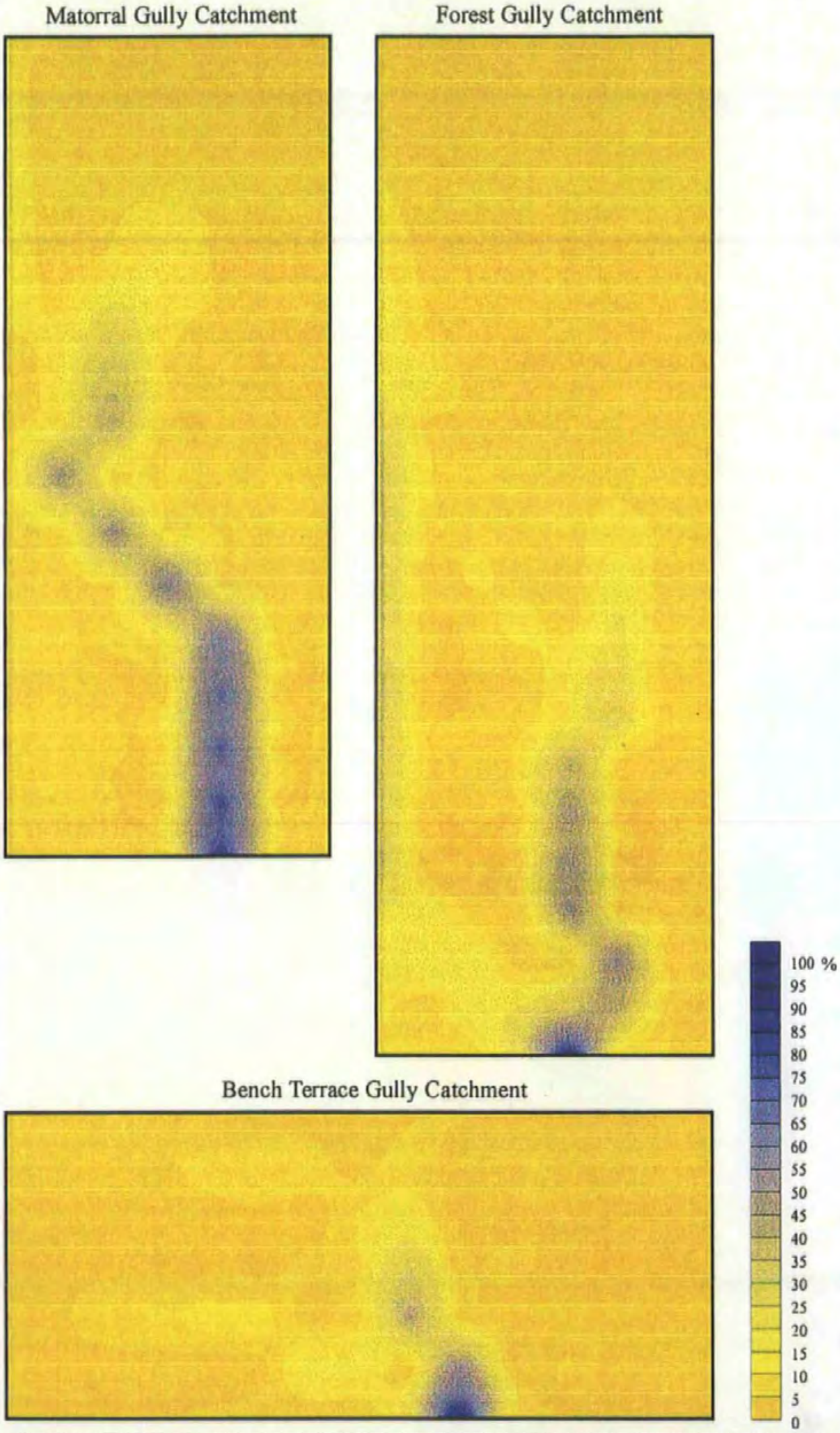
6.3.1.3 Soil Moisture and Upslope Contributing Area

Both Burt and Butcher (1985) and Nyberg (1996) have concluded that upslope drainage area was more important in determining the distribution of soil moisture than any other topographic variable. The upslope contributing area refers to the area upslope, which contributes surface flow to a 5x5m pixel cell centred on a node point within the gully grid. The calculation of upslope contributing area was based on a procedure (D∞) developed by Tarboton (1997) for use with rectangular grid digital elevation models.

"Upslope area is calculated by proportioning flow between two downslope pixels according to how close the flow direction is to the direct angle of the downslope pixel" (Tarboton, 1997).

Should the flow direction fall along a direct angle ie. either a cardinal or diagonal angle then the flow from that cell all drains to one neighbour (Tarboton, 1997). Figure 6.9 shows contour plots with the percentage of upslope area contributing to each 5x5m pixel within each of the gully catchments. These contour plots therefore show the predominant overland flow pathways within the catchments. Furthermore, Seyfried and Wilcox (1995) have reported that at the catchment scale pathways of sub-surface drainage are similar to the pathways of surface flow. The contour plots may therefore also show the percentage of upslope area contributing sub-surface drainage to each 5x5m pixel within the gully catchments. Consequently the regions with the largest upslope contributing area may be expected to be high in soil moisture since potentially a large proportion of the gully's surface and sub-surface flow drains to these pixels. These contour plots may therefore be used to predict the wettest areas within the gullies (figure 6.9). However, the patterns of soil moisture shown for each of the three gullies in figures 6.1, 6.3 and 6.4, does not mirror the pattern shown in the plots of upslope contributing area. This dissimilarity in the predicted and observed patterns is reflected by the weak correlations in table 6.11. In the matorral and bench terrace gully none of the soil moisture sampling dates are significantly correlated with upslope contributing area. In the forest gully low but significant correlations between soil moisture and upslope contributing area do occur, indicating some similarity between the contour plots. The generally poor correlations between soil moisture and upslope contributing area suggests that neither surface run-on or sub-surface drainage are important factors in determining the distribution of soil moisture within the gully catchments.

Figures 6.9. Contour plots showing the percentage of upslope area contributing surface and sub-surface flow to each 5x5m pixel within the gully catchments.



This possibility has been further examined by 1) correlating the *changes* in soil moisture between two consecutive dates with upslope contributing area during which there was no rainfall to assess the role of sub-surface drainage in determining soil moisture patterns and 2) by correlating again the *changes* in soil moisture between two consecutive dates with upslope contributing area during which there was approximately 19mm of rainfall to assess the role of surface run-on in determining soil moisture patterns. The measurement dates of soil moisture used in these correlations were chosen from the wet period when conditions were overcast so as to minimise the role of evapotranspiration as a possible alternative factor causing the changes in soil moisture. The occurrence of run-on and sub-surface drainage is also more likely during wet conditions when the soils are near to saturation. The two consecutive dates over which there was no rainfall are February 2 1996 and February 4 1996. Changes in soil moisture within the catchments during this period should consequently show a strong positive relationship with upslope contributing area. In contrast the correlations in table 6.12 between the changes in soil moisture over this period and upslope contributing area within the matorral and forest gullies are poor and not significant. In the bench terrace gully the correlation is significant but is however negative, suggesting that areas, which have a large upslope contributing area, displayed a decrease in soil moisture during this period rather than the expected increase. Sub-surface drainage would therefore appear to be insignificant in determining the distribution of soil moisture within the gully catchments. This may be attributed to the contrasting texture of the interbedded sediment horizons found within this region. The spatial arrangement of these sediment horizons may result in a discontinuity in sub-surface hydrological pathways. The margins of two sedimentary horizons which have differing textures may act as a hydrological boundary, within which soil water is retained and the movement of water across the boundary is prevented or limited due to differences in hydraulic potential between the two horizons (Hillel, 1982; Brady, 1990) (Plate 6.1). It is therefore not uncommon to find fine textured and relatively wet sediment horizons located above and upslope of coarse textured and relatively dry horizons. The correlations suggest that the differences in hydraulic potential between sedimentary horizons may be great enough to prevent downslope drainage even during wet conditions. Ritsema and Dekker (1995) have reported that where strong spatial differences in soil moisture occur, then the lateral redistribution of water may be inhibited by the presence of isolated dry zones. The consecutive dates over which approximately 19mm of rainfall fell are January 28 1996 and January 30 1996. Since in the previous example sub-surface drainage was not found to be a significant factor in explaining the changes in soil moisture between consecutive dates, then the changes in soil moisture observed on January 30 1996 may potentially be attributed to surface run-on. However, in table 6.12 the correlations between the change in soil moisture over this period and upslope contributing area within each gully catchment are poor and not significant. These correlations confirm that the spatial pattern of soil moisture within the gully catchments cannot be attributed to sub-surface drainage or surface run-on. Nyberg (1996) has also reported poor correlations between the changes in soil moisture over consecutive dates and topography. Furthermore, working in a semi-arid environment, Scoging (1989) has noted that the occurrence of throughflow is limited. Barling *et al.* (1994) have also reported that throughflow velocities are so low that subsurface flow is independent of the upslope contributing area.

Table 6.11. Correlations between soil moisture and upslope contributing area for each gully catchment.

Soil Moisture Sampling Dates	Matorral Upslope Contributing Area	Forest Upslope Contributing Area	Bench Terrace Upslope Contributing Area
March 8 1995	----	0.26**	----
May 20 1995	-0.01	----	----
July 12 1995	-0.05	0.22*	0.01
September 8 1995	-0.10	0.28**	0.05
September 14 1995	-0.02	0.29**	0.02
October 27 1995	-0.03	0.17*	0.03
October 28 1995	-0.06	0.18*	0.07
October 30 1995	-0.01	0.22*	0.10
November 1 1995	0.01	0.20*	0.10
November 4 1995	0.01	0.19*	0.11
January 26 1996	0.02	----	-0.05
January 27 1996	-0.03	0.07	-0.06
January 28 1996	-0.05	0.10	-0.01
January 30 1996	-0.02	0.11	-0.04
February 1 1996	-0.07	----	----
February 2 1996	-0.04	0.06	0.02
February 4 1996	-0.02	0.09	-0.08
March 28 1996	0.08	0.24**	0.01
March 30 1996	0.01	0.23*	0.00
April 1 1996	-0.02	0.20*	-0.02

* = significant at $p<0.05$ (95%)
** = significant at $p<0.01$ (99%)

Table 6.12. Correlations between changes in soil moisture over consecutive dates with upslope contributing area for each gully catchment.

Soil Moisture Sampling Dates / Change in Soil Moisture	Matorral Upslope Contributing Area	Forest Upslope Contributing Area	Bench Terrace Upslope Contributing Area
January 28 – January 30 1996	0.12	0.07	0.12
February 2 – February 4 1996	0.04	0.12	0.28*

* = significant at $p<0.05$ (95%)

6.3.2 Soil Moisture and Topography

Microscale - Minigrids

The minigrids are located on the slopes of gully walls within the three catchments. The slope angles at individual points within the minigrids show a wide range from a minimum of 16° in the matorral minigrid to 48° in the forest minigrid. Within each of the catchments the minigrids are located towards the base of the slopes and in the matorral and forest catchments the base of the minigrids cover a gully channel. The minigrids therefore cover a diverse range of topographical characteristics to which soil moisture patterns may be related.

6.3.2.1 Soil Moisture and Elevation

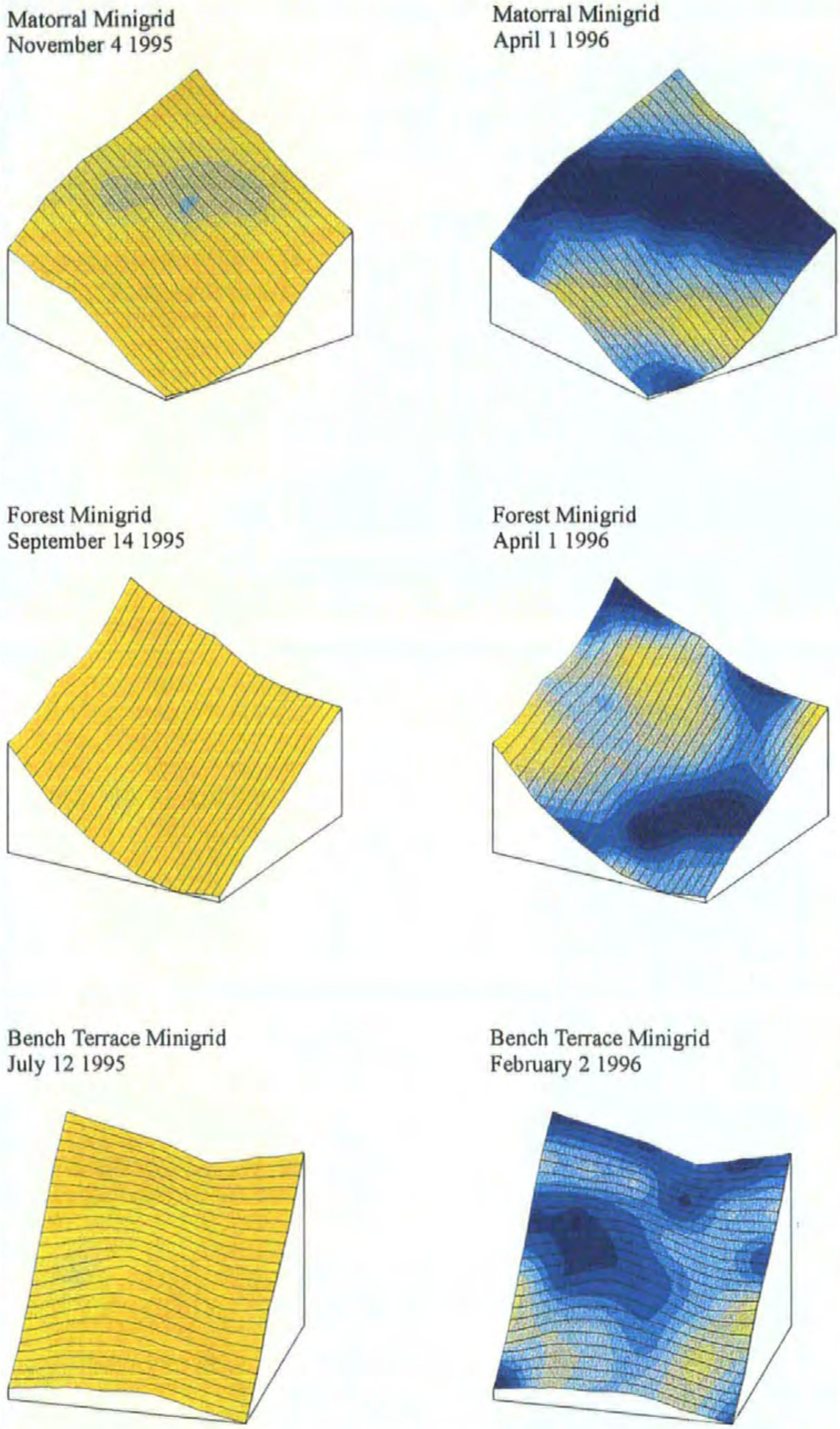
Soil moisture is significantly correlated with elevation on all sampling dates within the bench terrace minigrid and with all sampling dates during dry conditions in the matorral minigrid (table 6.13). These correlations are however positive, and therefore similar to the mesoscale, points at higher locations within the minigrids are wetter than those points at lower locations. Figure 6.10 shows contour plots of soil moisture from a typical dry and wet sampling date overlaid onto digital elevation models of the minigrids topography. These figures clearly show wet areas located upslope of dry areas within the matorral and bench terrace minigrids, which may be high in soil moisture, particularly within the matorral minigrid (>30%). Soil moisture is therefore being retained at upslope locations and/or is draining at downslope locations. The moisture patterns within these minigrids do not therefore correspond to their topographical characteristics. Within the matorral and bench terrace minigrids the positive correlations between soil moisture and elevation becomes significantly weaker during wet conditions, due to the expansion of wet areas across the minigrids ($p<0.05$) (table 6.13, figures 6.6 and 6.8). In the forest minigrid the correlations between soil moisture and elevation are negative but generally not significant (table 6.13), although wet areas may still develop in upslope locations (figure 6.10). Thus within the forest minigrid soil moisture patterns may also not correspond with the topography.

Table 6.13. Correlations between soil moisture and elevation within each gully Minigrid.

Soil Moisture Sampling Dates	Matorral Elevation	Forest Elevation	Bench Terrace Elevation
March 8 1995	----	0.12	----
May 20 1995	0.57**	----	----
July 12 1995	0.52**	-0.01	0.58**
September 8 1995	0.32*	-0.12	0.49**
September 14 1995	0.45**	-0.08	0.60**
October 28 1995	0.58**	-0.29*	0.58**
October 30 1995	0.47**	-0.23	0.57**
November 1 1995	0.49**	-0.22	0.56**
November 4 1995	0.54**	-0.25	0.58**
January 27 1996	0.20	-0.11	0.35*
January 30 1996	0.20	-0.10	0.45**
February 2 1996	0.25	-0.08	0.37*
February 4 1996	0.22	-0.11	0.38*
March 28 1996	0.32*	-0.15	0.43**
March 30 1996	0.37*	-0.21	0.48**
April 1 1996	0.26	-0.12	0.34*

* = significant at $p<0.05$ (95%).
** = significant at $p<0.01$ (99%).

Figure 6.10: Contour plots of soil moisture from a typical dry and wet sampling date overlaid onto digital elevation models of the Minigrids topography.



6.3.2.2 Soil Moisture and Slope Angle

Figure 6.10 shows that within the three minigrids wet areas may be found in steeply sloping parts of the minigrids and dry zones within areas of gentler gradients. Within the matorral and forest minigrids none of the correlations between soil moisture and slope angle were significant and in the bench terrace minigrid only one soil moisture sampling date was significantly correlated with slope angle (table 6.14). The soil moisture patterns at the microscale in both dry and wet conditions therefore have no relationship with slope angle.

Table 6.14. Correlations between soil moisture and slope angle within each Minigrid.

Soil Moisture Sampling Dates	Matorral Slope Angle	Forest Slope Angle	Bench Terrace Slope Angle
March 8 1995	----	0.22	----
May 20 1995	0.25	----	----
July 12 1995	0.14	0.20	-0.18
September 8 1995	-0.07	0.09	-0.09
September 14 1995	0.03	0.16	-0.14
October 28 1995	0.05	-0.08	-0.28
October 30 1995	0.09	-0.01	-0.25
November 1 1995	0.10	-0.01	-0.20
November 4 1995	0.16	0.03	-0.19
January 27 1996	0.24	-0.16	-0.19
January 30 1996	0.27	-0.15	-0.34*
February 2 1996	0.25	-0.14	-0.22
February 4 1996	0.27	-0.14	-0.28
March 28 1996	0.25	-0.12	-0.20
March 30 1996	0.19	-0.15	-0.28
April 1 1996	0.22	-0.17	-0.22

* = significant at $p<0.05$ (95%).
** = significant at $p<0.01$ (99%).

6.3.2.3 Soil Moisture and Upslope Contributing Area

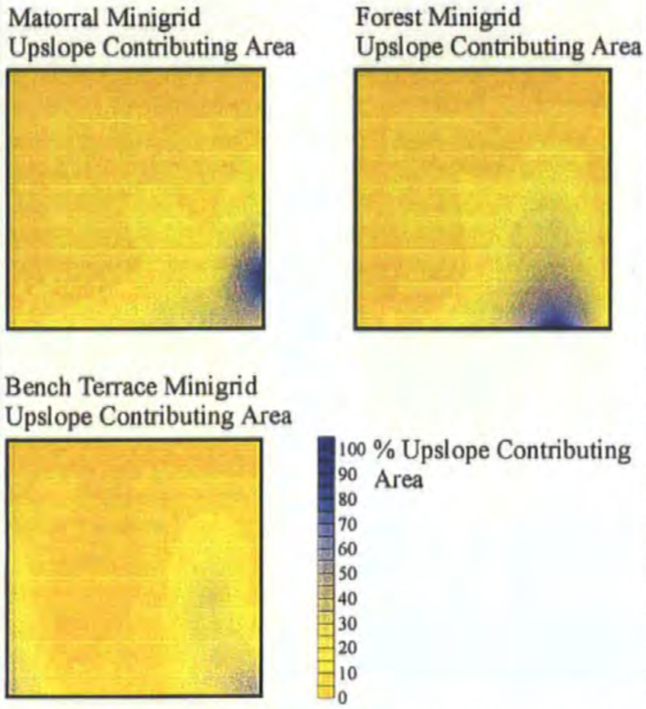
Upslope contributing area within the minigrids was calculated using the technique developed by Tarboton (1997) following the procedure used at the gully catchment scale. At the minigrid scale the upslope contributing area refers to the area upslope which may contribute surface and sub-surface flow to a 1x1m pixel within the minigrid. The regions with the largest upslope contributing area may therefore be expected to be high in soil moisture. Consequently these contour plots may be used to predict the wettest areas within the minigrids. Similar to the results found at the catchment scale, the pattern of soil moisture shown for each of the three minigrids (figures 6.3.1, 6.3.2 and 6.3.3) do not mirror the patterns shown in the plots of upslope contributing area (figures 6.11). This dissimilarity between the observed and predicted patterns is reflected by the poor correlations in table 6.15. Only 13% and 50% of the correlations between soil moisture and upslope contributing area were significant in the matorral and bench terrace minigrids respectively, and none within the forest minigrid. The few significant correlations in the matorral and bench terrace minigrids are all negative which indicates that those pixels which have a high upslope contributing area are lower in soil moisture.

Table 6.15. Correlations between soil moisture and upslope contributing area within each Minigrid.

Soil Moisture Sampling Dates	Matorral Upslope Contributing Area	Forest Upslope Contributing Area	Bench Terrace Upslope Contributing Area
March 8 1995	----	0.00	----
May 20 1995	-0.34*	----	----
July 12 1995	-0.23	0.06	-0.40**
September 8 1995	0.12	0.10	-0.32*
September 14 1995	-0.01	0.06	-0.41**
October 28 1995	-0.17	0.13	-0.34*
October 30 1995	-0.18	0.09	-0.37*
November 1 1995	-0.21	0.06	-0.37*
November 4 1995	-0.31*	0.10	-0.39*
January 27 1996	-0.04	0.08	-0.14
January 30 1996	-0.02	0.08	-0.18
February 2 1996	-0.05	0.06	-0.06
February 4 1996	-0.05	0.09	-0.16
March 28 1996	-0.11	0.19	-0.22
March 30 1996	-0.07	0.21	-0.20
April 1 1996	-0.04	0.11	-0.12

* = significant at $p<0.05$ (95%).
** = significant at $p<0.01$ (99%).

Figure 6.11. Contours plots showing the percentage of upslope contributing area draining to each 1x1m pixel cell within each Minigrid.



6.3.2.4 Summary

The generally poor correlations between the topographic parameters and soil moisture may be due to the measurement of only the top 15cm of soil. At greater depths topography may be more significant in determining the distribution of soil moisture. Nevertheless, the poor relationships between surface soil moisture, elevation, slope angle and upslope contributing area suggests that topographic factors are of little significance in determining the spatial and temporal soil moisture patterns observed at both the micro and meso scales. Distinctive wet zones may be found in upslope locations on steep slopes within each of the catchments and is a characteristic which, particularly within the minigrids, is more pronounced during dry conditions. Soil moisture is retained within these upslope locations and evidence of drainage to downslope locations is minimal. During wet conditions the downslope locations within the catchments may also become wet. However, the soil moisture patterns and the poor correlations with upslope contributing area suggest that these wet locations downslope are due to the excessive amount of rainfall during this period and not to sub-surface drainage or surface run-on. Topography may therefore only determine the concentration of runoff and not the location of source areas (Amerman, 1965). Similarly both Berndtsson and Chen (1994) and Ritsema and Dekker (1995) have reported no significant correlations between the spatial pattern of soil moisture and topography. Amerman (1965) has reported that runoff producing areas were located randomly in relation to topography. Charpentier and Groffman (1992) who have also found no correlation between soil moisture and topography have instead attributed the variation in soil moisture to factors such as soil texture, structure and vegetation cover.

6.3.3 Soil Moisture and Vegetation

Vegetation both directly through its aerial and sub-aerial parts and indirectly through organic constituents has been reported to influence the spatial variability of soil moisture in several ways. These include interception storage and evapotranspiration losses (Reynolds, 1970; Hawley *et al.*, 1983; Rabada and Gallart, 1993), the concentration of water through stemflow and root channels (Herwitz, 1986), promoting runoff via litter flow and soil hydrophobicity (Krammes and Debano, 1965; Pierce, 1967; Coelho Netto, 1987; Terry, 1992), increasing the water holding capacity (Hudson, 1994), and promoting soil structure, infiltration and soil permeability (Blackburn, 1975; Johnson and Gordon, 1988; Dunne *et al.*, 1991; Morin and Kosovsky, 1995; Nicolau *et al.*, 1996). In this section soil moisture will be correlated with three vegetation characteristics, the percentage vegetation cover, percentage litter cover and organic carbon, to determine if these variables are significant controlling factors in the spatial distribution of soil moisture.

6.3.3.1 Soil Moisture and Vegetation Cover

Correlations between soil moisture and the percentage vegetation cover for each of the gully catchments are shown in table 6.16. In the matorral gully significant correlations between soil moisture and vegetation cover only occur on measurement dates during dry conditions. Soil moisture in the bench terrace gully is not significantly correlated with vegetation cover on any of the sampling dates. Francis *et al.* (1986) have also reported poor correlations (0.2) between vegetation cover and soil moisture. The forest gully differs from the matorral and bench terrace gullies in that soil moisture is significantly correlated with vegetation cover on over 70% of the sampling dates. Similar to the matorral gully these correlations are generally stronger during dry conditions. The stronger negative correlations between soil moisture and vegetation cover within the three gully catchments during dry compared to wet conditions, suggests that the role of vegetation in determining soil moisture patterns is limited to dry conditions when the effects of canopy storage, evaporation of intercepted rain and the moisture demands of the plants are greatest. Zhang and Berndtsson (1988) have also reported that the influence exerted by vegetation cover on soil moisture variation may be greatest when investigating only the upper soil layers and during dry or drying out periods. The persistence of strong negative correlations between soil moisture and vegetation cover during wet conditions within the forest gully which in contrast does not occur in the matorral gully allows a distinction to be made between the role of *Pinus* trees and matorral scrub in determining soil moisture patterns. Matorral scrub appears to only have a negative effect on soil moisture patterns during dry conditions becoming unimportant as a controlling factor in soil moisture patterns during wet conditions. The role of *Pinus* trees in contrast persists to a similar degree in both dry and wet conditions.

Table 6.16. Correlations between soil moisture and vegetation cover for each gully catchment.

Soil Moisture Sampling Dates	Matorral Vegetation Cover	Forest Vegetation Cover	Bench Terrace Vegetation Cover
March 8 1995	----	-0.31**	----
May 20 1995	-0.18*	----	----
July 12 1995	-0.12	-0.28**	0.00
September 8 1995	0.05	-0.05	-0.02
September 14 1995	-0.05	-0.17*	0.05
October 27 1995	-0.23*	-0.24**	-0.16
October 28 1995	-0.25**	-0.33**	-0.15
October 30 1995	-0.21*	-0.37**	-0.14
November 1 1995	-0.21*	-0.37**	-0.11
November 4 1995	-0.16	-0.37**	-0.06
January 26 1996	-0.04	----	-0.01
January 27 1996	-0.04	-0.14	-0.02
January 28 1996	0.03	-0.14	0.01
January 30 1996	0.00	-0.14	0.00
February 1 1996	0.04	----	----
February 2 1996	0.03	-0.13	0.03
February 4 1996	-0.04	-0.17*	-0.01
March 28 1996	-0.06	-0.28**	0.00
March 30 1996	-0.09	-0.26**	-0.10
April 1 1996	-0.08	-0.26**	-0.05

* = significant at p<0.05 (95%)
** = significant at p<0.01 (99%)

The effects of vegetation on soil moisture are generally localised, being restricted to the area over which the plants aerial and sub-aerial parts cover (Blackburn, 1975; Johnson and Gordon, 1988). The contrasting role of vegetation in determining soil moisture patterns during dry and wet conditions may therefore be best illustrated at the local scale. Figure 6.12 shows a cross section from the forest gully watershed. The topographic profile, vegetation cover and soil moisture pattern recorded on a date during dry conditions (Oct 28 1995) and on a date during wet conditions (Jan 28 1996) are shown. The soil moisture over this 35m long cross section varies from approximately 8% to 18% on October 28 1995 and from 31% to 37% on January 28 1996. The variability in soil moisture cannot be attributed to topography since all of the points are located at a similar elevation and are on a uniform slope. As the soil texture along the cross section is also similar at all of the points, the variability in soil moisture is likely to relate to vegetation characteristics. During dry conditions the soil moisture pattern along the cross-section is more variable than during wet conditions reflecting the greater influence exerted by vegetation cover on soil moisture patterns during this period. Furthermore, during the dry condition, the points with the highest soil moisture are located in an area where there is an opening in the forest canopy cover and therefore interception and evaporation losses will be lower at these points than the other points where the percentage vegetation cover is higher. At these smaller scales vegetation may therefore be a significant factor in determining soil moisture patterns.

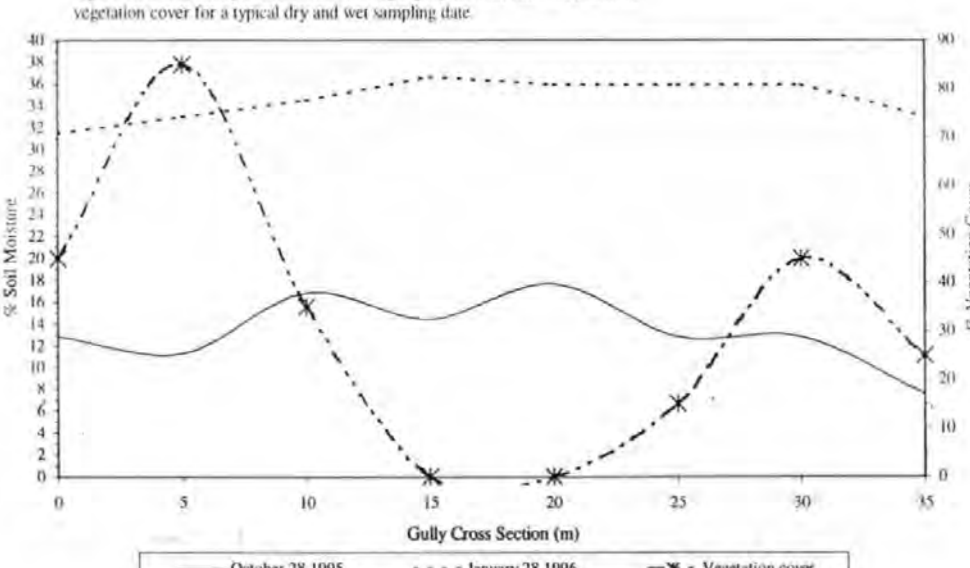


Figure 6.12. Variability in soil moisture along a gully cross-section in relation to vegetation cover for a typical dry and wet sampling date.

The switching effect on soil moisture patterns caused by differences in soil texture discussed in Chapter 5, section 5.2, may also be caused by differences in rooting density. Figure 6.13 shows an example of a switching effect in soil moisture patterns caused by differences in root density within the forest gully catchment. During dry conditions, point B which is closer to a tree and has a greater root density than point A, has a lower soil moisture content due to a higher uptake of soil water by the greater number of roots. During wet conditions however, point B has a higher soil moisture content than point A, thus switching the moisture pattern. The switching is due to soil root interfaces acting as channels for water flow, which is similar to stemflow. The trees demand for moisture is also lower during wet conditions resulting in less evapotranspiration. Point B may also wet up more rapidly than point A, particularly after dry periods when the soil surrounding the roots has shrunk leaving an air gap allowing the rapid penetration of water into the soil. Bouten *et al.* (1992) have also reported switching effects in soil moisture patterns caused by the preferential uptake of water by trees from areas high in soil moisture. Nyberg (1996) in contrast however, working in a catchment dominated by Norway spruce found no correlation between water content and distance to the nearest tree.

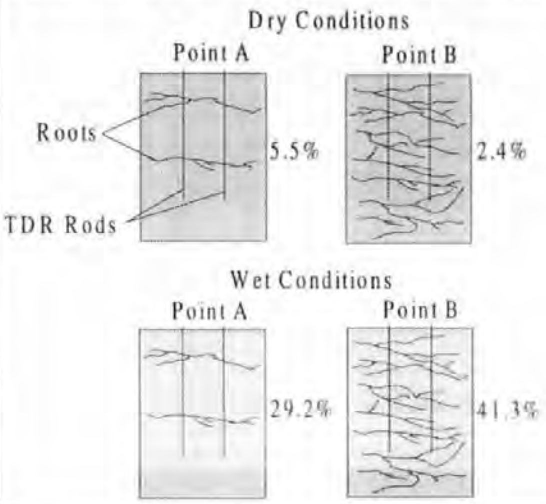


Figure 6.13. A switching effect in soil moisture patterns caused by roots.

6.3.3.2 Soil Moisture and Litter Cover

Putuhena and Cordery (1996) have reported that a litter cover consisting of pine needles may have an interception capacity of 2.8mm. If the volume of rainfall is less than the interception capacity of the litter cover, then the water may be stored within the litter and evaporated with little infiltration into the soil. However, evaporation from a bare soil surface may be higher than from a surface covered with litter (Ward and Robinson, 1990). The litter cover may therefore act to conserve soil moisture. Litter cover may also act as a reservoir, storing rainwater, which is slowly released into the underlying soil, maintaining soil moisture (Coelho Netto, 1987; Putuhena and Cordery, 1996). The litter cover may also act to reduce raindrop impact protecting the soil surface from crusting and sealing and hence maintaining the infiltration rate (McIntyre, 1958; Le Bissonnais and Singer, 1992, 1993). In contrast water repellent organic residues within the litter may be leached into the underlying soil, forming an organic coating over the soil particles inducing soil hydrophobicity, which may restrict infiltration and increase surface runoff (Krammes and Debano, 1965; Terry, 1992). The underlying soil may therefore remain dry (Krammes and Debano, 1965; Ritsema and Dekker, 1996). Furthermore in the absence of soil hydrophobicity, Nicolau *et* *al.* (1996) working in the south of Spain have reported that shrub and bush litter may favour runoff. Pierce (1967) and Coelho Netto (1987) have also reported surface runoff over litter surfaces even though the underlying soil was relatively dry. Litter cover may therefore have two contrasting effects on soil moisture, one effect may be to maintain or possibly increase soil moisture whilst the other may limit infiltration, reducing soil moisture. Furthermore the effects of litter cover on soil moisture may show a temporal dependency (Putuhena and Cordery, 1996). During dry conditions the interception capacity and potential hydrophobicity of the litter cover may be highest and therefore areas of higher litter cover may have a lower soil moisture. During wet conditions however, the hydrophobicity and interception capacity of the litter cover will be at its lowest and areas of greater litter cover may have a higher soil moisture. The correlations in table 6.17 show that in general litter cover has little effect on soil moisture within the gully catchments and the correlations that do occur may be positive or negative, ie. litter cover may be associated with both high and low soil moisture. In the forest and matorral gullies 71% and 100% of the negative correlations respectively occur in dry conditions when the interception and evaporation losses from the litter cover are highest. The positive correlations in wet conditions indicate that the litter's storage capacity is exceeded releasing moisture into the soil.

Table 6.17. Correlations between soil moisture and litter cover for each gully catchment.

Soil Moisture Sampling Dates	Matorral Litter Cover	Forest Litter Cover	Bench Terrace Litter Cover
March 8 1995	----	-0.16	----
May 20 1995	-0.11	----	----
July 12 1995	-0.14	-0.25**	0.04
September 8 1995	0.49**	0.24**	0.30**
September 14 1995	0.14	0.00	0.24**
October 27 1995	-0.08	-0.10	0.09
October 28 1995	-0.07	-0.17*	0.10
October 30 1995	-0.08	-0.27**	0.06
November 1 1995	-0.10	-0.31**	0.04
November 4 1995	-0.17*	-0.35**	0.03
January 26 1996	0.00	----	0.05
January 27 1996	0.06	0.06	0.06
January 28 1996	0.16	0.03	0.10
January 30 1996	0.06	0.04	0.06
February 1 1996	0.20*	----	----
February 2 1996	0.16	0.06	0.10
February 4 1996	0.00	0.02	0.06
March 28 1996	0.13	-0.01	0.20*
March 30 1996	0.14	0.00	0.15
April 1 1996	0.21*	-0.02	0.14

* = significant at $p<0.05$ (95%)
** = significant at $p<0.01$ (99%)

6.3.3.3 Soil Moisture and Organic Carbon

Organic carbon is a measure of the finer organic materials within the soil and has been reported to be particularly important in the stability of soil aggregates (Ternan *et al.* 1996a). In chapter 4 organic carbon was reported to be the most significant factor in determining the aggregate stability of the soils within the gully catchments and therefore plays a critical role in maintaining the structure of the surface soil. Table 6.18 shows the correlations between organic carbon and soil moisture for each gully catchment. In each of the gullies less than 23% of the soil moisture sampling dates are significantly correlated with organic carbon. Organic carbon is therefore only a minor factor in determining soil moisture distribution within the gully catchments. Where significant correlations do occur these are negative and significantly stronger in dry compared to wet conditions ($p<0.05$). Areas high in organic carbon will therefore in general have a lower soil moisture content than areas low in organic carbon. The greater stability associated with organic carbon suggests that soils high in organic carbon will have a greater number of larger pores since the breakdown of aggregates and the subsequent in-washing of fine particles, resulting in an increase the number of small pores, will be relatively minor in occurrence (Le Bissonnais and Singer, 1992, 1993). In chapter 4, organic carbon was associated with an increased number of transmission pores (>60μm). These pores do not retain water and drain under the force of gravity (Hillel, 1982; Rowell, 1994). Therefore soils with a greater number of medium to large pores may, particularly during dry conditions, have a lower soil moisture since these pores will be empty.

Table 6.18. Correlations between soil moisture and organic carbon for each gully catchment.

Soil Moisture Sampling Dates	Matorral Organic Carbon	Forest Organic Carbon	Bench Terrace Organic Carbon
March 8 1995	----	-0.12	----
May 20 1995	-0.20	----	----
July 12 1995	-0.28*	-0.32*	-0.22
September 8 1995	0.28*	0.10	-0.11
September 14 1995	0.00	-0.12	-0.19
October 27 1995	-0.07	-0.14	-0.26
October 28 1995	-0.12	-0.17	-0.33*
October 30 1995	-0.15	-0.30*	-0.33*
November 1 1995	-0.17	-0.35**	-0.34*
November 4 1995	-0.23	-0.38**	-0.31*
January 26 1996	-0.03	----	-0.10
January 27 1996	0.02	0.10	-0.13
January 28 1996	0.04	0.04	-0.04
January 30 1996	-0.04	0.06	-0.10
February 1 1996	0.03	----	----
February 2 1996	0.02	0.11	-0.02
February 4 1996	-0.08	-0.01	-0.11
March 28 1996	0.01	-0.15	-0.06
March 30 1996	0.05	-0.11	-0.15
April 1 1996	0.04	-0.14	-0.08

* = significant at $p<0.05$ (95%)
** = significant at $p<0.01$ (99%)

6.3.3.4 Summary

Within the forest gully catchment the percentage vegetation cover is the most important vegetation characteristic in determining soil moisture patterns. In contrast to matorral scrub the negative relationship between soil moisture and *Pinus* trees continues during wet periods suggesting that afforestation may exert a sustained influence on soil moisture patterns. Furthermore vegetation generally explains a greater percentage of the variation in soil moisture during dry compared to wet conditions, suggesting that the effects of vegetation on soil moisture patterns are more evident during dry weather conditions when medium to low soil moisture prevails and evapotranspiration effects are highest. Litter cover and organic carbon appear to have little effect on soil moisture patterns within the gully catchments. The correlations presented above suggest that vegetation characteristics explain a greater proportion of the variability in soil moisture than topographic parameters and may therefore be considered as more important factors in determining soil moisture patterns within the gully catchments.

6.3.4 Soil Moisture and Soil Properties

Variability in soil properties, particularly those directly related to soil hydrology can result in significant variations in soil water content (Beckett and Webster, 1971; Greminger *et al.* 1985; Vachaud *et al.* 1985; Burrough, 1993). In this section several soil properties including, saturated hydraulic conductivity, bulk density, pore size distribution and soil texture are correlated with soil moisture to establish their significance as potential controlling factors in determining the spatial distribution of soil moisture.

6.3.4.1 Soil Moisture and Saturated Hydraulic Conductivity (K_{sat})

In chapter 4, values of K_{sat} were found to be highly variable within all three gully catchments and in the matorral and bench terrace gullies were not significantly correlated to any other soil or vegetation property. In the forest gully however, K_{sat} was significantly positively related to the volume of roots and organic carbon, both of which were related to an increased number of transmission pores. Within the forest gully therefore K_{sat} was also significantly positively related to the percentage of transmission pores. K_{sat} is the maximum rate of water conductivity through a soil and may be used as a measure of how quickly infiltrated water is redistributed away from the soil surface (Selby, 1982; Jabro, 1992; Rowell, 1994). Areas with a low soil moisture may therefore coincide with areas, which have a moderate to high K_{sat}. Table 6.19 shows correlations between soil moisture and K_{sat} for each gully catchment. In the matorral gully the correlations show a positive relationship between soil moisture and K_{sat} which is significant, particularly during wet conditions. This positive relationship implies, surprisingly, that areas of high K_{sat} are also high in soil moisture. This unusual relationship may in some areas be related to the presence of just one or two large transmission pores within the sampled cores which contribute to a high K_{sat} whilst the soil surrounding these large pores may be dominated by residual pores which retain water. The drainage effects of the transmission pores may therefore be outweighed by the greater number of residual pores resulting in a high soil moisture together with a high K_{sat}. This phenomenon has been observed in soils which are vulnerable to cracking (Wilding, 1985). Soils vulnerable to cracking generally have a fine texture with a high residual porosity. The cracks however represent areas, which have a high rate of water conductivity. The water flowing in these cracks during storm events may often move into the surrounding soil matrix and into the residual pores. In the locality of cracks soil moisture may therefore be high and coincidental with a high rate of conductivity (Wilding, 1985).

Table 6.19. Correlations between soil moisture and saturated hydraulic conductivity for each gully catchment.

Soil Moisture Sampling Dates	Matorral Ksat	Forest Ksat	Bench Terrace Ksat
March 8 1995	----	-0.17	----
May 20 1995	0.22	----	----
July 12 1995	0.15	-0.36	-0.11
September 8 1995	0.29	0.06	0.32
September 14 1995	0.12	-0.27	0.13
October 27 1995	0.48*	-0.25	0.00
October 28 1995	0.45*	-0.28	-0.10
October 30 1995	0.32	-0.35	-0.16
November 1 1995	0.27	-0.47*	-0.13
November 4 1995	0.18	-0.47*	-0.19
January 26 1996	0.49*	----	-0.11
January 27 1996	0.44*	-0.39*	-0.03
January 28 1996	0.44*	-0.38*	-0.12
January 30 1996	0.51*	-0.41*	-0.12
February 1 1996	0.45**	----	----
February 2 1996	0.43*	-0.42*	-0.17
February 4 1996	0.47*	-0.44*	-0.12
March 28 1996	0.58**	-0.40*	0.07
March 30 1996	0.58**	-0.26	-0.11
April 1 1996	0.45*	-0.25	-0.07

* = significant at p<0.05 (95%)
** = significant at p<0.01 (99%)

In the forest gully 47% of the sampling dates show negative correlations between soil moisture and K_{sat} which are generally stronger during wet compared to dry conditions. In contrast to the matorral gully, drier soils within the forest gully are generally related to areas of high K_{sat}. These correlations may be stronger during wet conditions since the rate of conductivity (K_{sat}) will be greatest during this period and consequently the movement of water away from surface horizons will be rapid. In the bench terrace gully no significant correlations are found between soil moisture and K_{sat}.

K_{sat} may be an important factor in determining the distribution of soil moisture within the matorral and forest gullies, although the correlations are low suggesting that much of the variability in soil moisture is still unexplained. In the bench terrace gully, K_{sat} appears to have little if any effect on soil moisture patterns.

6.3.4.2 Soil Moisture and Bulk Density

Table 6.20 shows correlations between soil moisture and bulk density within the gully catchments. In the matorral gully none of the correlations between soil moisture and bulk density are significant. Ritsema and Dekker (1994) also found no correlation between soil moisture and bulk density. In the forest gully, soils with a high bulk density are generally correlated with high soil moisture which may be a reflection of soil texture and consequently porosity. Fine textured soils may be relatively compact and exhibit a high residual porosity, which may result in a high bulk density together with a high soil moisture. In the bench terrace gully soil moisture is significantly negatively correlated on 55% of the sampling dates during wet conditions and therefore in contrast to the forest gully, soils with a higher bulk density generally have a lower soil moisture content. This may be an indication of crusting and sealing of the soil surface which may restrict the movement of water into the soil, maintaining a relatively low soil moisture content below the initial soil surface (Le Bissonnais and Singer, 1992). However the mean aggregate stability within the bench terrace gully is relatively high at 71% (Chapter 4), and suggests relatively stable aggregates. Surface sealing is therefore unlikely to occur through aggregate breakdown and the subsequent infilling of surface pores, but may however result from the swelling of the top few centimetres of the soil caused by saturation which may occur during wet conditions. Below the near-saturated surface horizon the soil may remain relatively dry (Brady, 1990) and therefore the average soil moisture measured by TDR may be low.

Table 6.20. Correlations between soil moisture and bulk density for each gully catchment.

Soil Moisture Sampling Dates	Matorral Bulk Density	Forest Bulk Density	Bench Terrace Bulk Density
March 8 1995	----	0.26	----
May 20 1995	0.12	----	----
July 12 1995	0.30	0.40*	-0.08
September 8 1995	-0.05	0.03	0.09
September 14 1995	0.09	0.28	-0.16
October 27 1995	0.20	0.37	0.06
October 28 1995	0.14	0.33	0.16
October 30 1995	0.19	0.38*	0.00
November 1 1995	0.22	0.41*	-0.03
November 4 1995	0.23	0.41*	-0.06
January 26 1996	-0.12	----	-0.42*
January 27 1996	-0.14	0.20	-0.36
January 28 1996	-0.10	0.18	-0.41*
January 30 1996	-0.08	0.28	-0.45*
February 1 1996	-0.09	----	----
February 2 1996	-0.03	0.24	-0.38
February 4 1996	-0.12	0.25	-0.42*
March 28 1996	-0.11	0.40*	-0.42*
March 30 1996	-0.18	0.30	-0.14
April 1 1996	-0.18	0.22	-0.22

* = significant at p<0.05 (95%)
** = significant at p<0.01 (99%)

6.3.4.3 Summary

The generally poor correlations between soil moisture and K_{sat} and bulk density indicate that these properties, which are often used as guides for soil structure (Landon, 1993; Rowell, 1994), are poor indicators of soil moisture patterns within this region. These properties therefore have little influence in determining the spatial pattern of soil moisture within the gully catchments. These surprisingly poor correlations between soil moisture and K_{sat} and bulk density may be attributed to very localised factors such as soil cracking and surface sealing which may have a significant and overriding effect on soil moisture regardless of the soil hydraulic conductivity or bulk density.

6.3.4.4 Soil Moisture and Pore Size Distribution

The pore size distribution of a soil will be an important factor in determining its moisture content since it is the pores through which water flows and in which water is retained (Hillel, 1982; Reeve and Carter, 1991; Rowell, 1994). As previously stated in chapter 4 the total porosity (which is also the percentage volumetric soil moisture at saturation) has been divided into transmission pores (pores >60μm in diameter), storage pores (pores 0.2-60μm in diameter), and residual pores (pores <0.2μm in diameter), based on the pore size classification system used by Thomasson (1978) and Rowell (1994). In the following sections soil moisture is correlated with each of these pore size classes including total porosity to determine their significance as controlling factors in the spatial distribution of soil moisture.

Transmission Pores

Transmission pores allow the rapid flow of water through the soil permitting drainage and in some cases allowing water to bypass the soil matrix (Beven and Germann, 1982). By allowing water to bypass the soil matrix, transmission pores may therefore assist in maintaining a relatively low soil moisture. The effectiveness of transmission pores in soil drainage may be expected to be greatest during wet conditions and in sub-surface horizons where the moisture content is highest and hence the rate of conductivity is greatest. During dry conditions the pores are likely to be inactive and their main effect on soil moisture will be through the volume of soil that they occupy. During dry conditions therefore transmission pores may show a negative relationship with soil moisture since a greater percentage of transmission pores will be a larger volume of empty pores. Table 6.21 shows correlations between soil moisture and the percentage of transmission pores in the surface and sub-surface soil for each gully catchment. In the surface horizon, only 31% and 23% of the sampling dates in the matorral and forest gullies respectively, show significant correlations between soil moisture and transmission pores, all of which are negative and occur during wet conditions. In the bench terrace gully the soil moisture data is uncorrelated with transmission pores in the surface horizon on all of the measurement dates. In the sub-surface soil correlations between soil moisture and transmission pores in all of the gullies are much stronger. Within the matorral and forest gullies soil moisture on all sampling dates is significantly negatively correlated with the percentage of transmission pores in the sub-surface horizon. In the bench terrace gully soil moisture data from all measurement dates during wet conditions are also significantly negatively correlated with transmission pores. These strong correlations suggest that transmission pores are a significant factor in determining soil moisture patterns, particularly within the matorral and forest gully catchments where the importance of transmission pores in determining soil moisture patterns persists in both dry and wet conditions.

Table 6.21. Correlations between soil moisture and transmission pores for each gully catchment.

	← surface horizon →			← sub-surface horizon →		
Soil Moisture Sampling Dates	Matorral Transmission Pores	Forest Transmission Pores	Bench Terrace Transmission Pores	Matorral Transmission Pores	Forest Transmission Pores	Bench Terrace Transmission Pores
March 8 1995	----	-0.42*	----	----	-0.69**	----
May 20 1995	-0.31	----	----	-0.64**	----	----
July 12 1995	-0.37	-0.11	0.13	-0.76**	-0.53*	-0.60**
September 8 1995	-0.08	-0.08	-0.35	-0.65**	-0.47*	-0.16
September 14 1995	-0.26	-0.21	-0.05	-0.73**	-0.61**	-0.35
October 27 1995	-0.30	-0.13	-0.28	-0.61**	-0.43*	-0.21
October 28 1995	-0.22	-0.10	-0.35	-0.62**	-0.41*	-0.40*
October 30 1995	-0.26	-0.16	-0.38	-0.69**	-0.44*	-0.35
November 1 1995	-0.30	-0.23	-0.22	-0.69**	-0.54*	-0.31
November 4 1995	-0.27	-0.24	-0.19	-0.70**	-0.54*	-0.47*
January 26 1996	-0.42*	----	0.12	-0.71**	----	-0.49*
January 27 1996	-0.42*	-0.37	0.08	-0.69**	-0.66*	-0.42*
January 28 1996	-0.40	-0.30	0.07	-0.67**	-0.58**	-0.44*
January 30 1996	-0.46*	-0.38*	0.07	-0.73**	-0.70**	-0.46*
February 1 1996	-0.43*	----	----	-0.70**	----	----
February 2 1996	-0.47*	-0.32	-0.01	-0.75**	-0.68**	-0.32
February 4 1996	-0.49*	-0.42*	0.09	-0.74**	-0.72**	-0.45*
March 28 1996	-0.37	-0.40*	-0.11	-0.74**	-0.74**	-0.61**
March 30 1996	-0.21	-0.26	-0.06	-0.62**	-0.69**	-0.55**
April 1 1996	-0.07	-0.12	0.03	-0.47*	-0.55**	-0.39*

* = significant at $p<0.05$ (95%)
** = significant at $p<0.01$ (99%)

Storage Pores

Storage pores retain water under the force of gravity and may provide a valuable source of water to plants particularly during dry conditions (Rowell, 1994). Table 6.22 shows correlations between soil moisture and the percentage of storage pores. Most of the correlations are weak and not significant, particularly in the matorral gully. All significant correlations but one are found on sampling dates during wet conditions. These correlations suggest that storage pores have only a minor role in determining the soil moisture patterns observed within the gully catchments. Since storage pores retain water which is available to plants, the volume of soil moisture within these pores may therefore depend upon the vegetation cover and root network. The patchiness of vegetation cover in dry environments may therefore give rise to high variability in the amount of water held in storage pores. Correlations between soil moisture and storage porosity may therefore be expected to be weak. In wet conditions however, the spatially variable uptake of water from storage pores is reduced as less evapotranspiration occurs and the storage pores are constantly recharged. Correlations between soil moisture and storage pores during wet conditions are therefore stronger. The correlations between soil moisture and storage porosity shown in table 6.22 generally reflect the relationships between these two variables described above.

Table 6.22. Correlations between soil moisture and storage pores for each gully catchment.

	◄ surface horizon		►	◄ sub-surface horizon		►
Soil Moisture Sampling Dates	Matorral Storage Pores	Forest Storage Pores	Bench Terrace Storage Pores	Matorral Storage Pores	Forest Storage Pores	Bench Terrace Storage Pores
March 8 1995	----	0.14	----	----	0.14	----
May 20 1995	-0.11	----	----	-0.18	----	----
July 12 1995	-0.18	0.10	-0.04	-0.34	-0.06	0.03
September 8 1995	0.14	0.22	0.49*	-0.26	0.08	0.15
September 14 1995	-0.13	0.14	0.19	-0.32	-0.04	0.05
October 27 1995	0.17	0.13	0.27	0.09	0.04	0.03
October 28 1995	-0.08	0.07	0.20	-0.08	-0.05	-0.06
October 30 1995	-0.09	0.03	0.15	-0.20	-0.06	0.07
November 1 1995	-0.05	0.03	0.09	-0.14	-0.06	-0.07
November 4 1995	-0.12	0.09	0.10	-0.31	-0.03	0.02
January 26 1996	-0.14	----	0.45*	0.03	----	0.51*
January 27 1996	-0.23	0.45*	0.54*	-0.01	0.45*	0.53**
January 28 1996	-0.15	0.51*	0.41*	0.00	0.49*	0.49*
January 30 1996	-0.14	0.46*	0.49*	0.05	0.46*	0.55**
February 1 1996	-0.18	----	----	-0.02	----	----
February 2 1996	-0.11	0.46*	0.42*	0.01	0.44*	0.55**
February 4 1996	-0.15	0.45*	0.56**	0.06	0.45*	0.60**
March 28 1996	0.04	0.22	0.47*	0.08	0.22	0.42
March 30 1996	0.07	0.24	0.38*	0.11	0.22	0.30
April 1 1996	-0.01	0.25	0.37*	-0.05	0.20	0.28

* = significant at $p<0.05$ (95%)
** = significant at $p<0.01$ (99%)

Residual Pores

Residual pores are pores which retain water. The high suctions (>15 bar) needed to release water from these pores infers that they may retain water even during dry conditions (Landon, 1993; Rowell, 1994). Residual pores may therefore be expected to display a positive relationship with soil moisture, the strength of which may persist through time. Table 6.23 shows that soil moisture on all sampling dates is significantly positively correlated with the percentage of residual pores with the exception of the surface horizon within the matorral gully. The strength of the correlations between soil moisture and residual pores is also similar in both dry and wet conditions. The correlations between soil moisture and the percentage residual pores are strong (p<0.01) implying that the percentage of residual pores may be a significant controlling factor in explaining the soil moisture patterns within the gully catchments. Furthermore within these soils the percentage of residual pores tends to be higher than the percentage of transmission or storage pores (Chapter 4) which suggests that residual pores may play a more significant role in determining soil moisture patterns than either transmission or storage porosity.

Table 6.23. Correlations between soil moisture and residual pores for each gully catchment.

	← surface horizon →			← sub-surface horizon →		
Soil Moisture Sampling Dates	Matorral Residual Pores	Forest Residual Pores	Bench Terrace Residual Pores	Matorral Residual Pores	Forest Residual Pores	Bench Terrace Residual Pores
March 8 1995	----	0.74**	----	----	0.85**	----
May 20 1995	0.44*	----	----	0.76**	----	----
July 12 1995	0.51*	0.69**	0.81**	0.89**	0.84**	0.82**
September 8 1995	0.18	0.64**	0.68**	0.70**	0.68**	0.27
September 14 1995	0.35	0.72**	0.87**	0.86**	0.82**	0.58**
October 27 1995	0.33	0.68**	0.75**	0.62**	0.78**	0.53**
October 28 1995	0.39	0.64**	0.72**	0.63**	0.76**	0.63**
October 30 1995	0.44*	0.69**	0.76**	0.75**	0.80**	0.60**
November 1 1995	0.48*	0.74**	0.79**	0.75**	0.84**	0.68**
November 4 1995	0.45*	0.76**	0.82**	0.84**	0.85**	0.74**
January 26 1996	0.22	----	0.77**	0.76**	----	0.70**
January 27 1996	0.19	0.84**	0.75**	0.79**	0.86**	0.64**
January 28 1996	0.24	0.79**	0.75**	0.76**	0.79**	0.68**
January 30 1996	0.24	0.83**	0.76**	0.75**	0.86**	0.65**
February 1 1996	0.23	----	----	0.77**	----	----
February 2 1996	0.26	0.83**	0.60**	0.76**	0.86**	0.53**
February 4 1996	0.22	0.85**	0.75**	0.78**	0.87**	0.64**
March 28 1996	0.39	0.80**	0.79**	0.67**	0.88**	0.66**
March 30 1996	0.36	0.80**	0.85**	0.55*	0.90**	0.77**
April 1 1996	0.30	0.73**	0.66**	0.56*	0.83**	0.66**

* = significant at p<0.05 (95%)
** = significant at p<0.01 (99%)

Total Porosity

Total porosity has a similar relationship with soil moisture to that shown by residual pores (table 6.24). This may be expected within these soils since the residual porosity is the dominant pore size. The correlations with total porosity however differ from those with residual porosity in that the strength of the correlations within all of the gully catchments is significantly greater in wet compared to dry conditions. This difference is probably caused by the addition of storage pores, which also showed an increase in the strength of the correlation with soil moisture during wet conditions.

Table 6.24. Correlations between soil moisture and total porosity for each gully catchment.

	← surface horizon →			← sub-surface horizon →		
Soil Moisture Sampling Dates	Matorral Total Porosity	Forest Total Porosity	Bench Terrace Total Porosity	Matorral Total Porosity	Forest Total Porosity	Bench Terrace Total Porosity
March 8 1995	----	0.47*	----	----	0.51*	----
May 20 1995	0.23	----	----	0.53*	----	----
July 12 1995	0.09	0.63**	0.56**	0.49*	0.58**	0.63**
September 8 1995	0.50*	0.65**	0.47*	0.35	0.49*	0.33*
September 14 1995	0.32	0.61**	0.61**	0.49*	0.46*	0.52*
October 27 1995	0.20	0.62**	0.44*	0.39	0.66**	0.56**
October 28 1995	0.19	0.58**	0.33	0.42	0.62**	0.47*
October 30 1995	0.19	0.56**	0.31	0.45*	0.62**	0.56**
November 1 1995	0.09	0.57**	0.39	0.49*	0.57**	0.61**
November 4 1995	0.12	0.60**	0.44*	0.49*	0.60**	0.61**
January 26 1996	0.41	----	0.80**	0.64**	----	0.88**
January 27 1996	0.47*	0.73**	0.81**	0.68**	0.72**	0.87**
January 28 1996	0.41	0.76**	0.73**	0.66**	0.74**	0.88**
January 30 1996	0.39	0.73**	0.79**	0.62**	0.68**	0.86**
February 1 1996	0.45*	----	----	0.62**	----	----
February 2 1996	0.36	0.76**	0.60**	0.59**	0.71**	0.82**
February 4 1996	0.41	0.70**	0.83**	0.66**	0.67**	0.88**
March 28 1996	0.42*	0.58**	0.68**	0.50*	0.55**	0.66**
March 30 1996	0.49*	0.68**	0.70**	0.43*	0.63**	0.79**
April 1 1996	0.52*	0.73**	0.63**	0.47*	0.68**	0.75**

* = significant at p<0.05 (95%)
** = significant at p<0.01 (99%)

6.3.4.5 Summary

Differences in pore size, particularly the percentage of transmission and residual pores appears to be a significant factor in determining the soil moisture patterns observed within the gully catchments. Relatively dry soils may be related to areas with a higher percentage of transmission pores whereas relatively wet soils may be associated with areas which have a higher percentage of residual pores. Furthermore the importance of transmission pores and in particular residual pores in determining soil moisture persists in both dry and wet conditions. The volume of soil moisture retained within storage pores may be dependent upon the spatially variable uptake of water by plants which consequently shows a seasonal trend. Soil moisture is generally therefore only significantly positively correlated with storage pores during wet conditions. The particularly strong correlations between soil porosity and soil moisture suggest that this factor is more important in determining variations in soil moisture than either topography or vegetation.

6.3.4.6 Soil Moisture and Soil Texture

The water holding capacity and water content of a soil can be greatly affected by its stoniness and clay content (Kadmon *et al.*, 1989). Therefore in areas where significant differences in soil texture occur, then it is likely that they will be a dominant factor in controlling soil moisture variability (Beckett and Webster, 1971; Greminger *et al.*, 1985). Furthermore Vachaud *et al.* (1985) and Munoz-Pardo *et al.*

(1990) have reported that the temporal persistence of soil moisture spatial patterns were determined by the spatial distribution of silt and clay. In the following sections soil moisture is correlated with the percentage clay, silt, sand and gravel content to determine their significance as controlling factors in the spatial distribution of soil moisture.

Clay content

Table 6.25 shows the correlations between soil moisture and the percentage clay within the gully catchments. Soil moisture is significantly positively correlated with clay content on all measurement dates in the matorral and bench terrace gullies. Although these correlations are significant their values are generally low, implying that clay content has only a minor role in explaining the variability in soil moisture. In the forest gully the clay content is not significant in determining the distribution of soil moisture during wet weather conditions, although significant correlations occur during dry weather conditions. The weaker correlations between soil moisture and clay content within the forest gully may be attributed to the very low mean clay content (2.67%) found within this catchment (chapter 4).

Table 6.25. Correlations between soil moisture and clay for each gully catchment.

Soil Moisture Sampling Dates	Matorral Clay	Forest Clay	Bench Terrace Clay
March 8 1995	----	0.33*	-----
May 20 1995	0.49**	----	----
July 12 1995	0.47**	0.47**	0.57**
September 8 1995	0.35*	0.26	0.39*
September 14 1995	0.42**	0.42**	0.51**
October 27 1995	0.39*	0.40**	0.49**
October 28 1995	0.44**	0.37*	0.48**
October 30 1995	0.47**	0.43**	0.52**
November 1 1995	0.46**	0.43**	0.53**
November 4 1995	0.46**	0.44**	0.52**
January 26 1996	0.56**	----	0.41**
January 27 1996	0.60**	0.14	0.43**
January 28 1996	0.54**	0.13	0.37*
January 30 1996	0.58**	0.12	0.43**
February 1 1996	0.54**	----	----
February 2 1996	0.57**	0.08	0.41**
February 4 1996	0.59**	0.12	0.43**
March 28 1996	0.49**	0.25	0.35*
March 30 1996	0.51**	0.33	0.37*
April 1 1996	0.57**	0.38	0.36*

* = significant at p<0.05 (95%)
** = significant at p<0.01 (99%)

Silt content

Table 6.26 shows the correlations between soil moisture and the percentage silt within the gully catchments. In each of the gully catchments soil moisture on all sampling dates is significantly positively correlated with the percentage silt. Vachaud *et al.* (1985), Zhang and Berndtsson (1988) and Munoz-Pardo *et al.* (1990) have also reported a close relationship between variations in soil moisture and silt content. Furthermore, the strength of the correlations is significantly higher in the matorral catchment compared to the forest and bench terrace catchments, and may be a reflection of the higher average silt content found within this catchment (chapter 4).

Table 6.26. Correlations between soil moisture and silt for each gully catchment.

Soil Moisture Sampling Dates	Matorral Silt	Forest Silt	Bench Terrace Silt
March 8 1995	----	0.49**	----
May 20 1995	0.74**	----	----
July 12 1995	0.70**	0.66**	0.59**
September 8 1995	0.48**	0.36*	0.41**
September 14 1995	0.60**	0.58**	0.50**
October 27 1995	0.62**	0.53**	0.62**
October 28 1995	0.64**	0.54**	0.60**
October 30 1995	0.70**	0.59**	0.65**
November 1 1995	0.69**	0.62**	0.64**
November 4 1995	0.71**	0.66**	0.68**
January 26 1996	0.86**	----	0.67**
January 27 1996	0.85**	0.36*	0.68**
January 28 1996	0.82**	0.38*	0.63**
January 30 1996	0.88**	0.38*	0.67**
February 1 1996	0.79**	----	----
February 2 1996	0.85**	0.30*	0.62**
February 4 1996	0.87**	0.39**	0.68**
March 28 1996	0.81**	0.55**	0.64**
March 30 1996	0.76**	0.58**	0.60**
April 1 1996	0.77**	0.56**	0.61**

* = significant at $p<0.05$ (95%)
** = significant at $p<0.01$ (99%)

Sand content

Table 6.27 shows the correlations between soil moisture and the percentage sand within the gully catchments. Soil moisture is negatively correlated with the percentage sand in both the matorral and forest gully catchments, although these correlations are only significant within the forest catchment. In contrast correlations between soil moisture and sand content within the bench terrace catchment are positive, although only a few are significant. In general the correlations between soil moisture and sand content are low and not significant implying that sand content has only a small influence in determining the spatial patterns of soil moisture. In chapter 4 sand content was shown to have a positive correlation with storage porosity. The generally weak correlations between sand content and soil moisture may therefore be a result of the variable uptake of water from the storage pores by vegetation.

Table 6.27. Correlations between soil moisture and sand for each gully catchment.

Soil Moisture Sampling Dates	Matorral Sand	Forest Sand	Bench Terrace Sand
March 8 1995	----	- 0.41**	----
May 20 1995	- 0.26	----	----
July 12 1995	- 0.25	- 0.28	0.17
September 8 1995	- 0.22	- 0.39**	0.23
September 14 1995	- 0.26	- 0.31*	0.24
October 27 1995	- 0.13	- 0.33*	0.06
October 28 1995	- 0.25	- 0.33*	0.11
October 30 1995	- 0.24	- 0.28	0.18
November 1 1995	- 0.22	- 0.28	0.21
November 4 1995	- 0.22	- 0.29	0.21
January 26 1996	- 0.07	----	0.46**
January 27 1996	- 0.15	- 0.56**	0.36*
January 28 1996	- 0.05	- 0.54**	0.42**
January 30 1996	- 0.14	- 0.55**	0.32*
February 1 1996	- 0.08	----	----
February 2 1996	- 0.16	- 0.58**	0.31
February 4 1996	- 0.17	- 0.57**	0.33*
March 28 1996	- 0.19	- 0.37*	0.30
March 30 1996	- 0.23	- 0.36*	0.19
April 1 1996	- 0.18	- 0.34*	0.30

* = significant at $p<0.05$ (95%)
** = significant at $p<0.01$ (99%)

Gravel content

Table 6.28 shows the correlations between soil moisture and the percentage gravel content within the gully catchments. Soil moisture on all sampling dates within the matorral and bench terrace gullies is significantly negatively correlated with the percentage gravel content. In the forest gully significant negative correlations between soil moisture and gravel content predominantly occur during dry conditions. Drier soils may therefore be associated with sediments, which have a higher proportion of gravel content. Rock fragments (particles greater than 2mm in diameter) can have an ambivalent effect on soil hydrological processes depending on their size, composition and location within the soil profile (Poesen and Lavee, 1994; Poesen *et al.*, 1994; Brakensiek and Rawls, 1994; Ingelmo *et al.*, 1994). Several authors have therefore reported a reduction in infiltration and a subsequent increase in surface runoff as a consequence of the presence of rock fragments (Brakensiek and Rawls, 1994; Ingelmo *et al.*, 1994; Moustakas *et al.*, 1995). Furthermore Ingelmo *et al.* (1994) have reported that an increase in the rock fragment content of Rana sediments results in a decrease in the soils gravitational and available water. Soil moisture may therefore be expected to show a negative correlation with gravel content. Within the matorral and bench terrace gullies the gravel content of sediments plays a major role in determining the spatial pattern of soil moisture which is more evident during wet conditions when the relationship is stronger (table 6.28). Within the forest gully catchment the effect of gravel content on soil moisture patterns is largely restricted to dry conditions, which may reflect the ambivalent effect of gravel content on soil moisture referred to earlier.

Table 6.28. Correlations between soil moisture and gravel for each gully catchment.

Soil Moisture Sampling Dates	Matorral Gravels	Forest Gravels	Bench Terrace Gravels
March 8 1995	----	-0.20	----
May 20 1995	-0.60**	----	----
July 12 1995	-0.57**	-0.42**	-0.54**
September 8 1995	-0.36*	-0.11	-0.42**
September 14 1995	-0.46**	-0.33*	-0.50**
October 27 1995	-0.53**	-0.31*	-0.52**
October 28 1995	-0.50**	-0.29	-0.51**
October 30 1995	-0.56**	-0.35*	-0.58**
November 1 1995	-0.57**	-0.38*	-0.59**
November 4 1995	-0.58**	-0.41**	-0.61**
January 26 1996	-0.78**	----	-0.69**
January 27 1996	-0.75**	-0.02	-0.67**
January 28 1996	-0.75**	-0.07	-0.64**
January 30 1996	-0.78**	-0.04	-0.65**
February 1 1996	-0.72**	----	----
February 2 1996	-0.74**	0.04	-0.61**
February 4 1996	-0.76**	-0.03	-0.65**
March 28 1996	-0.69**	-0.27	-0.61**
March 30 1996	-0.62**	-0.30*	-0.54**
April 1 1996	-0.67**	-0.30*	-0.59**

* = significant at $p<0.05$ (95%)
** = significant at $p<0.01$ (99%)

6.3.4.7 Summary

Considerable differences in soil moisture over relatively short distances, caused by changes in soil texture have been reported by Price and Bauer (1984), Nash *et al.* (1989) and Dekker and Ritsema (1996). Within the gully catchments soil texture appears to be a major factor in determining the spatial distribution of soil moisture. Areas of relatively high soil moisture may therefore be related to soils dominated by clay and silt sized particles, whereas drier areas may be generally associated to soils dominated by sand and gravel sized fractions. The significance of soil texture in determining soil moisture patterns within gully catchments and the importance of gullying and gully morphology in exposing these sediment horizons is illustrated in figures 6.14 and 6.15. The increased variability in soil moisture down-gully in both dry and particularly wet conditions shown in figures 6.14 and 6.15 for the forest and matorral gullies may be attributed to changes in soil texture. In the forest gully catchment soil moisture is relatively uniform along its watershed until the head of the gully where a distinct increase in the variability of soil moisture occurs. The similar soil moisture values along the watershed are due to a relatively uniform soil texture within this part of the catchment. The similar texture along the watershed may be attributed to the near horizontal inter-bedding of the sediments within this region and the gentle slope of the watershed which consequently exposes only one or two of these sediment horizons along its length. The variability in soil texture is therefore low. Deep gully incision however exposes several of these sediment horizons which may have very different textures and structure. The increased variability in soil texture caused by gully incision is therefore responsible for the increased variability in soil moisture within the gully. In the matorral gully the variability in soil moisture increases as the gully's morphology changes from a bulbous to a 'V' shaped topography. The upper bulbous shaped part of the gully is shallow and therefore only one or two sediment horizons are exposed. The variability in soil texture within this part of the gully is therefore small. The lower 'V' shaped part of the gully is however deep and coincides with the steepest part of the hillslope. Several sediment horizons are therefore exposed resulting in a greater variability in soil texture and hence a greater variation in soil moisture. Within this region therefore, gully incision exposing several sediment horizons will naturally increase the spatial variability in soil moisture. The pattern of soil moisture may be further complicated within the gullies as erosion and deposition increases the textural variation.

Figure 6.14. Soil moisture distribution within the forest gully catchment.

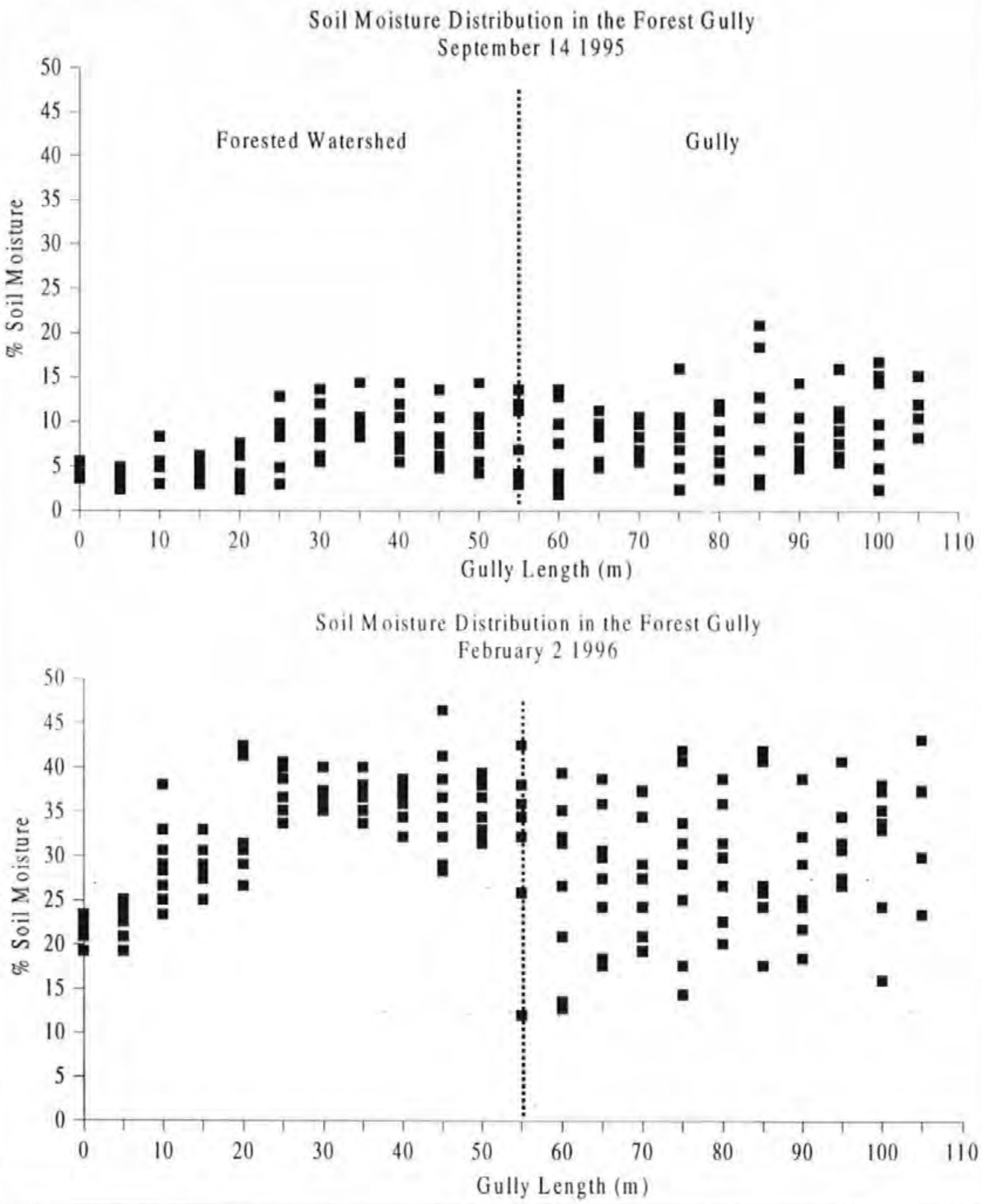
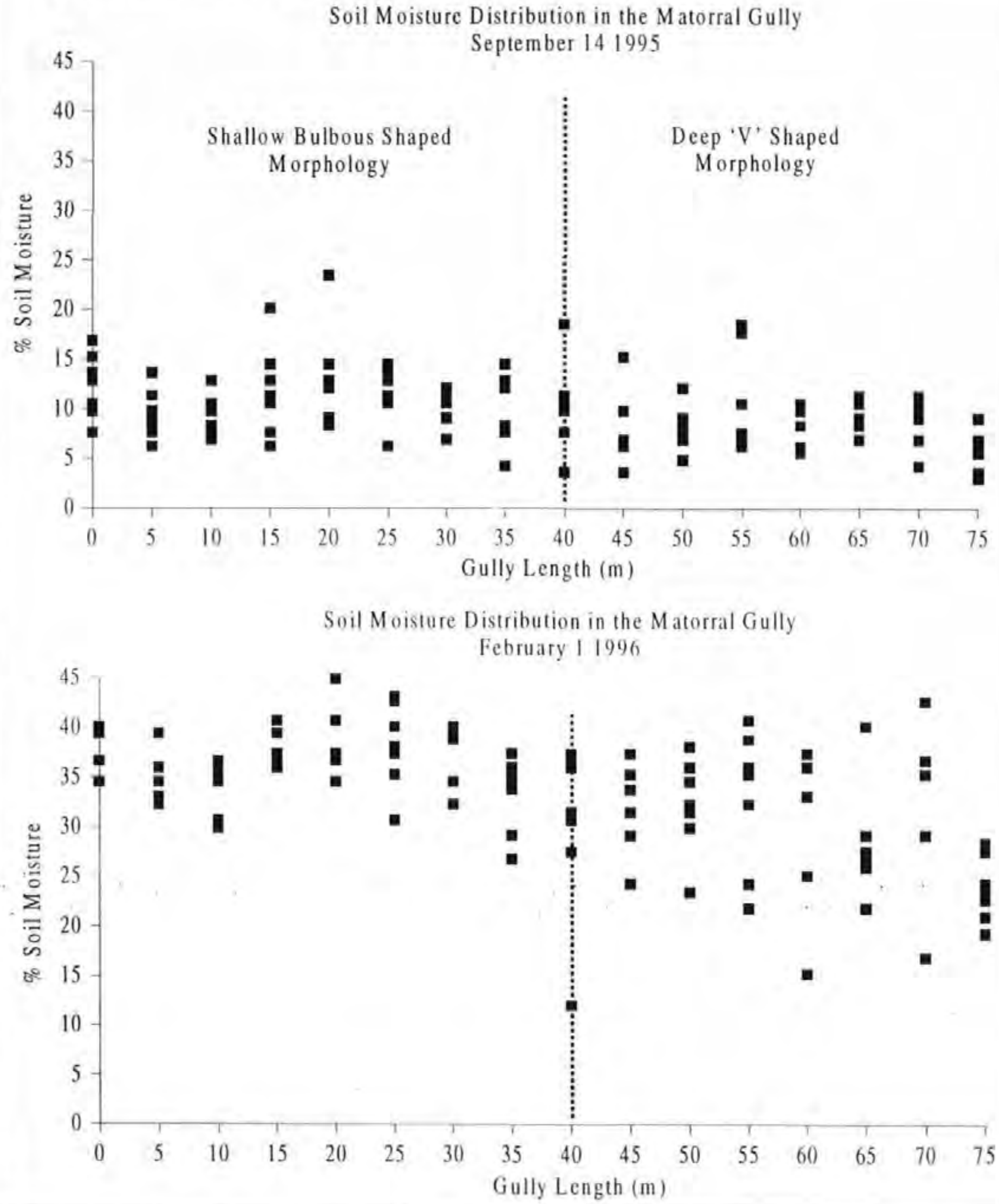


Figure 6.15. Soil moisture distribution within the matorral gully catchment.



6.4 The Significance of Soil Porosity

In the previous sections the correlation analysis have pointed to soil porosity as being a significant factor in determining the spatial distribution of soil moisture within the gully catchments. In chapter 4 the pore size distribution of the soils within the gully catchments was shown to be strongly related to soil texture. These findings indicate that finer textured soils may be expected to have a higher residual porosity in comparison to coarse textured soils, which have a greater storage and transmission porosity. Soil texture and soil porosity are therefore interrelated and jointly they may account for a greater percentage of the variation in soil moisture than either of them do singularly. The moisture content of the soils therefore directly reflects the soil porosity and size distribution of the pores, which are dependent upon several variables, the principal of which is soil texture. Furthermore the movement and retention of water within these pores is governed by several more variables including vegetation and the infiltration process.

In several of the variables studied the strength of the correlation with soil moisture is not persistent through time but changes depending upon whether conditions are dry or wet. This lack of temporal persistence in the strength of correlations is exhibited by all of the variables in a at least one of the gully catchments. In all cases the correlations are always strongest during dry conditions with the exception of storage pores, total porosity and gravel content where the correlations are stronger during wet conditions. During wet conditions those variables which have the effect of reducing soil moisture will have only a minimal influence on the overall moisture content since the soil may be considerably wet and is frequently recharged. Those variables which increase or retain water will also have a minimal influence on soil moisture during wet conditions since the soils may be near or at saturation and are therefore near to their maximum limit of soil moisture. Many of the variables are therefore only significant controlling factors in determining soil moisture patterns during dry conditions, eg. vegetation. During wet conditions many of the variables have only a minimal effect if any influence on soil moisture patterns. During wet conditions therefore several points within the gullies may have similar moisture contents regardless of differences between them in vegetation characteristics, soil properties and topographic characteristics.

6.5 Conclusions

Within all three gully catchments soil moisture is highly variable both temporally and spatially. Over distances as short as 1m, points may differ in soil moisture by as much as 26%. The soil moisture content at individual points within the gully catchments may also be highly variable through time. The soil moisture at some points can vary over a range as great as 30%, whilst other points may only vary by 15% soil moisture over the same period of time. The high spatial variability in soil moisture produces a mosaic pattern, consisting of relatively wet and dry areas. Within this mosaic pattern the relatively wet areas may be found immediately adjacent to relatively dry areas resulting in an often fragmented pattern. During dry conditions the wet and dry areas within the forest and bench terrace gullies are spatially isolated as indicated by the short range of spatial correlation in soil moisture during this period. The soil moisture pattern is therefore discontinuous. On some sampling dates during dry conditions, soil moisture may also be spatially discontinuous within the matorral gully. At other times however, dry areas may be spatially continuous within the matorral gully during this period as reflected by the range of spatial correlation in soil moisture which can be as high as 56m. During wet conditions the soil moisture pattern within each gully becomes more continuous as extensive wet areas develop. In the matorral gully this is reflected by an increase in the range of spatial correlation of soil moisture within the upper half of the catchment. In the lower half of this catchment however, the soil moisture pattern remains fragmented although relatively large wet areas may still occur. Within the forest gully in particular the spatial continuity in soil moisture is much greater in wet conditions compared to dry conditions as indicated by a doubling in the range of spatial correlation in soil moisture during this period. In the bench terrace gully, although the range of spatial correlation in soil moisture in wet conditions is similar to dry conditions, the wet areas within this gully are extensive during this period and more continuous than in dry conditions. Within each gully catchment therefore, the spatial continuity of soil moisture displays a temporal dependency. During dry conditions the mosaic soil moisture pattern is fragmented and spatially discontinuous. Greater spatial continuity and less fragmentation in soil moisture patterns occurs during wet conditions as extensive wet areas develop. Changes in the degree of variation in soil moisture patterns through time has implications for sampling methodologies. Greater variability in soil moisture during dry conditions requires a denser network of sampling in order to accurately portrayal the spatial pattern. In contrast, during wet conditions fewer samples are required since soil moisture values will be similar over larger areas (Reynolds, 1970).

Although the minigrids are a 5x magnification of the soil moisture patterns observed at the mesoscale, the complexity and characteristics of the spatial patterns at this microscale are similar to those observed at the gully catchment scale. Based upon the three scales of measurement used in this study (25m, 5m, 1m) the temporal and spatial variability of soil moisture within this region may therefore be considered as scale-invariant, ie. the magnitude of variability in soil moisture persists at all measurement scales. Similarly at each measurement scale the spatial pattern of soil moisture is temporally persistent, although a notable difference occurs in the spatial pattern from dry to wet conditions which may be attributed to the expansion of wet areas, resulting in a less fragmented pattern during wet conditions. Furthermore, the temporal persistence of soil moisture patterns at each scale implies that the factor(s) determining these patterns are not only stationary through time but may also be the same for each scale.

Pore size characteristics are the most important factor in determining the temporal and spatial patterns of soil moisture at the meso and micro scales. Unfortunately no information is available on pore size characteristics for the macroscale. In addition, pore size characteristics are strongly related to soil texture and these two properties combined may account for a significant proportion of the variability in soil moisture. Areas of drier soil may therefore be related to sediments with a high transmission porosity or coarse particles, whereas areas of relatively wet soil can be related to sediments dominated by residual pores and fine particles. Topographic and vegetation characteristics are only of secondary importance in determining soil moisture patterns. Generally the effects of vegetation on soil moisture patterns are more evident during dry weather conditions when medium to low soil moisture prevails and evapotranspiration losses are highest. Elevation, slope angle and upslope contributing area are only of minor importance in determining soil moisture patterns within the gully catchments. In several locations, significantly wetter areas may be found on steeper slopes and upslope of drier areas. The expansion of wet areas during wet conditions is primarily caused by the frequent and excessive amount of rainfall during this period and not by sub-surface drainage or surface run-on. Topographic parameters may therefore be poor indicators of the temporal and spatial patterns of soil moisture and consequently may prove to be unreliable for predicting the hydrological response from catchments within this region.

Although the strength of correlation between soil moisture and some properties shows temporal instability, changing between dry and wet periods, the most significant factors determining soil moisture patterns show a time-invariant relationship in their strength of correlation with soil moisture. These factors therefore remain as the most significant factors in determining soil moisture patterns in both dry and wet conditions.

Several of the properties examined display a positive relationship with soil moisture in one gully catchment, but a negative relationship in another catchment eg. K_{sat}. These properties are therefore not universal in their relationship with soil moisture across the study region. Instead they display a site-specific relationship with soil moisture. This has important implications for sampling strategies within this region and for within other heterogeneous environments. Within these areas, sampling at only one or a few sites severely restricts the extent to which results can be extrapolated beyond the sampled area, since relationships may be site specific and hence could be quite different or even opposite in adjacent areas, as reported here.

Gully incision, exposing several sediment horizons with different textures as in the forest gully catchment, may be responsible for increasing the spatial variability in soil moisture. Furthermore, gully morphology may also play an important role in determining the degree of spatial variability in soil moisture. The matorral gully has shown that a shallow bulbous shaped morphology, where just one or two sedimentary horizons are exposed, can have a lower spatial variability in soil moisture than a deep 'V' shaped morphology, where several sedimentary horizons are exposed. Within this region therefore, gullying may naturally increase the spatial variability in soil moisture. McBratney (1992) has similarly argued that certain natural although degradative processes, such as gullying, may increase heterogeneity.

Having described the temporal and spatial patterns of soil moisture and their principal causal factors, the implications of these observed spatial patterns for the hydrology, erosion and management of gullied areas are discussed in the following chapter, together with the possibility of manipulating soil variation to create a self regulating system for runoff and erosion control.

Chapter 7

Soil Moisture Variability and Hydrological Continuity: Implications for Runoff and Erosion, Hydrological Monitoring and Management

7.0 Introduction

In semi-arid areas, the combination of a non-uniform distribution of vegetation (Francis and Thornes, 1995), an often highly irregular terrain (Bryan and Yair, 1982; Campbell, 1989) and complex geological, pedological and management histories have frequently given rise to considerable spatial variability in the physical and hydrological properties of soils (Berndtsson and Larson, 1987). Heterogeneity within the soils physical and hydrological properties can result in pronounced differences in infiltration and soil moisture as reported in Chapter 6 and by Blackburn, (1975); Lavee and Yair, (1990); Wood *et al.* (1990); Bryan, (1994); Grayson *et al.* (1997); and Ternan *et al.* (1997). The hydrological response of semi-arid landscapes to rainfall events may therefore be spatially non-uniform (Bryan and Yair, 1982; Yair and Lavee, 1985; Johnson and Gordon, 1988; Cerda, 1995; Bergkamp *et al.*, 1996). An understanding of the spatial distribution of source areas is critical in determining the extent of overland flow and its effectiveness as an eroding agent (Morgan, 1995; Nicolau *et al.*, 1996).

Soil moisture in particular is a key factor in determining the surface runoff response to a given precipitation event. According to Phillips (1992), runoff and soil moisture are two mutually interdependent variables and without information on soil moisture variability, prediction and interpretation in catchment hydrology is problematic. In northeast Spain, Llorens and Gallart (1992), have reported that in a Mediterranean mountainous catchment, the hydrological response is

"fully controlled by antecedent moisture conditions".

Ternan *et al.* (1997) have also reported that prevailing soil moisture conditions are of considerable importance in runoff generation in the study region of this current research. In Australia, Barling *et al.* (1994) have argued that meaningful hydrological predictions are dependent upon our

"ability to characterise the spatial variability of soil water content".

Similarly, Grayson *et al.* (1997) also working in Australia, have argued that

"near surface soil moisture is a major control on hydrological processes at both the storm event scale and in the long term".

Characterising spatial patterns of soil moisture and hence the spatial arrangement or connectivity of source areas is necessary therefore not only for understanding, but also for predicting catchment runoff (Merz and Plate, 1997; Grayson *et al.*, 1997).

Bergkamp (1995) has reported that spatial patterns may change at different time scales. This in particular may apply to spatial patterns of soil moisture which may oscillate between two or three states especially in strongly seasonal climates ie. from dry to wet (Grayson *et al.*, 1997). A question considered to be important for hydrology by Grayson *et al.* (1997) is how the temporal variation in soil moisture affects the spatial patterns of soil moisture. In the previous chapter temporal variations in the spatial patterns of soil moisture were reported and described. Following this a logical progression of thought renders a further and perhaps more important question 'what are the implications, if any, of the spatial pattern in soil moisture and their changes through time for the hydrology, erosion and management of catchments?'. The aim of this chapter is to address this question.

This chapter is divided into three sections. The first section reports and describes the occurrence of mosaic patterns of hydrological response and the significance of hydrological continuity and thresholds in determining catchment runoff. The second section uses the soil moisture patterns for the three gully catchments described in Chapter 6, to illustrate and verify the importance of hydrological continuity and thresholds in determining the extent of catchment runoff and erosion. The final section of this chapter reports on the significance that the conclusions from the previous two sections may have for the hydrological monitoring and management of gullied catchments.

7.1 Mosaic Patterns of Hydrological Response

In 1965, Amerman, working in a catchment in Ohio, reported the occurrence of surface runoff from areas within the catchment which were located upslope of the stream channel. In many instances the runoff from these source areas was reabsorbed in adjacent areas downslope (Amerman, 1965). The occurrence of runoff within the catchment was therefore spatially non-uniform and could be characterised by a patchwork of contributing areas and areas capable of reabsorbing runoff. In the semi-arid rangelands of Nevada, Blackburn (1975) also reported the occurrence of spatially non-uniform runoff which was generated from degraded dune inter-space areas with infiltration into vegetated soils. Johnson and Gordon (1988) also working in sagebrush rangelands have reported a patchwork of zones of runoff and zones of infiltration, the distribution of which is related to the spatial pattern of vegetation cover. Inter-shrub areas were recorded as generating 2.5 times more runoff and 8 times more soil loss than shrub canopy zones. The greater runoff and erosion from the inter-shrub areas was attributed to the degraded nature of the soil which was characterised by a low organic matter content and a high bulk density. A patchwork of source areas and sinks related to the spatial pattern of vegetation cover has also been reported by Morin and Kosovsky (1995) who used surface applied dye to trace the flowpaths of surface runoff. In nearly all instances the runoff generated from degraded inter-shrub areas was reabsorbed by sinks of dense vegetation. In southern Spain, Cerda (1995), Nicolau *et al.* (1996) and Bergkamp *et al.* (1996) have all reported zones of surface runoff and zones capable of reabsorbing this runoff, the spatial pattern of which has been related to vegetation cover. In central Spain, Ternan *et al.* (1997), reported minimal overland flow and soil losses from dense undisturbed matorral, but in areas where disturbance to the vegetation cover occurred the soils were susceptible to high runoff and erosion losses. In bench terraced areas runoff was highly variable, being greatest on unvegetated plots and least on vegetated plots (Ternan *et al.*, 1997).

The occurrence of spatially non-uniform runoff characterised by a patchwork of source areas and sinks for overland flow, has been reported by Lavee and Yair (1990) and Yair (1992) although in these cases the spatial pattern of runoff was attributed to differences in lithology. Hodges and Bryan (1982) have also reported that the moisture regime of a lithologic unit is the critical factor determining runoff response to rainfall. Spatial patterns of runoff and sinks for overland flow have been recorded due to the effects of water repellency (Imeson *et al.*, 1992), differences in surface roughness caused by the passage of fire (Lavee *et al.*, 1995), the spatial occurrence of soil crusting (Bromley *et al.*, 1997) and differences between areas in a catchment in regards to their hydrological properties and soil moisture content (Freeze, 1980; Wood *et al.*, 1990; Llorens and Gallart, 1992; Gascuel-Odoux *et al.*, 1996; Merz and Plate, 1997; Grayson *et al.*, 1997). Spatially non-uniform runoff may therefore be attributed to a number of factors, most of which are inter-related. Where the occurrence of these factors is heterogeneous a spatial arrangement of source and sink areas may be found, which may be best described as a mosaic pattern of areas of contrasting hydrological response (Morin and Kosovsky, 1995; Lavee *et al.*, 1995; Nicolau *et al.*, 1996; Bergkamp *et al.*, 1996).

The areas of contrasting hydrological response which form a mosaic pattern may be delimited into units based on their differing hydrological response and spatial limits. These units can be termed hydrological response units or unit source areas (Amerman, 1965: Flugel, 1995). The spatial limits of hydrological response units may however be spatially dynamic (Morin and Kosovsky, 1995) and therefore the degree of fragmentation found within the mosaic pattern may vary for different time periods. It is the spatial arrangement of hydrological response units within the mosaic pattern and the degree of fragmentation within the mosaic pattern which plays a key role in determining the continuity of hydrological pathways and therefore the extent and severity of runoff and erosion (Amerman, 1965: Cerda, 1995; Morin and Kosovsky, 1995: Nicolau *et al.*, 1996, Bergkamp *et al.*, 1996; Merz and Plate, 1997, Grayson *et al.*, 1997).

7.1.1 Hydrological Continuity

Kirkby *et al.* (1996) have argued that in runoff and erosion studies an important consideration must be to determine how different parts of the slope or landscape are physically connected. In the mosaic patterns the spatial sequence of hydrological response units has been found to be a critical factor in determining the spatial extent of surface runoff (Morin and Kosovsky, 1995; Cerda, 1995; Lavee *et al.*, 1995; Nicolau *et al.*, 1996). Morin and Kosovsky (1995) have reported that greater discontinuity in hydrological pathways resulted in lower runoff. The continuity or discontinuity of hydrological pathways at the plot, hillslope or catchment scale is dependent upon the degree of fragmentation in the mosaic pattern encountered at each of these scales. The more fragmented the mosaic pattern the greater the heterogeneity in hydrological response due to the larger number of hydrological response units (Nicolau *et al.*, 1996). Under these conditions the spatial continuity of hydrological pathways will be very short and hence discontinuous. Where mosaic patterns of areas of contrasting hydrological response have been reported, the spatial extent of runoff and erosion is considered minimal. Lavee *et al.* (1995) have reported that overland flow generated by some source areas infiltrates after a short distance when a sink is encountered.

"The probability of overland flow reaching the stream channel is, therefore, very small" (Lavee et al., 1995).

In the fragmented mosaic pattern of hydrological response units described by Bergkamp *et al.* (1996),

"spatial discontinuity in hydrological pathways prevented the development of runoff over distances larger than one metre".

Similar findings have been reported by Yair (1992), Imeson *et al.* (1992), Llorens and Gallart (1992), Cerda (1995), Morin and Kosovsky (1995) and Nicolau *et al.* (1996). In each of these studies, runoff and erosion were found to be highly localised with minimal runoff and sediment reaching the channel, indicating that the runoff producing areas were spatially isolated and unconnected. In each case the mosaic pattern can be presumed to be highly fragmented. In plots, hillslopes or catchments where source areas are unconnected and hydrological pathways are discontinuous, resulting in minimal runoff and erosion, the area of study may be considered as spatially isolated (Sharma *et al.*, 1987). In spatially isolated areas, fragmentation in the mosaic pattern and the spatial arrangement of hydrological response units restricts the connectivity between runoff producing areas. Only those source areas located adjacent to the channel or catchment outlet will contribute to catchment outflow. Surface runoff from source areas which are spatially isolated and upslope of the channel will be reabsorbed by the surrounding non-source areas which act as sinks for overland flow and transported sediment, and the runoff will not contribute to catchment outflow (Amerman, 1965). For this reason Morin and Kosovsky (1995) have reported that

"although runoff was generated sporadically over the entire slope, the plot outlet received runoff from the downslope section only".

Even though the source areas may consistently generate runoff during every precipitation event, it is the spatial arrangement of sink areas which determines the amount of runoff recorded at the study outlet.

A decrease in the fragmentation of mosaic patterns may occur due to an increase in the number of one particular hydrological response unit or similarly through the expansion in area of a hydrological response unit. For example, further degradation may lead to an increase in the number or spatial extent of source areas and consequently fewer sink areas (Seyfried and Wilcox, 1995). As discussed earlier the spatial limits of hydrological response units may not be static, but may increase (decreasing fragmentation) or decrease (increasing fragmentation) through time. An increase in the number or spatial extent of a hydrological response unit will result in an increase in the spatial length of hydrological pathways. Where source areas are connected and hydrological pathways continuous, resulting in the potential for widespread catchment runoff and erosion, the study area may be considered as spatially interactive (Sharma *et al.,* 1987). Blackburn (1975) reported that an increase in the size of source areas resulted in an increase in sediment production. Nicolau *et al.* (1996) reported that the amount of runoff can be modified by the spatial distribution of bushes. If the bushes are linearly arranged along the slope then hydrological pathways are more continuous and runoff is greater than if the bushes follow a zig-zag pattern (Nicolau *et al.,* 1996). Lavee *et al.* (1995) have also reported that greater overland flow and sediment yields can be expected if there is a greater number of contributing areas. Merz and Plate (1997) and Grayson *et al.* (1997) have both measured spatial soil moisture patterns through time and have concluded that during wet periods hydrological pathways are more continuous since soil moisture is similar over large areas compared to dry conditions when the spatial pattern of soil moisture is more random. Consequently during wet conditions much higher runoff occurs (Merz and Plate, 1997; Grayson *et al.,* 1997).

Within this section the spatial extent and hence the severity of runoff and erosion has been shown to be dependent upon the spatial sequence of hydrological response units. A spatial sequence which promotes continuous hydrological pathways may result in widespread runoff and erosion. Alternatively a spatial sequence which promotes discontinuous hydrological pathways may result in minimal runoff and erosion. The spatial sequence of hydrological response units has also been shown to be potentially dynamic, changing through time. This review has however, ignored the existence of thresholds, above which widespread runoff can be expected to occur from all hydrological response units within the mosaic pattern, regardless of their spatial sequence. Identifying and understanding the implications of thresholds for runoff and erosion may therefore be as equally important as identifying the spatial sequence of hydrological response units.

7.1.2 Thresholds

Each hydrological response unit can be given a threshold value based on the conditions necessary for runoff to occur from that unit. When conditions are above this threshold value then runoff may be expected to occur from the unit. It is differences in these threshold values between hydrological response units which creates a mosaic pattern of areas with contrasting hydrological response. A range of threshold values may therefore be found within a mosaic pattern (Dunne *et al.*, 1991). Some hydrological response units will have a low threshold value (source areas) whereas others will have a high threshold value (sink areas). It is the spatial variability and the spatial sequence of these areas which can result in minimal runoff and erosion. Merz and Plate (1997) however, ask the question

"is there a threshold where the effects of spatial variability are decreasing to a negligible size".

Above a critical threshold value therefore, widespread runoff and erosion may occur regardless of the spatial sequence of hydrological response units.

Poesen *et al.* (1996) have reported that thresholds in rainfall exist and can be identified above which widespread runoff and erosion are initiated. Dunne *et al.* (1991) and Morin and Kosovsky (1995) have reported that at a given rainfall intensity only those areas with an infiltration rate lower than this rainfall intensity will generate runoff. As the intensity increases however, it exceeds the infiltration rate of an increasing proportion of the surface which subsequently generates runoff (Dunne *et al.*, 1991). When the rainfall intensity exceeds the hydrological response unit with the highest infiltration rate threshold, runoff will be generated over the entire study area (Morin and Kosovsky, 1995). At a critical threshold therefore, when the majority of the thresholds of the hydrological response units area exceeded, large areas will be contributing to surface runoff regardless of the spatial distribution in soil hydraulic properties. Major runoff and erosion events may therefore be related only to severe storms where rainfall intensity exceeds the infiltration threshold of the majority of the hydrological response units (Llorens and Gallart, 1997). Thresholds which are related to rainfall intensity infer a runoff generating mechanism which is primarily Hortonian overland flow in nature. In many cases however, exceeding critical thresholds may be related more to the antecedent conditions prior to storm events and therefore to a runoff generating mechanism which is primarily related to saturation overland flow.

Latron and Gallart (1995) have reported that only a small runoff coefficient was recorded from an intense rainfall event during a dry period. In contrast higher runoff coefficients were recorded from runoff events that occurred after a week of continuous rainfall. In southern Spain, Cerda (1997) has reported that infiltration rates are 27% lower in the wet season as compared to the summer. Consequently runoff is much higher during the wet season. Similarly, Blackburn (1975) has also reported a negative relationship between infiltration and antecedent moisture content, with the result that more runoff and sediment losses were recorded from soils which had a higher antecedent moisture content. Bryan (1994) has also reported consistently higher runoff coefficients during wet compared to dry conditions. Merz and Plate (1997) and Grayson *et al.* (1997) have reported that runoff is higher during wet periods when soil moisture is higher and similar over larger areas than during dry periods. In central Spain, Ternan *et al.* (1997) have reported that

"there is evidence to suggest that soil moisture thresholds exist above which runoff volumes and coefficients increase significantly".

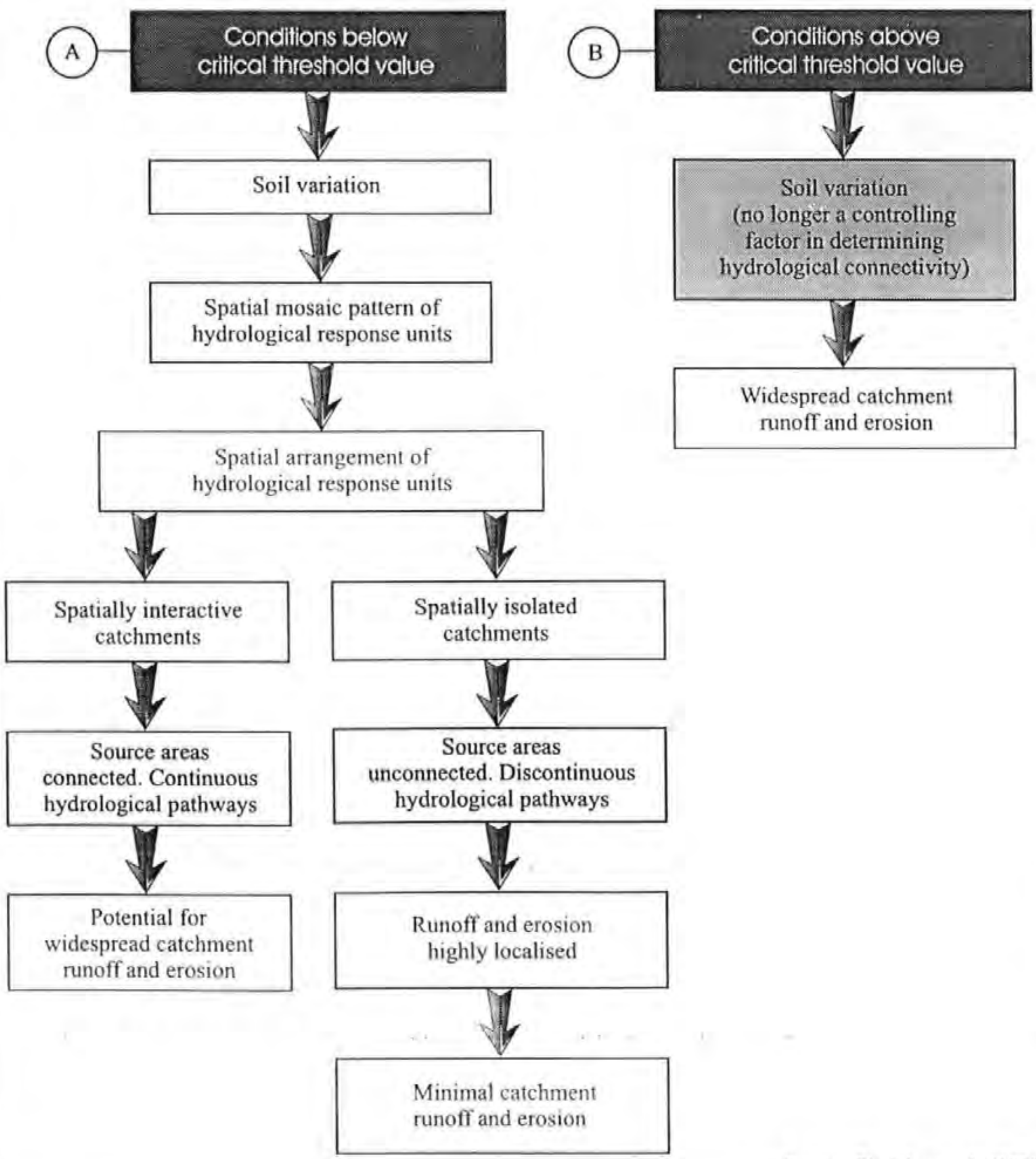
Exceeding critical threshold values, resulting in the onset of widespread runoff and erosion regardless of the spatial sequence of hydrological response units can be related to both rainfall intensity where Hortonian infiltration excess overland flow occurs and the frequency of rainfall events which determines antecedent conditions and hence saturation overland flow (Ireland *et al.*, 1939). In many environments, heterogeneity in soil hydraulic properties results in a combination of the two runoff generating mechanisms occurring during precipitation events (Freeze, 1980; Bryan and Yair, 1982; Lavee and Yair, 1990; M-Mena *et al.*, 1998).

7.1.3 Summary

At different spatial scales of study, areas of contrasting hydrological response may be found forming a mosaic pattern of hydrological response units. Depending upon the spatial sequence of these hydrological response units, the area of study may be either spatially isolated or spatially interactive. In spatially isolated catchments for example, source areas are unconnected and hydrological pathways are discontinuous, resulting in minimal catchment runoff and erosion. In spatially interactive catchments, source areas are connected and hydrological pathways continuous, resulting in the potential for widespread runoff and erosion. In addition the extent of hydrological connectivity within the catchment may be at any point along a continuum between the extremes of isolated and interactive, depending upon the magnitude-frequency relationships of the rainfall events and the critical threshold values above which widespread connection may occur. These relationships between mosaic patterns, the spatial sequence of hydrological response units, critical thresholds and the occurrence of widespread runoff and erosion are illustrated as a conceptual model in figure 7.1. Two key points may be concluded from this figure. Firstly, when conditions are above the critical threshold value, widespread runoff and erosion will occur regardless of the degree of soil variation. Secondly, when conditions are below the critical threshold value, the spatial extent of runoff and erosion is dependent upon the spatial sequence of hydrological response units.

In the second part of this chapter the continuity of hydrological pathways will be determined for the three gully catchments in this study, using the soil moisture data described in Chapter 6 and the principals of critical thresholds and the spatial sequence of hydrological response units outlined above.

Figure 7.1: Conceptual model of the relationships between soil variation, the spatial arrangement of hydrological response units, critical thresholds and the occurrence of widespread runoff and erosion.



Source: Fitzjohn *et al.*, (1998)

7.2 Hydrological Continuity and the Severity of Erosion within the Gully Catchments

In Chapter 6 the soil moisture data recorded within each of the three gully catchments was divided into measurements recorded during a dry period and those recorded during a wet period. Grayson *et al.* (1997) have also classified their soil moisture data into measurements recorded during dry and wet periods. During dry conditions the soil moisture pattern within each of the three gully catchments was characterised by a mosaic of relatively wet and dry areas. In this region, Ternan *et al.* (1997) have reported that soil moisture tends to be generally higher in degraded areas. Furthermore, Wood *et al.* (1990) have reported that areas of higher soil moisture have a greater likelihood of generating runoff. Blackburn (1975) has argued that areas of higher soil moisture may produce runoff more rapidly than adjacent drier areas because a greater number of pores are filled reducing the available water storage capacity. Sardo *et al.* (1994), Bryan (1994), Cerda (1997), Merz and Plate (1997) and Grayson *et al.* (1997) have all reported a greater volume and a rapid occurrence of runoff from areas higher in soil moisture. Furthermore, Henninger *et al.* (1976) have reported that areas of high soil moisture were correlated with source areas of surface runoff. The relatively wet areas in the mosaic patterns of soil moisture described in chapter 6 may therefore be considered as potential source areas of surface runoff. In contrast the relatively dry areas may be considered as sinks capable of reabsorbing the runoff from the wet areas. A mosaic pattern of contrasting hydrological response units therefore exists within each of the gully catchments.

7.2.1 Dry Conditions

During dry conditions a rainfall event with an intensity lower than the infiltration threshold of the dry areas is likely to generate runoff only from areas of relatively high soil moisture. During these conditions runoff was not observed in the catchments channels and no flow was seen at the catchments outlet. During these conditions therefore, hydrological pathways are discontinuous and the runoff generated by the source areas is reabsorbed by sinks preventing flow within the catchment channel. Evidence for discontinuity in hydrological pathways during dry conditions may be observed within the contour plots of soil moisture recorded during this period (section 6.1.2, chapter 6, page 151). Wet areas within these contour plots are relatively few in number and are surrounded by areas of drier soil. Furthermore, the relatively short range of spatial correlation in soil moisture during this period indicates small and spatially isolated areas of similar soil moisture. Where the range in spatial correlation of soil moisture is high during this period ie. on some measurement dates within the matorral gully, the range refers to the large and relatively continuous dry areas which may be found within this gully. The mosaic pattern of soil moisture is therefore generally highly fragmented during this dry period and characterised by small and unconnected source areas. The three gully catchments may therefore be considered as spatially isolated. Grayson *et al.* (1997) have described a soil moisture pattern with similar characteristics during dry periods for a catchment in Australia. During dry conditions within the three gully catchments, runoff is highly localised and restricted to the source areas. Only on rare occasions were widespread runoff and erosion observed during this period. These rare occasions were related to high intensity rainfall events when the majority of the hydrological response units infiltration thresholds are presumed to have been exceeded. Merz and Plate (1997) have also reported that a high intensity rainfall event produced widespread runoff regardless of the initial soil moisture content. During dry conditions therefore, the critical threshold value above which widespread runoff and erosion may be expected to occur from each of the gully catchments is dependent upon the intensity of rainfall. Below this threshold the spatial sequence of the hydrological response units is such that runoff is minimal. Within the study area the dry periods of soil moisture coincide with the summer months when the likelihood of convective rainfall is highest. Convective storms are usually characterised by a short duration but high intensity rainfall. The number of occasions therefore when the majority of the hydrological response units infiltration thresholds are exceeded, resulting in widespread runoff, may be presumed to occur frequently during this period (Yair and Lavee, 1985). Field observations however do not support this and only 7 storms with an intensity greater than 10 mm hr^{-1} were recorded during this period. Furthermore in southern Spain, Castillo *et al.* (1997) have reported that contrary to popular opinion 70% of the rainfall events in semi-arid and arid regions have an intensity of less than 10 mm hr^{-1}, indicating that much of the rainfall is of low intensity. Bryan (1994) has further argued that in the longer term significant erosion is primarily caused by moderate storms.

7.2.2 Wet Conditions

In the first section of this chapter it was suggested that the spatial limits of the hydrological response units may be dynamic responding to changes in hydrological conditions. During wet periods the spatial mosaic patterns of soil moisture within each of the three gully catchments becomes less fragmented as extensive wet areas develop covering large parts of the catchments (section 6.1.2, chapter 6, page 151). Grayson *et* *al.* (1997) have also reported a less fragmented pattern of soil moisture developing during wet periods. During these conditions the number and size of the wet areas has increased and subsequently greater connectivity may be found between these areas. Furthermore, within the three gully catchments the range of spatial correlation in soil moisture has generally increased, particularly within the forest gully catchment, indicating a greater spatial continuity in soil moisture over larger areas during this period. The occurrence of similar soil moisture values over large areas during wet conditions has also been reported by Grayson *et al.* (1997) and Merz and Plate (1997).The size and number of source areas during this period has therefore increased with a relative decline in the size and number of sinks.

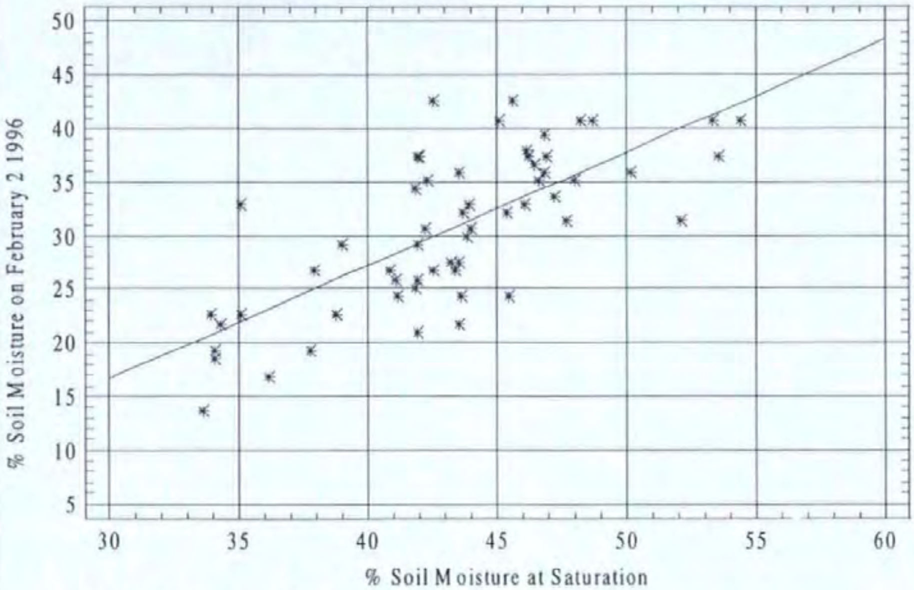
During wet periods the expansion of wet areas is caused by prolonged rainfall from successive storms, usually of low to moderate intensity. Despite different physical and hydraulic properties, the water storage capacity of the formerly dry zones may be filled or is close to this maximum and have thus become potential source areas of surface runoff. The exhaustion of soil water storage capacities in previously non-source areas has also been reported by O'Loughlin (1981). A strong and significant correlation (0.73, $p<0.01$) (figure 7.2) between the percentage volumetric soil moisture at saturation determined from the Pitman cores (soil depth measured 0-7cm) at 58 sample locations and the percentage soil moisture measured by TDR on a representative wet sampling date (February 2 1996), together with field observations (Plate 7.1), indicates that the surface soils within the three gully catchments are likely to be near saturation during wet periods. It is recognised that in figure 7.2 that the soil moisture values measured by TDR are nearly always lower than the soil moisture values measured at saturation. This discrepancy may be accounted for by the different soil depth and soil volume over which water content is averaged by the two measurement techniques. Water content at saturation measured by the Pitman cores is averaged over a soil depth (0-7cm) and soil volume (160 cm^3) which is smaller than that measured by the TDR (0-15cm and 977 cm^3 respectively). It is therefore not possible to say conclusively whether the soils within the gully catchments are saturated. It is only possible to give a likelihood of saturated conditions. The date of February 2 1996 is used to determine the likelihood of saturated conditions since the minimum, maximum and average soil moisture values within each gully catchment are highest on this date compared to other sampling dates (Chapter 6, tables 6.1, 6.2, 6.3, pages 148-149). February 2 1996 therefore represents the wettest soil moisture conditions measured within the catchments. Furthermore, table 7.1 shows the total rainfall which fell 2, 7 and 14 days prior to each soil moisture sampling date as well as a 30-day reciprocal-decay antecedent precipitation index (API_{30}) (Weyman, 1974). From this table a clear distinction can be made between dry (March 1995 - November 1995) and wet (January 1996 - April 1996) periods on the basis of antecedent rainfall. During the wet period rainfall of over 70mm in 14 days occurs prior to several soil moisture measurement dates. This persistently high level of antecedent rainfall together with the moderate to low hydraulic conductivity of these soils (as low as 0.03 mm hr^{-1} - Chapter 4) and field observations infers that saturated or near saturated conditions are likely to have occurred during the wet period.

Therefore, during wet periods, due to the near saturation of surface soils and rainfall with a low to moderate intensity, the critical threshold value above which widespread runoff will occur is presumed to be saturation point. For this study region Ternan *et al.* (1997) have reported that

"it seems that significant runoff events are associated with saturation of the surface soil horizon".

During wet periods therefore the occurrence of widespread runoff is dependent upon antecedent conditions, which are determined by the frequency of rainfall events (table 7.1). Cammeraat (1992) has also reported that runoff is strongly dependent upon antecedent soil moisture which is governed by the frequency and duration of storm events and thus consequently follows a seasonal regime, alternating between summer and winter.

Figure 7.2: Regression analysis between the percentage soil moisture at saturation and the percentage soil moisture measured by TDR on February 2 1996 using samples from all three gully catchments.



Note: Although some differences between values occur this is due to their derivation from different soil volumes.

Table 7.1. The total rainfall which fell 2, 7 and 14 days prior to each soil moisture sampling date, and the 30 day antecedent precipitation index (API_{30}).

Soil Moisture Sampling Dates	2 days (mm)	7 days (mm)	14 days (mm)	API_{30} (mm)
March 8 1995	5.7	17.1	N/A	6.9
May 20 1995	0.7	3.7	53.2	6.1
July 12 1995	5.9	6.4	37.9	7.6
September 8 1995	0.0	0.0	8.2	2.9
September 14 1995	0.0	0.0	0.0	7.5
October 27 1995	1.6	13.9	13.9	2.9
October 28 1995	0.0	13.9	13.9	2.5
October 30 1995	0.0	2.5	13.9	1.9
November 1 1995	0.0	1.6	13.9	1.4
November 4 1995	0.0	0.0	13.9	1.1
January 26 1996	12.0	41.0	100.0	17.5
January 27 1996	2.0	25.0	100.0	16.2
January 28 1996	1.0	24.0	101.0	32.3
January 30 1996	19.0	38.0	113.0	17.5
February 1 1996	0.0	22.0	80.0	12.3
February 2 1996	0.0	21.0	61.0	11.0
February 4 1996	0.0	19.0	43.0	9.0
March 28 1996	3.7	5.9	13.2	2.8
March 30 1996	0.2	6.2	9.1	13.9
April 1 1996	18.3	24.2	27.2	23.2

Plate 7.1. Surface ponding during the wet period providing field evidence of soil saturation.

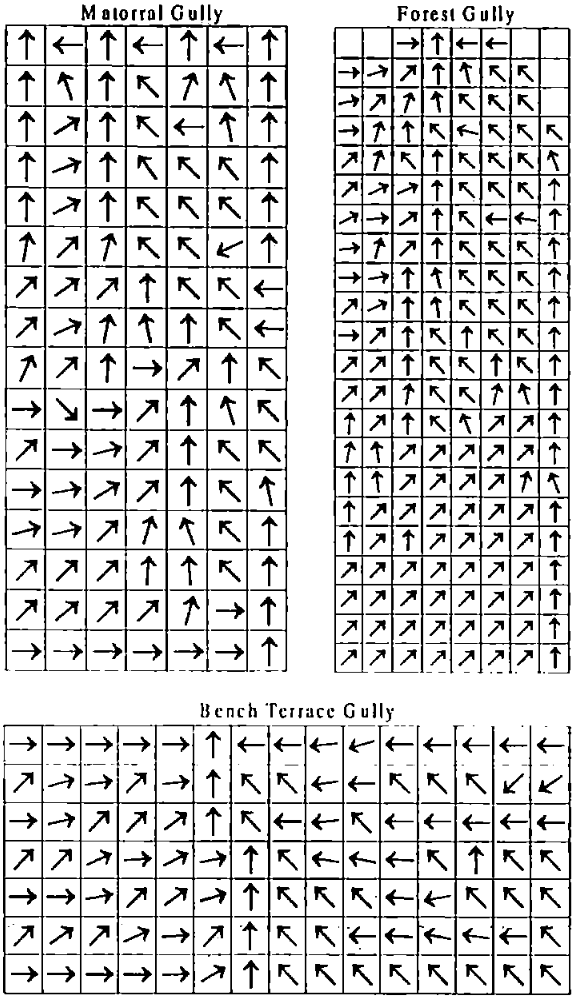
7.2.3 Implications for Runoff

Although the contour plots of soil moisture and variogram analysis provide some indication of the continuity in hydrological pathways during dry and wet periods, they provide little detailed information about connectivity between source areas and more importantly the connectivity of these source areas to the gully channels. Significant runoff and erosion from the gully catchments may be considered to occur when flow is observed at the catchment outlet. For this to occur the source areas of runoff must be either directly or indirectly through adjoining source areas hydrologically connected to the catchment channels. To establish the continuity of hydrological pathways within each gully catchment, a flow direction for every 5x5m cell within the gully grids was first determined using the method proposed by Tarboton (1997). Each cell is assigned a single flow direction reflecting the direction of the steepest downward slope based on eight triangular facets formed in a 3x3 pixel window centred on the pixel of interest (Tarboton, 1997). The direction of flow for every 5x5m cell within each of the gully catchments is shown in figures 7.3a, b, c. Runoff generation from an individual hydrological response unit will only occur when its threshold value is exceeded. Within this region antecedent soil moisture plays a significant role in generating runoff (Ternan *et al.*, 1997). The lack of field evidence for widespread runoff during dry conditions when soil moisture is generally low provides evidence of the role of soil moisture in generating runoff. As discussed earlier the threshold value above which runoff will occur from individual hydrological response units is therefore considered to be saturation point. To determine the saturation threshold value for each individual gully catchment, the volumetric soil moisture determined from the Pitman cores taken from within each catchment have been correlated with the percentage soil moisture measured by TDR on a representative sampling date during wet conditions (February 2 1996) (figures 7.4a ,b ,c). As in figure 7.2 the correlations are strong and significant ($p<0.01$) and again suggest that these locations are at or near saturation. It is recognised however, that contrasting areas of hydrological response forming a mosaic pattern, will by definition, have different critical threshold values (Campbell and Honsaker, 1982: Bryan and Yair, 1982). This is demonstrated by the range of soil moisture saturation values recorded from the Pitman cores (figures 7.4a, b, c). Within the gully catchments therefore some areas may have a very different soil moisture saturation threshold compared to other areas. However, due to practical constraints of sampling it was not feasible to determine the saturated soil moisture threshold value of every hydrological response unit within each gully catchment. This may however be an issue for consideration in any future research and these possibilities are discussed further in Chapter 8 (page 262).

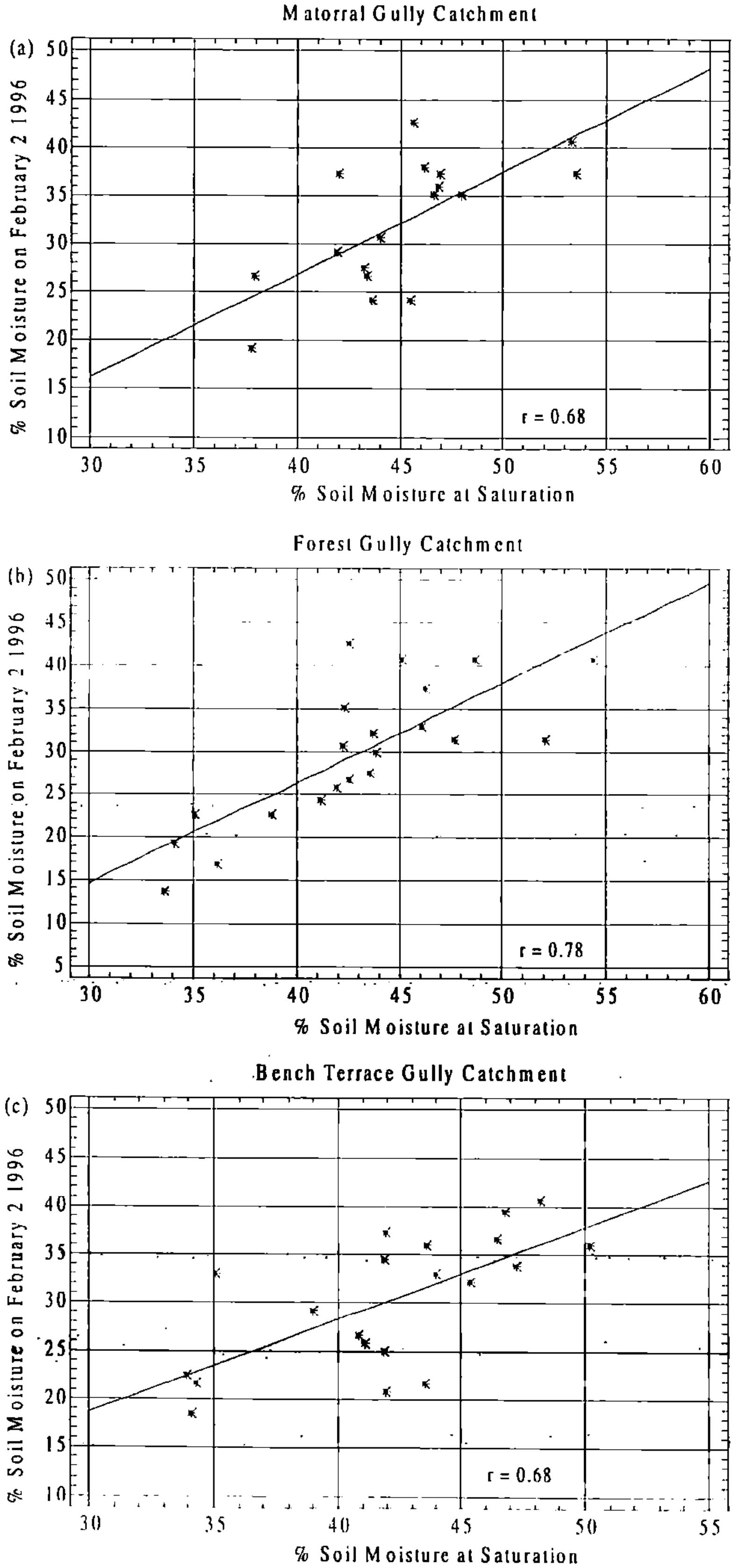
In light of this variation in soil moisture threshold values, the minimum, maximum and average soil moisture value measured by TDR on February 2 1996 within each gully catchment is used to construct three scenarios which cover the range of critical soil moisture thresholds above which runoff may be expected to occur. The minimum, maximum and average critical saturated soil moisture thresholds for the matorral gully catchment are therefore 19.1%, 42.5% and 32.2% respectively; 13.6%, 42.5% and 29.8% respectively for the forest gully catchment and 18.4%, 40.6% and 30.2% respectively for the bench terrace gully catchment. In the same study area Ternan *et al.* (1997) have also identified soil moisture thresholds above which runoff volumes increased significantly. For undisturbed matorral plots a soil moisture threshold of approximately 27% was considered critical for runoff generation. In the bench terraced area a slightly higher soil moisture threshold (34%) was identified (Ternan *et al.*, 1997). The average soil moisture thresholds reported here for the matorral and bench terrace gully catchments are in good agreement with the respective soil moisture thresholds reported by Ternan *et al.* (1997).

In addition, the saturated soil moisture values recorded at certain grid cells by the Pitman cores within each catchment have been interpolated (linear interpolation) to provide a saturated soil moisture value for the remaining unmeasured grid cells. Several saturation threshold values are therefore derived, ranging from 30% to 50% soil moisture. The results from this approach which differs from taking the minimum, maximum and average critical saturated soil moisture thresholds can be compared to the saturated soil moisture pattern on February 2 1996 derived by using the average saturated soil moisture threshold. This comparison is shown in figures 7.5c, 7.6c and 7.7c. However, similar to taking the average saturation threshold value this alternative approach, based on interpolating thresholds from the Pitman core data, may also assign a saturation threshold value to grid cells which is very different from the true value. In addition this alternative approach may be unreliable since for example, in the forest gully catchment the threshold values of 150 unmeasured grid cells have been interpolated from just 20 measured grid cells, the spatial distribution of which may not be favourable for interpolation.

Figure 7.3: The direction of overland flow for every 5x5m cell within each of the gully catchments.



Figures 7.4: Regression analysis between the percentage soil moisture at saturation and the percentage soil moisture measured by TDR on February 2 1996.



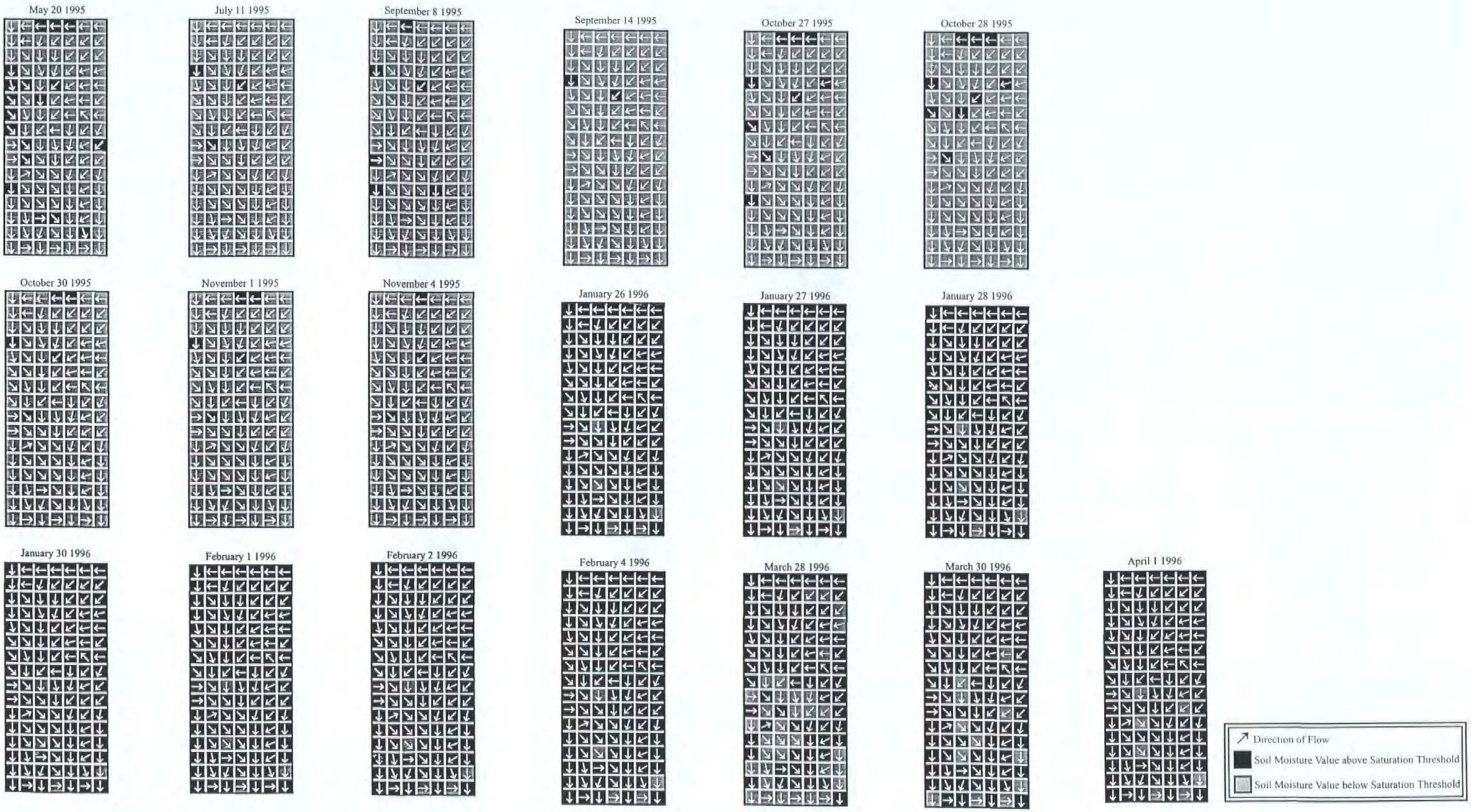
Note: Although some differences between values occur this is due to their derivation from different soil volumes.

For every soil moisture sampling date a soil moisture value was recorded at the centre of every 5x5m cell within each of the gully catchments. In figures 7.5a, b, c, 7.6a, b, c and 7.7a, b, c, three scenarios are presented in which the cells within each gully catchment which have a soil moisture value equal to or above the minimum, maximum and average critical threshold value for that catchment are shaded in black and may therefore be considered as areas which will generate runoff with the onset of rainfall. The cells which have soil moisture values below these critical thresholds are shaded in grey and may be considered as sink areas for the runoff generated from the source areas. It should be noted that the minimum and maximum critical threshold values represent the extremes to a range over which grid cells are saturated. Each of the gully catchments will in reality display a spatial pattern of saturation which lies somewhere in between the two extremes presented here. Since this actual spatial pattern cannot be determined the average critical threshold value may be considered as the best approximate of the gully catchments true hydrological behaviour. The discussions below are therefore based on the results obtained from the average critical threshold value.

It can be seen from these figures that relatively few cells have soil moisture values above the critical threshold identified for runoff generation during dry conditions. Even during the scenario when saturation point is based on the minimum soil moisture threshold are only a small percentage of the grid cells saturated during dry conditions. During dry periods therefore the generation of runoff via saturation overland flow is expected to be minimal within the gully catchments. Any widespread runoff which does occur is presumed to be generated by infiltration excess during high intensity rainfall events when the majority of the hydrological response units infiltration threshold is exceeded. In contrast during wet periods a far greater number of cells within each gully catchment have soil moisture values above the minimum and average critical threshold values. The potential for widespread runoff during wet conditions is therefore higher than during dry conditions and is a finding similar to that reported by Blackburn (1975), Bryan (1994), Cerda (1997), Merz and Plate (1997) and Grayson *et al.* (1997).

The spatial pattern of saturated grid cells on February 2 1996 as determined from the interpolated Pitman core data can be compared to the spatial pattern of saturated grid cells for the same date based on the average saturation threshold in figures 7.5c, 7.6c and 7.7c. Although February 2 1996 represents the date on which the highest soil moisture values were recorded by TDR, very few of the grid cells are saturated based on the thresholds derived from the interpolated Pitman core data. This may be accounted for by the different soil depth and soil volume over which soil moisture is derived from the Pitman cores compared to the TDR. Furthermore the small number of grid cells which are saturated based on the interpolated Pitman core data (only 9.8% in the matorral gully, 16.5% in the forest gully and 1.9% in the bench terrace gully) are unlikely to account for the widespread saturation and generation of catchment runoff observed within the field during this period (plates 7.1 and 7.2)

Figure 7.5a: Temporal and spatial patterns of grid cells with soil moisture values above and below the minimum critical saturation threshold (19.1%) within the Matorral gully catchment.



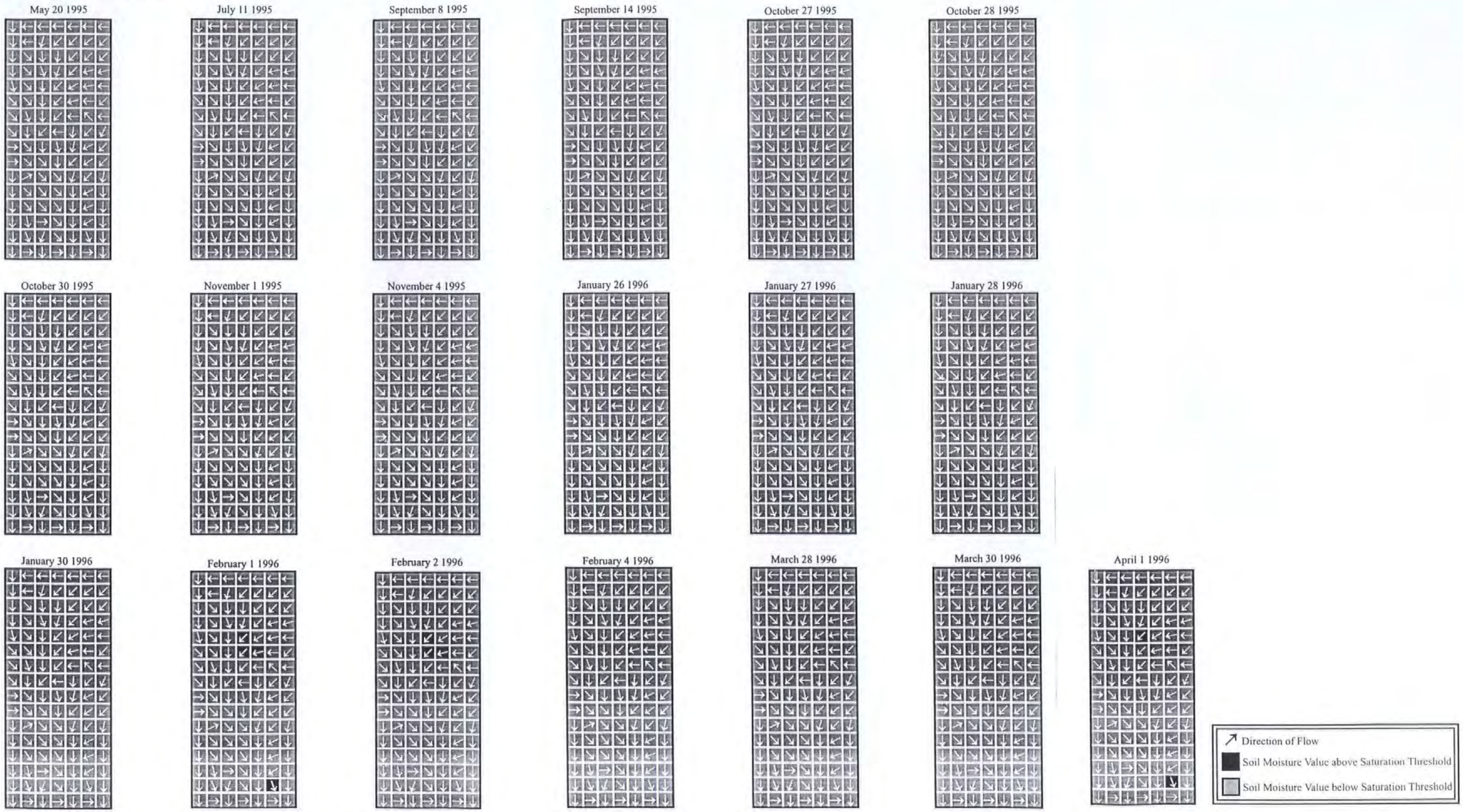


Figure 7.5b: Temporal and spatial patterns of grid cells with soil moisture values above and below the maximum critical saturation threshold (42.5%) within the Matorral gully catchment.

Figure 7.5c: Temporal and spatial patterns of grid cells with soil moisture values above and below the average critical saturation threshold (32.2%) within the Matorral gully catchment.

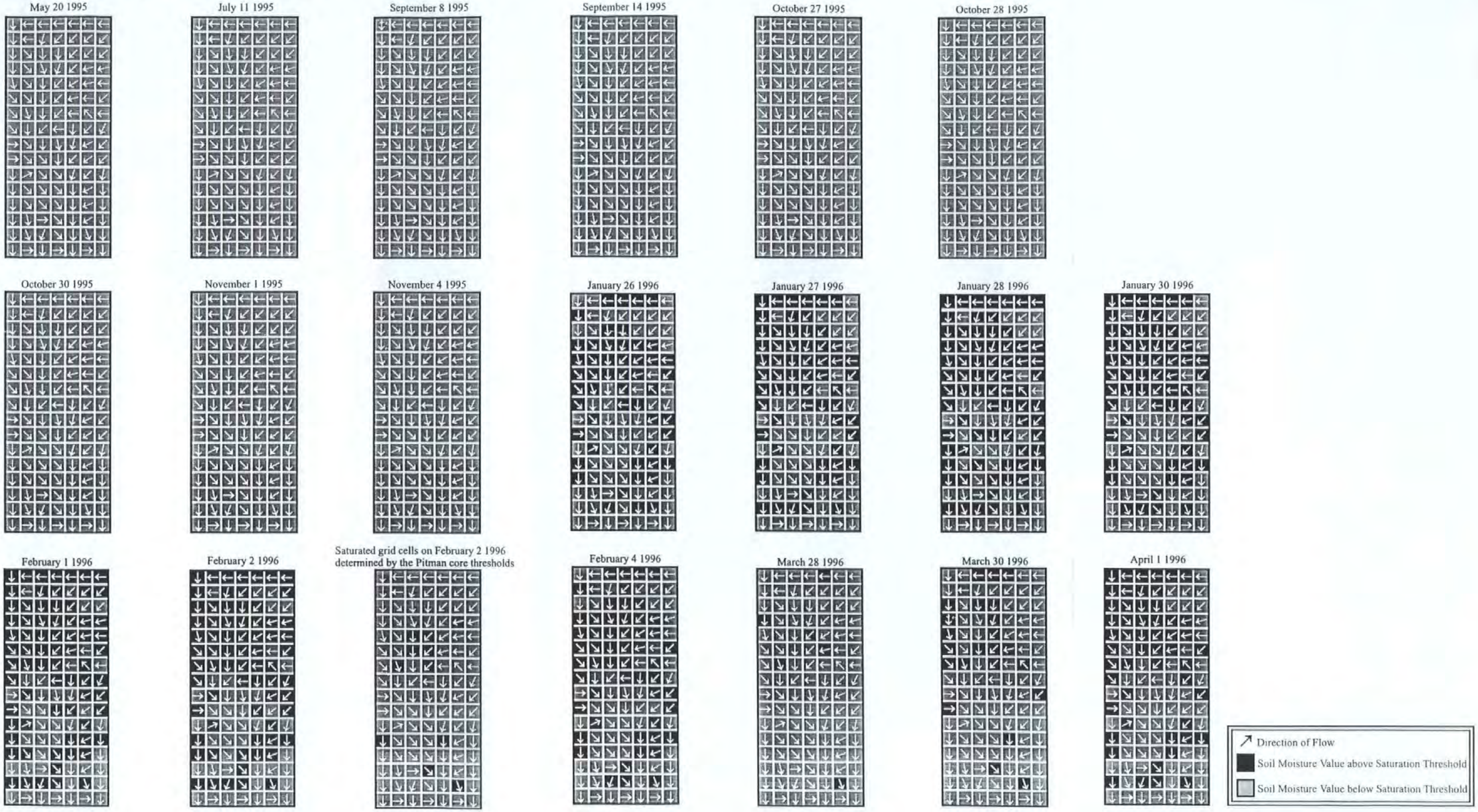


Figure 7.6a: Temporal and spatial patterns of grid cells with soil moisture values above and below the minimum critical saturation threshold (13.6%) within the Forest gully catchment.

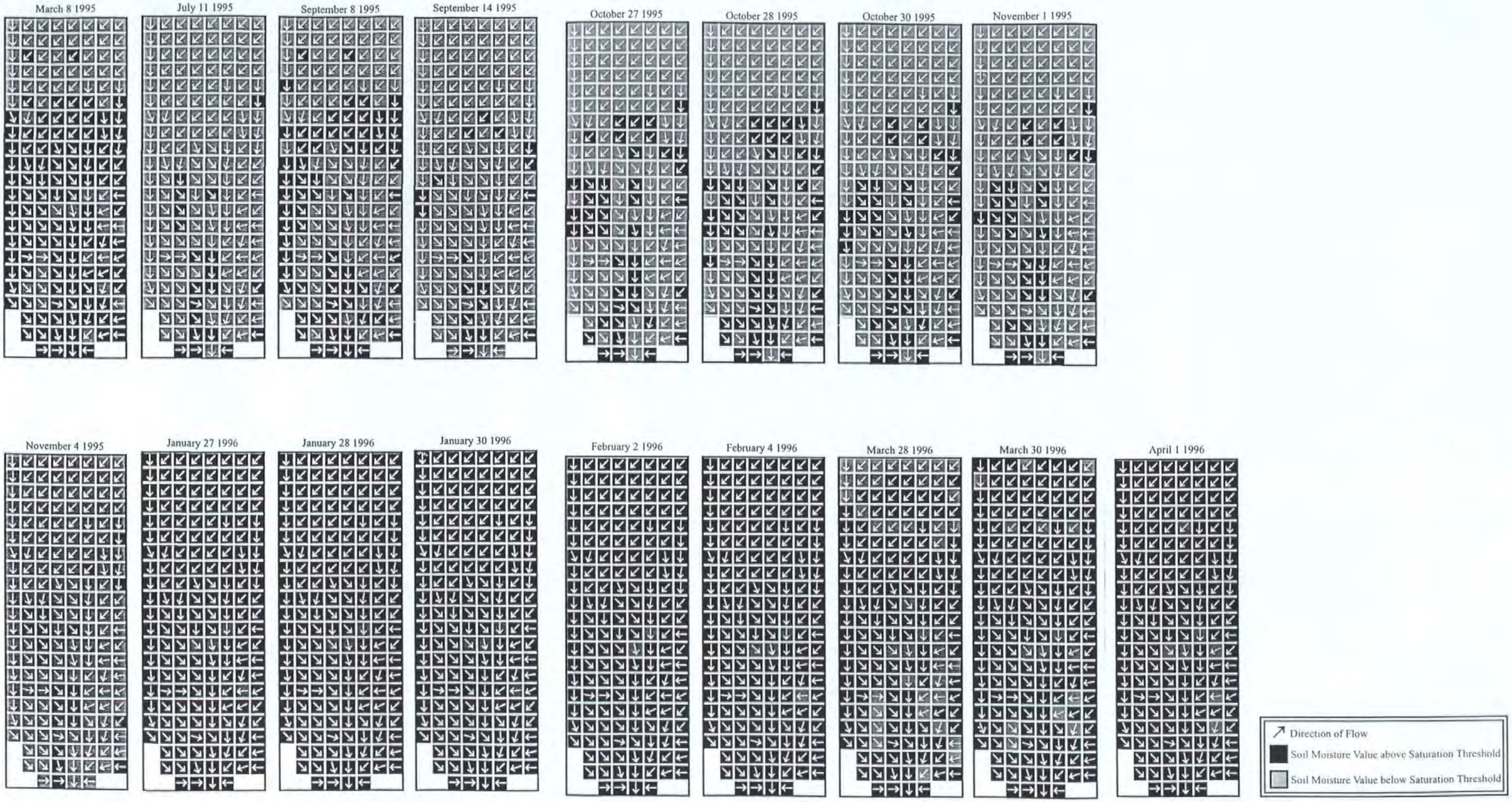


Figure 7.6b: Temporal and spatial patterns of grid cells with soil moisture values above and below the maximum critical saturation threshold (42.5%) within the Forest gully catchment.

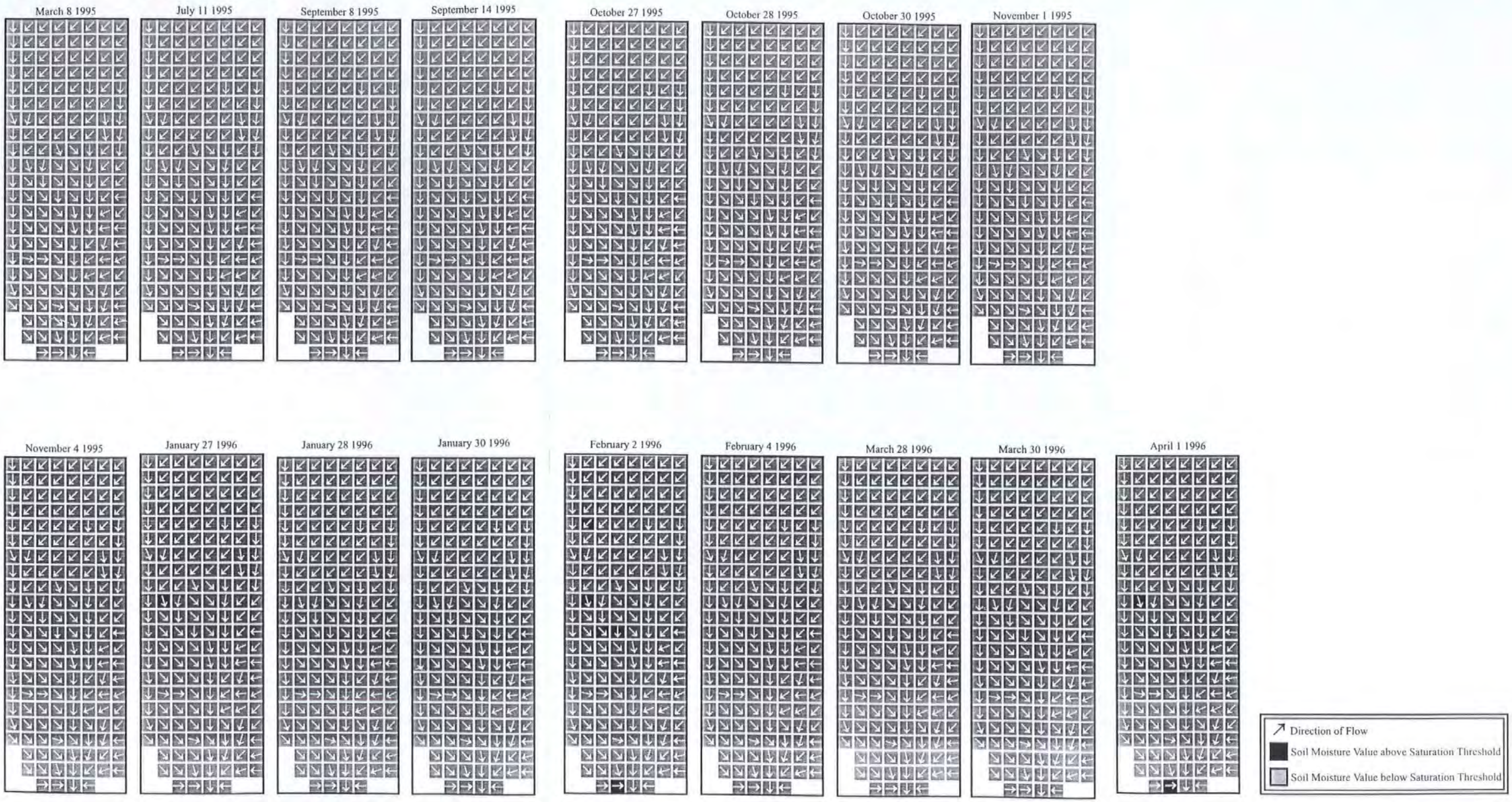


Figure 7.6c: Temporal and spatial patterns of grid cells with soil moisture values above and below the average critical saturation threshold (29.8%) within the Forest gully catchment.

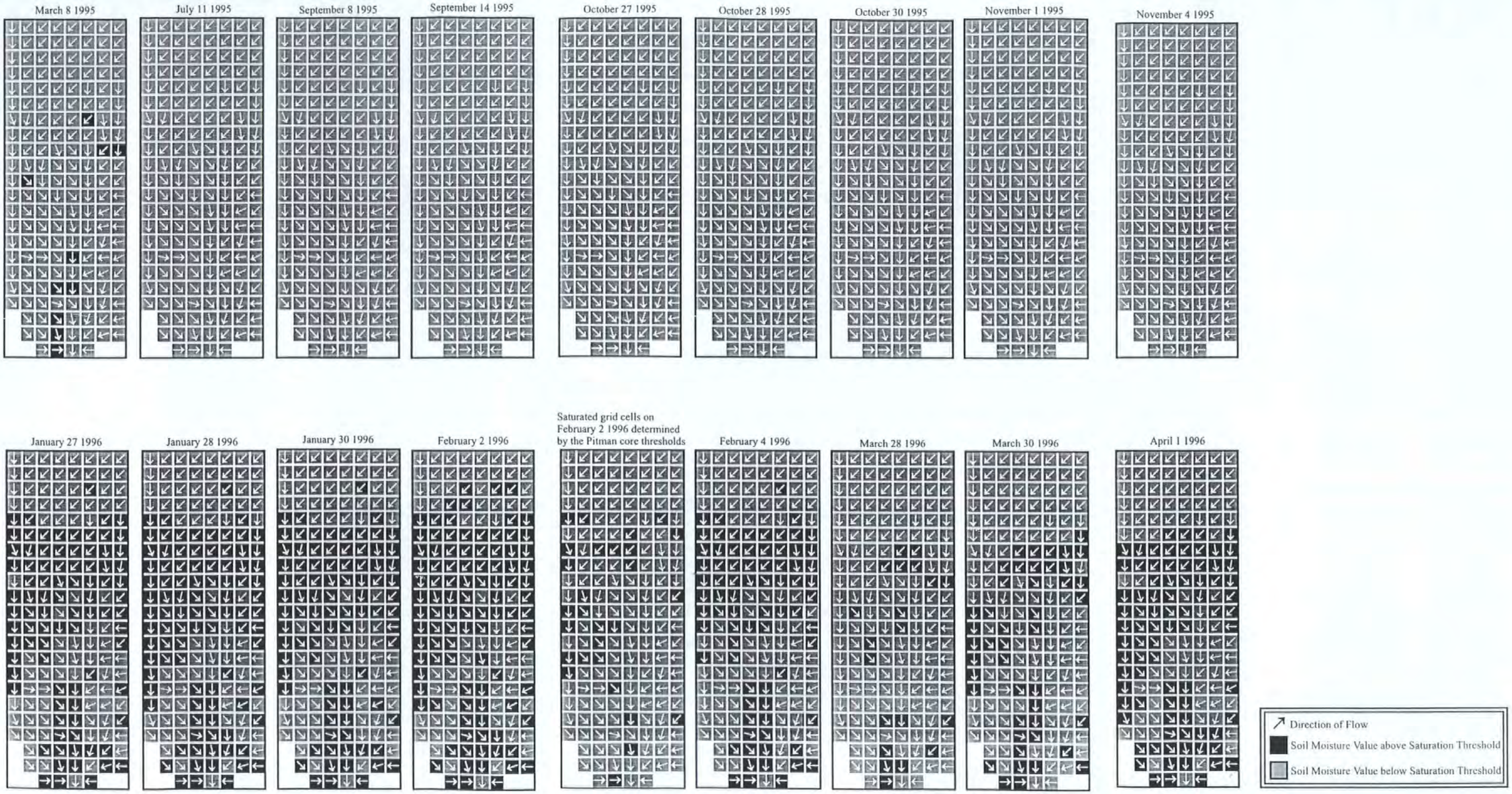


Figure 7.7a: Temporal and spatial pattern of grid cells with soil moisture values above and below the minimum critical saturation threshold (18.4%) within the Bench Terrace gully catchment.

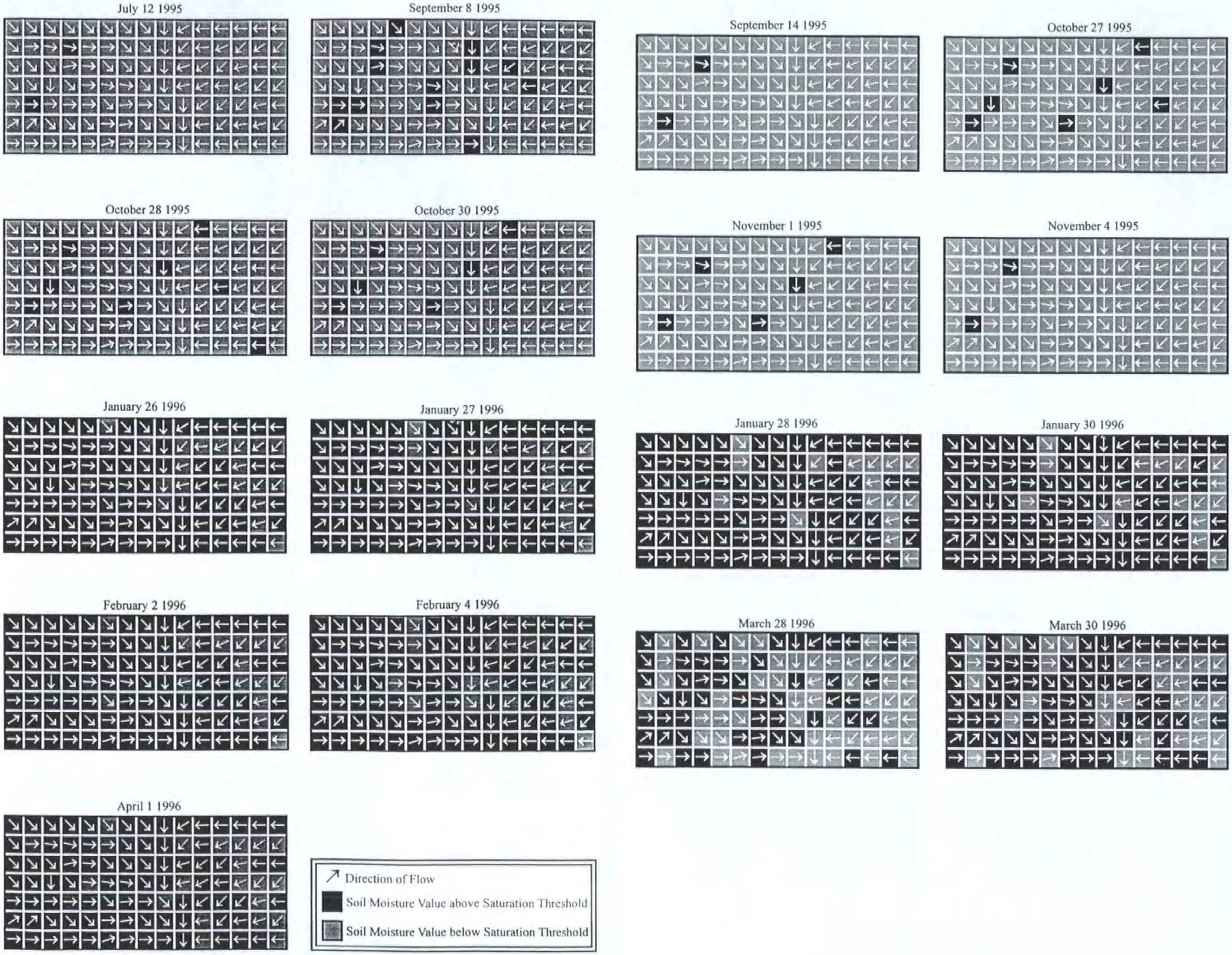


Figure 7.7b: Temporal and spatial pattern of grid cells with soil moisture values above and below the maximum critical saturation threshold (40.6%) within the Bench Terrace gully catchment.

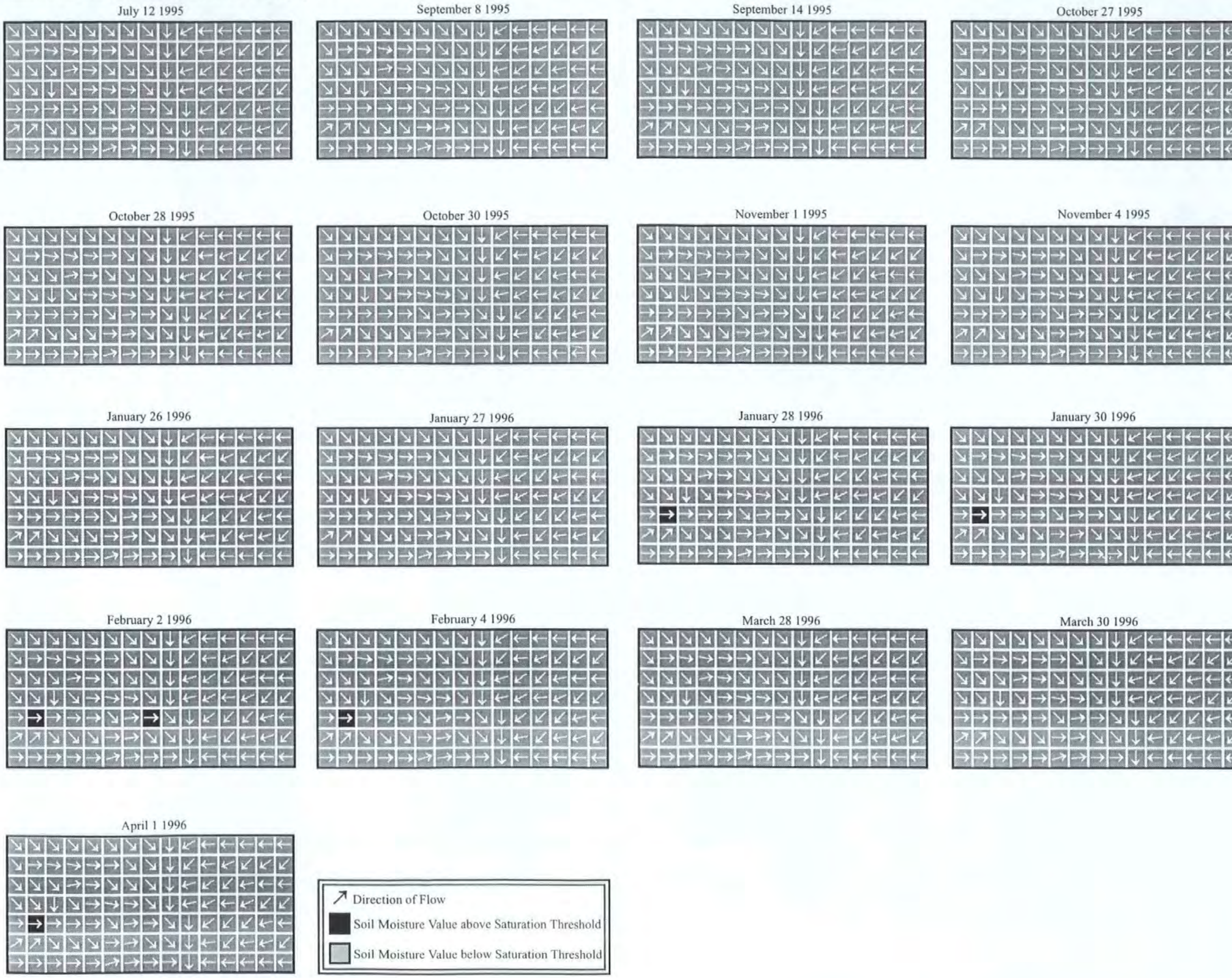


Figure 7.7c: Temporal and spatial pattern of grid cells with soil moisture values above and below the average critical saturation threshold (30.2%) within the Bench Terrace gully catchment.

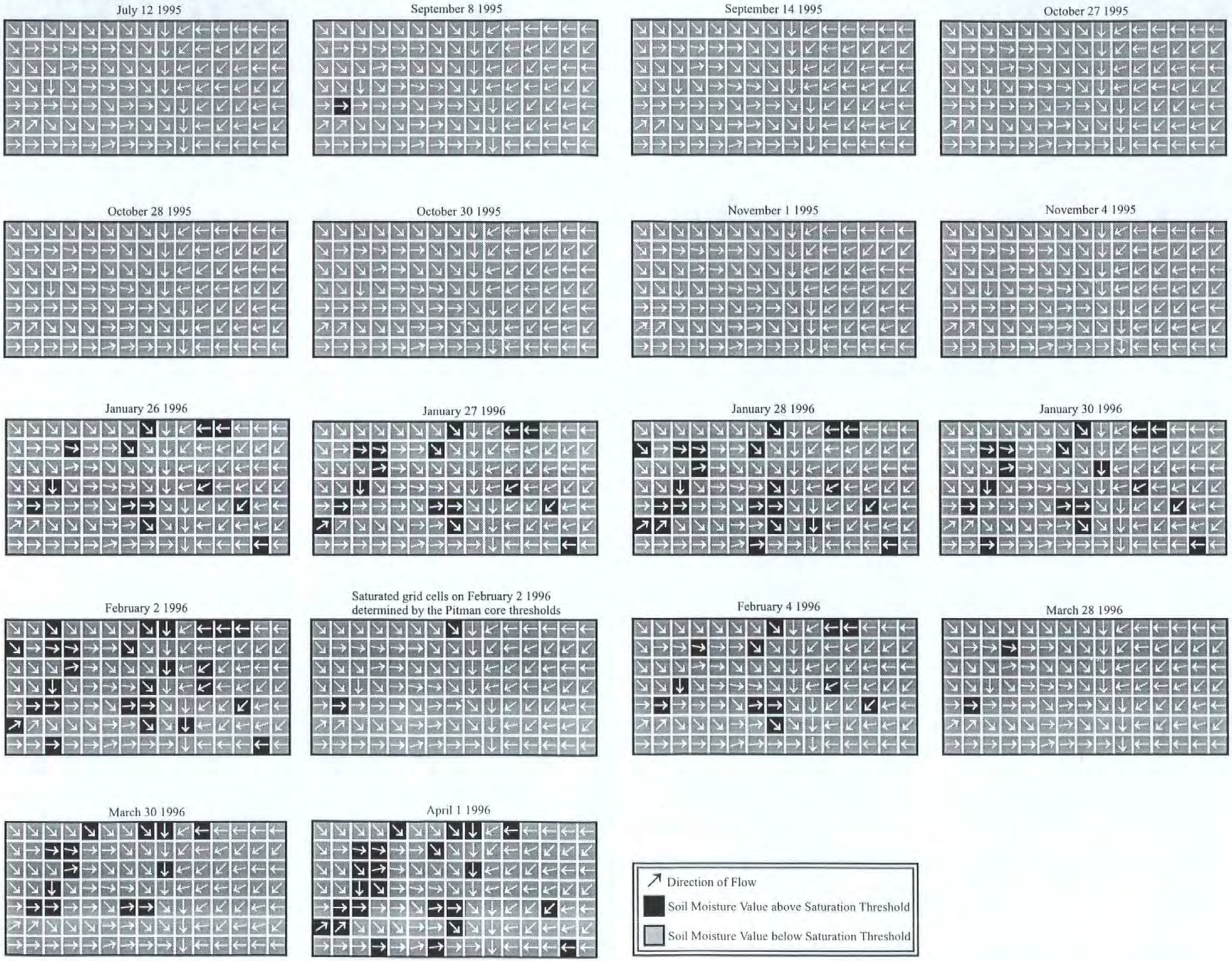


Table 7.2 shows for every sampling date within each gully catchment, the percentage of grid cells which have soil moisture values above the minimum, maximum and average critical threshold value and hence which may be considered as saturated. In the matorral and forest gullies none of the cells have a soil moisture value above the average threshold during dry conditions and in the bench terrace gully only 1% of the cells are above the average threshold on September 8 1995. In contrast, during wet conditions soil moisture values within the matorral and forest gully catchments may be persistently higher than the average critical threshold value for over 50% of these gullies catchment area, reaching a maximum of 66% in the matorral gully and 58% in the forest gully. During wet periods therefore more than 50% of the matorral and forest gullies catchment area may be frequently generating runoff. In the bench terrace gully however the maximum percentage of saturated grid cells (24.8%) is less than half the percentage found within the matorral and forest gully catchments during wet periods. Furthermore the percentage of the bench terrace gully's catchment area which is generating runoff is persistently less than 20% during these conditions. In comparison to the matorral and forest gully catchments, the bench terrace gully will therefore generate less runoff under similar rainfall conditions.

The number of source areas (saturated grid cells based on the average critical threshold) may increase dramatically over a short period of time within each of the gully catchments. After just 2 days for example a near doubling in the percentage of saturated grid cells can be seen within each catchment from March 30 1996 to April 1 1996. Similarly, the percentage of saturated grid cells may fall rapidly as observed between February 2 1996 and February 4 1996. During wet periods soil moisture values are high and are close to or at the average threshold value. Additional rainfall or a few days without rainfall may therefore dramatically change the percentage of source areas contributing runoff within each gully catchment. Hodges and Bryan (1982) have reported that the interval between storms is a critical factor in determining the severity and extent of runoff and erosion. Furthermore, run-on from source areas may raise the soil moisture value of downslope sink areas to a point above the threshold value. The sink areas, particularly those with a soil moisture value just below the average threshold, will therefore rapidly develop into source areas as a result of the combined infiltration from rainfall and upslope runon.

Table 7.2. The percentage of grid cells which have soil moisture values above the critical threshold value.

Soil Moisture Sampling Dates	Matorral Saturated Grid Cells (%)			Forest Saturated Grid Cells (%)			Bench Terrace Saturated Grid Cells (%)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
March 8 1995	----	----	----	5.9	65.3	0	----	----	----
May 20 1995	0	16.1	0	----	----	----	----	----	----
July 12 1995	0	2.7	0	0	11.8	0	0	1.9	0
September 8 1995	0	5.4	0	0	40	0	1	12.4	0
September 14 1995	0	1.8	0	0	10.6	0	0	1.9	0
October 27 1995	0	8	0	0	25.3	0	0	6.7	0
October 28 1995	0	8	0	0	30.6	0	0	7.6	0
October 30 1995	0	4.5	0	0	24.1	0	0	5.7	0
November 1 1995	0	4.5	0	0	19.4	0	0	4.8	0
November 4 1995	0	2.7	0	0	12.4	0	0	1.9	0
January 26 1996	45.5	95.5	0	----	----	----	12.4	79	0
January 27 1996	55.4	96.4	0	50.6	97.6	0.6	15.2	86.7	0
January 28 1996	66.1	96.4	0	54.7	98.2	0	21	84.8	1
January 30 1996	55.4	96.4	0	51.2	97.6	0	16.2	84.8	1
February 1 1996	64.3	96.4	3.6	----	----	----	----	----	----
February 2 1996	62.5	95.5	2.7	58.8	98.8	2.9	24.8	84.8	1.9
February 4 1996	48.2	95.5	0	44.7	97.6	0	11.4	81	1
March 28 1996	5.4	68.8	0	11.8	74.7	0	1.9	48.6	0
March 30 1996	20.5	89.3	0	26.5	91.2	0	12.4	68.6	0
April 1 1996	47.3	93.8	1.8	48.8	95.9	1.2	21.9	79	1

The percentage of grid cells with soil moisture values above the average critical threshold provides little information regarding the connectivity between these cells and more significantly with the gully channels. Table 7.3 therefore shows for every sampling date within each of the gully catchments the percentage of grid cells which are saturated and which either drain directly or indirectly, through adjoining saturated cells, to a gully channel. This connectivity provides a measure of the continuity in hydrological pathways within each of the gully catchments. During dry conditions the hydrological pathways within each of the gully catchments are discontinuous and none of the source areas are connected to the channel. During wet conditions the extent of continuity in hydrological pathways varies between the gully catchments and is closely related to the percentage of saturated grid cells. In the matorral gully, hydrological pathways are most continuous, with up to 54% of the source areas being hydrologically connected to the catchment channel. In the forest gully a maximum of 37.1% of the source areas may be hydrological connected to a channel and discontinuity in hydrological pathways is greatest within the bench terrace gully where only a maximum of 14.3% of the source areas may be hydrologically connected to a channel. The continuity in hydrological pathways may in part be greater in the matorral and forest gullies due to the greater number of channels within these catchments compared to the bench terrace gully. Hydrological pathways may therefore be shorter in the matorral and forest gullies and hence will have a greater likelihood of being continuous. Most significantly however, the continuity in hydrological pathways is related to the percentage of saturated grid cells which are significantly fewer in number within the bench terrace gully catchment (table 7.2). Furthermore, similar to table 7.2, the continuity of source areas within each of the gully catchments may increase or decrease dramatically within a few days during wet conditions. On March 30 1996 for example, 15% of the source areas within the matorral gully and 11% within the forest gully were connected. Just 2 days later on April 1 1996, the percentage of connected source areas increased to 40% and 30% within the matorral and forest gully catchments respectively (table 7.3). The continuity in hydrological pathways has therefore more than doubled over this short period of time. During wet periods when soil moisture values are close to their average threshold, continuity in hydrological pathways may therefore increase rapidly with the potential consequence of widespread runoff which can reach the catchment outlet. Burt and Butcher (1985) have also reported the rapid development of widespread connectivity resulting from further additions of rainfall during already very wet conditions. Similarly, discontinuity in hydrological pathways may also be rapid as can be observed from February 2 1996 to February 4 1996 within each of the gully catchments (table 7.3).

Table 7.3. The percentage of grid cells which are saturated and which either drain directly or indirectly through adjoining saturated cells to a gully channel

Soil Moisture Sampling Dates	Matorral Connected Cells (%)			Forest Connected Cells (%)			Bench Terrace Connected Cells (%)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
March 8 1995	----	----	----	2.9	61.2	0	----	----	----
May 20 1995	0	9.8	0	----	----	----	----	----	----
July 12 1995	0	1.8	0	0	7.1	0	0	0	0
September 8 1995	0	1.8	0	0	17.6	0	0	4.8	0
September 14 1995	0	0.9	0	0	5.9	0	0	0	0
October 27 1995	0	3.6	0	0	14.1	0	0	1.9	0
October 28 1995	0	4.5	0	0	17.6	0	0	1.9	0
October 30 1995	0	1.8	0	0	14.7	0	0	1.9	0
November 1 1995	0	1.8	0	0	10	0	0	1.9	0
November 4 1995	0	1.8	0	0	6.5	0	0	0	0
January 26 1996	33.0	90.2	0	----	----	----	7.6	56.2	0
January 27 1996	45.5	92	0	34.1	95.6		7.6	75.2	0
January 28 1996	54.5	92	0	37.1	100	0	9.5	75.2	0
January 30 1996	46.4	92	0	34.7	95.6	0	8.6	78.1	0
February 1 1996	52.7	92	2.7	----	----	----	----	----	----
February 2 1996	52.7	90.2	2.7	37.7	100	1.8	14.3	69.5	0.9
February 4 1996	36.6	90.2	0	24.7	95.6	0	7.6	57.1	0
March 28 1996	2.7	59.8	0	5.3	65.9	0	0	23.8	0
March 30 1996	15.2	73.2	0	11.2	84.1	0	6.7	40	0
April 1 1996	40.2	88.4	0.9	30.6	92.9	0.6	8.6	53.3	0

During wet periods therefore the continuity in hydrological pathways is finely balanced between being continuous resulting in widespread runoff and discontinuous resulting in minimal runoff. On several occasions during the wet period rainfall of moderate to low intensity was observed to cause catchment wide runoff resulting in considerable runoff and sediment discharge in the gully channels (Plate 7.2).

Llorens and Gallart (1992) have also reported a fast response with high runoff coefficients when the catchment reaches conditions near to saturation.

Plate 7.2. Runoff and sediment discharge within the Forest gully's main channel during the wet period.

7.2.4 Implications for Erosion

The evidence presented above suggests that the occurrence of widespread runoff will be greater during wet periods, when soil moisture conditions are more likely to be above the saturation threshold and subsequently hydrological pathways are more continuous than during dry periods. Consequently the severity and spatial extent of erosion may also be expected to be greater during wet periods compared to dry periods. Govers and Loch (1993) and Vandaele and Poesen (1995) have however reported that higher initial water contents leads to a higher erosion resistance. Erodibility and erosion may therefore be highest during dry summer periods when desiccation proceeds heavy rainfall (Vandaele and Poesen, 1995). Furthermore soil aggregates may be more stable at higher initial water contents due to a greater resistance to slaking forces (Truman *et al.*, 1990; Rasiah *et al.*, 1992). In contrast Bajracharya and Lal (1992) have reported that erodibility of a Miamian silt loam soil is highest under wet conditions during the winter and spring when soil strength is lowest. Ireland *et al.* (1939) have also reported that

"saturation caused by prolonged drizzling rains during the wet season provided conditions during which most of the gully erosion occurred".

Blackburn (1975) has further argued that under higher initial soil water conditions, the rapid generation of runoff allows a longer time to erode dispersed particles. Bryan and Yair (1982) have also reported that in Mediterranean environments, badland erosional processes are almost entirely confined to the winter or wet season.

At every soil moisture sampling point within each of the gully catchments erosion and/or deposition was recorded throughout the study period (Chapter 3, section 3.2 and 3.3.5). The measurement of erosion and deposition therefore covers the spatial extent of the gully catchments using 5m sampling intervals. To determine under which conditions the severity and spatial extent of erosion is greatest and therefore whether erosion can be related to soil moisture conditions, the erosion data have been separated into measurements recorded during dry periods (July 11 1995 to November 1 1995) and measurements recorded during wet periods (November 1 1995 to April 1 1996), based on the same division in sampling dates as used in the soil moisture data. Within each gully catchment in both dry and wet conditions the spatial pattern of net erosion was not significantly correlated to the spatial pattern of soil moisture on any of the sampling dates. This suggests that sediment sources are therefore generally not in the same location as source areas of surface runoff. Johnson and Gordon (1988) have also reported no significant differences in soil loss between areas with high and low soil moisture conditions. Scoging (1989) has further argued that the spatial pattern of erosion may be related to variations in sediment availability and the detachment – transport capacity relationship rather than the spatial pattern of source areas. Table 7.4 shows the net erosion, represented by surface lowering, recorded within each gully catchment during dry and wet periods. During both periods and within each gully catchment erosion is greater than deposition which implies that sediment is either exiting the gully catchments (even during dry periods) or deposition is occurring at a spatial scale shorter than 5m. Furthermore, net erosion can be seen to be significantly higher during wet periods compared to dry periods within each gully catchment. In the matorral gully catchment an 84% increase in net erosion occurs during the wet period. In the forest and bench terrace gullies the increase in net erosion during the wet period is 70% and 57% respectively. The severity of erosion is therefore greatest during wet periods when the three gully catchments may be considered as spatially interactive and hence when the frequency of widespread runoff is highest. In New South Wales, Australia, Murphy and Flewin (1993) have also reported greater erosion during wet conditions than if the same rain had fallen when the soil was dry. During dry periods, the majority of the hydrological response units soil moisture values are well below the threshold conditions necessary to generate runoff. Together with discontinuous hydrological pathways, runoff will be minimal and consequently the severity of erosion will be lower. Furthermore, the erosion data in table 7.4 suggests that the erosion caused by rainfall events of high intensity during dry periods when the majority of the catchments area may also be contributing runoff is minor in comparison to the erosion caused during wet periods. Murphy and Flewin (1993) have reported that periods of low intensity but frequent rainfall can cause saturation driven runoff leading to higher rates of soil erosion than would be expected from analysis of rainfall intensity alone.

Table 7.4. The net erosion (erosion minus deposition) recorded within each gully catchment during dry and wet periods.

Net Erosion (Erosion-Deposition)	Matorral Gully (mm)			Forest Gully (mm)			Bench Terrace Gully (mm)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Dry Periods (July 11 1995 – November 1 1995)	**-0.9**	**+11**	**-13**	**-1.1**	**+4**	**-19**	**-2.5**	**+22**	**-26**
Wet Periods (November 1 1995 – April 1 1996)	-5.6	+13	-37	-3.8	+29	-41	-5.8	+33	-56
Difference between Dry and Wet Periods	-4.7	----	----	-2.7	----	----	-3.3	----	----
Increase from Dry to Wet Periods (%)	84%	----	----	70%	----	----	57%	----	----

Table 7.5 shows within each of the gully catchments the number of sampling locations recording erosion during dry and wet periods and therefore provides information concerning the spatial extent of erosion

during these two conditions. Within each gully catchment the spatial extent of erosion is significantly higher during wet conditions compared to dry conditions. In the matorral gully a 34% increase in the number of sites measuring erosion occurs during the wet period. In the forest and bench terrace gullies a 42% and 28% increase respectively in the number of areas undergoing erosion occurs during wet periods. During wet periods therefore, when hydrological pathways are more continuous and the occurrence of widespread runoff is more prevalent, the spatial extent of erosion will be greater than during dry conditions when the catchments may be considered as being spatially isolated. Temporal changes in the extent and magnitude of soil erosion has been recognised and reported by several authors (Ireland *et al.*, 1939; Thornes, 1980; Campbell and Honsaker, 1982; Bryan and Yair, 1982; Yair and Lavee, 1985).

Table 7.5. The number of sampling locations recording erosion (spatial extent) during dry and wet periods.

Spatial Extent of Erosion (Number of Eroding Sites)	Matorral Gully	Forest Gully	Bench Terrace Gully
Dry Periods (July 11 1995 – November 1 1995	49	37	56
Wet Periods (November 1 1995 – April 1 1996)	74	64	78
Difference between Dry and Wet Periods	25	27	22
Increase from Dry to Wet Periods (%)	34%	42%	28%

7.2.5 Summary

A mosaic pattern of areas of contrasting hydrological response, as reflected in the spatial pattern of soil moisture, can be observed within each of the gully catchments. During dry conditions the mosaic pattern is fragmented and source areas are spatially isolated resulting in discontinuous hydrological pathways. In addition the majority of the hydrological response units soil moisture values during this period are well below the average saturation threshold necessary to generate runoff. During dry periods therefore, the catchments may be considered as spatially isolated and when runoff and erosion does occur, it is highly localised and minimal in its severity and spatial extent. During these conditions widespread runoff and erosion may only occur when the intensity of rainfall events exceeds the majority of hydrological response units infiltration threshold. The relatively low frequency and short duration of these events ensures however, that the runoff and erosion which occurs during dry periods is small in comparison to the runoff and erosion occurring during wet periods.

During wet periods the spatial extent and number of source areas within each of the gully catchments increases as more and more hydrological response units soil moisture values near the average saturation threshold. The potential for widespread runoff and erosion is therefore much greater than during dry periods. In addition the continuity of hydrological pathways also increases as large areas of similarly high soil moisture occur. The potential for widespread runoff and erosion to be transported outside of the catchments is therefore also greater during wet periods. Furthermore the development of continuous or discontinuous hydrological pathways has been shown to be rapid during wet periods as rainfall events are frequent, maintaining soil moisture values constantly close to the saturation threshold. During wet periods the three gully catchments may be considered as spatially interactive and the occurrence of widespread runoff and erosion is dependent upon the frequency of rainfall events and hence the times during which conditions are above the critical threshold values.

Different hydrological responses may therefore be expected to occur from the gully catchments and will show a temporal dependence upon whether conditions are above or below the critical threshold. In the following and final section of this chapter the implications of mosaic patterns of areas of contrasting hydrological response, continuity in hydrological pathways and the existence of thresholds for hydrological monitoring and management will be discussed.

7.3 Implications for Hydrological Monitoring and Management

7.3.1 Scale Issues

Hydrological response units have been reported over a range of scales from within runoff plots as small as 1.5m^2 (Morin and Kosovsky, 1995; Bergkamp *et al.*, 1996), to hillslopes (Blackburn, 1975; Cerda, 1995) and catchments (Imeson *et al.*, 1992; Yair, 1992). In this study a mosaic pattern of soil moisture reflecting contrasting areas of hydrological response has been reported for the micro (1m), meso (5m) and macro-scales (25m). The mosaic pattern formed by areas of contrasting hydrological response appears therefore, to be scale-independent ie. a mosaic pattern of contrasting hydrological response units may be found at all scales. Furthermore the hydrological response units in a mosaic pattern found at one scale form one level in a nested hierarchical scalar system, the complexity of which increases with increasing scale (Campbell and Honsaker, 1982; Bergkamp, 1995). At large scales eg. catchments, there will be greater complexity with several nested levels of mosaic patterns. At each level, the factors determining the mosaic pattern may differ resulting in different magnitudes and processes of runoff at each scale (Seyfried and Wilcox, 1995; Poesen *et al.*, 1996; Nicolau *et al.*, 1996). For example, at the microscale the mosaic pattern may be determined by differences in the stability of soil aggregates (Poesen *et al.*, 1996), whereas at the hillslope and catchment scale the mosaic pattern may be related to topography, soil and vegetation patterns (Nicolau *et al.*, 1996; Kirkby *et al.*, 1996). At each larger scale the factors that determine runoff at that scale may override the factors generating runoff at smaller scales (Seyfried and Wilcox, 1995; Nicolau *et al.*, 1996). Furthermore, for a storm to initiate catchment scale runoff and erosion it must overcome the spatial arrangement and threshold values of hydrological response units at all smaller scales. Widespread runoff and erosion at the catchment scale therefore requires prolonged or larger magnitude storms, whereas widespread runoff and erosion at smaller scales, with fewer nested levels, may be initiated by shorter duration or lower magnitude storms. Catchment scale events may therefore occur irrespective of the spatial arrangement or threshold values of mosaic patterns at all smaller scales. Based on this concept, Wood *et al.* (1990) proposed the existence of a Representative Elementary Area (REA).

"The REA is the scale at which spatial patterns no longer have to be considered and similarity can be assumed" (Wood et al., 1990).

The REA occurs at the scale where variation in the response between areas falls to a level which is considered acceptable (Wood *et al.*, 1990). At scales above the REA therefore, nonspatial statistics such as the mean and variance can be used to adequately describe the hydrological response (Seyfried and Wilcox, 1995). At scales smaller than the REA however, the spatial patterns of variability must be measured and considered when describing the hydrological response at these scales (Wood *et al.*, 1990; Seyfried and Wilcox, 1995). The concept of the REA may therefore be considered as analogous to the concept of thresholds with however, one exception. The concept of the REA assumes decreasing variability with increasing scale (Seyfried and Wilcox, 1995). Increases in scale however, introduces new sources of heterogeneity (Seyfried and Wilcox, 1995; Mahmood, 1996). It is well known that two samples taken adjacent to each other will be more similar than samples taken further apart (Journel and Huijbregts, 1978; Trangmar *et al.*, 1985; Oliver and Webster, 1991; Cambardella *et al.*, 1994). The existence of an REA is therefore dependent upon the degree of heterogeneity encountered within an area. For this reason Woolhiser *et al.* (1996) have reported that the REA concept is likely to be less valid in arid and semi-arid regions where variability in the factors controlling runoff generation is greater. Furthermore, Bergkamp (1995) has reported that in semi-arid regions it is the spatial structures at small scales which control the hydrological behaviour of the system at different scales. The concept of the REA may therefore not be useful in semi-arid areas and it is suggested that the concept of thresholds presented here relating to a nested hierarchical scaled arrangement of mosaic patterns is more applicable.

The existence of mosaic patterns of areas of contrasting hydrological response has serious implications for the use of small bounded plots used to characterise runoff from an area (Amerman, 1965; Bonell and Williams, 1987). Within the mosaic pattern, plots may be constructed, unknowingly, over source areas giving the impression of an area under severe degradation when in effect the spatial arrangement of runoff producing areas at the hillslope or catchment scale may be such that hydrological pathways are discontinuous, resulting in minimal runoff and erosion. Several studies have reported that the runoff and erosion estimated from plot studies overestimates the runoff and erosion at the hillslope and catchment scale (Evans, 1995; Poesen *et al.*, 1996; Gascuel-Odoux *et al.*, 1996). Furthermore, since plots are studies conducted at the small scale, the thresholds above which runoff occurs will be lower and hence exceeded more frequently than the threshold conditions necessary to generate runoff at larger scales (Campbell and Honsaker, 1982). The likelihood of continuous hydrological pathways within plots is also greater than can be expected at the hillslope or catchment scale due to the shorter distances involved. Mosaic patterns of areas of contrasting hydrological response may also be found within plots (Morin and Kosovsky, 1995; Bergkamp *et al.*, 1996; Nicolau *et al.*, 1996). The runoff being generated from the plot, depending upon the spatial arrangement of the hydrological response units, may only occur from a few source areas located near the plot outlet and not the entire plot (Morin and Kosovsky, 1995; Nicolau *et al.*, 1996). Similarly results from equipment monitoring for discharge and sediment yield within gully catchments may be affected by the location of source and sink areas in relation to the positioning of the equipment. Careful attention should therefore be paid to the spatial arrangement of hydrological response units within the area of study and within the plot itself, and specifically to their location from the channel or the plot outlet.

7.3.2 Threshold Issues

It has been established (figure 7.1, conceptual model) that when conditions are below the critical threshold value, the severity and spatial extent of runoff and erosion is dependent upon the spatial arrangement of hydrological response units. Above the critical threshold value however runoff and erosion will occur regardless of the spatial arrangement of hydrological response units. Knowing the spatial pattern of hydrological response units is therefore only relevant and useful when conditions are below the critical threshold. Spatial variability can be disregarded when conditions are above the critical threshold (Merz and Plate, 1997). This may have implications for the methodology used in hydrological studies for areas where thresholds, above which runoff is generated, are low. In many semi-arid and in particular arid regions, large areas are degraded. The term degraded infers an environment with low thresholds. In many semi-arid and arid environments thresholds may therefore be low and consequently widespread runoff may occur frequently (Campbell and Honsaker, 1982). In this situation quantifying spatial variability in soils and vegetation may not be important and therefore hydrological studies and models in these areas may disregard spatial variability as being a factor in determining hydrological response. Similarly if the majority of the runoff and erosion from an area is caused by only 2 or 3 storms which always exceed the critical threshold, then quantifying spatial patterns in topography, soils and vegetation may also be unnecessary. Low thresholds above which runoff is generated have been reported in southern Spain. Nicolau *et al.* (1996) identified a rainfall amount of 10mm which was necessary to generate runoff. M-Mena *et al.* (1998) identified a threshold of just 5mm rainfall above which runoff was generated. These thresholds however were determined from plot studies and it should be noted that as the scale of study increases the thresholds necessary to generate widespread runoff may also increase. In semi-arid and arid environments high spatial variability in topography, soils and vegetation may occur, but thresholds are generally low and frequently exceeded which is why many of these areas are undergoing severe degradation. Within these regions quantifying spatial variability may only be useful in very large scale hydrological studies where the critical threshold may not always be exceeded and therefore where spatial variability and consequently discontinuous hydrological pathways may be determining the hydrological response.

7.3.3 Management Implications

In agricultural systems high variability in the soils physical and hydraulic properties is undesirable since it creates dissimilar growing conditions making farming activities more complex (McBratney, 1992). In terms of the ecological value of an area, soil variability may however be beneficial, with distinct soil variations supporting a diversity of ecosystems (Ibanez *et al.*, 1995). McBratney (1992) and Bergkamp (1995) have also reported that a heterogeneous environment is more likely to be resilient to external disturbances than a homogeneous environment. The results presented here and elsewhere (Yair, 1992;

Imeson *et al.*, 1992; Cerda, 1995; Bergkamp *et al.*, 1996, Nicolau *et al.*, 1996) suggest that soil variability may also be advantageous in runoff and erosion control. Lavee *et al.* (1995) and Bergkamp *et al.* (1996) have argued that the heterogeneity of hydrological response induced by spatial structures restricts the severity and spatial extent of erosion. By creating a spatial mosaic pattern of contrasting hydrological response units, soil variability may therefore create a self regulating system in which runoff producing areas are surrounded by buffer zones capable of re-absorbing the runoff (Bergkamp *et al.*, 1996).

The use of buffer zones for erosion control is well documented for humid temperate (e.g. Morgan, 1992) and tropical (e.g. Bonell *et al.*, 1983) environments. These buffer zones usually take the form of vegetation strips which run parallel and adjacent to stream channels with the aim of absorbing runoff and trapping sediment from upslope locations (Vought *et al.*, 1995). Norris (1993) has reported however, that buffer zones positioned close to source areas of surface runoff may be more successful in absorbing runoff and preventing erosion than buffer zones located some distance from the source areas. In semi-arid areas, numerous studies (e.g. Campbell, 1989) have demonstrated that the soil materials in these environments, when exposed, are often highly erodible with severe erosion occurring over very short distances. Creating a spatial mosaic pattern in which buffer zones are adjacent to potential runoff producing areas, as identified from spatial soil moisture patterns, may therefore provide the most effective management strategy in runoff and erosion control for semi-arid environments. Establishing mosaic patterns may be achieved by manipulating vegetation in selected locations to create sinks for overland flow and sediment disposition (Dunne *et al.*, 1991; Nicolau *et al.*, 1996). Where this spatial mosaic pattern occurs naturally, disturbance to the area should be avoided, since a change in the mosaic pattern may increase runoff and erosion (Cerda, 1995). To reduce disturbance, the management of areas displaying a spatial mosaic pattern, should adopt a spatially sensitive approach, allowing practices to vary according to site conditions (Robert, 1993; Burrough, 1993). Management should also aim to increase the threshold value of hydrological response units, reducing the frequency of those times when widespread runoff and erosion may occur.

Where land management in semi-arid areas is primarily concerned with runoff and erosion control, three management aims may therefore be identified.

1. To promote a spatial mosaic pattern of contrasting hydrological response units, increasing spatial variation. Areas vulnerable to runoff will therefore be spatially isolated and hydrological pathways will be discontinuous. Runoff and erosion will be localised and the runoff and sediment reaching the catchment outlet will be minimal. Increasing the spatial variation in land use's may also have the added benefit of improving the ecological value of an area by increasing habitat diversity (Ibanez *et al.*, 1995).

2. Management should also aim to raise the threshold value of the hydrological response units within the spatial mosaic pattern, ie. promote better soil physical and hydrological properties, so that the occurrence of widespread connectivity within the study area is less frequent. Adopting a management approach which is spatially sensitive may best achieve this aim, whilst causing minimal disturbance to the spatial mosaic pattern. It should be noted that management practices which increase spatial variation and thus the spatial isolation of runoff producing areas are of little value in preventing runoff and erosion if the threshold value is very low and hence is exceeded frequently.

3. Identifying spatial patterns of hydrological response and critical thresholds allows the prioritisation and site specific design of erosion control measures (Scoging, 1989; Bryan, 1994; Vandaele and Poesen, 1995). Ireland *et al.* (1939) have reported that seasonal variation in gully activity resulting from seasonal differences in rainfall and runoff suggests that

   "by careful timing of gully control measures man might take advantage of the work already done by nature".

   When conditions are below the critical threshold, the self regulating system established by spatial variability requires little management. Scarce resources used to combat runoff and erosion can therefore be specifically prioritised and designed for those time periods and conditions when the critical threshold values are exceeded (Bryan, 1994). Within the study region therefore soil conservation measures may only be necessary during wet periods and should be designed to combat the occurrence of widespread runoff and erosion during these periods.

In semi-arid environments past land use practices have often removed much of the natural variation, predominately for agricultural production. The increasing abandonment of this land, presents an opportunity for land managers to re-create and increase the spatial diversity of land units not only to protect the soil but also to enhance biodiversity.

7.4 Conclusions

Mosaic patterns consisting of areas of contrasting hydrological response, reflected by spatial patterns of soil moisture, have been identified at the micro, meso and macro-scales within this study region. The spatial differences in soil moisture are primarily related to variations in soil texture and pore size characteristics. Within the mosaic patterns the wet areas may be considered as potential source areas of surface runoff whereas the drier areas are believed to be sinks capable of absorbing runoff. A pattern of areas with contrasting hydrological response is therefore encountered. Depending upon the spatial sequence of these hydrological response units, source areas may be spatially isolated and consequently hydrological pathways will be discontinuous. The severity and spatial extent of runoff and erosion may therefore be expected to be minimal. Each hydrological response unit however may be given a threshold value above which runoff will be generated. When the majority of the hydrological response units threshold values are exceeded, hydrological pathways are continuous and widespread runoff and erosion will occur regardless of the spatial sequence of the hydrological response units. Measuring spatial patterns of soil moisture may therefore prove to be a useful surveying procedure for identifying the spatial pattern of source areas and sinks and hence the continuity of hydrological pathways. Measurements made during wet conditions in particular may identify critical threshold values above which widespread runoff may be expected to occur.

During dry periods the majority of the hydrological response units soil moisture values are below the critical saturation threshold. In addition the spatial sequence of hydrological response units promotes spatial isolation of source areas and consequently discontinuous hydrological pathways. Together these circumstances result in minimal runoff and erosion during dry periods. The occurrence of widespread runoff and erosion during these periods is relatively infrequent and may be related to high intensity rainfall events during which the majority of the hydrological response units infiltration thresholds are presumed to be exceeded. During wet periods frequent rainfall events ensure that in the majority of the hydrological response units soil moisture values remain above or close to the saturation threshold. Continuous hydrological pathways may therefore develop rapidly during this period allowing the subsequent occurrence of widespread runoff and erosion regardless of the spatial sequence of hydrological response units.

Spatial variability in soil properties or vegetation patterns may therefore create a self-regulating system in which runoff producing areas are surrounded by buffer zones capable of re-absorbing the runoff. Creating a spatial mosaic pattern in which buffer zones are adjacent to potential runoff producing areas may therefore prove to be the most effective management strategy in runoff and erosion control for semi-arid environments. This system however is only effective when conditions are below the critical threshold values. During those periods when conditions are below the threshold, the need for soil conservation measures will be minimal. Management and resources may therefore be prioritised and erosion control measures designed for those time periods when conditions are above the critical threshold and hence when widespread runoff and erosion can be expected. Within the mosaic pattern the runoff producing areas may be managed so as to increase their threshold value reducing the likelihood of the threshold being exceeded. This may be achieved by using vegetation to improve the soils hydraulic properties, with the aim of reducing soil moisture and increasing hydraulic conductivity.

In many semi-arid and arid environments, although high spatial variability in topography, soils and vegetation may occur and therefore the potential for self-regulating systems to develop may be high, thresholds are generally low and hence frequently exceeded. Where this occurs, quantifying spatial patterns in hydrological studies with the aim of interpreting hydrological response or for inclusion within hydrological models may prove to be unproductive, particularly at small scales.

Chapter 8

Synthesis and Conclusions

8.0 Introduction

In semi-arid environments, variability in vegetation cover, terrain, soils and management practices results in a spatially non-uniform hydrological response to rainfall. Quantifying the spatial pattern of hydrological response is important for identifying those areas within the landscape which are vulnerable to runoff and erosion. Soil moisture is considered to be a key factor in determining hydrological response and its spatial distribution is a function of the soil's physical and hydrological properties. The spatial and temporal measurement of soil moisture may therefore be used to identify contrasting areas of hydrological response. An experiment was established to describe soil moisture variability in a badlands environment characterised by a diversity of pedological materials, terrain, vegetation and land management practices. The spatial and temporal variability in soil moisture was recorded at three scales with the following aims; to determine the spatial variability in soil moisture at different scales; to determine the factor(s) controlling the variability in soil moisture at each scale; to identify zones of surface runoff; to quantify the significance of spatial patterns and threshold values for the continuity of overland flow pathways; to determine whether the spatial extent and severity of erosion is related to soil moisture patterns. Fulfilment of these aims will further an understanding of the hydrological and geomorphological processes operating in semi-arid landscapes.

8.1 Soil Moisture Variability and Spatial Patterns

At each measurement scale, the macroscale (transect line, 25m sampling interval), the mesoscale (gully catchments, 5m sampling interval) and the microscale (minigrids, 1m sampling interval), two distinct groups of soil moisture conditions emerged related to dry (March-November) and wet (January-April) weather conditions. Maximum variability in soil moisture between immediately adjacent sampling points (>20% volumetric content) was similar at each measurement scale. At the mesoscale and microscale the spatial pattern of soil moisture could be described as a mosaic pattern in which relatively dry areas (<10% soil moisture) were found immediately adjacent to relatively wet areas (>25% soil moisture).

During dry weather conditions the spatial variability in soil moisture at each measurement scale was generally higher than during wet weather conditions. At the mesoscale and microscale the mosaic pattern of soil moisture was therefore more fragmented during dry weather conditions and was characterised by a short range of spatial correlation in soil moisture (15-20m). During wet weather conditions the mosaic pattern of soil moisture at the mesoscale and microscale is more uniform compared to dry conditions as extensive wet areas develop within the catchments. The increase in the spatial extent of wet areas during this period was most clearly observed within the forest gully catchment where the range of spatial correlation in soil moisture doubled from 15m to over 30m. In summary, the spatial variability of soil moisture is scale-invariant; the magnitude of variability in soil moisture persists at all measurement scales. Furthermore, the spatial continuity of soil moisture displays a temporal dependency; the mosaic soil moisture pattern is more fragmented and spatially discontinuous during dry than wet conditions.

8.2 Factors Controlling the Spatial Patterns of Soil Moisture

Identifying the factors which control the spatial and temporal patterns of soil moisture described above will aid in the understanding of how land management practices may change these spatial patterns. Certain characteristics identified in the soil moisture data set may be used to provide a first indication of the factor(s) controlling the spatial patterns of soil moisture. The scale-invariant nature of the variability in soil moisture suggests that the factor(s) controlling soil moisture may also be scale-independent ie. the factor(s) controlling the variability in soil moisture at the microscale may be the same as those at the macroscale. The spatial pattern of soil moisture at each scale is also temporally persistent ie. the spatial pattern remains similar through time. This indicates that the factor(s) determining the spatial pattern must also be spatially stationary through time.

Within this study region pore size characteristics, which were strongly related to soil texture, are the most significant factor in determining the spatial variability of soil moisture. Areas of drier soil were related to sediments with a higher percentage of transmission pores and/or coarse sized particles, whereas areas of relatively wet soil were related to sediments dominated by residual pores and fine sized particles.

The role of vegetation in determining soil moisture patterns was largely restricted to dry weather conditions when soil moisture values were medium to low and evapotranspiration losses were high. The non-uniform uptake of moisture by vegetation may partly explain the greater variability in soil moisture patterns observed during dry periods. During wet periods vegetation plays only a minor role in determining soil moisture patterns since evapotranspiration losses are low and soil moisture is frequently recharged. Organic carbon may indirectly influence soil moisture values since this property is strongly correlated with pore size characteristics.

Topographic characteristics such as elevation, slope angle and upslope contributing area / length were of only minor importance in determining surface soil moisture patterns within the gully catchments. Even at the macroscale, where topography may be expected to play a greater role in determining soil moisture patterns, none of the topographic parameters were strongly related to soil moisture. The generally poor correlations between topography and soil moisture may be due to the measurement of only the top 15cm of soil. At greater depths topography may be more significant in determining the distribution of soil moisture. A similar finding has been reported by Berndtsson and Chen (1994) when measuring soil moisture at depths of less than 1m.

A striking characteristic of the study area is the near horizontal interbedding of sediment horizons which may strongly contrast in their textural composition over relatively short distances. This contrast in texture and the associated pore size characteristics are the principal controls of soil moisture patterns within this region and overrides the known influence of vegetation and topography on soil moisture. By exposing several sediment horizons with different textures, gully incision may increase the spatial variability in soil moisture. Furthermore differences in gully morphology (shallow-bulbous compared to deep 'V' shape) may also play an important role in determining the degree of spatial variability in soil moisture.

8.3 Implications for the Hydrological Response of the Study Region

The spatial arrangement and connectivity of runoff producing areas is critical in determining the spatial extent of overland flow and its effectiveness as an eroding agent. Within the spatial patterns of soil moisture, wet areas may be considered as potential source areas of surface runoff whereas the drier areas are believed to be sinks capable of re-absorbing runoff. These wet and dry areas may be delimited into units based on their differing hydrological response and spatial area. The wet and dry areas may therefore be termed 'hydrological response units' and can be given a threshold value determined by the conditions necessary for runoff to occur, eg. the threshold value may be the maximum infiltration rate or saturation. Overland flow from a hydrological response unit may only occur when the threshold value is exceeded. The spatial sequence of the hydrological response units will determine whether hydrological pathways are continuous or discontinuous. In a system where pathways are discontinuous, source areas are spatially isolated and the runoff reaching the channel may therefore be expected to be minimal. Only those source areas located adjacent to the channel or catchment outlet will contribute to catchment outflow. Surface runoff from source areas which are spatially isolated and upslope of the channel will be re-absorbed by the surrounding areas which act as sinks for overland flow and transported sediment. During dry conditions the soil moisture pattern is fragmented, promoting discontinuous hydrological pathways. Source areas are therefore spatially isolated resulting in minimal runoff reaching the catchments channels. In addition, since the majority of the soil moisture values are below saturation, the threshold value governing the generation of surface runoff is determined by the infiltration rate of the hydrological response units. During dry conditions runoff is therefore predominately generated as infiltration excess overland flow. During the dry period the generation of runoff was observed to be highly localised and only on rare occasions during high intensity storms did this runoff leave the catchments.

During wet periods, despite different physical and hydraulic properties, the formerly dry zones have reached saturation and thus become source areas of surface runoff. Source areas are no longer spatially isolated and continuous hydrological pathways may develop rapidly during this period. Widespread runoff generated by saturation overland flow will occur regardless of the spatial sequence of the hydrological response units. During this period rainfall was observed to cause widespread runoff resulting in considerable flow within the gully channels.

Based upon the hydrological response described above, two key findings have emerged from this research:

1. In semi-arid areas spatial variability in soil properties or vegetation patterns may be beneficial for runoff and erosion control by creating a self-regulating system in which runoff producing areas are surrounded by buffer zones capable of re-absorbing the runoff. In degraded and eroding areas the creation of a spatial mosaic pattern in which buffer zones are adjacent to potential runoff producing

areas may therefore provide the most effective management strategy for runoff and erosion control in semi-arid environments. Careful planting in selected locations may be used to create a mosaic pattern of sinks for overland flow and sediment deposition. Increasing spatial variability to promote discontinuity in hydrological pathways is only an effective strategy for runoff and erosion control when conditions are below a critical threshold value. High spatial variability in soil properties and vegetation patterns may often be found in semi-arid environments, however, the thresholds necessary to generate runoff may often be low and hence frequently exceeded. Management strategies should therefore also aim to raise the threshold value of the hydrological response units within the spatial mosaic pattern ie. promote better soil physical and hydrological properties so that the occurrence of widespread connectivity is less frequent.

2. Within the study region the temporal measurement of soil moisture patterns has revealed a transition which may infer a seasonal switching in runoff generating processes from infiltration excess overland flow during the dry summer period to saturation overland flow during the wet winter period. It is well documented that soil saturation is the principal runoff generating mechanism in humid temperate environments whereas infiltration excess overland flow is frequently reported as being more significant in arid environments. In the seasonal climate of the study region conditions of both humidity and aridity can occur giving rise to a situation where both runoff generating processes may operate. The inference of a seasonal switching in the runoff generating processes can be related to soil moisture values which remain persistently below a critical saturation threshold during dry conditions. During this period runoff is therefore likely to be predominantly generated by infiltration excess overland flow. Saturation overland flow becomes the likely predominant runoff generating mechanism during the wet period due to frequent, long duration, low intensity rainfall. Seasonally arid climates may therefore represent an environment between arid and humid temperate in which both infiltration excess and saturation overland flow runoff generating processes occur. Net erosion data shows that the severity and spatial extent of erosion is higher during the wet winter period when the continuity of hydrological pathways is greatest and when saturation overland flow is the principal runoff generating mechanism.

8.4 Wider Implications and Future Research

8.4.1.Catchment Management:

A key management strategy for degraded semi-arid areas is the creation of a mosaic pattern in which 'sink areas' for runoff and sediment deposition are located adjacent to source areas. In stable environments with a dense vegetation cover a mosaic pattern may already exist due to the spatial arrangement of the vegetation canopy cover and plant stems/trunks. Extensive forest plantations or continuous areas of natural shrubland may therefore, prove to be a more effective management strategy than the creation of mosaic patterns. However, at the watershed scale the creation of mosaic patterns allows several landuses to co-exist within the same region. Patches of forest land, agricultural land and shrubland can be spatially arranged to minimise the continuity of hydrological pathways whilst allowing potentially degrading management practices (eg. arable farming) to continue. The concept of mosaic patterns may therefore be included within watershed management policies to allow both agricultural practices to continue as well as to minimise the continuity of hydrological pathways reducing the spatial extent and severity of runoff and erosion at the watershed scale.

Determining which factors control the spatial variability in hydrological response is vitally important for the sustainable management of an area. For example, in an environment where soil texture is uniform over large areas, then management practices which directly influence the spatial pattern of vegetation cover may be critical in determining the spatial extent of runoff generation, since the hydrological response is likely to be spatially dependent upon the vegetation.

Within the study region the spatial extent and severity of runoff and erosion within gully catchments may be related to the stage of gully development. Gullies in the early stages of development and hence those which have only dissected one or two sediment horizons are more likely to have continuous hydrological pathways than well developed gullies which have dissected several sediment horizons. The runoff and erosion hazard from gullies in the early stages of development is therefore likely to be higher than that of well developed gullies. Gullies in the early stages of development or with a shallow bulbous morphology should therefore be a priority for management policies aimed at reducing runoff and soil loss. Well developed gullies with an increased inherent spatial variability in soil texture, vegetation and terrain, may develop a self-regulating system in which minimal runoff and sediment discharges from the catchment outlet.

8.4.2. Hydrological Processes:

Quantifying the spatial variability of soil moisture within several different land uses, for example, from an agricultural field to a dense forest, would provide valuable information on the continuity of hydrological pathways within these land uses and their vulnerability to degradation. This information may also be used to determine the best location for these landuses in relation to channels and each other so as to reduce the continuity of hydrological pathways at the watershed scale. Land uses identified as buffer areas ie. landuses capable of re-absorbing runoff from adjacent land uses, and their most effective location within a watershed, can be specified for inclusion in policies which directly impact upon the land use management of a region.

The use of TDR probes at depths greater than 15cm would provide information on the spatial pattern of subsurface soil moisture and subsequently the continuity of subsurface hydrological pathways. These deeper probes would also provide information on the depth of soil saturation during the wet winter period. The relationship between topography and soil moisture at depth could also be established by the use of deeper probes. A spatial pattern in soil moisture at depth which is similar to that found at the surface would suggest that soil texture is the primary control on soil moisture throughout the profile.

Although the correlations between TDR measured soil moisture and saturated soil moisture values measured by the Pitman cores together with the spatial monitoring of net erosion and field observations provide some measure of the severity and spatial extent of runoff as well as the likelihood of saturated conditions, discharge measurements collected using a weir at the gully catchments outlet could be used to test the significance of these spatial patterns in soil moisture and threshold conditions in relation to the amount of runoff generated. However, weirs are limited in that they give no indication of the spatial occurrence of runoff generation within a catchment. It is therefore not possible to tell whether the whole of the catchment is generating runoff or whether it is only specific areas within the catchment, in some instances this may only be the area immediately adjacent to the weir. The usefulness of discharge data collected from weirs may be greatly improved if used in combination with runoff detectors. By using runoff detectors placed at specific locations within a catchment it may be possible to identify the spatial pattern of runoff generation and its temporal fluctuation as conditions change from dry to wet. Through using a combination of weirs and runoff detectors it would therefore be possible to corroborate the significance of spatial and temporal patterns in soil moisture in relation to both runoff generation and the type of runoff generating mechanism (i.e. saturated overland flow).

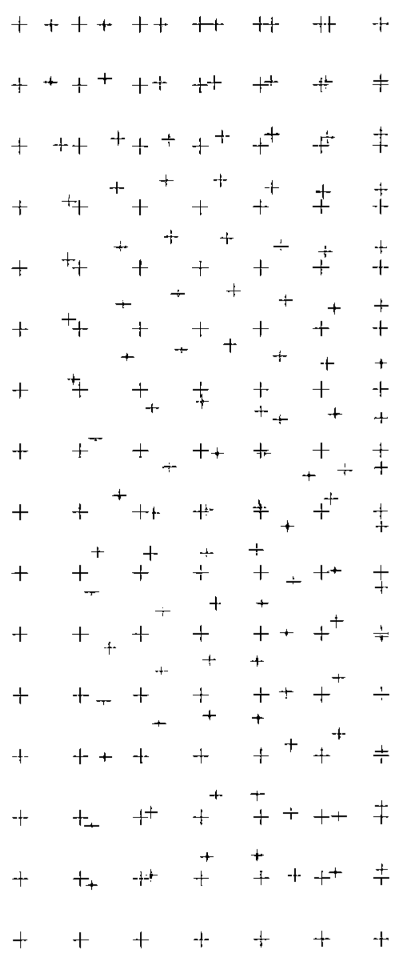
8.5 Summary

This research has shown that at the gully catchment scale a grid sampling strategy was an effective method for quantifying the spatial variability of soil moisture. This method provided complete spatial coverage and allows the spatial arrangement of source and sink areas to be identified. The use of a grid sampling strategy also favours and simplifies the later use of geostatistical techniques for analysing the spatial correlation of the data set.

Semi-arid environments are often vulnerable to land degradation and increasingly desertification from past and present land management practices and from the threat of future climatic changes. Quantifying the spatial and temporal variability of key soil properties may improve our understanding and interpretation of the often complex hydrological behaviour exhibited within these environments. Furthermore, knowledge on the variable response of these regions may aid in their sustainable management through the use of effective runoff and erosion control measures. The research undertaken within this thesis provides a framework from which these goals may be achieved.

Appendix 1.1: Displacement of the Matorral grids when using an artificial rectangular grid as compared to unit ground lengths in the field.

Matorral Gully Grid



Location of grid points as laid down in the field based on unit ground lengths

Location of grid points when using an artificial rectangular grid

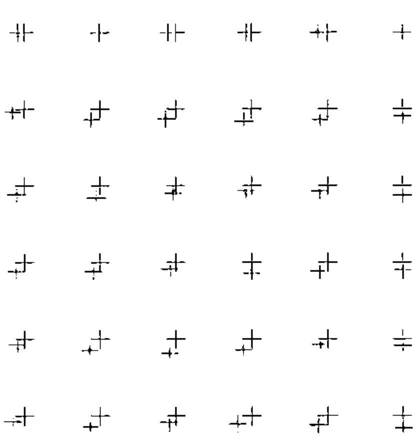
Degree of gully grid displacement:

Field Grid:
x maximum = 27.45m
y maximum = 70.54m

Artificial Grid:
x maximum = 30m
y maximum = 75m

Maximum difference in the x direction between the two grids = 5.88m
Maximum difference in the y direction between the two grids = 6.66m

Matorral Minigrid



Degree of Minigrid grid displacement:

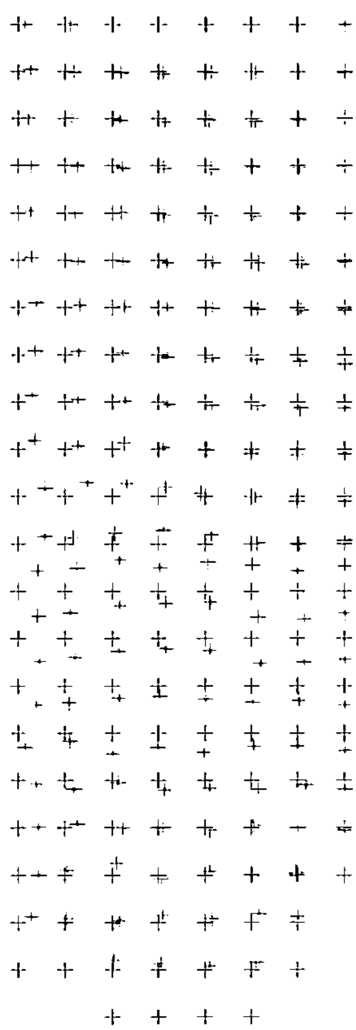
Field Grid:
x maximum = 5.17m
y maximum = 5.16m

Artificial Grid:
x maximum = 5m
y maximum = 5m

Maximum difference in the x direction between the two grids = 0.20m
Maximum difference in the y direction between the two grids = 0.18m

Appendix 1.2: Displacement of the Forest grids when using an artificial rectangular grid as compared to unit ground lengths in the field.

Forest Gully Grid



Location of grid points as laid down in the field based on unit ground lengths

Location of grid points when using an artificial rectangular grid

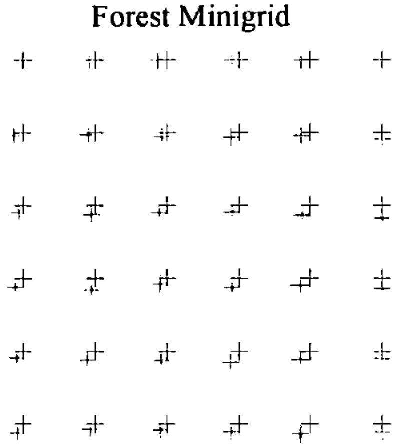
Degree of gully grid displacement:

Field Grid:
x maximum = 34.34m
y maximum = 99.56m

Artificial Grid:
x maximum = 35m
y maximum = 105m

Maximum difference in the x direction between the two grids = 2.80m
Maximum difference in the y direction between the two grids = 6.25m

Forest Minigrid



Degree of Minigrid grid displacement:

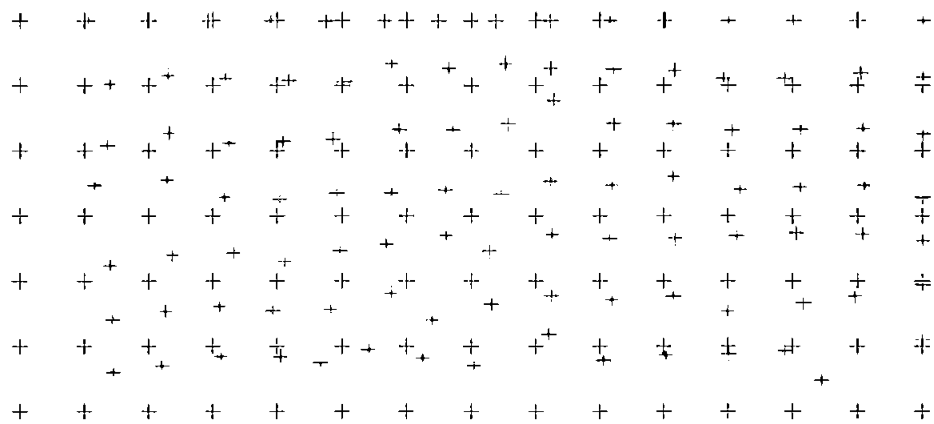
Field Grid:
x maximum = 5.14m
y maximum = 5.13m

Artificial Grid:
x maximum = 5m
y maximum = 5m

Maximum difference in the x direction between the two grids = 0.14m
Maximum difference in the y direction between the two grids = 0.17m

Appendix 1.3: Displacement of the Bench Terrace grids when using an artificial rectangular grid as compared to unit ground lengths in the field.

Bench Terrace Gully Grid



Location of grid points as laid down in the field based on unit ground lengths

Location of grid points when using an artificial rectangular grid

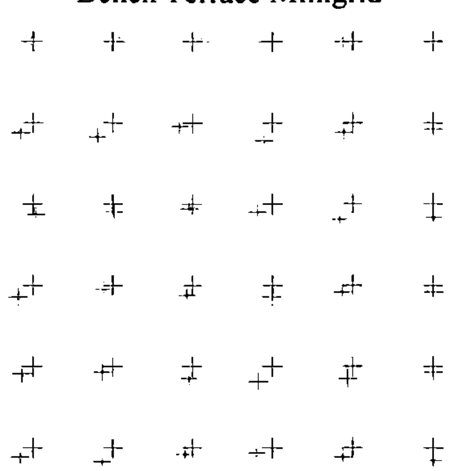
Degree of gully grid displacement:

Field Grid:
x maximum = 64.74m
y maximum = 26.97m

Artificial Grid:
x maximum = 70m
y maximum = 30m

Maximum difference in the x direction between the two grids = 7.24m
Maximum difference in the y direction between the two grids = 5.52m

Bench Terrace Minigrid



Degree of Minigrid grid displacement:

Field Grid:
x maximum = 5.19m
y maximum = 5.17m

Artificial Grid:
x maximum = 5m
y maximum = 5m

Maximum difference in the x direction between the two grids = 0.20m
Maximum difference in the y direction between the two grids = 0.21m

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