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THE EFFECTS OF WHOLE TREE HARVESTING ON SITE HYDROLOGY AND SOIL STRUCTURE AT BEDDGELERT FOREST, N. WALES, UK

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THE EFFECTS OF WHOLE TREE HARVESTING ON SITE HYDROLOGY AND SOIL STRUCTURE AT BEDDGELERT FOREST, N. WALES, UK.

by

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To Robert

ABSTRACT

THE EFFECTS OF WHOLE TREE HARVESTING ON SITE HYDROLOGY AND SOIL STRUCTURE AT BEDDGELERT FOREST, N. WALES, UK.

JULIA ELIZABETH HODGKINS

The ITE biogeochemistry group monitoring solute movement at Beddgelert Forest provided an opportunity to study the hydrology of a steep section of hillslope in a high rainfall environment. The aim of the experiment was to characterise and compare the hillslope hydrologies of one forested and one whole tree harvested site. Particular attention was paid to the influence of trees both directly on soil water pathways and indirectly on soil characteristics

Atmospheric inputs were monitored for the slope and individual plots for one year. In spite of high rainfall volumes, the slope was not waterlogged indicating a soil with high conductivity. However, frequent macropore flow was not observed at the site. Tensiometer results showed that the mineral soil remained unsaturated. Therefore, a type of preferential flow dominates at both sites. A one dimensional modelling approach to soil water movement confirmed that mesopores within the soil could conduct a large volume of water rapidly. Modelling demonstrated the importance of soil structure especially a large pore size distribution.

Analyses of active soil water pathways based on tensiometer results were inconclusive. Downslope moisture gradient combined with high conductivity suggested that large quantities of water could be transmitted. Similarly, the well structured surface soil and marked horizon development also indicate lateral flow may be dominant.

The study showed that saturated hydraulic conductivity was highly variable at both the forest and whole tree harvested sites. Analysis of semi-variograms indicated that most of the variance occurred at a sampling distance of 50 cm (i.e. individual tree roots and slate fragments were causing variations in K_S). Investigations of soil structure found more vertical cracks in the forest soil compared to the whole tree harvested site. At the more detailed ped scale, fractal dimensions of both sites were similar. Based on these results combined with temporal moisture content data the research has demonstrated that first, the hydrological regime at both sites were similar. Second, the direct impact of trees was limited. Third, the large cracks at the forest site were not significant. The major result of this research was that at both sites vertical flow in the Ah/Ea horizon dominates and a significant amount of water moved laterally within the Eag, B_S and C horizons. This result has major implications for the solute chemistry and movement of acid deposition in that soil water born solutes will tend to enter water courses more rapidly than if vertical flow predominated.

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signed............

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CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

This thesis is concerned with the effects of clearfelling. A standing area of forest was compared to an area that had been felled, by investigating: (i) components of the water budget (ii) soil hydrology and (iii) soil characteristics. It is important to consider the effects of clearfelling because the forested area of the UK has doubled during this century, from just 1.1 million ha in 1895 to about 2.1 million ha in 1995. Strategic arguments for growing increased amounts of timber have also been forcefully made by the Centre for Agricultural Strategy (CAS, 1980). Since then there has been widespread concern about the overall forestry strategy (Mather, 1991), lack of any policy to control afforestation (Brotherton, 1986), sustainability in the future (Newson, 1992) and environmental costs (Nature Conservancy Council, 1986). The majority of the recently afforested land consists of conifer plantations which are located in the uplands. Upland ecosystems are more sensitive and less stable than lowland soils and habitats. Clearfelling is of particular importance, since many afforested areas are now reaching maturity and are ready for harvesting. With second crop rotation looming, it is vital that the effects of clearfelling are established In September 1990, the Government published a White Paper on the Environment, which detailed two main forestry policy aims (This Common Inheritance, 1990). These were (i) the sustainable management of our existing woods and forests and (ii) a steady expansion of tree cover to increase the many diverse benefits that forests provide (Forestry Commission, 1991). There have also been conflicts regarding water use between forest and water industries.

1.2 HYDROLOGICAL IMPACT OF FORESTRY IN UPLAND BRITAIN

There are three main problems relating to soil hydrology that are directly caused by forestry: (i) acidification of soil water, streams and lakes (ii) decreased water-yields and (iii) erosion caused by ditching and road construction. Many research questions have been raised about the effects of upland conifer afforestation on site hydrology (Law, 1958; Neal *et al.*, 1986 & 1992; McCulloch and Robinson, 1993), sediment production (Newson, 1992), biogeochemical cycling (Stevens and Hornung, 1988), ecology (Goldsmith and Wood, 1983; Nature Conservancy Council, 1986; Essex and Williams, 1992; Peterken, 1993), soil chemistry (Grieve, 1978; Hornung *et al.*, 1987) and the effects of acid deposition (Rosenquist, 1978; Nilssen *et al.*, 1982; Christopherson and Neal, 1990; Soulsby 1992). Adams (1993) addressed many of the potential problems that can arise in land use planning due to the lack of forest hydrology knowledge. Attention was drawn to the poor understanding of different hydrological effects due to variations in patterns of climate, soil and terrain. The need for effective and appropriately planned data collection and monitoring programmes in forests were discussed. One of the key factors for all of these issues is the identification of hydrological pathways. This thesis aims to develop the identification of hydrological pathways which are critical to the understanding of different hydrological effects.

1.2.1 Importance of Soil Hydrological Pathways

One explanation for increased acidity of streams after felling is that there is a change in the soil hydrological pathways (Neal, 1992). The research investigation presented in this thesis is concerned with examining the soil hydrology of a conifer plantation situated at Beddgelert, North Wales. This research was partly field-based and therefore follows in the tradition of forest hydrology studies by Law (1958) and Hewlett (1961).

Forest soils in upland Britain have similar characteristics. All of the established hydrological research sites, such as Plynlimon and Llyn Brianne (Mid-Wales), Beddgelert (North Wales), Kershope (Cumbria) and Balquhidder (Scotland), have an area of the catchment that comprises of the following soils: peat, gley, ironpan, ferric stagnopodzol and brown podzols. There have been three recent upland hydrological studies investigating soil hydrological pathways. Each project has focused on a particular soil or group from upland Britain: (i) Ironpans and gleys (Soulsby, 1992a & 1992b) (ii) ferric stagnopodzols (Chappell, 1990) and (iii) peats (Muskutt *et al.*, 1990). This thesis focuses on a stagnopodzol, part of the brown podzolic group, and therefore contributes to a complete range of hydrological studies on different upland soils.

This research is also a development of the work by Chappell (1990) which was based in the Hafren Forest, mid-Wales. Chappell, 1990 found gross differences in forest and grassland hydrology at the catchment scale. Storm generation was discussed from adjacent sites, of Sitka Spruce forest and an area of unimproved grassland. The work was crucial in showing that marked horizon development could control water movement down a hillslope and that the effect of individual conifer trees could enhance the lateral deflection of flow. A number of key issues, however, were not fully explored, concerning the role of the trees intercepting and redistributing the water in the profile and the role of the soil structure in determining flow pathways. An investigation was required at the more detailed hillslope scale to identify important flow pathways in forested areas and to examine the changes which take place after clearfelling.

1.3 HILLSLOPE HYDROLOGY

1.3.1 Pathways at the Hillslope Scale

Various routeways for soil water have been proposed. One of the first major contributions to hydrology was by Horton (1933). His infiltration theory stated that overland flow was generated when rainfall intensity exceeded the infiltration capacity of the soil. This theory rapidly gained credibility because it neatly explained the shape of the unit hydrograph and it remained the dominant theory of streamflow generation until the 1960s. Although the importance of overland flow was almost universally accepted at that time, others were drawing attention to the contribution of subsurface flow in areas of high infiltration capacity (Hursh, 1944). Hursh and Hoover (1941) demonstrated that significant lateral flow was generated in the top 30 cm of the soil.

Stronger field evidence proposing throughflow as the dominant theory of stormflow generation was established in the 1960s. Whipkey (1965) found that in soil which exhibited a discontinuous decrease in hydraulic conductivity with depth, if suitable antecedent moisture and rainfall conditions existed, saturation would build up from the base of these soil layers. Water velocity was dependent on hydraulic conductivity and the depth of water in these soil layers. He found that high intensity storms falling on wet soil yielded the equivalent of up to 16% of the rainfall as runoff in 24 hours, and that the individual soil layers produced individual peaked hydrographs. The limitations of this work are now recognised, particularly with regard to the extremely high rainfall intensities that were used.

Harr (1977) relied on natural rainfall intensities for his experiment, unlike Whipkey (1965), and he stressed the dominance of unsaturated flow. Carson and Kirkby (1972) also point out that throughflow is usually unsaturated, unless it is near to streams or at the base of a very permeable soil horizon. Hewlett and Hibbert (1967) found from their work on forested soils, that upslope soil water pushed lower slope soil water out in a piston action. They termed this displacement of old water by incoming rain as "translatory flow". Anderson and Burt (1977b) also constructed a laboratory slope model to test the results obtained by Hewlett and Hibbert to determine whether unsaturated flow is the dominant flow mechanism at the later stage of drainage. Results from this model, and hydraulic conductivity determinations, indicated that saturated flow controls slope discharge throughout drainage.

Hewlett (1961a, 1961b) showed how the lower slopes near to the stream could produce runoff early in the storm period while infiltration was still occurring on the higher area, which indicated that subsurface flow must be occurring. He suggested that the saturated soil providing baseflow expands or contracts in response to the interactions between recharge, soil moisture and precipitation. This has been termed the variable source area concept. Hewlett and Hibbert (1963) supported their earlier field observations when they experimentally observed throughflow in a long trough of undisturbed soil by applying artificial precipitation. Betson (1964) has shown that saturation overland flow from only a small proportion of the catchment area was sufficient to contribute to stormflow, which has been termed the partial area or contributing area concept. Further research by Ragan (1968) and Weyman (1970) supported this concept. Weyman (1973) found that either distinct soil horizons or impermeable bedrock are essential for the initiation of lateral flow and found a correlation between throughflow on a hillslope and the storm hydrograph. At the same site, Anderson and Burt (1977a) found topography to be an important control on soil moisture conditions and the resulting streamflow response. They found convergence of flow into hollows and divergence of flow off spurs. Dunne and Black (1970) have found that under certain circumstances of rainfall and contributing area saturation overland flow may dominate the storm runoff of catchments. Kirkby and Chorley (1967) proposed three topographical areas where saturation overland flow maybe expected, without rainfall intensity exceeding the infiltration capacity. These areas are located in zones at the slope base next to stream channels, in concavities and topographical hollows, and in areas of thin soil cover.

Shallow water tables are often observed to respond in a highly disproportionate manner to precipitation events (Gillham, 1984). Gillham (1984) presented physical evidence to show that if the capillary fringe (zone of tension saturation) extends to the ground surface, then the addition of a very small amount of water can result in an immediate and large rise in the water table. His field experiments and work of others suggest that the capillary fringe effect could have a major effect on the process of streamflow generation and contaminant transport (Abdul and Gillham, 1989). This finding also has implications for calculations of groundwater recharge and consumptive use, if based on water table response and assumed specific yield, they could be substantially in error. Abdul and Gillham (1984) used laboratory experiments to investigate the groundwater-surface water interactions during the process of streamflow generation. Their experiments showed that the discharge of pre-event water to the stream preceded event water and that at the beginning, pre-event water was the predominant component of the streamflow. They also found from their tracer experiments that the significance of pre-event water increases with a decreasing rainfall rate and that for a very low rainfall rate pre-event water was the main component of the stream hydrograph. However, adequate field evidence for this mechanism is lacking.

Mosley (1979) provided further information on the relative importance of the rapid subsurface flow as a streamflow-generating mechanism. His study considerably extended the work of Freeze (1972, 1974) and Pearce *et al.* (1986), regarding the relative significance of subsurface flow as a contributor to stormflow. Using dye tracer experiments at the Mai Mai catchment (New Zealand), Mosley (1979) found that water moved at rates up to three orders of magnitude faster in macropores than through the soil matrix. The sensitive and rapid response of subsurface flow to variations in precipitation suggested flow through macropores dominated, as opposed to flow through the soil matrix. This water was new input water and no evidence for translatory flow was observed. Slow drainage of water from the hillslope was by unsaturated flow. Some saturated flow occurred nearest to the soil bedrock interface, which appeared to account for delayed flow on the storm hydrograph. Subsurface flow was found throughout the catchment with storms greater than 3.3 % net precipitation, and so was regarded as the dominant mechanism. In 1982, Mosley found that soil water moved through a number of different pathways. Macropores were important and in some places accounted for up to 40 % of flow. Antecedent moisture conditions and the relevant importance of the various pathways at a given site, which are dependent on soil characteristics, macropore network and the parent material at the base of the slope, affect the variability of flow velocity and the percentage of input appearing as rapid outflow. Flow velocities were monitored at undisturbed, logged, and logged/burned/planted sites, but no significant statistical differences were found. This could be due to insufficient time lapse for changes in the root system to have a hydrological effect since logging.

Pearce *et al.* (1986) carried out a comprehensive study at Mai Mai into runoff processes. In contrast to the work by Mosley (1982), they found that catchment outflow reflected a well-mixed reservoir with a mean residence time of four months; only three percent of storm runoff could be considered as new water and this could be accounted for by saturated overland flow. Rapid subsurface flow such as macropore flow, in their view, could not explain streamflow response in the Mai Mai study area. A further case study of hillslope and low-order stream response at this site is reported by Sklash *et al.* (1986). They found that marked aerial variations in Deuterium concentration composition of throughflow emphasised the aerial variability in hillslope response to individual storms and sequences of storms.

McDonnell (1990) tried to accommodate the two opposing views on the importance of the subsurface pathways and suggested that perched water tables, developed during rainfall on hillslopes, could lead to saturated flow of old water into macropore channels. There are various problems with this explanation, including the way in which old water in the matrix converges in the preferential flow paths. As an alternative approach, Dowd (1990) considered that rapid mixing occurs between old water held in the soil matrix and the recently input water flowing across the surface of the aggregates. They studied the movement of a Bromide tracer in a forest in Georgia and reported a theorised preferential flow mechanism which could explain the phenomenon. Using stable Oxygen as a tracer, Addison (1995) extended these ideas with a small block experiment in which she demonstrated immediate and significant mixing of old and new water during macropore flow. Kendall and McDonnell (1993) have provided a theoretical framework to determine the relative significance of the bypass and matrix subsurface flow pathways based on monitoring conservative tracer movement.

1.3.2 Pathways in the Soil Profile

At the soil profile scale, there is considerable debate about detailed pathways and soil water movement in forest hydrology. The Darcian approach considers average flow through a uniform porous media, whereas there is considerable evidence, as detailed above, that rapid flow routes operate particularly in forest soils. Beven and Germann (1982) reviewed the literature on macropores and provided evidence to suggest that such pores play an important role in the hydrology of some field soils. Macropores have an important effect on water flow when there is a maintained supply of water to them (Germann and Beven, 1981). They stressed that macropores can have important implications for geochemical interactions and the movement of pollutants. The authors suggested that the next step in this line of research was to collect experimental information on how macropores operated hydrologically (Beven and Germann, 1982).

The important role played by macropores in water movement is now well established. Beven and Germann (1982) noted the need for a coherent theory of flow through structured soils that would make the macropore domain concept redundant and, while this is still a laudable ideal, the concept of rapid bypass flow along macropores seems to be serving soil scientists well in a variety of experiments on water and solute transport (Lafolie and Hayot, 1993; Haria *et al.*, 1994). However, there is currently some debate about the role of the various sizes of channel which occur in soils. For example, the importance of pipeflow is discussed by Sidle *et al.* (1995) while, at the other extreme, flow in homogeneous coarse grained soil is considered by Liu *et al.* (1994). The term preferential flow is often used as a generic term for describing the process by which water moves through the soil because the term does not imply any scale of the pore involved. According to Luxmoore and Ferrand (1993), there are at least two scales of macropore flow. The first is macropore channelling in which water moves through a network of biopores about 1 mm or more in width. Second there is mesopore channelling in which water moves through pores from 60 μm to 1 mm. Wilson and Luxmoore (1988) estimated the spatial variability in porosity of actively conducting soil macro and mesopores on a field scale at two contrasting forested watersheds (Melton and Walker) from ponded and tension infiltration measurements. The infiltration rates were found to be log normally distributed for all soil water tensions. The variability of infiltration at the Walker Branch watershed was greater than that at the Melton Branch watershed. Walker Branch had higher macropore flow rates and macroporosities, whereas Melton Branch possessed higher mesopore flow rates. The soils with low macroporosity were capable of conducting large quantities of water because of the relatively small number of macropores that were active (Wilson and Luxmoore 1988). More recently, the importance to rapid water flow of a small number of macropores has been confirmed for an agricultural soil by Deeks (1995).

Some of the original work on macropore flow was conducted over one hundred years ago by Lawes *et al.* (1882), who discovered that a substantial part of the water added to soil profiles moved immediately through open channels and only interacted slightly with the soil matrix water. Detailed hydrological studies of channelling flow were first conducted by Hursh (1944) and Gaiser (1952). A qualitative study on vertical root channels was conducted by Gaiser (1952) and it was found that when root channels decayed, they contained materials relatively more permeable than those in the surrounding matrix. It was suggested that these channels serve as pathways for the rapid movement of a large part of the free water in the soil profile. Whipkey (1967) recognised the importance of water movement through macropores in forest soils during heavy rains. He called this movement subsurface stormflow. Aubertin (1971) later confirmed this movement in his qualitative study on the nature and extent of macropores in mixed hardwood forest soils. He emphasised that when considering conductivity of forested soils, where old open channels exist, the number, size, and orientation of open channels in addition to the soil texture must be studied. because of their integral role in water movement.

Further detailed research work by De Vries and Chow (1978) on a forested mountain soil in coastal British Columbia showed a proportion of infiltrated water to be conducted through pathways of low resistance to flow. These channels were formed from decayed roots. The root channel flow dominated during the non-steady state phase of a rain event and decreased to a minimum as steady state was approached. During the drainage phase of the event, the channels did not contribute to downward flow. The matrix wets up from the surface of the H horizon of the forest floor and from the wet peripheries of the tree trunk-to-root channels. The greatest resistance to flow was in the H horizon of the forest floor and the Ae horizon of the mineral soil, which suggested that root channels tend to have their openings in the surface of the H horizon. Simulated disturbance of the forest floor down to the mineral soil, such as from felling, caused the soil water pathways to shift from root channels to the soil matrix due to the closure of root channel openings.

1.4 FOREST HYDROLOGY

Forest hydrology has been the subject of considerable interest to a multitude of disciplines such as, environmental scientists, chemists and foresters. Experiments have been conducted in environments as diverse as the cool temperate upland plantations of Britain to the tropical rain forests of Australia. Much of the early work was undertaken in the United States by the Forest Service, particularly as part of the Long Term Ecological Research programme funded by National Science Foundation (Swank and Crossley, 1988). The seminal work on variable source areas conducted at Coweeta Hydrologic Research Laboratory, North Carolina, was very important in advancing ideas on how stormflow is generated (Hewlett and Hibbert, 1963; Hibbert, 1967; Hewlett and Nutter, 1970). Swank and Crossley (1988) also used a paired catchment approach to show the fundamental hydrological control exerted by trees. To raise the profile of forest hydrology many of the major forest hydrology findings have been reviewed in a special volume of Journal of Hydrology dedicated to the subject (McCulloch and Robinson, 1993).

In the UK, with the exception of the work on Stocks reservoir by Law (1956), the significance of forests on site hydrology was largely ignored until the establishment of the Institute of Hydrology (IH) in about 1964. In his research, Law found that forests use more water than grassland and applied the results to the economic implications of reduced water yield for reservoirs surrounded by plantations. Forest hydrology was given an impetus during the 'International Hydrological Decade (1965-75)' with the establishment of research programmes at Plynlimon and Thetford forest by the IH. In the UK this impetus of hydrological based research generated concern over erosion and reservoir sedimentation, which was caused by site preparation such as road building and ditch preparation, particularly those structures running perpendicular to the contours (Newson, 1992). Such work has led to new codes of planting and tighter forestry planning restrictions where applicable.

During the 1980s, there was much concern about the ecological effects of acid deposition and the role of forests in enhancing the problem. Acid rain is the result of burning fossil fuel for power generation, which produce sulphur dioxide, and car engines, which release nitrous oxides. Studies in upland Britain have shown that large scale afforestation has enhanced soil and stream acidification (Harriman and Morrison, 1982; Stoner and Gee, 1985; Nilssen *et al.*, 1982 and Hornung *et al.*, 1987) by scavenging atmospheric aerosols (Harriman and Morrison, 1992; Nilssen *et al.*, 1982; Stoner and Gee, 1985) and acidifying the soil (Hornung *et al.*, 1987) and streams (Christopherson and Neal, 1990). "It is now widely accepted that forests are associated with increased acidification of streams in areas subject to significant atmospheric pollution" (McCulloch and Robinson, 1993, p207).

The problem of acid deposition provided a unifying approach to many forest hydrological investigations. More recently there has been a return to the more classical hillslope hydrological experiments, such as those by Elsenbeer *et al.* (1994) and Bazemore *et al.* (1994) which have investigated the role of stormflow generation in forested headwater catchments and work by Robson *et al.* (1994) on spatial variations in throughfall chemistry. To some extent, the work by Bazemore and others must be set in the wider hydrological context of how stormflow is generated. At the crux of the issue is the determination of the dominant water pathways operating down a hillslope.

1.4.1 Effects of Vegetation

Vegetation may act passively to alter the hydrology of an area by intercepting and redistributing incident precipitation or may act directly through biological transpiration and changing the soil structure. Various researchers have studied the effects of different vegetation covers on hydrology such as grassland (Bouma and Dekker, 1978), bracken (Arnett, 1974; Williams *et al.*, 1987) and heather (Calder *et al.*, 1982), but the majority of studies have considered the role of trees (Swank and Crossley, 1987; Calder, 1992). The impact of different vegetation management practices such as burning (Imeson, 1974) and harvesting techniques must also be taken into account.

1.4.2 Interception, Throughfall and Stemflow

Trees intercept considerable quantities of water: the amount depends on a number of factors including the tree species, age, canopy characteristics, density as well as meteorological factors such as precipitation amount and intensity. Interception losses from Sitka Spruce in the UK range from 25% (Hudson, 1988) to 46% (Williams, 1983). Incoming precipitation is redirected along the needles, twigs, branches and stems and reaches the ground as throughfall or stemflow. The stemflow component is not evenly distributed but is concentrated near the stem (Ford and Deans, 1978). The amount of throughfall recorded for Sitka Spruce ranges from 40% (Ford and Deans, 1978) to 56% (Chappell, 1990). The partitioning of precipitation into throughfall and stemflow depends on branching habit, because trees with branches at an acute angle produce larger volumes of stemflow due to funnelling (Herwitz, 1986). Important physiological factors include smoothness of the bark and capacity for absorption. Recorded stemflow amounts are highly variable both within forests and between different stands but the proportion of stemflow in Sitka Spruce stands is generally about 5 - 7% (Law, 1957; Chappell, 1990), although Ford and Deans (1978) measured a total of 27%.

The major work on transpiration by trees in the uplands of Britain is by Calder (1992). The process for individual trees is well documented but there are many difficulties estimating transpiration loss from forest canopies. Losses from Sitka Spruce trees at Plynlimon vary from 17% gross precipitation, based on a lysimeter study (Calder, 1976) to 5% calculated from a water balance study (Hudson, 1988). Transpiration losses from grassland may be equal or greater than adjacent forests. This finding is rather different to conventional wisdom which assumes that trees with greater canopy roughness and deeper rooting of trees usually experience greater loss. Hudson (1988) noted that transpiration from a grass catchment was about 16% of gross precipitation while the adjacent Sitka Spruce forest attained only 5%. Research at the Balquhidder catchment in Highland Scotland also found that there was little difference in the water utilisation between the forested and grassland site. Process studies revealed that the enhanced evaporation from forest canopy interception was matched by evapotranspiration of the heather at the grassland site (Whitehead and Calder, 1993).

1.4.3 Trees and Soil Hydrology

The effect of trees on the forest floor and their influence on soil structure and water pathways has been widely recognised but quantitative information is rather lacking. Walsh and Voight (1977) showed that the litter layer may retain large amounts of water before releasing it. The amount of water held in the litter layer depends on the proportion of litter that is fresh, well humified or decomposed due to their varying adsorption rates. Rates of infiltration may be reduced or enhanced when compared with grassland depending on factors such as hydrophobicity, type of structure and porosity. At the surface, organic matter decomposes the resulting phenols and organic acids promote a marked hydrophobicity. Similarly, a number of studies have shown that coniferous forests can lead to structural deterioration (Grieve, 1978; Hornung *et al.*, 1986). Other effects of afforestation include enhancing podzolization, although the evidence for this is debatable (Essex and Williams, 1992), reducing microporosity of the A_2 horizon and making the eluvial horizon less permeable (Adams and Raza, 1978).

The influence of trees also depends directly on the tree root distribution and penetration. The distribution of roots in a vertical, compared to a horizontal, direction is dependent on tree species, phenology and soil conditions. Sitka Spruce roots grow laterally as the species lacks a tap root, although vertical development is restricted by anaerobic and indurated horizons. Tree root distribution is also controlled by availability of nutrients. The majority of the finer roots grow near the surface where they can compete to absorb both water and nutrients. Water is abstracted from the soil and thus the roots act as sinks.

Roots may also be considered as a source of water since the flow of water along exterior surfaces of roots and through old root channels has been found to enhance subsurface flow. In an experiment by Dowd *et al.*, (pers. comm.) in Georgia, USA, high concentrations of

Lindane were recorded in the soil at the base of trees due to combined stemflow source plus macropore root flow. The role of tree roots in preferential flow is not known but may depend on the presence of live and old root channels (Aubertin, 1971), hydrophobicity of locally dried soil and soil structure. Trees can affect the structural characteristics of the soil by compressing particles together as the trees sway during windy conditions.

1.4.4 Hydrology and Forestry Practices

The various phases of forest management from site preparation and establishment of the plantation through thinning and brashing to harvesting have considerable effect on the hydrology of an area. When plantations are established, road construction and site drainage can increase runoff. Extensive drainage of upland sites in Britain has lead to higher discharge and more peaked response (Leeks and Roberts, 1987). Forest stands are usually thinned ten to fifteen years after being established in order to improve the growth and quality of timber. Removal of tree and brashing may not affect the hydrology since interception losses due to the cut trees and branches remain high.

Considerable work has been carried out to investigate the hydrological effects of harvesting because of the impact on water supplies. The majority of this work has been undertaken using the paired catchment method. This method involves a comparison of the hydrology between two very similar forest catchments before and after felling in one watershed. The behaviour of the two catchments is calibrated prior to harvesting. The effect of removing the trees is studied in terms of water yield and response of the storm hydrograph. Hewlett and Helvey (1970) investigated the effects of forest clearfelling at Coweeta Hydrologic Laboratory. Statistical analysis showed that after clearfelling stormflow volume increased significantly by 11% and peak discharge increased by 7%. Few differences were found in time to peak, recession time and quickflow duration after clearfelling, which suggested that no changes in stormflow mechanism had occurred, but rather simply an increase in runoff from the felling.

1.5 SCALE AND VARIABILITY

With the advent of process based hydrological models in the 1970s and 1980s requiring information on hydraulic conductivity, many research investigations were concerned with describing the spatial variability of soil hydraulic properties. Nielsen *et al.* (1973) found that throughout the field, water content variations were normally distributed with depth and horizontal distance, whereas hydraulic conductivity and soil water diffusivity were log-normally distributed. The differences in these distributions has implications when designing and conducting experimental research and the variations must be reflected in the sampling strategy and the scale used to measure these variables. At Davis, California, the seemingly uniform 10 ha of agricultural land that was investigated, manifested large variations in hydraulic conductivity. Conversely, Baker and Bouma (1976) found hydraulic conductivity to be statistically identical within and between two subsurface horizons of two silt loam soils despite distinct differences in structural morphology and different processes of genesis. These data would suggest that little variability occurs within $K_{S.}$ However, there is no further research which supports this argument. Later, Baker (1978) also concluded hydraulic conductivity calculated from nine soil series data sets exhibited relatively high variability within series. Using multivariate analysis, soil series groups of similar hydraulic conductivity were determined. These results demonstrated that soil series can be arranged to form functional groups based on similar hydraulic conductivities. However, this grouping maybe an over-generalisation when values of K_S are needed for modelling soil water fluxes. Bresler *et al.* (1984) found that the most dominant chemical and physical soil factors associated with the greatest influence on variability in soil hydraulic conductivity were electrical conductivity and the percentage of sand. This would seem to suggest that an indirect measurement of K_S via electrical conductivity and/or percentage sand could provide a simple method of determining K_S if the theory were to be applicable to all soil types.

Generally, these findings have shown the enormous spatial variability that exists in the soil hydraulic properties. Scale of measurement may lead to further problems when investigating hydrological processes. Variability among replicate samples tends to increase as sample volume decreases (Reeve and Kirkham, 1951; Anderson and Bouma, 1973; Baker, 1977 and Hawley *et al.*, 1982). Perroux and White (1988) found that the scale of measurement should increase when moving from the unsaturated to the saturated phase, due to the macropores exerting preferential flow on soil water movement. This relationship between sample volume and a parameter's variability can be described through the concept of a representative elementary volume (REV), as derived from continuum theory (Bear, 1972). The continuum approach divides flow into microscopic and macroscopic regimes. The former is highly variable and dependent upon the content of the elemental (sample) volume. However, the latter is an average of all the microscopic variation in a continuous assembly of voids and is commensurately less variable as consideration shifts from one macroscopic element to another. The appropriate REV may be expressed in terms of soil structure descriptions made by the soil survey (Anderson and Bouma, 1973; Bouma, 1982). Bouma (1985) defines an elementary unit of soil structure (ELUS), such as individual grains or peds, to help establish guidelines for estimating a REV. Chappell and Ternan (1992) incorporated scale into various landscapes and hydromorphic processes by characterising soil hydraulic properties for representative soil types using the soil catena as the framework for measurement.

Lauren *et al.* (1988) measured the spatial variability of saturated hydraulic conductivity in situ in clay soil with macropores. The aim of the investigation was to find which size of sample column was the REV. They found that the optimum sample size for measuring saturated hydraulic conductivity in the field studies was a 50 x 50 x 20 cm column, which was slightly larger than the previously estimated REV for this particular soil, but well within practical limits of the measurement technique. Smaller samples taken from within the larger samples (REV) and measured in the laboratory were reported to be extremely unreliable and not at all comparable with the larger field measured samples. They also noted that the macrovoid area or percentage of silt or clay could be used to predict the spatial distribution of saturated hydraulic conductivity in the field.

Wood *et al.* (1988) have investigated the existence of a representative elementary area (REA) based on the digital terrain model of Coweeta Hydrologic Laboratory, coupled with synthetic realisations for rainfall and soils. They reported that an REA does exist in the context of the runoff generation response of catchments, that the REA is strongly influenced by the topography, and that the variabilities of soils and rainfall inputs between sub-catchments have only a secondary role in determining the size of the REA.

Geostatistics have been used to good effect to determine spatial dependency of separate measurements and describe variability (Webster, 1977; Beven, 1989). McBratney *et al.* (1981) describe a method for designing optimum sampling schemes based on the theory of regionalized variables, and assumes that spatial dependence is expressed quantitatively in the form of a semi-variogram. First, an approximate scale of spatial variation should be known. This variation can be obtained by using two transect lines from which to collect soil samples. The exact scale and pattern of variation of the continuous spatial variable can be determined efficiently over several orders of magnitude by a nested analysis of variance where stages incorporate spatial scale (Oliver and Webster, 1986).

Luxmoore and Sharma (1980) examined whether the integrated response of scaled soils distributed independently could characterise the hydrological behaviour of a catchment containing these soils. For both catchments the simulated runoff from the log-normal distribution of soils was closer to the measured value than the runoff from the mean, median or mode of soils. At present, many hydrological models use the mean value of K_S

to predict runoff and this research suggests it is more appropriate to consider the log normal distribution in the model rather than the mean. The comparisons between measured and simulated soil water contents showed significant differences even though the streamflow was similar. Sharma *et al.* (1983) measured sorptivity (S) and saturated hydraulic conductivity (K_S) in situ, in grids of 1 m^2 and 10 m^2. In general, at the closer spacing S and K_S were adequately approximated by normal function, while the log-normal was found to be a better function for data sets with larger spacings. Sharma *et al.* (1987) simulated water flow using a three dimensional Richard's Equation. The simulations showed that the rate of subsurface flow from the 30^o hillslope during and following rainfall were significantly enhanced with an increase in spatial dependence (more like soil units together with the same/similar K_S value). Subsurface drainage was increased with increases in rainfall intensity and slope complexity (when 30^o pitch was added). For hillslopes, the effect of spatial dependence in soil hydraulic characteristics was smaller with 30^o horizontal pitching than without. A hillslope with a random distribution of hydraulic characteristics produced a greater lag time in subsurface flow generation. Loague (1988) reported that at the hillslope scale, knowledge of the distribution of soil hydraulic property data appeared more important than that of rainfall data in simulating surface runoff generation and that discharge was closely related to soil hydraulic properties.

1.6 HYDROLOGICAL MODELS

There are a number of different modelling approaches used in hillslope hydrology and in part, they depend on how the physics of flow is represented and the way in which spatial variability is incorporated. Two broad categories of models exist (Anderson and Burt, 1987): the stochastic and the process-based distributed models. Stochastic models have a random element built into them so that successive runs of the model produce a distribution of outputs related to the stochastic components. The stochastic element removes the unique relationship between input and output values. This stochastic element can be produced in the model input, in the process or in the parameter values (Kirkby *et al.*, 1987). Byers and Stephens (1983) advocate that there is a spatial correlation structure inherent in natural soils and that by treating hydraulic conductivity as a stochastic process a more complete description of variability ensues.

Distributed models utilise soil properties measured in the field. Within distributed models there are various ways to include spatial variability into hydrological models. In theory, this element of spatial variability can be incorporated deterministically for all catchment properties, but the problems associated with measurement and dimensionality have restricted the deterministic description to properties such as the topography and vegetation (Anderson and Rogers, 1987). Beven (1989) argues for the need for deterministic models to take into account the horizontal variability at the sub-grid scale of 100 m by 100 m at the same scale as that of the vertical soil profile which is 1 m in depth.

Alternatives exist, such as the stochastic-deterministic model (Hopmans and Stricker, 1989; Holden *et al.,* 1995), the lumped model (Beven, 1989) and the transfer function model (Jury and Roth, 1990). A stochastic deterministic model comprises of random, generated variables and measured variables The lumped model involves the definition of representative or effective parameters, usually determined from model calibration, to describe the variability of an area. Two more model subdivisions have been referred to by Clark (1972). One is a probability-distributed model, where the data are not related in space. The other is a geometrically-distributed model, which expresses variability in terms of the orientation of the network points one to another and their distances apart.

1.6.1 Macropore Models

At the level or scale of the soil profile, flow paths through the matrix and individual macropores cannot be ignored but need to be represented whilst modelling so as to include their influence on soil water movement. The important role of the macropores in water and solute transport is now well established and many of the models use a two domain model to simulate the movement. The micropores form one domain, conforming to hydraulic principles based on Darcy's Law, and the second domain represents preferential flow in macropores. The interactions that occur are modelled between the two domains holding the immobile and mobile water and modelled in various ways, depending mainly on the way in which solutes are understood to diffuse from aggregates (Lafolie and Hayot, 1993). This two domain concept to represent a combined micropore/macropore system was suggested as long ago as 1946 by Muskat (quoted in Beven and Germann, 1981). Results from Beven and Germann's (1981) model predict that the greatest volume of infiltration occurs for those micropore/macropore soils with intermediate hydraulic conductivities. They suggest that because the total available storage in the macropores is relatively small once they are saturated, further infiltration into the macropores is governed by the rate of loss into the surrounding micropores. The relative magnitude of the macropore effect will vary with the specific nature of the macropore system (depth, macroporosity, variability with depth) and boundary conditions imposed at the surface. These data were compared to two very different sets of field experiments by Burger (1922-1940) and Ehlers (1975) and produced a reasonable correlation (Germann and Beven, 1981b).

Yeh and Luxmoore (1982) outlined two approaches to modelling water flow and chemical transport in mesopore-macropore media. The first was the single continuum approach, which is applied to cases when the precise distribution of macropores can be mapped. The second, the double continuum approach, is applied to cases where only statistically average macroporosity can be determined. Yeh and Luxmoore's work showed that these models are capable of simulating fast water movement and speedy chemical migration through macropores in this two domain media. Their simulations suggested that macropores can increase the interactions of incoming water and chemicals with soil profiles facilitating drainage and delaying the start of lateral flow and surface runoff processes relevant to a soil without macropores.

Beven and Clark (1986) modelled infiltration into a homogeneous matrix with macropores. They used the Green-Ampt assumptions to predict infiltration rates through the walls and bases of channels, resulting in a mathematical description of the way which infiltration develops in the soil and how channels fill with water, until eventually overland flow begins. The channels were assumed to be vertical and circular with a constant diameter, but their depths and radii were allowed to vary over the population, the channels could also be randomly distributed. They concluded that the presence of channels can lead to significant increases in predicted channel volumes.

Leeds-Harrison *et al.* (1986) experimentally found a strong linear relationship between hydraulic conductivity and specific yield (drainable porosity) of large cores of Evesham clay. This relationship was used as a parameter input to a layered drainage model for mole drained soils. Results from their model indicate that soils of lower drainable porosity and hydraulic conductivity produced higher peaked hydrographs with steeper recession limbs. They looked at the implications of soil loosening on the drainage response in heavy clay soils.

Jarvis and Leeds-Harrison (1987a) outlined their two domain model of water movement in a drained clay soil. They showed that their model predictions were highly sensitive to the soil structure (e.g. crack spacing and width), and also moderately sensitive to both the rainfall intensity and an empirical component related to the degree of saturation in the cracks. This model was tested in the field by Jarvis and Leeds-Harrison (1987b) and was found to satisfactorily predict peak drain outflow rate and subsequent drainage recession, although there was a tendency for the model to underestimate the start time of drainage. Good agreement with the measured recharge profiles was generally found. Jarvis (pers.

comm.) has continued to develop his MACRO model which is based on the two domain concept of water movement. Holden *et al.* (1995) comment that the model seems to over predict the amount of discharge monitored at the surface of a soil and that prediction is better at depth.

Addiscott (1977) developed a very straightforward two domain model known as SLIM. It is referred to as a tipping bucket model because the soil profile is regarded as behaving like a tipping bucket; rainfall infiltrates the soil until the soil reaches field capacity and then the subsequent rain bypasses the soil matrix. Addison (1995) verified this model for an intensively mole drained grassland soil at Okehampton, mid-Devon. She reported that the water yield calculated by SLIM was similar to that averaged for storms which occurred in March and November, but that the volumes predicted for individual storms was in great error. In particular, the peak flow arrived too early and peak discharge was too great.

1.7 MACROPORE FLOW AND DYE TRACING

Various techniques have been employed to verify the two domain flow concept ranging from qualitative to quantitative in both the laboratory and the field. Each approach has its own merits and limitations. Qualitative investigations use dyes to trace flow paths. Reynolds (1966) tested 12 fluorescent dyes in the laboratory for their stability under conditions of alternate wetting and drying, and persistence of fluorescence in an acid soil. He found that Pyranine was the most useful dye in the field since it could be detected several months after application and could be photographed using ultra violet light. He found in his study that the greatest movement of dye occurred around tree trunks and due to lateral movement within the humus layer.

Corey (1967) illustrates different types of non fluorescent dyes and how effective they are in tracing flow paths in acid soils. From this work he proposes an empirical criterion for choosing potentially suitable dyes for studying water movement. Smart and Laidlow (1977) compared 8 fluorescent dyes in the laboratory and field experiments to access their utility in quantitative tracing work. They recommended Amino G acid, Lissamine FF and Rhodamine WT as being the most useful. Bouma and Dekker (1978) used Methylene Blue as a tracer, applying it at different rates and quantities to determine the infiltration patterns of water into four dry clay soils with different macrostructures. They found that the number of stained bands could be manipulated with different rates and quantities of dye, but the number always remained low with a maximum of 2%.

Omoti and Wild (1979a) offer a technique to identify solute pathways through columns of sieved soil aggregates using fluorescent dyes and then under UV light photographing their presence. Pyranine was found to be the most successful dye in short term laboratory experiments because of its high fluorescence and comparatively low adsorption coefficient. Omoti and Wild (1979b) used Fluorescene and Pyranine as solute markers in field experiments under winter rainfall and irrigation. UV photography showed preferential flow of Fluorescene caused by earthworm channels, fissures and loosely packed soil with varied pore sizes. Although adsorption of the dye occurred, when compared to chloride a conservative tracer a similar pattern was found. Trudgill (1987) compared the behaviour of three fluorescent dyes (Rhodamine WT, Lissamine FF and Amino G acid) for use in soil water tracing. He discussed their limitations and found that Lissamine FF and Amino G acid were preferred for soil column work because of their low adsorption, and Rhodamine WT had a higher adsorption, but is best for use in the field because organic fluorescence backgrounds were high.

Breakthrough curves have been used to quantitatively express the pore size distribution, tortuosity and connectivity of macropores. Bouma and Wosten (1979) sampled large undisturbed soil columns with two different types of macrostructure in moist clay. Using repeated measurements of saturated hydraulic conductivity, they characterised the flow patterns based on chloride breakthrough curves. Effective pore size distributions were calculated from the breakthrough curves. They recommended that field work should take direct measurements of breakthrough curves with empirical extrapolation to soils with identical texture, mineralogy and macrostructure. This is because replicate columns sampled in a large geographical area and with two types of macrostructure showed significantly different flow phenomena. Bouma (1980) has tried to overcome the difficulties of determining hydraulic properties in swelling clay soils which are due to seasonal variations in pore geometry and to soil structure heterogeneity. He prepared large *in situ* columns to measure K_{sat} and K_{unsat} near saturation, using the crust test. Sample size was determined by soil descriptions. Bouma (1980) discusses examples which illustrate the use of soil morphology to characterise preferential flow. His work was developed by Booltink (1994) who investigated soil structure and flow patterns using Methylene blue. Deeks (1995) has shown that preferential flow along macropores can only be characterised quantitatively when tracers are used within the flow system. She reported that adequate information could not be derived from standard descriptions of soil structure but rather required a combination of the binary transect method and expensive micromorphometric techniques.

1.8 HYDROLOGICAL RESEARCH REQUIRED

This review has described the various hydrological pathways and associated mechanisms identified in the literature as operating at the hillslope and plot scale. Central to the discussion is the way in which the dominance of the different flow pathways change as the scale varies. At the hillslope scale, the importance of the larger pores is subsumed by the process of averaging discharge over a large volume of soil. At the plot scale, however, the characterisation of the macropore flow routes is fundamental to an explanation of water movement within soil profiles. Unfortunately, it is impossible to determine directly where unsaturated or indeed saturated water flow is occurring and hence the need to resort to sophisticated monitoring approaches. Discussion of water pathways, processes and patterns of movement relies on accurately monitoring flow and characterising the soil structure. Hence part of the thesis is devoted to describing the various monitoring techniques used in the field and procedures adopted in the laboratory.

The research investigation described in this thesis is concerned to describe the hydrology of a section of hillslope at Beddgelert Forest, North Wales and to examine the water pathways at a forest and a whole tree harvested site. The study will seek to relate hydrological differences between the two sites to differences in the vegetation, as well as in soil structure. Characterisation of the pathways and mechanisms controlling the transport of water and solutes is of considerable interest to biogeochemists studying the movements of acid deposition to streams.

1.9 FOREST MANAGEMENT

These hydrological systems can be altered by influence of management. In forestry terms, there is increasing debate between the conventional method of harvesting (CH) and whole tree harvesting (WTH). Whole tree harvesting is where all above ground parts are removed in one action. The technique used for harvesting trees is the same whether it is the whole tree or just the stem. On steep slopes, such as those at Beddgelert, a cablecrane is usually used to lift complete or parts of trees off the site. These are ropeway systems where timber is removed by moving cables, powered by a stationary winch. Timber is carried wholly or partially clear of the ground (Hibberd, 1991). At the research site the trees were lifted clear of the ground to avoid damage In practice, stems are often dragged with their butt end on the ground. The difference between WTH and CH is that with CH the branches, needles and stem <7 cm diameter are cut off, and this felling debris, known as brash, is spread across the site. This forms a brash carpet and provides a protective layer over the soil. It is the removal of this protective layer that may cause the type of harvesting to change the soil structure and the soil hydrological pathways. Harvesting machinery, such as forwarders, are used to remove timber on flat sites rather than cablecrane.

Until recently, whole tree harvesting was not practised in upland forests in the UK. Beddgelert was a one-off experiment. However, there have been moves toward WTH in mid-Wales and other parts of the UK. The FC suggest that "WTH is likely to be increasingly used in British Forests" (Dutch, 1995). There has recently been proposals to build a "chipping plant" in Cumbria (M Clarke, pers.comm.), this would produce wood chips from the brash of WTH trees. Potentially, WTH could be applied to all the Brown earth group, and most of the Ironpan soils and Intergrade group. These soils make up around 70 % of the forested area in North and Mid-Wales (Pyatt, 1977). Therefore, the potential for WTH is substantial (110,000 hectares in North and Mid-Wales). Whole tree harvesting has been more widely practised outside the UK, particuluarly in the Scandinavian Coutries. Here, short rotation coppice or plantations are used for fuel or electricity generation. In Finland, the biofuel source will increase substantially over the next 5 years, when by the year 2000 Finland are hoping to phase out Nuclear power and replace it with wood,a sustainable crop (M Clarke, pers. comm.). For wood to be economically viable for biofuel, the whole tree needs to be utilised, and therefore the WTH technique is favourable.

The main advantages of WTH are that the system provides a clear site on clearfelling, which makes restocking easier and cheaper, and that the crown contains a great deal of fibre, cellulose and calories, which increases the yield per acre. The crown can be used for chipboard, but also as a biofuel and for mulching. In terms of practical forestry, these are significant advantages (Clarke pers. comm.). However, there are disadvantages to WTH. There are more nutrients in the fine branches and foliage compared to the stem wood (Carey, 1980), so when the crown is removed these are lost from the nutrient cycle. This has implications for site nutrition and future tree growth. WTH may also affect site productivity through damage to the soil structure by removing the protective brash carpet which would spread the load of the machinery and prevent soil compaction and poaching (Anderson, 1985; Skinner *et al.*, 1989).

Two contrasting trends are emerging in the attitudes to the management of upland conifer forests. One view, which is very much the influence of foresters, is where WTH is regarded as an appropriate form of harvesting on drier soils (brown earths, brown podzolics and some peaty podzols such as stagnopodzols), which can support the weight of extraction vehicles. Peats, peaty gleys and gleys rapidly become rutted with WTH. The other view, which stems from environmentalists and formed part of the Environment White Paper (1990), concerns the sustainability of forests. Sustainable forestry has been interpreted in this thesis as encompassing conservation of nutrients for future crops and in terms of initial biodiversity prior to tree regeneration. Whole tree harvesting is less sustainable than CH because of the removal of nutrients held within the crown. The absence of a brash layer may also alter the micro-climate through the lack of shelter for newly planted trees or alteration of soil temperature. The clear site left after WTH however, provides better biodiversity in the early years, until tree regeneration becomes established. In terms of forest recreation, WTH provides a more aesthetically pleasing site. Ground vegetation may inhibit initial tree growth by competition during the establishment phase but may also act as a temporary nutrient store that 'mops-up' nutrients early on and then releasing them later as the tree canopy suppresses the vegetation (Fahey *et al.*, 1991; Emmett *et al.*, 1991). The aims of the Environmental White Paper contradict each other, because to have biodiversity in the initial stages of tree growth, i.e. WTH, then the lack of remaining brash reduces the sustainability of forests due to the loss of nutrients. No guidelines to date have been produced by the Forestry Commission on promoting sustainable forestry due to the lack of relevant research. Further research is required before guidelines are produced. It is essential that the effects of WTH on soil structure and soil hydrology are studied to determine whether there are any other adverse effects of WTH.

Three areas of research have emerged from the effects of harvesting and specifically WTH. These are (i) nutrient removal (Stevens *et al.*, 1995; Stevens and Hornung, 1990; Stevens *et al.*, 1988) - the decline in soil fertility due to removal of timber and brash from the site, (ii) leaching losses (Anderson, 1985) - nutrient loss via ground water after the breakdown of brash left on site after CH and (iii) forest nutrition (Proe and Dutch, 1994) or the effects on timber growth due to removal of nutrients by WTH. However, there has been no research into the effects of WTH on soil structure and soil hydrological pathways, which this project attempts to redress.

1.10 RESEARCH AIMS AND OBJECTIVES

This research seeks to quantify the components of the water budget and to examine water pathways within a section of hillslope at Beddgelert Forest, North Wales. Within this forest, two adjacent sites were chosen on seemingly uniform soil and slope conditions. The first site was forested with mature Sitka Spruce trees and the second was a WTH area. Throughout the study, similar experimentation was conducted at the two sites to observe the hydrological processes and highlight any differences between the forested and harvested sites. Differences at an appropriate detailed scale will be explained in terms of the influence, if any, of the forest on the hydrology as well as on the soil structure.

The objectives of the investigation are as follows:-

1 To quantify and investigate the pathways of the hydrological inputs, outputs and soil recharge for a hillslope in Beddgelert Forest.
2 To establish and quantify the direction of soil water movement at both sites and to establish the relative importance of soil water pathways.
3 To assess and quantify the spatial variability of K_S within and between the two sites and relate the differences to management.

4 To describe and quantify the soil structure at both sites and relate to the quantity of water movement.

The first aim of the research was to describe and quantify the hydrological inputs, outputs and soil recharge. Beddgelert Forest is situated less than 2 km from the summit of Snowdon and receives about 3000 mm of precipitation each year. There are a number of important hydrological questions regarding how much of this water infiltrates the soil and drains down the slope and how much is lost as interception and evapotranspiration. In hydrological terms, the area can be viewed as a typical example because precipitation and stream discharge are similar to other upland forested sites. However, there are several interesting questions regarding why the soil was rarely observed to be saturated and the nature of the pathways conducting the water away so rapidly. This study will also aim to identify and explain any differences in hydrological inputs between these two sites.

The second aim of the thesis was to describe and quantify the direction of soil water movement at the very detailed plot scale at both sites. This exercise will determine whether WTH causes any changes in soil moisture status and will help to establish the relative importance of soil water pathways (i.e. the degree of lateral and vertical soil water movement). The amount of water can be calculated from a knowledge of the hydraulic gradient and the hydraulic conductivity. Hydraulic conductivity is a measure of the average rate of water movement through a volume of soil. However, there are a number of problems measuring the hydraulic potential and in determining the hydraulic conductivity. Several problems arise when measuring hydraulic conductivity, partly due to the techniques used but more particularly because it is known to produce variable results in space and depth (Nielsen *et al.*, 1973; Russo and Bresler, 1981).

As a result of the importance of saturated hydraulic conductivity (K_S), the third aim of the research was to quantify the spatial variability of K_S at the forest and WTH sites. Due to the great variability of K_S, a large number of samples both on the horizontal and the vertical planes are required to present a full picture of the scale and variability of K_S. Furthermore, the picture is more complex when the soil is anisotropic (i.e. hydraulic conductivity varies depending on the soil samples axis).

Hydraulic conductivity takes into account the more rapid flow paths, in which the flow bypasses the soil aggregates, and the slower routes through the soil matrix. Very detailed studies are needed to determine whether the soil water moves predominantly through the soil macropores or the soil matrix. Similarly, the factors controlling such movement must be assessed in terms of forest management, site conditions and soil characteristics. Investigators working at the Mai Mai catchment, Tawhai State, New Zealand have sometimes disagreed about the importance of different soil water pathways. The findings of Sklash *et al.* (1986), suggested a dominance of "old" water, contradicting Mosley (1979; 1982), who suggested that streamflow was generated by rapid transmission of "new" water through macropores. It is still unclear what mechanisms govern soil water movement in forest catchments. Furthermore, the questions still remain: what are the effects of WTH on these pathways and does forest management influence K_S.

The fourth aim was to describe the soil structure at different scales because of its influence on hydraulic conductivity (Bresler *et al.*, 1984; Byers and Stephens, 1983 and Beven and German, 1982; Booltink, 1993; Holden, 1995). Other soil characteristics may also affect water movement and these include percentage silt, sand, pore neck size and electrical conductance. Results by Laurens *et al.* (1988) suggest that macrovoid area or percentage silt or clay could be used to predict the spatial distribution of K_S in the field. However, no universal link has been established between soil structure and K_S, and whether this relationship determines soil water movement. Different scales of investigation were used to help identify the characteristics influencing soil water movement.

Results analysed to fulfil these aims will stress the influence of forest management. In particular, the discussion will focus on determining whether the flow pathways governing the soil water movement at the forest and WTH site are the same and whether the soil structure retains this influence of the trees over the medium term. Such research will contribute to the general debate about the movement of water, nutrients and pollutants in forests as well as more detailed questions regarding the significance of macropore and matrix flow. The results may have important implications for sustainable forest management and the effects of whole tree harvesting.

1.11 BACKGROUND TO BEDDGELERT STUDY

One of the studies to investigate the impact of forestry in upland Britain was a collaborative project between the Forestry Commission (FC) and the Institute of Terrestrial Ecology (ITE) and was based at Beddgelert Forest. This project was unique because one aspect of this research was to consider the effects of whole tree harvesting (WTH) and to compare this method to conventional harvesting (CH). Clearfelling will be used in this thesis as a general term for both WTH and CH. The increased interest in WTH was instigated by the development of a mechanical process, which allowed all above-ground parts of the tree to be utilised, including the stem, needles and branches from the crown to produce low grade chipboard.

More specifically this research project is directed at answering some of the questions that have arisen from on-going research by the Biogeochemistry and Land Use Research Group at the Institute of Terrestrial Ecology (ITE), Bangor. One aspect of the group's work has been to identify the biogeochemical effects of WTH and CH. Considerable quantities of nitrate were observed leaching from the harvested area compared with the Sitka Spruce forest. Stevens and Hornung (1988) noted that this leaching occurred below the rooting zone and increased with depth suggesting the importance of vertical flow. However, work at other steeply sloping sites confirms that lateral flow is dominant (Chappell *et al.*, 1990; Miyazaki, 1993). Only limited hydrological data has been collected at this Beddgelert site and there is a need for a detailed description of site hydrology. This project therefore will contribute to the ecological investigations which were conducted at Beddgelert Forest.

1.12 THESIS STRUCTURE

The thesis is divided into five key areas:

(1) Forest hydrology research (Previous Section) is set within a historical context and the theoretical developments concerning soil water pathways are described (Chapter 1). The discussion progresses from consideration of the wider issues of hillslope hydrology through a description of macropore flow to a detailed survey of the literature on soil structure. The background literature concerning scale and variability of saturated hydraulic conductivity is reviewed within the context of representative elementary volumes.

(2) Beddgelert Forest is described and the role of the soil physical characteristics particularly the soil moisture characteristics were investigated (Chapter 2).

(3) The overall experimental design and individual field and laboratory experiments are outlined (Chapter 3).

(4) The hydrological inputs at both sites are calculated (Chapter 4). The change in soil water content through time is described and soil water movement quantified at both sites based on measurement of soil water potential (Chapter 5). Saturated hydraulic conductivity and its spatial variability are quantified for each site in Chapter 6. Soil structure at both sites is described in Chapter 7 and water pathways were traced using a dye in Chapter 8.

(5) Although the results are detailed at the end of each chapter, they are synthesised in

Chapter 9 to provide an overview to the conclusions and implications of this study. Finally, further possible research arising from this study will be discussed.

CHAPTER 2

RESEARCH SITE AND SOIL CHARACTERISTICS AT BEDDGELERT FOREST

2.1 INTRODUCTION

In 1986, the Institute of Terrestrial Ecology (ITE) Bangor commenced a research project, with the Forestry Commission (FC), to examine the environmental effects of clearfelling and whole tree harvesting (WTH) of Sitka Spruce (*Picea sitchensis*) plantations at upland sites. This collaboration arose from the FC's need to forecast the ecological costs of intensive harvesting and ITE's interest in the ecological disturbance caused following clearfelling. This chapter reviews the physical geography of the research site including climate, geology and soil of the region and the local site. Detailed descriptions of the physical characteristics of the soil will also be presented. Inclusion of this information will allow an early understanding of the basic soil type and its context within the parameters of this study.

Regional Situation

This study was conducted in collaboration with ITE at Beddgelert, North Wales and was designed to complement existing studies at the Institute of Terrestrial Ecology (ITE) experimental site. Beddgelert Forest (NGR SH550500) is 12 km inland from the north west coast of North Wales, in the foothills of Snowdonia (Figure 2.1, Plate 2.1). The area has an oceanic climate, mountainous relief and is underlain by Ordovician slate. The experimental site was located in Cwm Du at Beddgelert Forest. Four blocks were whole tree harvested at Beddgelert Forest in 1980; one of these blocks was chosen in order to identify the effects of whole tree harvesting on hillslope hydrology and soil structure. For the purpose of the study, an adjacent block of 50 year old Sitka Spruce (*Picea sitchensis*) plantation was used to act as a control. Sites were selected adjacent to one another in order

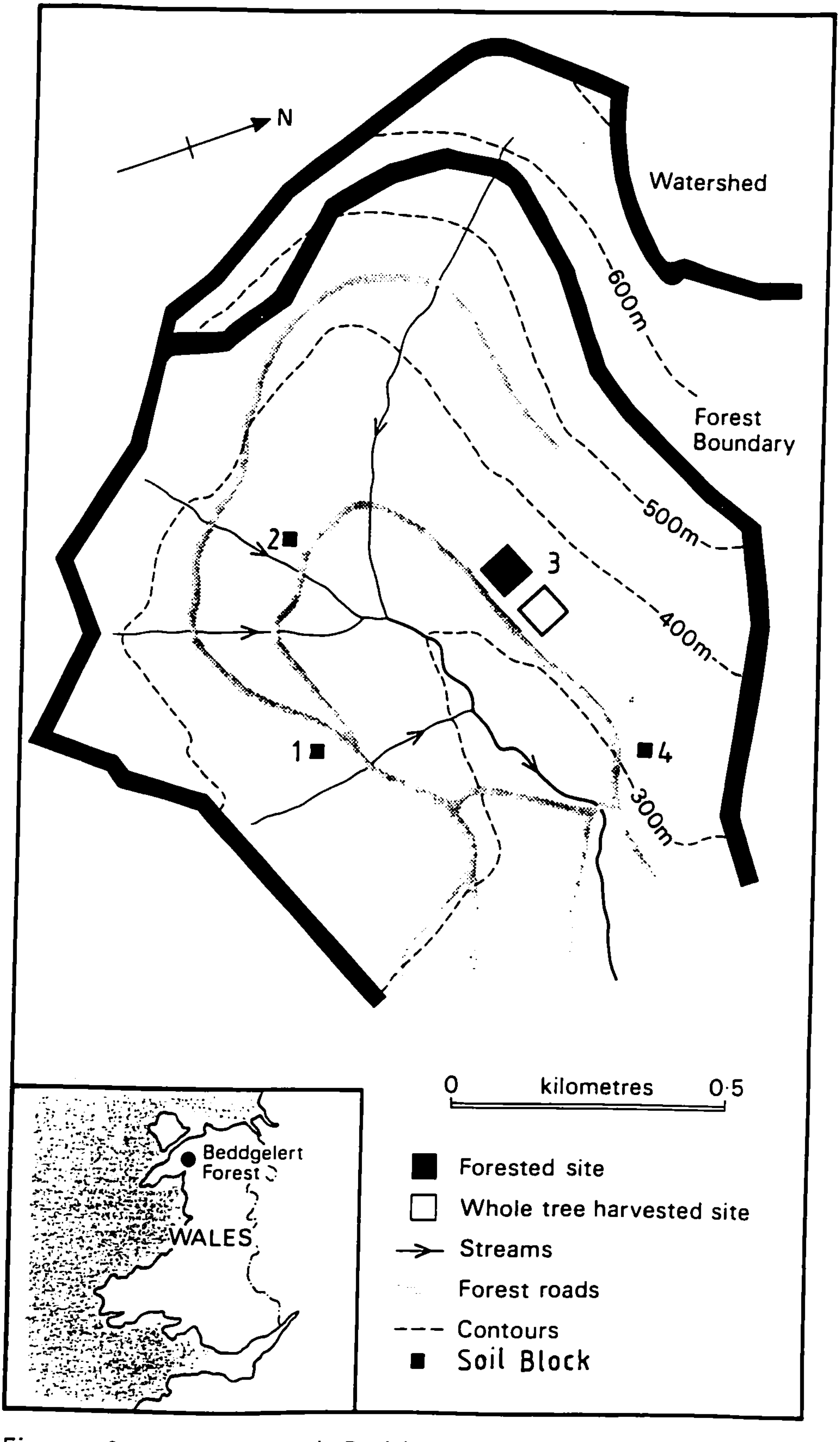


Figure 2.1 The site at Beddgelert (Source: Stevens & Hornung, 1988)

Plate 2.1 Cwm Du at Beddgelert Forest

to minimise naturally occurring soil variability, differences in precipitation amounts and topography.

Local Site

The hillslope selected for the purposes of this study appeared to be the most uniform in terms of bedrock geology, slope and soil characteristics. The slope profile was straight as opposed to convex or concave. A straight hillslope was chosen to eliminate additional variables, such as the effects of vertical ridges and troughs This selection was to enable a better understanding of the fundamental mechanisms governing soil water movement. Once this flow mechanism had been understood, it would be possible to apply to other topographies, such as hollows and spurs. Work by Hornung (pers. comm.) at Beddgelert Forest has shown that the soil at the site selected for this research is the most uniform in the cwm (Figure 2.2). The experimental site is situated in a north east facing cwm (Figure 2.1).

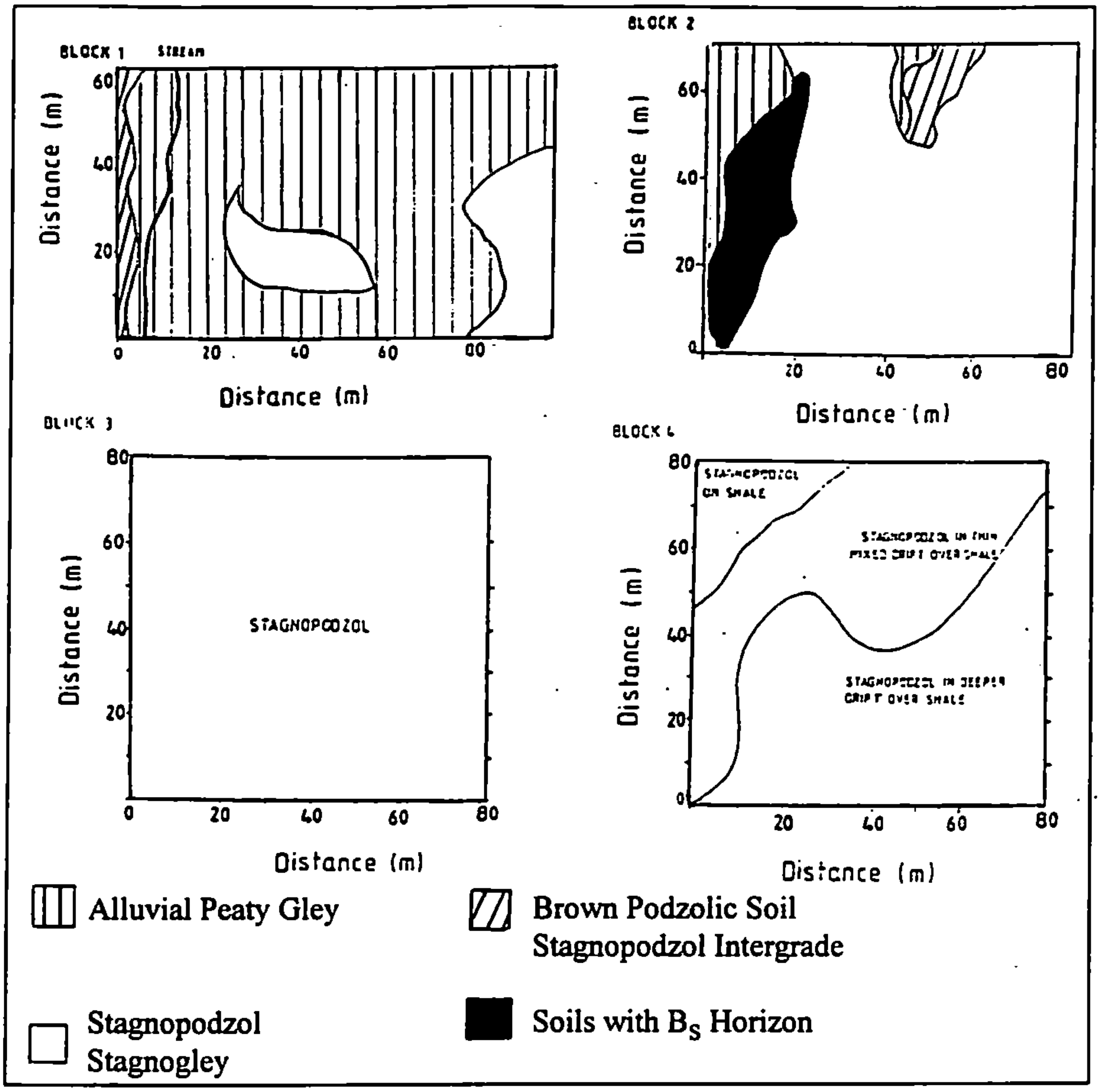


Figure 2.2 Distribution of soil types at Beddgelert Forest (See Figure 2.1 for location of blocks).

2.2 CLIMATE

2.2.1 Regional Climate

The climate of North Wales is characterised by a cool temperate regime with a shortened growing season, low temperatures, a high annual rainfall with strong and frequent winds (Manley, 1952). Coastal areas of North Wales tend to be drier than the hills, but are exposed to strong westerly winds from the sea. Added to this, the orographic effect of the hills and mountains ensures that these areas are often cloudy, cold and exposed. With increasing height above sea level, average temperature falls and precipitation increases such that the average rainfall (over 21 years, from 1945 to 1965) on Grib-goch, a ridge of Snowdon, some 2 Km from Beddgelert was 4229 mm (Ball *et al.*, 1969). Mean temperature, soil type and topography are the main factors determining suitability of husbanded vegetation and therefore land use.

2.2.2 Local Climate and Hydrology

Beddgelert Forest in common with other mountainous areas in North Wales, is wet and cold for much of the year and has a typical upland climate with an oceanic influence. However, due to the position of Cwm Du, the study site is relatively sheltered from these strong winds. The mean annual rainfall at Beddgelert Forest was 2800 mm between 1982 and 1986, while mean annual air temperature and mean annual soil temperature were similar at 8 ^{o}C (Stevens and Hornung, 1988). The area is drained by a second order stream whose flow ranged from about 0.2 m^3s^{-1} to 2 m^3s^{-1}. This water was supplied from highly responsive tributary streams and several springs during winter storms (Plate 2.2). One spring at the base of the experimental hillslope flowed from January to March. Peak flows were estimated at 10 l s^{-1} in early January (Plate 2.3 and 2.4). The source was reasonably diffuse at the base of a quarry and so was not measured.

Plate 2.2 Perennial spring

Plate 2.3 View up-stream towards perennial spring

Plate 2.4 Perennial stream disappearing down sink hole

2.3 GEOLOGY

2.3.1 Regional Geology

North Wales has undergone major geological changes and, as a result, the area has a complex geology. Volcanic activity metamorphosed sands and silts laid down in an earlier period. Folding and uplifting of the land mainly took place in the Caledonian era and, to a lesser extent, during the Hercynian period. Extensive erosion and deposition occurred during periods of glaciation and de-glaciation, and, more recently, the hillslopes have been reworked by periglacial processes (Section 2.4.1).

2.3.2 Local Geology

The glacial cwm at Beddgelert is dominated by Ordovician slates, with small areas of dolerite intrusions (dykes) (Shackleton, 1959). These grey thinly bedded basal Ordovician sediments were deposited during a marine transgression over the tilted, eroded fault blocks of Cambrian strata. At Beddgelert, the Glanrafon Beds consisting of slates and sandstones dominate, which are part of the Caradoc series (Smith *et al.* 1961).

2.4 GEOMORPHOLOGY AND TOPOGRAPHY

2.4.1 Regional Geomorphology and Topography

Frost shattering of rocks during the late Devonian period has produced small sub-angular scree which is characteristic of many of the present day hillslopes in North Wales, including those at Beddgelert Forest. The scree was moved downslope by solifluction, a process which occurred during the summer, when periodic thawing above the permafrost resulted in a viscous mobile layer moving downslope by gravity. The head is of variable thickness and is commonly a mixture of stones, roughly orientated downslope, in a loamy mixture. Steep slopes are mainly composed of a thin layer of angular rock fragments, whereas valley bottoms contain deep deposits of valley infill (i.e. reworked till). Compact subsurface layers or fragipans are found at the junction of permanently frozen and seasonally thawed ground (Fitzpatrick, 1956). The presence of fragipans can allow saturated water to build up causing the possibility of macropore flow and has important implications for slope hydrology (Williams, 1983). Orientation of stones and the shattered bedrock or "shillet" may control subsurface saturated water movement.

2.4.2 Local Geomorphology and Topography

Beddgelert Forest lies between an altitude of 100 m and 550 m and the experimental sites were at an altitude of about 350 m. The majority of the forest lies on steep-sided slopes. Average slope angle of the forest and clearfelled sites was 30°. Within the forest, glacial and colluvial deposits occur widely, together with extensive postglacial stabilised scree. The research hillslope is south facing and is covered by a relatively shallow layer of scree which, following soil investigations and exposures, was found to extend to bedrock. A seismic survey determined the first layer of bedrock below the surface, along a transect from the river to the top of the hillslope. On the hillslope, the depth to slate bedrock varies around a mean of 2.15 m (Figure 2.3).

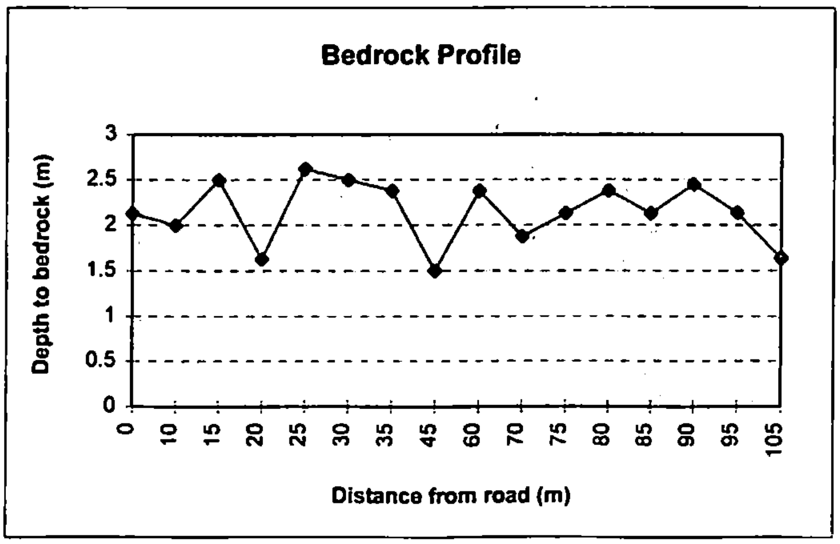


Figure 2.3 Bedrock profile.

Downslope of the road, towards the river, the depth to slate bedrock varies around a mean of 4.3 m (Figure 2.3). Plate 2.5 shows the exposed face of the frost shattered scree slope where it meets the road. The majority of the larger pieces of weathered slate are orientated downslope. Below the forest, next to the road, an area of 20 m^2 has been quarried for slate (Plate 2.6). This quarry was used as hard core for the development of roads throughout the forest.

Plate 2.5 Exposed scree at the base of the hillslope

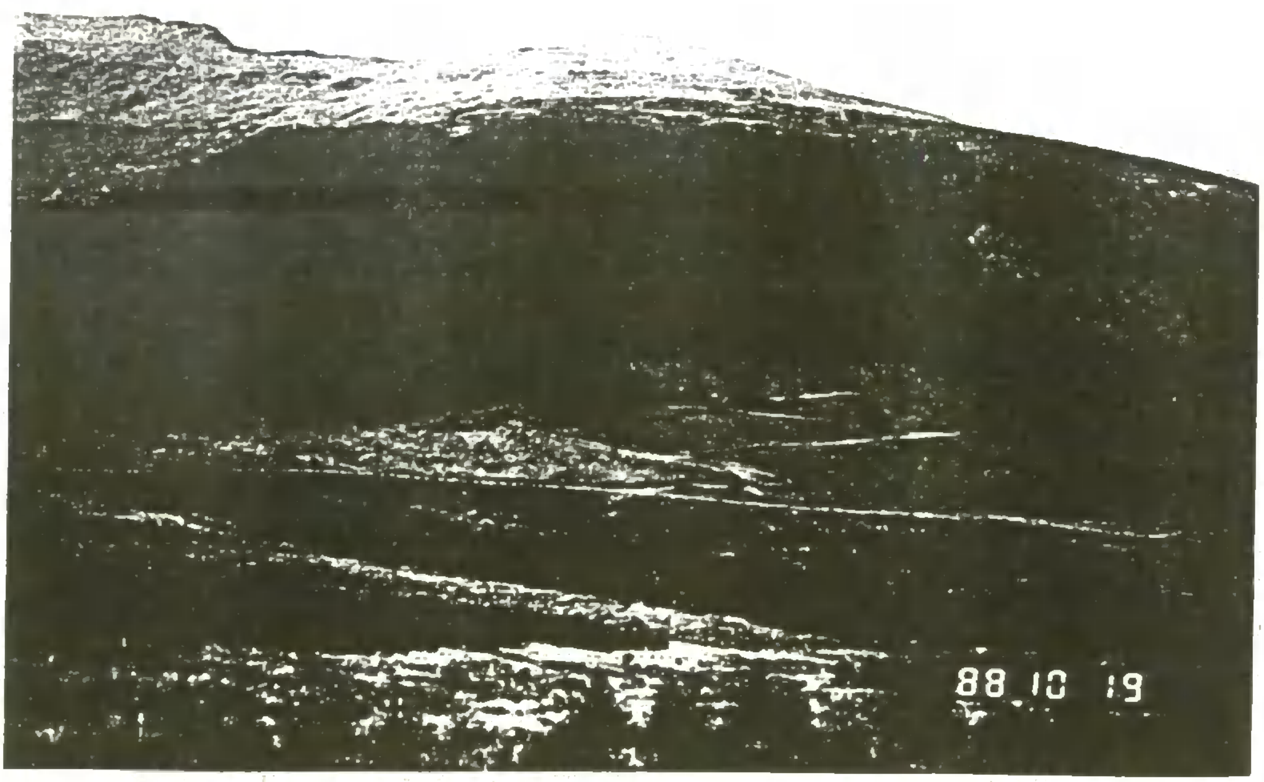


Plate 2.6 Small slate quarry used for hardcore on forest roads

2.5 REGIONAL SOIL TYPE

Substantial areas of North Wales are characterised by podzolic soils, including ferric humic stagnopodzol and podzol (*sensu stricto*) (Rudeforth *et al.*, 1984), which are due to a combination of cool temperatures, high rainfall, steep valley sides and rock debris from the Palaeozoic mudstones, shales, and slates. Soils at Beddgelert Forest are dominantly ferric stagnopodzols of Hafren Association (Avery, 1980). This visual observation was supported by soil chemical analysis undertaken by Nys (pers. comm.). Within Cwm Du at Beddgelert Forest, 28 profiles have been described and sampled for pedological and chemical analysis and 24 of these were found to be stagnopodzols (Nys pers. comm.). Table 2.1 shows the percentage soil type found at Beddgelert Forest.

TABLE 2.1 Percentage soil type at Beddgelert Forest

75%	Stagnopodzol
15%	Stagnohumic gley
5%	Alluvial gleys
4%	Brown soils
1%	Rankers

(from Nys personal communication, 1989)

Figure 2.1 indicates the location of the soil sampling points, and the spatial distribution of the soils, based on the survey presented in Figure 2.2. Table 2.2 shows some of the characteristics of the soils at Beddgelert Forest (Section 2.6). The main soil type situated at Beddgelert forest is the Hafren Series and it occupies steep slopes with slate bedrock. The Hafren series is characterised by a dark coloured humose surface horizon, greyish eluvial horizon over a yellowish red B_S horizon (Rudeforth *et al.*, 1984). Table 2.3 shows a typical profile description at one of ITE's sample points on the study hillslope.

Loss on Ignition (LOI) is an indication of the soil's organic content, but the amount of material lost is temperature dependant (Ball, 1966). In this experiment, a standard temperature of 375^{o}C was used. LOI in the surface horizon (0 - 4 cm) was 64 %, whereas the horizons of the mineral soil (4 - 40 cm) ranged between 0.4 % to 14.5 % (see Table

2.2). In all soil profiles, the organic matter content decreased with depth. These values are low for an upland area, compared with those reported by Rudeforth *et al.* (1984) of the Hafren Series. The LOI values suggest that, although organic matter has accumulated at the surface, the soil is aerobic for most of the year suggesting that it is well drained given the high input of rainfall.

TABLE 2.2 Soil characteristics at Beddgelert Forest

Non-gley soils (24 profiles)					
Horizon	O	Ah	E	B	C
Lower Boundary Depth (cm)	2	10	19	46	75
Texture					
stone (% by vol.)	0	0.4	1.8	5.4	4.2
course sand (% by wt)	0	2.0	7.7	26.4	32.4
medium sand	0	4.5	10.3	17.3	23.9
fine sand	0	6.5	8.8	11.3	17.7
course silt	0	12.3	10.8	11.3	9.0
fine silt	0	47.4	41.5	24.4	14.3
clay	0	27.3	21.0	9.3	2.8
Bulk Density ($g\ cm^{-3}$)	0.42	0.68	0.82	0.66	0.66
Mass of Fine Earth (Kg)	8.4	54.2	72.4	168.6	183.5
Loss on Ignition 950°(%)	73.1	17.6	10.2	8.0	4.8
Loss on Ignition 375°(%)	64.1	14.5	4.7	2.0	0.4
Carbon (%)	38.0	6.2	2.4	1.4	0.3
Nitrogen (%)	1.7	0.6	0.3	0.2	0.0
C:N ratio	21.8	11.3	8.9	7.6	9.7
pH in Water	3.3	3.7	3.9	4.1	4.1

(from Nys personal communication, 1989)

Table 2.3 A profile description of stagnopodzol soil from study sites

Location: Beddgelert Forest, Gwynedd (SH 554 513)

Profile No: Block 3, 6/0

Altitude: 310m Slope: 21° Aspect: 155°

Parent material: Ordovician shale scree

Location drainage: Normal Profile drainage: Poor above, well drained below

Land use: Forestry - Sitka Spruce (Picea sitchensis)

Horizons:
cm

1 - 0
01 + 0f Matted, Sitka Spruce needles and twigs.
(350)

0 - 2
O Very dark grey (5 yr. 3/1) organic loam; stoneless; structureless, massive; moist, greasy; a few small and medium woody roots; peaty organic matter content; moderate porosity; abrupt, smooth boundary.
3, 6/0, 1 (351)

2 - 14
Ah/Ea Dark greyish brown (10 yr. 4/2) silty clay with common fine distinct ochreous mottles; slightly stony with a few gravel-sized and small platy shale fragments; medium moderate sub-angular structure; moist, firm; a few small and medium, and rare fine woody roots; moderate organic matter content, low porosity; a few Fe concretions, and rare bands of Fe (1mm x 20mm); horizon becomes darker at base; abrupt, wavy boundary.
3, 6/0, 2 (352)

14 - 24
Eag Yellowish brown (10 yr. 5/5) silty clay loam with common fine distinct ochreous and a few fine distinct black (Mn) mottles; stony with a few gravel-sized and medium, and common small platy shale fragments; fine weak angular structure; moist friable; a few small and rare fine woody roots; low organic matter content; moderate porosity; clear, wavy boundary.
3, 6/0, 3 (353)

24 - 38
Bs Red (2.5 yr. 4/6) sandy silt loam; extremely stony with common small, medium and large platy shale fragments; fine weak crumb structure; moist, very friable; a few fine and small, and rare medium woody roots; low organic matter content; high porosity; clear wavy boundary. 3, 6/0, 4 (354)

38 - 68
Bs/C Brown to dark brown (7.5 yr. 4/4) loamy sand; extremely stony with common gravel-sized, small, medium and large platy shale fragments; structureless, single grain; moist, loose; rare fine and small woody roots; low organic matter content; very high porosity; mainly shale with a little ochreous material between; diffuse smooth boundary.
2, 6/0, 5 (355)

68 - 80+
C/R Extremely stony with abundant gravel-sized, small, medium and large platy shale fragments; structureless; moist, loose; no roots; low organic matter content; very high porosity; loose, shale scree material with little or no fine material.
3, 6/0 (356)

(from Nys personal communication, 1989)

The soils at Beddgelert are characterised by their low pH. The surface horizon has a pH of 3.3 in water and the mineral soil ranges between 3.7 to 4.1. (Table 2.2). Throughout the soil profile pH increases with depth. This trend is associated with leaching of cations from the surface and associated decrease in organic matter. Low pH is due to the acid parent material with low base content together with high rainfall and leaching of the soil minerals.

The C:N ratio provides an index of decomposition. Values can range from 60:1 for fresh litter to about 15:1 for humus. The ratio is a useful index of the resource value of the vegetation. High ratios (50:1) are associated with acid litter derived from conifers and provide a poor nutrient source for misofauna whereas low ratios (15:1) are associated with fertile high nutrient soils. The C:N ratio in the surface horizon is 21.8 (Table 2.2) and the mineral soil horizons range between 7.6 and 11.3. Thus in the mineral horizons the level of decomposition is relatively high, and a well structured soil has become established.

2.6 LOCAL SOIL CHARACTERISTICS

2.6.1 Soil Characteristics of the Forest Site

The forest soil is predominantly a ferric stagnopodzol of the Hafren series (Avery, 1980). Below a thin litter layer of needles and twigs, there is 4 cm of organic loam. This loam is structureless, has high porosity, a bulk density of 0.42 g cm^3 and contains fine roots and medium woody roots (Table 2.3 and 2.4).

The Ah/Ea horizon is dark grey with fine ochreous mottles, where iron has been reduced to ferrous oxide indicating the soil structure is causing localised saturation. Measurements at this site show a bulk density of 0.68 g cm^3 and the porosity as 62 % (Table 2.2 and 2.5). These values are both similar to that found by Chappell (1990) in the Hafren soil series at Plynlimon and may be considered typical of this area. There were a few small and medium roots with rare fine woody roots. A large percentage of the soil matrix comprises of silt (62.18 %) (Table 2.4), and it has a silt loam texture. The structure of this horizon is medium moderate sub-angular.

Table 2.4 Textural classification of the forest soil (means of 4 replicate samples)

Horizon	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Textural Name
O	0	0	0	0	Humus
Ah/Eg	9.65	15.86	62.18	12.31	Silt loam *
Eag	27.62	17.16	41.43	13.79	Clay loam *
Bs	81.36	10.36	7.35	0.93	Sandy shale

* Soil Survey of England and Wales Textural Name

The Eag horizon is light grey/yellow brown, again with fine ochreous mottling and a few black (Mn) mottles (Table 2.3). The Eag horizon is more stony than the upper horizons, with 27.62 % gravel content (Table 2.4). There are also common small platey shale fragments and a few small and rare fine woody roots. The result is a fine weak angular structure with a porosity, (68%) and bulk density (0.82 g cm^{3}) (Table 2.2 and 2.5). Again, this is similar to that found by Chappell (1990). The Eag horizon has a slightly higher clay content than the Ah/Ea horizon (Table 2.4) and is therefore classified a clay loam. As expected, there is less organic matter than the upper horizons (Table 2.3). It is interesting to note that although the bulk density is higher than the Ah/Ea horizon the porosity is also higher which is unusual as porosity is normally inversely proportional to bulk density.

Table 2.5 Physical properties of the forest soil (means of 2 replicate samples)

Horizon	Bulk Density (g cm^{-3})	Porosity (%)	Organic content (%)
O	0.42	0.68	33.12
Ah/Eg	0.68	0.62	14.26
Eag	0.82	0.68	9.93
Bs	0.66	0.58	7.07

The B_S horizon is a ochreous sandy slaty loam, which is very friable and has a weak crumb structure (Table 2.3). The matrix is extremely stony, with a gravel content of 81.36 % and medium to large slate fragments (Table 2.4). The B_s horizon has a porosity of 58 % (Table 2.5), again these values are similar to that found by Chappell (1990).

The bulk density is 0.66 g cm^3 (Table 2.3 and 2.5), which is low considering its position in the soil profile. The soil pit was limited to 50 cm in depth due to the large amount of slate and shaley material at this depth, so it was not possible to characterise the soil beyond this. Material at 50 cm displayed a downslope orientation and was surrounded by a densely packed fine earth matrix, which shows a periglacial origin. The hammer seismograph survey revealed that the slate bedrock was approximately 2.15 m below the surface (Figure 2.3).

In summary, the Ah/Ea horizon was bordered by the O and Eag horizon, which both have higher porosities. The Ah/Ea horizon possibly has a uniform soil matrix (i.e. without macropores), and acts as a semi-impermeable layer, which depending on resistance would deflect some of the soil water laterally along the horizon. There should therefore be evidence of localised saturation at the O/Ah/Ea boundary. This horizon still had a high measured value for pore space (62 %), yet mottling within this horizon suggested saturation for long periods, which could be explained by variations in porosity in the Ah/Ea horizon. Overall, the Ah/Ea horizon had the greatest amount of fine material (74.49 % of clay and silt) and the least amount of larger material (25.51 % of sand and gravel). The Eag horizon was higher in bulk density than the Ah/Ea, which would be expected the Eag horizon it being lower in the soil profile. The higher porosity of the Eag horizon could be due to either variability within the soil horizons or sampling error due to the sample volume not fully representing the Ah/Ea horizon. There was a dramatic increase in percentage gravel and slate fragments from the Eag to the B_S horizon, which makes the soil far more permeable. Dependant on the degree of semi-impermeability of the Ah/Ea horizon, available soil water can flow vertically under the influence of gravity when saturated. The porosity of the B_S horizon is low in comparison to the other horizons and it has a very low bulk density. Below the B_S horizon there is evidence of an intermittent fragipan. Therefore at this depth the level of permeability reduces and there is more likelihood of a strong lateral component.

2.6.2 Soil Characteristics of the Whole Tree Harvest and Forest Sites

In this section, repetition is avoided by only discussing relevant differences between the two sites, since many of the soil characteristics are similar. The soil at both sites is a stagnopodzol of the Hafren series and features are similar to those shown in Table 2.3. The O, Eag and Bs horizons are alike at both sites in terms of texture, whereas there are variations in the Ah/Ea horizon (Table 2.4 and 2.6). The Ah/Ea horizon varies between the two sites, due to the differences in large gravel-size fragments. This site has only a negligible amount of gravel sized-fragments: 0.44 % compared to 9.65% at the forest site. The low amount of these particles could reduce the drainage of the Ah/Ea horizon at the whole tree harvested site. The sand and clay content of the whole tree harvest site soil also varies slightly: 5.38 % and 34.18 % compared to the forest site 15.86 % and 12.31 %, respectively (Table 2.4 and 2.6). Again, less sand and more clay at the whole tree harvested site would reduce the drainage of the soil, depending on the type of soil structure present.

Table 2.6 Textural classification for the WTH soil (means of 4 replicate samples)

Horizon	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Textural Name
O	0	0	0	0	Humus
Ah/Eg	0.44	5.38	60	34.18	Silt clay loam
Eag	25.04	15.34	45.63	13.99	Clay loam
Bs	77.47	13.36	8.25	0.92	Sandy shale

* Soil Survey of England and Wales Textural Name

The organic content in the O and Ah/Ea horizons at the whole tree harvested soil is slightly higher, which may be a result of the different vegetation (Table 2.7). The porosity reflects this high organic content in the O horizon with a value of 82 % compared to 68 % in the WTH soil. However, the amount of organic matter in the Eag and Bs horizons is relatively low (Table 2.6 and 2.7) and these horizons are all lower in porosity in the WTH soil compared to the forest soil. Soil texture is the same at both sites in the Eag and B_S horizons and therefore these differences must be due to soil structure and roots, particularly the large woody roots due to living mature trees.

Table 2.7 Physical properties of the WTH soil (means of 2 replicate samples)

Horizon	Bulk Density (g cm^{-3})	Porosity (%)	Organic content (%)
O	0.42	0.82	58.75
Ah/Eg	0.68	0.56	19.63
Eag	0.82	0.59	8.33
Bs	0.66	0.51	6.35

The soil texture is the same at both sites (Table 2.5 and 2.7), with the exception of the Ah/Ea horizon. In this horizon, the whole tree harvested site soil has a higher percentage of clay than that of the forest, making it a silt clay loam rather than a silt loam and reducing the porosity of this horizon compared to that at the forested site.

In summary, the upper O an Ah/Ea horizons differ from the forest site in that they have a slightly higher organic content. The Ah/Ea horizon also has less of the larger components (i.e. sand and gravel), and has more of the finer ones such as silt and clay. These features makes the O horizon more porous than that at the forest site, whilst the textural differences make the Ah/Ea horizon less porous compared to that at the forest site. Texture varies little between the Eag and B_S horizons at both sites; yet the porosity for these at the whole tree harvested site is lower, due possibly to different soil structures. There are also less woody roots at the whole tree harvested site due to the absence of mature trees, which may be a contributing factor. However, in terms of relative porosity, the same pattern of porosity through the horizon layers occurs in both site soil profiles (Table 2.4 and 2.5), so relative to each other the two soil profiles produce similarities. The lack of any real differences in soil characteristics leads to the conclusion that the lack of trees at one of the sites has not caused any significant difference in soil type

2.7 SOIL HYDROLOGICAL CHARACTERISTICS

The storage and subsequent movement of water through the soil is influenced by the soil's physical characteristics (Hursh and Hoover, 1941), the slope of soil moisture content (θ) against soil water tension (σ) and energy gradient. These physical characteristics, such as aggregate shape and size, determine how the soil retains or releases water. Information on moisture retention is expressed by the mean of the soil moisture characteristic curve (SMCC), which was determined in the laboratory (Chapter 3). There are three main factors affecting the soil moisture release curve:- particle size distribution, organic carbon content and bulk density of the soil (Thomasson, 1978 and Rowell, 1994). These soil factors are all inter-related to the porosity and pore network. The pore network and moisture content (θ_V) govern the soil hydraulic conductivity (K). When the soil is saturated, all the pores are capable of conducting moisture. Hence the rate of water movement is at its maximum and is referred to as the saturated hydraulic conductivity (K_S). K_S can be determined in the field (Section 3.5). When a soil drains, there are fewer pores to allow water movement and therefore unsaturated hydraulic conductivity depends on the soil moisture content. The relationship between K_S and θ_V was determined in this experiment using the method developed by Campbell (1974). The spatial variability of Ks will be discussed in greater detail in Chapter 6.

2.7.1 Forest Soil Moisture Characteristic Curve and Soil Structure

The forest soil moisture characteristic curve presented in Figure 2.4 shows that there was a marked loss of water between 0 and 50 cm H_2O suction in all the horizons.

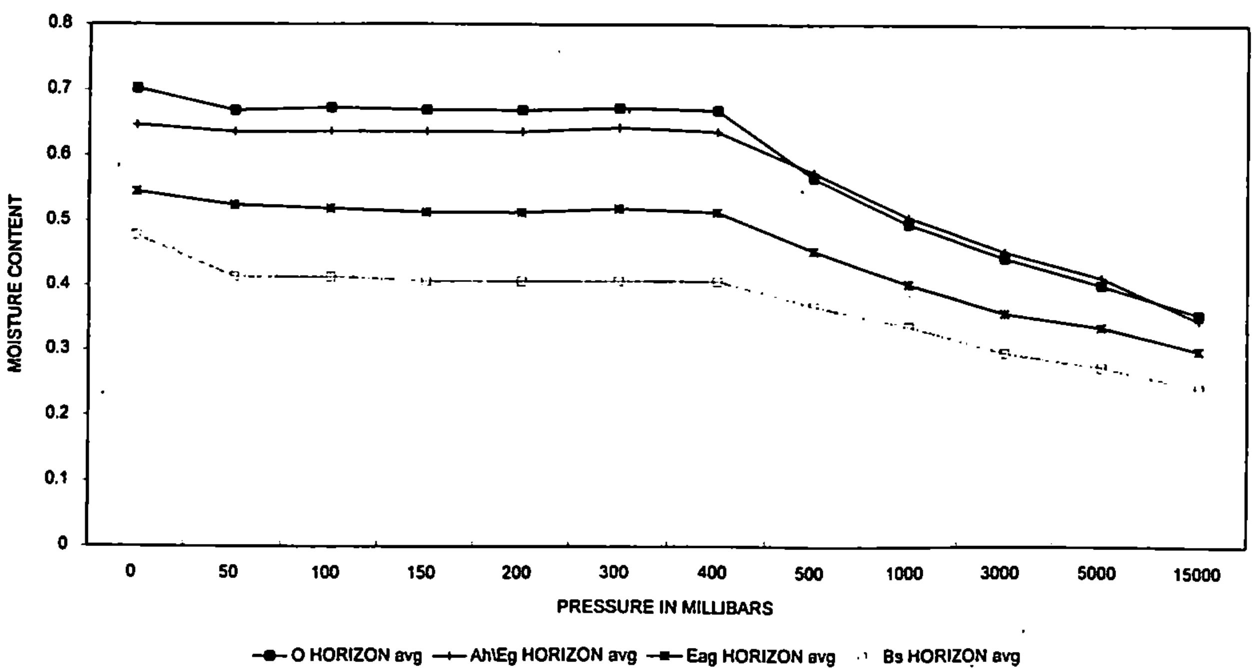


Figure 2.4 Forest soil moisture characteristic curve.

This sharp decrease in water retention at low tensions was due to the large pores draining first. The greatest loss of water occurred between 0 cm and 50 cm H_20 suction, as represented by the steepest gradient and occurred in the B_S and O horizons. This information in conjunction with the lower bulk density data (presented in section 2.6.1 & 2.6.2) demonstrates that there were considerably more large pores of the > 60 μm size, especially in the B_S horizon, than in the other two horizons. Further water loss was minimal up to 400 cm H_20 suction indicating few intermediate pores between 1 μm and 60 μm. Above 400 cm H_20 tension there was sufficient force to drain the smaller pores below 1 μm. There was approximately 90 % of the total volumetric water lost between 400 cm and 15000 cm in both the O and Ah/Ea horizons. Total water loss was much lower in the Eag and B_S horizons at 65 % and 80 % respectively which indicates a smaller percentage of very small pores. The Ah/Ea and Eag horizons are very similar in pattern, although the latter is far less retentive with less smaller pores than the underlying Eag. The horizonal porosity decreases with depth, with the exception of the Ah/Ea horizon confirming the earlier porosity data presented in Section 2.6.1 & 2.6.2.

In summary, all four horizons drain quickly between 0 and 50 cm suggesting that they all contain an element of macropores, with the largest percentage of large pores in the B_S horizon. When pores drain in the field, it is these larger pores that are emptied first, then the smaller pores, and *vice versa* on recharge. There is little fluctuation in the soil moisture characteristic curve from 50 cm H_2O to 400 cm H_2O, showing very little change in moisture content between these pressures.

If vertical flow exists at this site, the characteristic curve would show a decrease in moisture content with depth, because each horizon has a lower porosity with depth. This rule would be true at all pressure ranges, with the exception of the O and Ah/Ea horizon after 500 cm H_20 suction, which would be very rare since this would mean the soil is extremely dry. If part of the vertical flow was deflected to lateral flow at the interface between the O and Ah/Ea horizons, there would be a noticeable sharp discontinuity in hydrological characteristics with depth. Alternatively, if unsaturated lateral flow was to occur in this soil profile, water would move throughout the smaller pores which exist in all of the horizons, no discontinuity would exist and the decline would be roughly linear.

2.7.2 Whole Tree Harvested Soil Moisture Characteristic Curve and Soil Structure

The high porosity in the O horizon, compared to the forest site, is also reflected in the soil moisture characteristic curve (Figure 2.5).

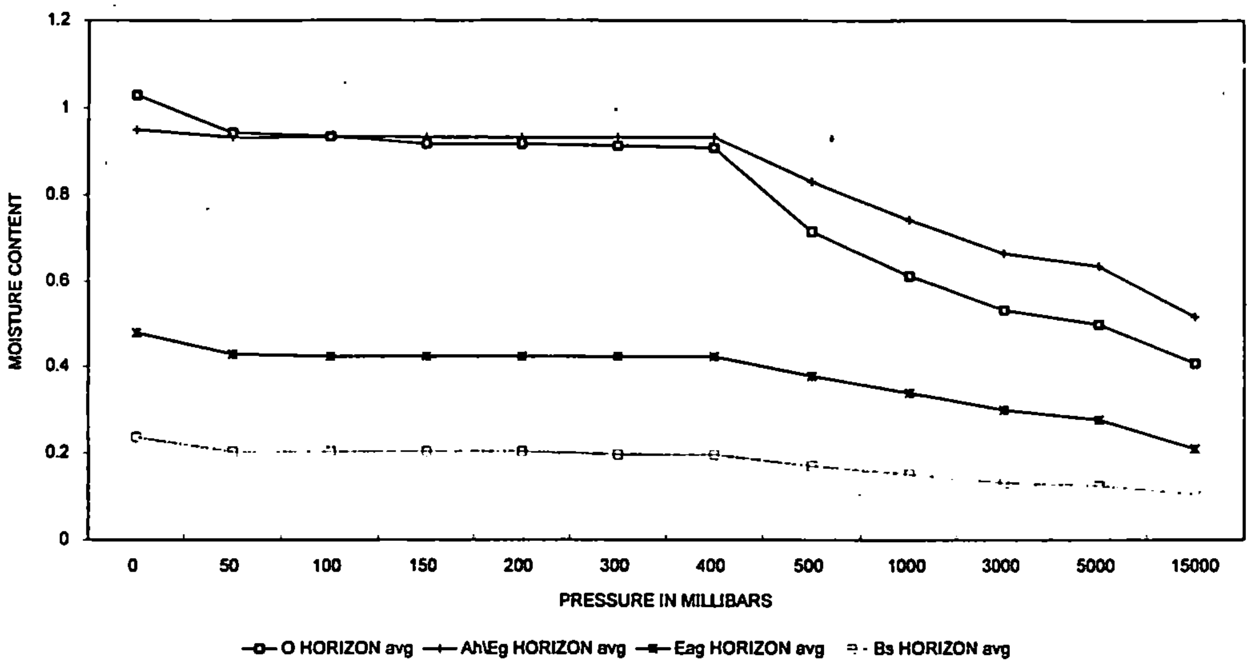


Figure 2.5 Whole tree harvested soil moisture characteristic curve.

The θ_V at saturation for the O and Ah/Ea horizon however, is approximately 100 % which is erroneous, since there is no space available for the solid particles. There is a pattern of decreasing soil moisture content with depth for the other horizons, which is the same as at the forest site. At the whole tree harvested site, there is a dramatic change between the Ah/Ea and Eag horizons, which would suggest that they behave quite differently in terms of soil wetting and drying. This result must be treated with caution, as it is difficult to say how much of this difference between these two horizons is due to error. The lower Eag and Bs horizons have a much lower moisture content (Figure 2.5) than those at the forest site (Figure 2.4), which does support the earlier porosity data. Since soil texture is similar at both sites, the lower soil moisture content suggests that there are possible differences in soil structure between the two sites. The main similarity between the forest and whole tree harvested soil moisture characteristic curves is the overlying pattern. Water content decreases throughout the soil profile, from the O to the B_S horizon. One small difference is that the O SMCC crosses the Ah/Ea horizon, albeit much sooner at 100 cm rather than 500 cm H_2O (Figure 2.5 and 2.4). All horizons decrease markedly between 0 and 50 cm H_2O, but it is the O horizon that shows the greatest decrease in water content and therefore has the largest pores rather than the B_S horizon as at the forest site. In fact, the B_S horizon at the whole tree harvested site has far fewer large pores than that at the forest site. The Ah/Ea loses very little water between 0 and 50 cm H_2O and therefore has only a few large pores. This is similar to the forest site. At 100 cm H_2O the O horizon starts to loose more water than the Ah/Ea horizon at the same pressure. This difference is more noticeable after a pressure of 400 cm H_2O is applied, despite both curves being steep, the O horizon does loose more water. There is fractionally greater water loss between 50 cm and 400 cm in the B_S horizon than at the forest site, suggesting there are more intermediate pores. The overall water loss at the WTH site from all the horizons, but particularly the Eag and B_S, is much lower than those at the forest site. Although the lower porosity data presented earlier to some extent supports this, it does not explain the large difference found between the B_S horizon at both sites. This difference cannot be explained solely by the textural classes since they are almost the same.

2.8 LAND USE MANAGEMENT AT BEDDGELERT FOREST

Beddgelert Forest was established by the FC between 1931 and 1936 on agriculturally unimproved upland grassland and heather. Land preparation was minimal: no ploughing and minimal ditching occurred in the Forest. Originally Sitka Spruce *[Picea sitchensis* (Bong.) Carr.)] and Norway Spruce [P*icea abies* (L.) Karst.] were planted in equal amounts. Subsequently, the stock has been reduced by thinning to 690 stems per hectare, Sitka Spruce now accounts for 90 % of the stand and the remainder are Norway Spruce.

Felling Procedures

As discussed in Section 1.9 whole tree harvesting involves extracting the whole tree minus bole and roots by overhead cablecrane, and results in the minimum of disturbance to the soil and remaining vegetation. The whole tree harvesting method leaves a "clear" site, which ensures clean planting conditions and encourages initial biodiversity and good regeneration of new trees. Clearfelling is the practice in which all the branches are removed post harvest *in situ* and just the trunk is removed. In terms of forest management, whole tree harvesting requires the minimum of intervention for re-growth. Also, from an economic point of view, the brash and needles can be sold as low grade chipboard, biofuel and mulch. The disadvantage of WTH is it is more likely to reduce the forests sustainability for long term crop rotation compared to conventionally harvesting (CH) Stevens *et al.*. (1995). However, research is on-going at ITE to determine the exact nutrient implications of WTH.

Within Beddgelert Forest, four experimental blocks were selected by the ITE and the FC, half of each experimental block was felled conventionally by clearfelling, the other half was whole tree harvested (Figure 2.1). The clearfelled area was replanted with Sitka Spruce (without recorded fertilisation) at a spacing of 1 m^2 in 1985, whereas the whole tree harvested area regenerated naturally and thinning was used to keep the trees at approximately 2 m apart.

2.8.1 Experimental Forestry Site

Sitka Spruce at the forest site were planted in 1936 and had attained maturity. Spacings between the trees were approximately 2 m, giving a density of about 700 stems per hectare. The mean tree height was 16 m (Stevens *et al.*, 1989). As with Beddgelert Forest in general, the site was not ploughed or ditched and indeed the soil was not moved or treated in any way when the crop was established. No fertiliser was applied at any time.

At the whole tree harvested site regenerated Sitka Spruce (*Picea sitchensis*) are growing, currently at a height of between 30 cm and 100 cm. The effects of these small trees would be minimal compared with the major impact of the previous crop. Vegetation between the young trees was primarily grass e.g. *Molinia caerulea, Festuca ovina* and *Agrostis capillaris* with other grasses being present. *Vaccinium myrtillus* and *Calluna vulgaris* were subdominant.

Sitka Spruce (*Picea sitchensis*) is a laterally rooting species as opposed to others such as oak which have a main tap root. At this site, many fine roots exist from the surface to about 10 cm below the surface (O and Ah/Ea horizon). From approximately 10 to 30 cm below the surface, there is a reduction in fine roots which coincides with the Ah/Ea and Eag horizons. If roots do not penetrate this layer, the trees become unstable in wind, possibly blowing over. At this site most trees have roots which have developed in this soil band through soil fissures. This enables roots to flourish in the better aerated soil below, thus stabilising the tree. Another band of dense roots occur from 30 cm to 50 cm (Eag and B_S), (Figure 2.6).

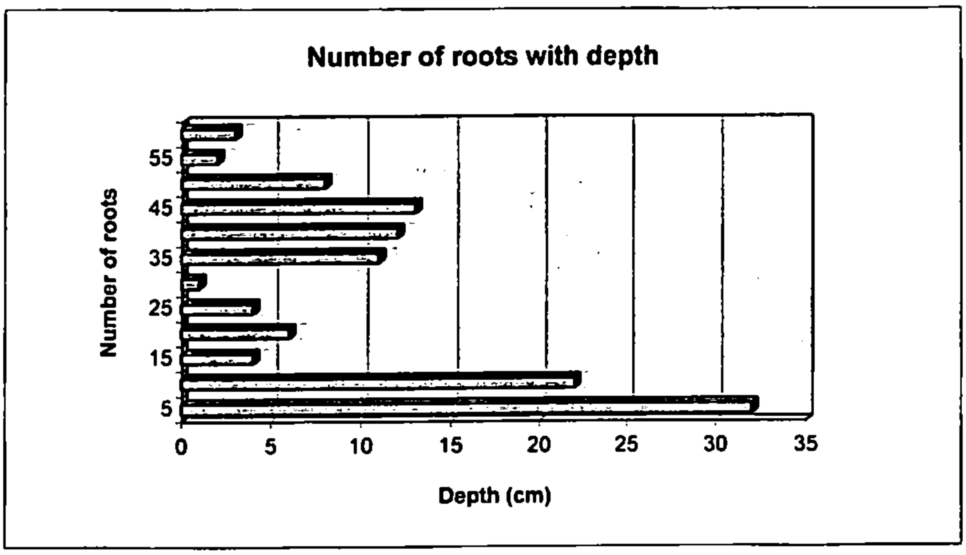


Figure 2.6 Number of roots with depth

At this site, root density was strongly correlated with soil oxygen (Anderson, pers. comm.) implying good soil structure. This result stresses that the soil was well drained in the subsurface soil, allowing rapid water movement. However the soil was not as well drained in the Ah/Ea and Eag horizons as the others.

2.9 SUMMARY

In summary, the experimental site had the following soil characteristics which promoted water movement:

1. Relatively low bulk density.
2. Relatively high porosity decreasing with depth, with the exception of the Ah/Ea horizon, which is less porous than the underlying Eag horizon.
3. A variable number of large pores in all horizons at both sites. The largest pores were found in the O and B_S horizons at both sites.
4. High fine root density, throughout the soil profile excluding the Ah/Ea where there were substantially fewer roots.

Both sites have similar soils of the Hafren series. Soil was formed from head material with stones being inclined downslope. Relatively porous soil suggests freely flowing water. However, the reduced porosity of the Ah/Ea horizon means it acts as a semi-impermeable layer to vertically moving soil water and would therefore deflect water laterally. Since this horizon is very close to the surface, lateral water movement would be overland. However, this senario was not observed at either the forest or WTH sites. In the subsoil, slate and shale is orientated downslope. In terms of water movement, these factors would promote lateral water movement in the subsoil. An increase in pH with depth indicates cation leaching and therefore demonstrates that an element of the high rainfall infiltrates and water moves vertically. The C:N ratio indicates a reasonable level of decomposition which is found in well structured soils suggesting the soil is freely draining.

Soil texture was similar at both sites, with the exception of the Ah/Ea horizon, where at the whole tree harvest site there were less gravel-sized fragments and sand, and more clay making it less permeable at the whole tree harvested site compared to the forest site. The variations in Ah/Ea horizon soil texture between the two sites were more likely to be a result of intrinsic variability than as a result of vegetation differences because texture is a component of elemental weathering and mineral parentage.

At the whole tree harvest site, there was a slightly higher organic content in the O horizon which produced a higher porosity. The higher porosity layer may allow this surface layer to transmit water quicker at the WTH site, thus drying out and wetting up quicker than at the forest site. In the remaining three WTH horizons, there was a slightly lower porosity compared to those at the forest site. Although texture differences can explain the lower porosity in the Ah/Ea horizon, it cannot for the Eag and B_S horizons. Therefore variations in soil structure or the presence of more woody roots at the forested site, may explain the difference.

At saturation, the soil moisture content decreases with depth at both sites. However, the number and size of pores may vary at the two sites. At the forest site, there were many large pores (greater than 60 μm) in the O and particularly in the B_S horizon, whereas at the whole tree harvest site there were more large pores in the O horizon and not as many large pores in the B_S horizon. The moisture content at saturation was much lower in the Eag and B_S horizon at the whole tree harvest site compared to the forest site confirming the lower porosities described earlier at the WTH site in these two horizons. There were few intermediate pores (1 μm to 60 μm) in any horizon at either site. There were, however, more intermediate pores in the B_S horizon at the whole tree harvested site compared to the forest site. This imbalance would suggest the WTH B_S horizon would retain water better when it is drier (i.e. in the summer months), compared to the forest B_S horizon. There were few large and intermediate pores in the Ah/Ea horizon at both sites, yet there was a difference in the porosity of this horizon between the sites, which suggests variations have not been identified by using the soil moisture character curve alone.

CHAPTER 3

METHODOLOGY

3.1 EXPERIMENTAL DESIGN

Aims

The aim of this project was to investigate the effects of whole tree harvesting on site hydrology and soil structure. The influence of trees on soil hydrology and soil structure characteristics before and following whole tree harvesting was investigated in order to describe the effect of harvesting on the hydrological pathways, including throughfall and soil water movement. The research's four aims and the associated approach, technique and scale of investigation are summarised in Table 3.1.

Approach

It was important that the research was conducted at an appropriate scale (Hillel, 1991), so that the variables were truly representative of field conditions. As the investigation developed, the scale changed from the large hillslope to a small detailed soil core in order to allow detailed understanding of the mechanisms occurring at an appropriate scale. Due to the financial and time constraints of this project, only a snapshot view of Beddgelert's hydrology could be taken. In order to understand the mechanisms of water movement, techniques need to be applied to allow study at a small scale. It was felt a scale of up to a section of hillslope was feasible with the available resources and time. Establishment of a sound water balance is a prerequisite of any small plot hydrological investigation (Table 3.1) and so the study began by focusing on the soil water status. Measurements were taken at the plot scale, since the techniques available average measurements over small areas or plots (Table 3.1). Soil variability, such as K_S, was assessed at the plot scale and at the large soil core scale, where individual values were linked to soil physical properties (Table

3.1). Soil peds were studied at a large core scale, and then at the most detailed scale pore morphology was quantified (Table 3.1).

Table 3.1 Aims, Approach, Technique and Scale

AIM 1. To investigate and quantify the hydrological inputs and outputs for a forest and whole tree harvested site.		
CHAPTER 4		
Approach	Technique	Scale
Rainfall	Storage gauge	
	Tipping bucket	Section of
Throughfall	Throughfall gauge	Hillslope
Stemflow	Stemflow collar	
Evapotranspiration	Thornthwaite	
Soil Water Recharge	Calculations	
AIM 2. To establish and quantify the direction of soil water movement at both sites, to assess the relative importance of soil water pathways and to model water movement at both sites.		
CHAPTER 5		
Approach	Technique	Scale
Soil moisture storage	Neutron probe	
Soil suction	Tensiometers	Plot
Influence of different soil characteristics	Modelling	
AIM 3. To understand and assess the spatial variability of Ks within and between the two sites and relate the differences to management.		
CHAPTER 6		
Approach	Technique	Scale
Saturated hydraulic conductivity (K_S)	Ring permeameter	Medium core
Variability of (K_S)	Geostatistics/semi-variogram	Plot
AIM 4. To describe and quantify the soil structure at both sites and relate to the quantity of water movement.		
CHAPTER 7 & 8		
Approach	Technique	Scale
CH 7		
Ped structure	Carbowax impregnation	Medium core
	Fractal dimensions	Ped
Pore geometry	Resin impregnation	Small core/Point
CH 8		
Pore connectivity and water pathways	Methylene blue stain	Point

This research investigated forest hillslope hydrology from a spatial and temporal perspective. Spatially, the investigation compared two sites: one site was forested with Sitka Spruce (*Picea sitchensis*) and the other had recently been whole tree harvested. The design of this project allowed the variations and similarities between the two different sites to be identified. Within each site the variations in water movement and soil hydraulic conductivity was addressed.

Temporally, the research was concerned with water movement and storage in the soil during 12 months from January 1990 to December 1990. Soil water content and suction was monitored regularly throughout the year. In terms of hydrology, one year is only a snapshot view of what happens over the longer period. However, one year covers the seasonal variations which may have different effects on soil water movement. To overcome the timescale problem, the inputs, rainfall, throughfall and stemflow, were compared to data collected at Beddgelert in preceding years to establish whether it is a average, excessively wet or dry year. Putting the data from this research into the context of that gained from previous years will establish their reliability and whether they are representative. It is also important to identify whether the pattern of rainfall is similar from one year to another, since total rainfall may mask any seasonal variations.

Research Design

As discussed above, the project was designed to include a number of levels of investigation, namely a section of hillslope, plot and soil core. These components were discussed in the previous section and are presented hierarchically in Table 3.1. Information on the hillslope section sets the context for more detailed studies on the processes of water movement. Figure 3.1 presents the instrumentation used across the study area.

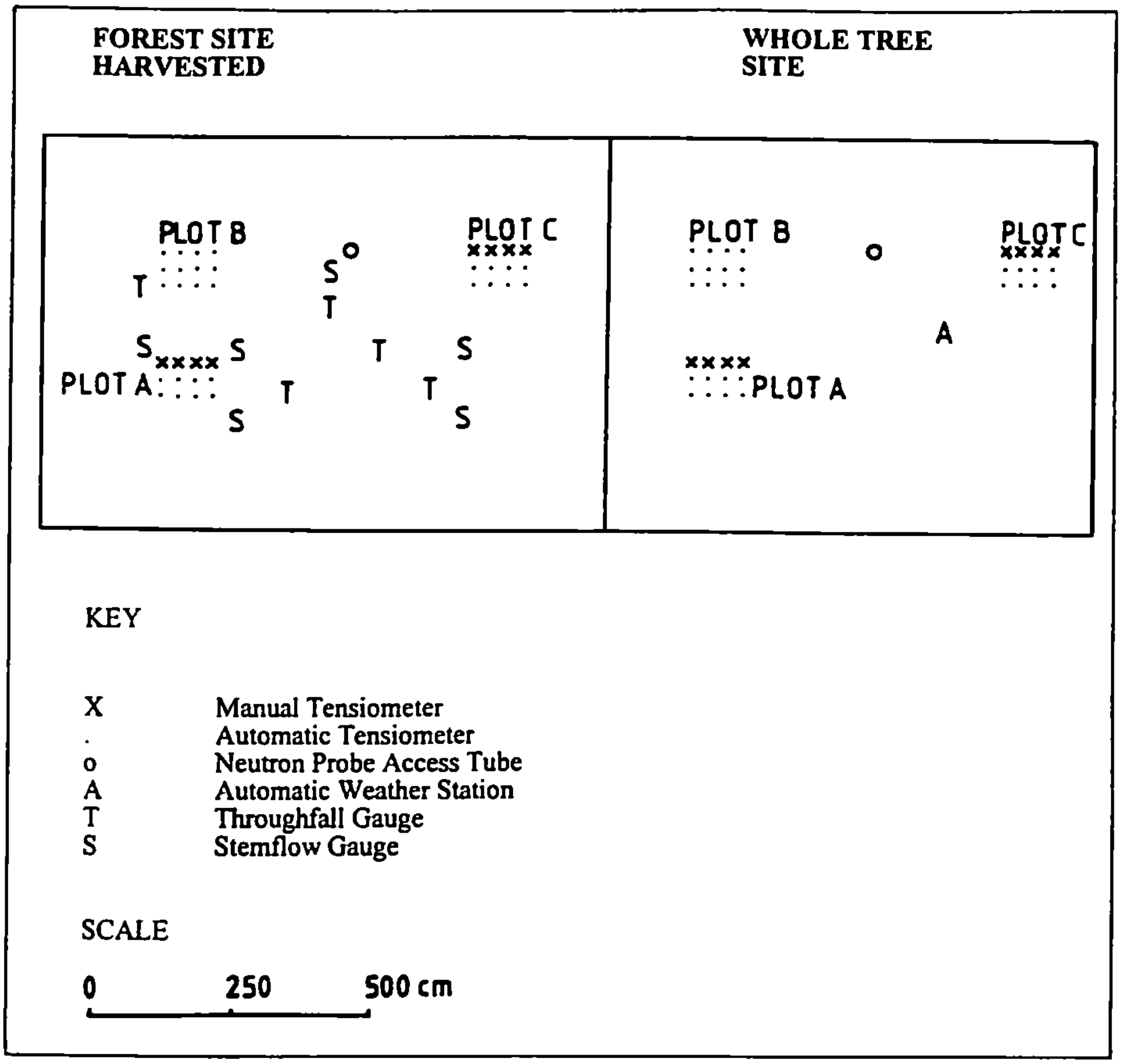


Figure 3.1 Instrumentation of the hillslope section study plots.

Various factors were considered in the selection of the location of each forest compartment and they are detailed below. Beddgelert Forest was selected for reasons discussed in Section 2.1 and is typical of many upland afforested sites in Britain. Since this research was concerned with explaining the influence of forest management in controlling water movement, a section of hillslope was an appropriate level of scale to begin investigation. The hillslope section was selected for reasons discussed in Section 2.5. A forest and a whole tree harvested (WTH) site were selected and these were situated adjacent to one another on the hillslope in order to determine the influence of the trees, especially their influence of the stemflow and root flow on water movement. Plots were demarcated at each site to measure the hydrology in a definable unit (Wheater *et al.*, 1987). At the forest site, the plots were situated between the trees and at the whole tree harvested site between the tree stumps. Three plots, 1.5 m x 1.5 m at each site, were instrumented to monitor water movement. Since water movement depends on the hydraulic conductivity (Section 3.5), the spatial heterogeneity of saturated hydraulic conductivity (K_S) (Section 3.5.1) was investigated within each site (Chapter 6). The methodology was chosen accordingly, and a nested hierarchical sampling strategy was used to determine the spatial structure of K_S and to determine the scale of greatest variability (Section 3.5.1). Pedological data were collected at the same location as K_S was measured, allowing bulk density, soil texture and root density to be correlated with K_S and so establishing the key controlling factors of K.

Structure of Chapter 3

Research methods are presented in the order of aims and chapters set out in Table 3.1.

3.2 HYDROLOGICAL INPUTS AND OUTPUTS

A water balance for the section of hillslope was calculated from the precipitation (Section 3.2.1), evapotranspiration (Section 3.2.2) and changes in soil moisture (Section 3.2.3). The aim of this technique was first, to determine the relative importance of the different inputs, throughputs, outputs and storage as well as to:

1. Determine the importance of soil water movement.
2. Calculate the degree of measurement error associated with each component of the hydrological cycle.
3. To set the hydrological budget in a wider context so that the results can be compared with other experiments

3.2.1 Rainfall

Gross Precipitation at the Clearfelled Site

An Automatic Weather Station (AWS) was used to record the climatic variables (Plate 3.1), which included rainfall volume per unit time, air and soil temperature, relative humidity, solar radiation, wind speed and direction (Table 3.1). These variables were automatically recorded and stored on a Campbell 21X data logger (Strangeways, 1985). The data logger was programmed to store each variable at 15 minute, hourly and daily averages. However, due to the more limited temporal information collected by the tensiometers (Section 3.3.1), less detailed information on precipitation was required, so that only daily averages will be presented in this thesis.

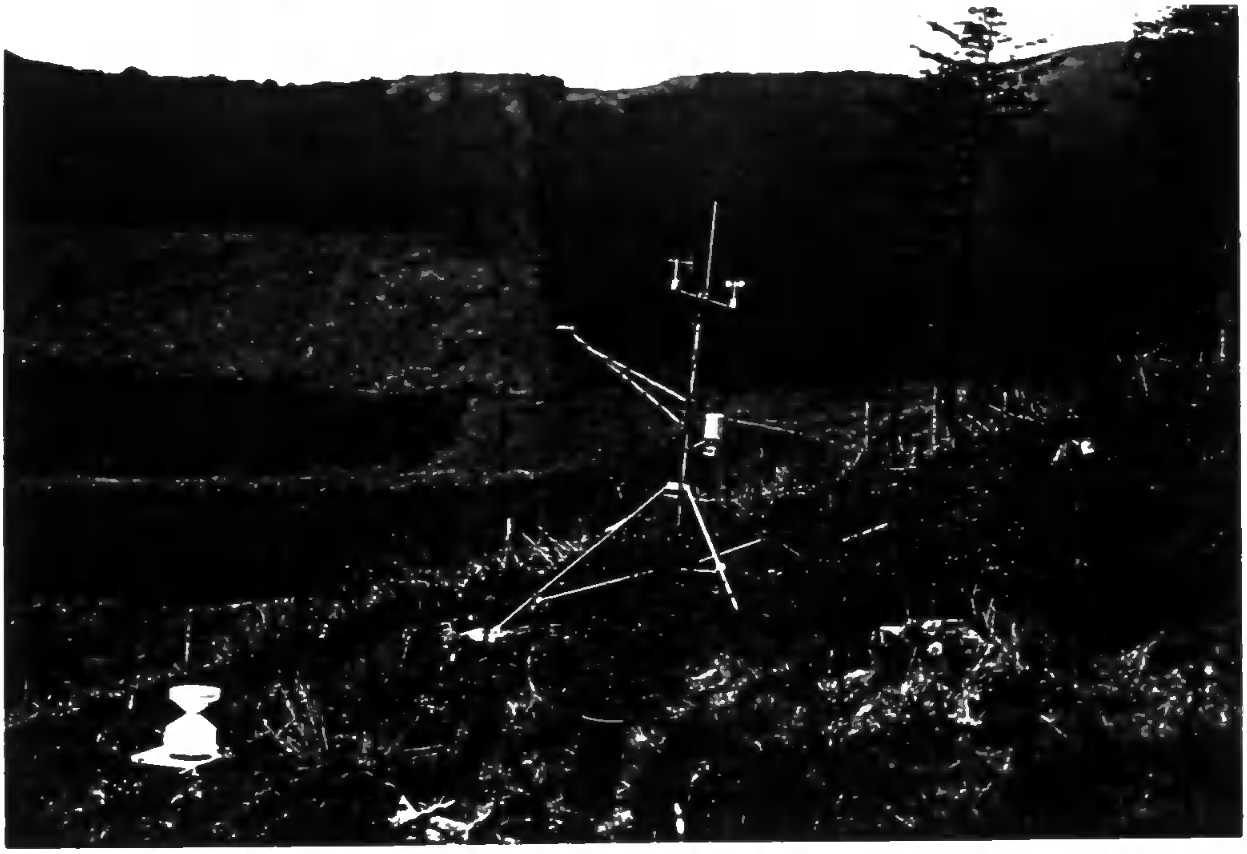


Plate 3.1 Automatic Weather Station

The Automatic Weather Station (AWS) used a tipping bucket rain gauge, which was known to marginally underestimate rainfall due to rainfall not being monitored, whilst the bucket was tipping. In addition, gross precipitation (that received above the vegetation canopy) was collected using a standard Meteorological storage gauge at the recommended height of 12 inches. This guideline was established by the Warren Springs Laboratory during research at an adjacent cwm where rainfall was measured fortnightly and acted as a check against the AWS Tipping Bucket rain gauge used for this research.

Net Precipitation beneath the Forest Canopy

At the forest site, net precipitation was measured below the tree canopy, which included throughfall, dripped from the canopy foliage, and stemflow, that flowed down the tree trunk (Table 3.1). The stemflow collectors used were designed and made by ITE (Bangor) and they were installed according to their guidelines (Reynolds and Stevens, 1987). Five throughfall collectors were randomly placed to obtain an average value for throughfall and six stemflow collars were randomly installed around the trees to obtain an average value of stemflow (Plate 3.2).

Plate 3.2 Stemflow and Throughfall collectors

This number of collectors was sufficient to obtain a representative sample of throughfall and stemflow volumes based on studies by Reynolds and Stevens at the site (1987) and the low statistical variability of throughflow between gauges. As yet there is no standard guide-line to the number of collectors which are required to obtain a representative sample of throughfall or stemflow. Table 3.2 shows a range of interception studies using these techniques and the number of collectors that the researchers used.

Table 3.2 Ranges of throughfall and stemflow gauges used in interception studies (Source: Reynolds and Stevens, 1987).

Species	Approx. age (years)	m^2/live tree	No. of trees gauged	Plot area (m^2)	Reference
Norway spruce	20	2.1	30	-	Reynolds and Henderson 1967
European larch	38	14.9	20	1821	" " "
Beech	55	10.9	17	-	" " "
Sitka spruce	14	2.8	10	64	Ford and Deans 1978
Sitka spruce	28	3.2	30	290*	Scanlan 1981
Norway spruce	36	2.5	6	289	" "
Japanese larch	29	4.4	6	221	" "
Sessile oak	uneven age	90.1	7	225	Carlisle *et al.* 1967
Scots pine	17	2.2	10-13	1700	Rutter 1963

*5 plots of approx this area; 6 instrumented trees per plot

3.2.2 Evapotranspiration (Et)

Potential evapotranspiration (Et) was calculated monthly using the Thornthwaite method (Thornthwaite, 1948). The AWS was set up to monitor for solar radiation in order to calculate daily Et, but the sensor failed at the commencement of the study and funds were unavailable for a replacement. Hence this method for calculating Et could not be used. Instead comparisons were made to other upland Et values to validate the evapotranspiration data set.

3.2.3 Soil Moisture Content (SMC)

Soil Moisture Content (SMC) is expressed as the fraction of a soil mass, volume or pore-space occupied by water. Several techniques exist to measure soil moisture (see Hillel, 1980; Curtis and Trudgill 1974). For this study, the Neutron moderation technique and gravimetric samples were used to measure soil moisture (Table 3.1).

<u>Neutron Moderation Technique</u>

Neutron moderation was first developed in the 1950s and is a non-destructive, efficient, quick, and reliable technique. For this study, a Wallingford Neutron Probe was used. The probe was positioned over an aluminium access tube and from which a source and detector are lowered into the ground to a specific depth. Readings were taken at 10 cm intervals down to a depth of 150 cm. At each depth a reading of 'counts per second' are taken over a specific time period. Two 70 cm access tubes per plot and one 150 cm access tube were used at the forest and whole tree harvested sites (Plate 3.3).

Plate 3.3 Neutron Probe in action

Fast neutrons are emitted from a source of Americium Beryllium. The neutrons slow down or 'thermalise' after colliding with various nuclei. Within soil, hydrogen ions in the form of water are the most efficient at thermalising the fast neutrons. The thermalised neutrons are then measured in counts per second by a detector over a specified time period by the neutron probe. Since the counts per second are relative to 100 % soil moisture content, the neutron probe was calibrated using a water count check each time the probe was used in the field. For this, a large dustbin filled with water was used, which had an aluminium access tube placed in the middle. A standard multiple reading technique was employed where ten readings over sixty-four seconds are averaged to form a mean. To obtain an actual value of soil moisture content, a gravimetric sample has to be taken. The Institute of Hydrology standard calibration curves for the appropriate texture of soil were used (Institute of Hydrology 1981). Due to problems of calculating gravimetric soil moisture, this method is more accurate than calculating individual calibration curves for the soil horizons at the study site (Reynolds pers. comm.).

To compare soil tension information with water content, measurements were taken from September 1989 to September 1990, so changes in soil moisture were described and quantified throughout the year. This method also allowed a calculation of the annual change in storage.

Due to researcher illness and alternative staffing being used, neutron probe readings were only taken at one access tube (10 to 150 cm depth), for both the forest and whole tree harvested site. This problem resulted in the spatial variability of soil moisture content within the two sites not being measured. Had the more comprehensive data been available, it would have been useful to allow comparison between spatial variability of SMC and the spatial variability of soil tension, hydraulic conductivity and soil structure.

3.2.4 Water Balance

The water budget equation is simple and non the less valid due to it's simplicity (Gilman, 1994). The equation states that:

Inputs = Outputs +/- Changes in Storage

$$P = E+Q \,^{+}/\text{-}\ \Delta SM$$

Where: P = Rainfall

E = Evapotranspiration

Q = Drainage

$^{+}/\text{-}\ \Delta$ SM = Change in Soil Moisture (3.1)

3.3 SOIL WATER FLUX DETERMINATIONS

The plot scale has been adopted for soil water flux determinations. Figure 3.1 shows the location and the original dimensions of these plots. The plots were positioned between either four trees or four stumps. Three plots were instrumented in an 'L' shape layout, because this is the optimum way of comparing soil water fluxes across and downslope. Therefore with minimum resources the spatial variability of soil tension were instrumented in two-dimensions, (i.e. across and downslope). The use of vertical banks of tensiometers introduced a third dimension of depth. The 'L' shape was made up of 3 plots, each plot having 3 nests of tensiometers, which were at a depth of 15, 30, 60 and 100 cm. The majority of the tensiometers were automated (Section 3.3.1). Two out of the three plots at each site had one bank of manual tensiometers to act as a check and back up should any problems develop with the automatic tensiometer network. Unfortunately, the multiplexers failed in the field and hence the automatic measurements were unsuccessful (Section 3.3.1). Fortunately, the tensiometer-transducer system worked well, although the data could only be collected manually and soil moisture potential was therefore measured less frequently than planned. Soil water flux was determined using the Richard's equation, which calculates transient vertical flow and is derived from Darcy's Law. The continuity equation is as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] - U(z, t)$$

where θ = Volumetric Water Content (m^3/m^3)

H = Hydraulic Head (mm)

K = Hydraulic Conductivity (mm/day)

t = Time (day)

z = Depth (mm), positive downwards

U = Sink term representing water lost per unit time by transpiration (d^{-1}) (3.2)

3.3.1 Soil Moisture Potential

The difference in soil moisture potential between two points (the hydraulic gradient) provides a driving force for the movement of soil water (Darcy, 1856; Buckingham, 1907). Soil moisture potential has three components: matric potential (ψ_m), elevation potential (ψ_e) and osmotic potential (ψ_o). Measurements of matric potential and elevation potential are needed to calculate soil water movement (i.e. flux). Several techniques exist to measure matric potential (see Curtis and Trudgill, 1974; Burt, 1978). However, the most common method is the tensiometer and this was adopted in this study. A tensiometer consists of a water filled tube which is connected at one end to a ceramic porous cup and the other end is linked to a measuring device which is ultimately sealed. A positive soil water pressure will cause a movement of water from the soil through the porous cup into the tensiometer. In contrast with a negative pressure around the porous cup, the water flows from high to low pressure, so water moves from the tensiometer to the soil. The new equilibrium pressure within the soil water is registered on either a manometer or a pressure transducer.

Tensiometers

Ultimately, Soil Moisture Corporation mercury manometer type tensiometers were successfully used (See next Section on manual tensiometers). However, the original field design was to use a complex array of automatic pressure transducer type tensiometers to measure soil water matric potential. Seventy two tensiometers were installed at the minimum distance of 30 cm apart, as this spacing is known not cause cross interference that would possibly affect the validity of results. The tensiometers were placed vertically at a depth of 15, 30, 60 and 100 cm in the soil, which corresponds to the Ah/Ea, Eag, B_S and C horizons. This data was obtained from preliminary soil data from Beddgelert and data collected from a similar soil at Plynlimon (Chappell pers. comm.). All the tensiometers were installed by auguring a hole slightly wider than the tensiometer, positioning the unit and then pouring a slurry of fine silt between the tube and hole wall, to cover the porous pot. This process allows a good contact to be made between the soil and the porous pot. The sides around the tensiometer were backfilled using the same soil that was removed from the hole and in the order it came out. Two centimetres below the surface bentonite pellets were placed around the tensiometer and then covered with soil. These swell when wet to make a seal and prevent water from running down the sides of the tensiometer, producing spurious results.

During the use of the tensiometer in this study the fundamental question of what a tensiometer measures was highlighted. Does the tensiometer measure the smaller pores only or the medium sized pores, or is the reading an average of the tension of water held in all the pores in close proximity to the porous cup? Unfortunately under the constraints of this project this question remains unanswered, and so the data supplied must be viewed with this ambiguity in mind. Figure 3.1 shows the position of these tensiometers within the plots. Each pressure transducer was linked to a multiplexer system which acts as a switch enabling the data logger to read all 72 tensiometers within a couple of minutes. Unfortunately the multiplexer failed to work due to damp and cold field conditions. The pressure transducers could be read manually with either a data logger or a digital volt meter. The difficulty of manually taking readings and therefore the intermittent nature of such readings, however, meant that the values were not used. Therefore the back up system of manual tensiometers was ultimately utilised.

Manual Tensiometers

Two arrays of manual mercury manometer tensiometers, one per plot, were installed at each site (Figure 3.1) initially to act as a comparison with the automatic tensiometers The manual units are known to be reliable. These tensiometers were calibrated individually in the field before and after installation to determine the manameric depression (see MEXE, 1963), which is caused by impure mercury or dirty tubes. This small network of manual tensiometers became almost the only source of soil moisture potential due to the failure of the automatic transducer tensiometers.

Automatic Tensiometers

Twenty four Sensym SCX15DNC pressure transducers were used for the automatic type tensiometers. These were calibrated and set up using the same method as Dowd and Williams, (1989). Each tensiometer had one sealed pressure transducer attached to the top, using a rubber bung. The equipment was then linked via a multiplexer to a CR10 data logger. (Dowd and Williams ,1989).

3.4 MODELLING TECHNIQUES

Data from this study were used as an input to already existing soil moisture flux models, such as LEACHM (Wagenet and Hutson, 1987). LEACHM, or LEAching and CHemistry Model, is a process based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Using this software various scenarios can then be modelled to allow an artificial exploration of the processes governing the hydrological mechanisms at Beddgelert Forest.

3.5 HYDRAULIC CONDUCTIVITY (K)

Hydraulic conductivity (K) of soil defines the ability of a soil to transmit water. Saturated hydraulic conductivity (K_S) defines the soil's optimum ability to transmit water. Hydraulic conductivity (K) is the ratio of the flux to the hydraulic gradient (which is the driving force). Figure 3.2 shows the relationship between soil moisture content and K. Figure 3.3 shows the relationship between soil water suction and K. The fundamental law of fluid motion through a porous medium was established experimentally by Darcy (1856), (Section 5.4). From Darcy's Law it can be seen that to calculate flux, a value of hydraulic conductivity or K is needed.

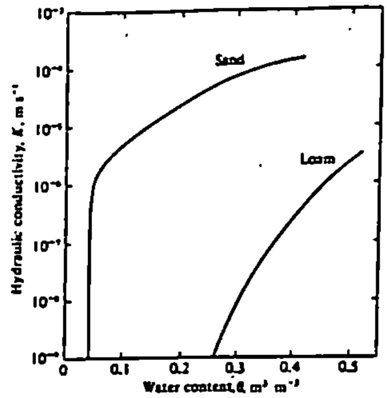


Figure 3.2 Relationship between soil moisture content and hydraulic conductivity (Source: Marshall and Holmes, 1988).

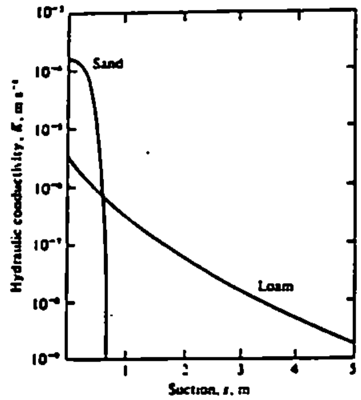


Figure 3.3 Relationship between soil water suction and hydraulic conductivity (Source: Marshall and Holmes, 1988).

Ring Permeametry

Ring Permeametry was used in this study to determine K_S (Table 3.1). This technique involves using large soil samples (30 cm in diameter and 10 cm in height) from the field. Large cores are advantageous because proportionately less area has been disturbed during excavation and this therefore reduces the edge effect (Berryman *et al.*, 1976; Talsma, 1969). A larger sample *per se* also allows analysis at different scales within the sample and a relatively large sample which encompasses a greater volume of soil is inherently more representative of a given soil area (Bear, 1972). Further details on different techniques to measure hydraulic conductivity can be obtained from various sources (see Berryman *et al.*, 1976; Klute, 1965; Talsma, 1960 and Boersma, 1965a & b).

The ring permeameter method in this instance involved the insertion and careful excavation of a metal ring 30 cm in diameter and 15 cm deep. The soil core within the ring was saturated and a constant 5 cm head of water was maintained above the soil sample using a long plastic tube with a smaller tube inside to release the trapped air. Discharge per unit time is measured by recording the drop in water level in the tube, which is maintaining the constant head (Plate 3.4). Conductivity is determined using Darcy's Law since flux and gradient are both known.

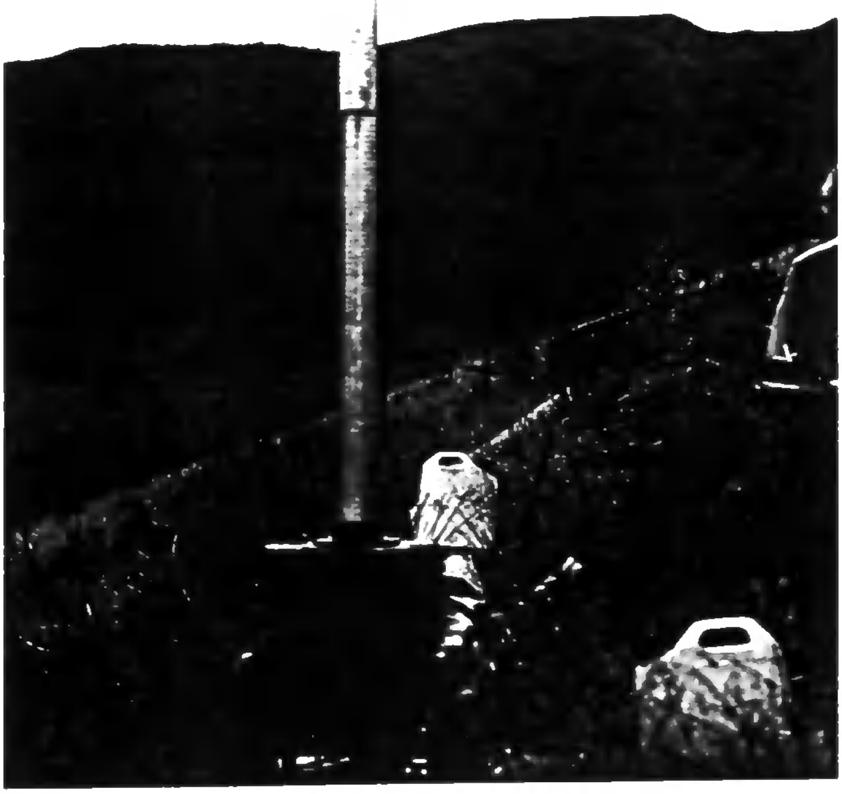


Plate 3.4 Ring Permeameter in action

3.5.1 Spatial Variability of Saturated Hydraulic Conductivity (K_S)

Hydraulic conductivity is known to be spatially variable (Nielsen *et al.*, 1973; Baker, 1978). For example, Russo and Bresler (1981) found that spatial variability of soil hydraulic properties exists and that there is some order to these properties. A qualitative impression of the spatial structure of hydraulic properties can be found with reference to a semi-variogram. A semi-variogram can be drawn to illustrate the relationship between variance and log distance, or the increasing distance between sampling points.

The scale and pattern of saturated hydraulic conductivity was investigated using a nested sampling strategy. A nested sampling strategy lends itself to identifying where the greatest variability is in terms of scale through the semi-variogram. This sampling technique was first adopted by soil scientists in 1937 by Youden and Mehlich and later modified by Oliver and Webster (1986). The modified version combines a nested and linear approach to determine the scale and form of variation. An approximate scale of spatial variation is obtained economically by a nested analysis of variance, where different stages incorporate changes in the spatial scale (Oliver and Webster, 1986). The scale of greatest variability can be found from a semi-variogram (Oliver and Webster, 1986). Further detail on this method can be found in the work by McBratney *et al.* (1981) and Webster (1977 & 1985). The variability of saturated hydraulic conductivity was determined only in the first 10 cm of soil, due to the high proportion of slate combined with the crumbly nature of the soil, it was physically not possible to collect a representative sample.

At a depth greater than 10 cm, it was very difficult to insert the metal ring and remove the sample without physically disturbing it. The top 10 cm of soil was sampled spatially to determine the scale of greatest variability (i.e. whether there was more variability across the hillslope or at each stage). Four stages were chosen: A, B, C and D; A being the top of the hierarchy and D being the bottom. The distance between points A was 50 m, being the largest linear distance accomadatable within the plot dimensions. Further point to point dimensions were then 0.25 of the previous, so B=12.5 m, C=3.1 m and D =0.8 m apart. These points were chosen in the field by firstly, taking a random point for the first A and thereafter moving in a random direction for 50 m for another A point. From each point A, a point B was found by moving in a random direction 12.5 m. The C points were found by moving 3.1 m in a random direction from a point B. D points were found by moving 0.8 m from the point C (Figure 3.4a). This nested hierarchical system was used for sampling K_S

at four plots within the whole tree harvested site. This process creates another stage within the hierarchical sampling strategy (Figure 3.4b).

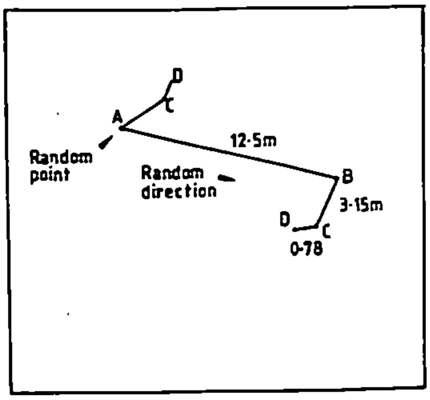


Figure 3.4a Saturated hydraulic conductivity sampling design and location.

FOREST SITE **WTH SITE**

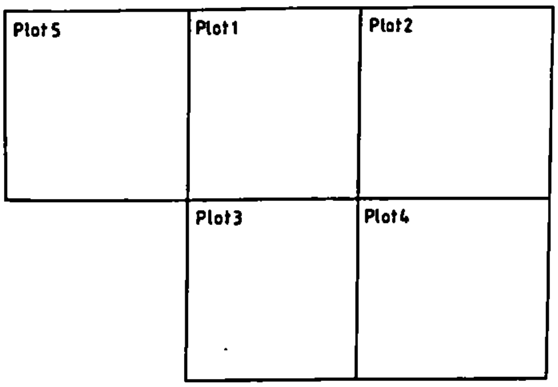


Figure 3.4b Location of each plot.

Ideally, this sampling strategy would have been repeated at the forest site to allow good comparison between the forest and whole tree harvested sites. However, due to researcher illness, there was insufficient time to repeat this extremely labour intensive sampling strategy. This resulted in just one plot being sampled (i.e. one A point being used in combination with its subsequent B, C and D points). At the main 'A' points, another sample was taken between 10 and 20 cm to determine the Ks vertically.

3.6 PEDOLOGICAL ANALYSIS

Several techniques were used to describe the soil physical characteristics described in Chapter 2; these include Bulk Density (Db) determination, texture analysis, root density analysis, soil moisture characteristic determination, soil macromorphological and micromorphological analysis.

3.6.1 Bulk Density, Texture Analysis and Fine Root Density

Samples for bulk density, texture analysis and root density were collected at the same place within each plot as point A K_S (Figure 3.4b). A total of 60 samples, three samples in the O, Ah/Ea, Eag, B_S and C horizons were collected at Beddgelert forest. A Pitman Corer was used to take samples for bulk density. These samples were weighed for their field mass and then dried at 105^o Celsius for 24 hours and re-weighed to determine their mass. Dry bulk density was calculated as dry mass of soil divided by volume of soil, as calculated from the corer ring.

Soil samples were collected from each of the five soil pits for textural analysis. About 10 g of soil was oven dried, weighed and treated with hydrogen peroxide. The soil samples were soaked in Calgon and wet sieved according to the British Standards Method (BS1377, 1975). Each individual fraction was then dried and re-weighed. Those particles less than 63 μm were analysed further using the Sedimentagraph to determine the finer particle size.

Fine root density was calculated using the cores taken for bulk density analysis. Fine root density was determined by estimating the root coverage as a percentage of the soil basal area.

3.6.2 Soil Moisture Characteristics

Soil moisture capacity is the relationship between soil moisture potential and soil moisture content. The soil moisture capacity is usually represented graphically in the form of a curve and is known as the 'soil moisture characteristic curve' (SMCC). This graph can be determined in two ways namely sorption (wetting) and desorption (drying) which result in the 'moisture retention curve' and the 'moisture release curve'. These two SMCCs are usually different due to hysteresis, which can be caused by the geometric non-uniformity of the individual pores, contact-angle effect, entrapped air, and swelling and shrinkage. For practical reasons the moisture release curve is usually determined rather than the 'retention' curve, since sand tables can be drained more easily and pressure plates controlled.

Soil moisture capacity may also be determined in the field (Nielsen *et al.*, 1973; Rogowski *et al.*, 1974), but it is usually determined in the laboratory. Advantages of the laboratory method include more careful control on the drying system.

<u>Laboratory Determination of the SMCC</u>

Twenty four American Pitman soil cores (5 cm in diameter and 3 cm in height) were taken from the forest and the whole tree harvested site, at the same location as other soil hydraulic property data to determine the soil moisture capacity by laboratory techniques. All the samples were equilibrated and weighed at -5, -10, -15, -20, -30, -40, -60, and -80 cm H_2O negative potential (or suction) using a sand tension table. Values of soil moisture capacity from this technique were then compared with those obtained from the field. The samples were then equilibrated and weighed at negative potentials of -1000, -2500, -5000, -10,000, and -15,000 cm H_2O, using a 'Soil Moisture Equipment' pressure plate (Figure 3.5).

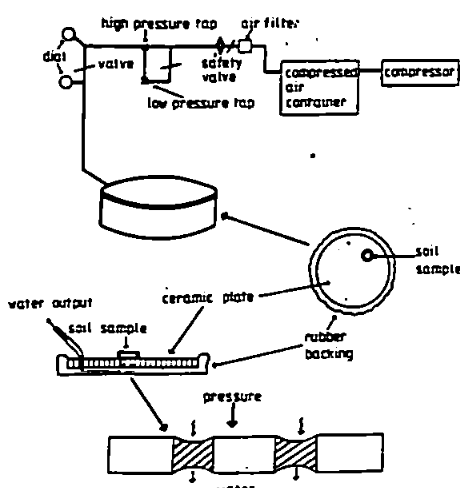


Figure 3.5 Pressure plate.

It is not possible to measure such high suction moisture capacities in the field, due to the lack of equipment and techniques capable of exerting such high vacuums in the field situation. Standard 'Soil Survey of England and Wales' procedures were used both to construct and operate the tension table and pressure plate apparatus (Hall *et al.*, 1977).

3.6.3 Macromorphological Analysis

To overcome the problem of the small size of samples used in the micromorphology analysis, two samples from ring permeametry (30 cm in diameter and 10 cm in height = 6750 cm ^{3}), one from the forest and the other from the whole tree harvested site, were used for Carbowax 6000 impregnation (Table 3.1). The field samples were immersed in a weak solution of Carbowax and then the strength was gradually increased over a period of four weeks until 100 percent Carbowax was applied. After two months, the wax had set and a vertical slice was cut through the middle of the sample by hand to prevent the wax from melting. Crystal violet dye was gently rubbed onto each face to highlight the pore spaces under UV light. Each slice was photographed under UV light to quantify the size and shape of the structural aggregates.

3.6.4 Micromorphological Analysis

Forty soil cores (diameter 5 cm, depth 3 cm) were collected from the forest and whole tree harvested sites simultaneously with soil samples for K_S, bulk density and soil texture characterisation (Section 3.6.1 & Table 3.1). Bullock and Murphy (1976) recommend 500 soil samples, but due to the limited resources it was not possible to use this many samples. Soil was sampled following the procedure outlined in Murphy (1986). These samples were initially immersed in a weak solution of acetone and the concentration was gradually increased over a three week period until 100 per cent acetone was used to replace any water present. Crystic resin and ultra-violet dye was then applied under pressure to each of the samples. They were then left to set at room temperature in a fume cupboard. A catalyst was not used since the increased heat generated may have disrupted the soil structure.

After about two months, the samples had set and excess resin was removed. Each soil core was sawn horizontally into five pieces using a circular saw and cooling oil. Four surfaces from each block were ground and polished using cooling oil and carbide powder on a potters wheel. Black and white photographs were taken of each soil slice under ultra-violet (UV) light. A program was designed for the Quantiment 570 Image Analyser that measured pore length, breadth, height and width. Features such as pores and cracks were represented by the different shades of grey on the photograph. Each photograph was calibrated on the Quantimet to take account of the enlargement of scale from photographing the soil core. Then for each soil slice, the above measurements were recorded. This information was processed using Quattro Pro to calculate pore type, shape and porosity.

3.7 DYE STUDIES

Dye studies have been used to complement the techniques already used to understand the mechanisms of soil water pathways (Table 3.1). The results from the dye study act as a good visual link between the soil water pathway data and the morphological information. For a discussion on the soil water tracers and dyes available refer to Section 1.7. Methylene Blue was chosen because it can be seen and therefore allows a quick estimation of contact areas between the soil water and soil. This technique has been used to advantage by Booltink (1993).

3.7.1 Methylene Blue

Methylene Blue was applied to a one metre square plot at the forest and the whole tree harvested sites. A concentration of two grams per litre of water was applied evenly using a watering can. The plot was left for several storms and then carefully excavated and photographed to reveal where the dye had penetrated.

3.8 SUMMARY

In summary, this chapter has described the experimental field design and the individual techniques used in both the field and laboratory. The experimental design was based on a nested sampling procedure in which the larger scale, a section of hillslope, was divided into two compartments: mature forest and whole tree harvested (Table 3.1). Within each site, three plots were set up to monitor water movement using tensiometers. The manual tensiometers were monitored for the period of December 1989 to December 1990. In reality, these measurements were taken at specific points in time during this period. It was necessary to understand the spatial structure of the hydraulic properties across the site. Therefore a hierarchical sampling scheme was devised to examine K_S. Samples of soil were collected in the field and analysed for bulk density, loss on ignition, fine root density and soil texture, using standard methods. At the most detailed scale, a sophisticated analysis of soil structure was undertaken to investigate the pore network of soil (Table 3.1). Resinated samples were sectioned and pore size and shape quantified with a Quantimet 570. Soil water tracing was used to aid identification of soil water pathways (Table 3.1). The problems encountered during the application of these techniques and the subsequent loss of potential data fall into three main categories, those being: (i.) inappropriate technique, used due to unforeseen circumstances encountered whilst employing certain standard techniques (e.g. large slate fragments in soil stopping soil cores from being taken). More appropriate techniques or modifications could have been made however, points (ii.) and (iii.) invariably obviated this. (ii.) lack of resources (iii.) incapacitating illness experienced by the researcher.

CHAPTER 4

ATMOSPHERIC INPUTS AND OUTPUTS

4.1 INTRODUCTION

Within the framework of the research presented in Section 3.2, a study of the hydrological water balance is fundamental to an understanding of the quantities of water moving through the hydrological cycle, and the pathways being followed at the various points along this cycle. Important parameters in this discussion include a description of how much precipitation enters Beddgelert Forest and how the precipitation is distributed throughout the study year. Since these factors affect the soil water processes, their characterisation is a prerequisite to understanding soil water fluxes at this site.

Chapter 4 aims to investigate and quantify three components of the water balance at the hillslope: namely rainfall, throughfall and stemflow. The influence of trees on precipitation will be examined. Rainfall volumes and the intensity of inputs at the grassland will be quantified. Chapter 5 will continue to discuss the measurement of the components of the water budget and examines the change in soil moisture storage.

4.1.2 Hillslope Water Budget

The concept of a water budget for a hillslope embodies the principle of the conservation of mass (Section 3.2.4). In essence, the balance is a straightforward black box approach in which the inputs, outputs and changes in storage are measured. The importance of internal mechanisms such as macropore/matrix flow will be examined in the context of saturated/unsaturated conditions, as detected by the neutron probe technique in Chapter 5.

This chapter will address the following objectives:-

1. The quantification and analysis of rainfall and its seasonal patterns at the WTH site.
2. The description and analysis of throughfall and stemflow quantities and their spatial pattern at the forest site.
3. The establishment of the relative importance of the water balance.
4. The quantification of soil water recharge and a discussion of the errors associated with the calculations.

4.2 CLIMATE AT BEDDGELERT HILLSLOPE

Climate was described in general terms in Chapter 2. This chapter will present the climatic variables recorded for the Beddgelert forest site over the study period, January 1st 1990 to December 31st 1990. This information is based on data recorded by the five functioning sensors of the Automatic Weather Station (AWS) since the solar radiation sensor was not functioning for the reasons discussed in Section 3.2.1. Data will be presented sequentially in the same order as aims presented in Section 4.1.2.

4.3 PRECIPITATION ERRORS AND CALIBRATION

Total rainfall collected by the AWS for 1990 was 2799 mm (Table 4.1). Annual rainfall at the adjacent Warren Springs site was slightly lower, 2395 mm (Table 4.2).

Table 4.1 Mean monthly climatic conditions at Beddgelert Forest

MONTH	AIR TEMP (C)	REL. HUMID. (%)	WIND SPEED (M/S-1)	WIND DIR. (0-180°)	SOIL TEMP (C)	P (MM)	PEt (MM)
JAN	5.6	99.1	3.6	129.2	6.1	538.7	19.7
FEB	5.4	98.4	5.0	131.5	6.3	409.4	23.1
MAR	6.1	99.1	3.7	136.2	7.7	105.9	32.1
APR	5.8	87.0	3.2	148.2	8.9	92.8	36.1
MAY	N.A.	N.A.	N.A.	N.A.	N.A.	108.9	59.8
JUN	11.6	106.1	2.5	134.0	17.3	178.4	86.5
JUL	13.7	102.4	3.4	156.0	19.8	317.3	99.5
AUG	14.9	107.2	2.6	167.4	21.1	141.9	96.4
SEPT	11.2	100.9	2.8	174.1	18.4	135.9	62.2
OCT	10.7	104.3	3.3	141.6	17.0	312.2	49.3
NOV	6.2	95.3	3.2	155.0	12.8	231.8	23.4
DEC	3.8	93.2	3.1	144.6	9.9	226.1	12.7

NA = No data available due to problems with the data logger

Table 4.2 Rainfall collected by Warren Springs

START DATE	RAINFALL (mm)	COMMENTS
03/01/90	125.7	
10/01/90	127.1	
17/01/90	136.9	snow in funnel
24/01/90	87.0	snow in funnel
31/01/90	53.5	
07/02/90	99.5	
14/02/90	108.9	
21/02/90	66.3	snow in funnel
28/02/90	2.7	
07/03/90	15.4	
14/03/90	47.7	
21/03/90	22.2	snow in funnel
28/03/90	18.4	snow in funnel
04/04/90	6.3	
11/04/90	27.4	
18/04/90	20.5	
25/04/90	22.5	
02/05/90		sample inadvertently discarded
09/05/90	16.4	
16/05/90	0.0	
23/05/90	28.0	
30/05/90	50.0	
06/06/90	28.9	
13/06/90	15.6	
20/06/90	64.4	
27/06/90	53.8	
05/07/90	57.5	
11/07/90	4.1	
19/07/90	0.0	
25/07/90	45.5	
01/08/90	0.0	
08/08/90	33.5	
15/08/90	60.4	
22/08/90	37.2	
29/08/90	29.1	
05/09/90	21.1	
13/09/90	13.4	
18/09/90	63.0	
25/09/90	0.0	
03/10/90	97.9	
11/10/90	41.1	
17/10/90	3.8	
24/10/90	58.5	
31/10/90	37.8	
07/11/90	72.3	
14/11/90	97.2	
21/11/90	5.1	
28/11/90	4.4	
06/12/90	76.8	snow in funnel
12/12/90	0.0	snow in funnel
19/12/90	194.6	snow in funnel
28/12/90	96.2	

Total Rainfall 2395 mm

Warren Springs data for 1990 are shown in Table 4.2, and the mean rainfall data for the 1989 to 1992 period are shown in Table 4.3. Over this period, the mean Warren Springs data were 2315 mm, demonstrating that 1990 was an average year, neither particularly wet or dry. Previous rainfall data collected at Beddgelert Forest (Section 2.2.2), also confirmed that 1990 was typical in terms of annual rainfall quantity.

Table 4.3 Warren Springs annual Precipitation at Beddgelert

YEAR	P (mm)
1989	2479.7
1990	2414.1
1991	2027.5
1992	2338
MEAN	2314.8

Variations in precipitation are due to differences in aspect, altitude, and design/efficiency of rainfall collector. Although the two sites are only 400 m apart, they will experience slightly different climatic conditions. The study site used for this theses is south-facing, whereas the Warren Springs site is east-facing. The predominantly northerly winds affecting the Warren Springs site mean it is far more exposed than the study site used in this research. Warren Springs' rain-gauge is exposed, on a ridge located 100 m higher than the Beddgelert site, whereas the AWS raingauge is positioned within the shelter of the cwm. These physical differences in location also explain the variations in snowfall.

Researchers at the Warren Springs Laboratory tested the accuracy of the storage gauge and found that it collected between 80 % and 97 % of rainfall depending on wind speed. Under-recording occurred at both sites due to the 'venturi effect'. During high intensity rainfall, it is also possible that the capacity of the tipping bucket raingauge on the AWS was exceeded, thus under-recording. Depending on wind speed, the Warren Springs Raingauge will collect between 80 % and 97 % of actual Precipitation. When this is applied to the mean precipitation between 1989 and 1992, the range of actual precipitation was between 2384 mm to 2778 mm. Over this four year period the mean precipitation underestimation was 2581 mm. This is similar to that recorded by the AWS and therefore the AWS data are deemed sufficiently accurate to use in this study.

The precision of the two rainfall gauges was examined statistically in respect of rainfall quantity. Comparable data sets were correlated, and the coefficient Rs ranged between 0.63 and 0.93, with an average of Rs = 0.81. This is significant at 0.01 % (Table 4.4 and Figure 4.1).

Table 4.4 Correlation coefficients for AWS and Warren Springs precipitation

Julian Day	Rs
368-473	0.929
529-550	0.840
571-669	0.626
688-726	0.841
368-726	0.809

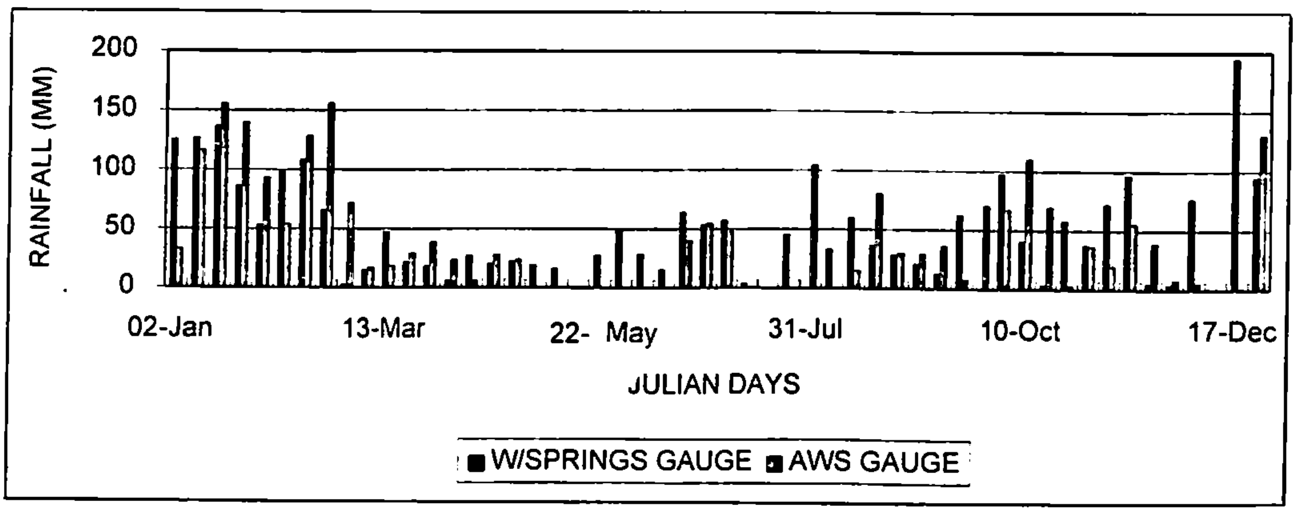


Figure 4.1 AWS rainfall and Warren Springs rainfall

There was a perfect correlation between seasonal rainfall recorded in the Warren Springs gauge and that recorded in the AWS gauge (Table 4.5).

Table 4.5 Seasonal comparison of precipitation from the Warren Springs gauge and AWS

SEASONS	W/SPRINGS	AWS
WINTER	1174.2	1152.3
SPRING	294.3	305.4
SUMMER	430	413.1
AUTUMN	515.6	504.3
TOTAL	2414.1	2447.3

The correlation between sites supports the assumption that the rainfall data collected from the AWS is accurate and can be used with confidence in this study.

4.4 GROSS PRECIPITATION AT THE HILLSLOPE

Precipitation was in the form of direct rainfall at the WTH and forest site, for all but two days when snowfall occurred.

4.4.1 Rainfall Pattern

During the 12 month period from 1/1/90 to 31/12/90, 2800 mm of precipitation fell at the research site (Table 4.1 & Figure 4.2 shows daily rainfall and Table 4.1 shows the total monthly rainfall). January and February were the wettest months, when 539 mm and 409 mm of rainfall fell, (Table 4.1 & Figure 4.3).

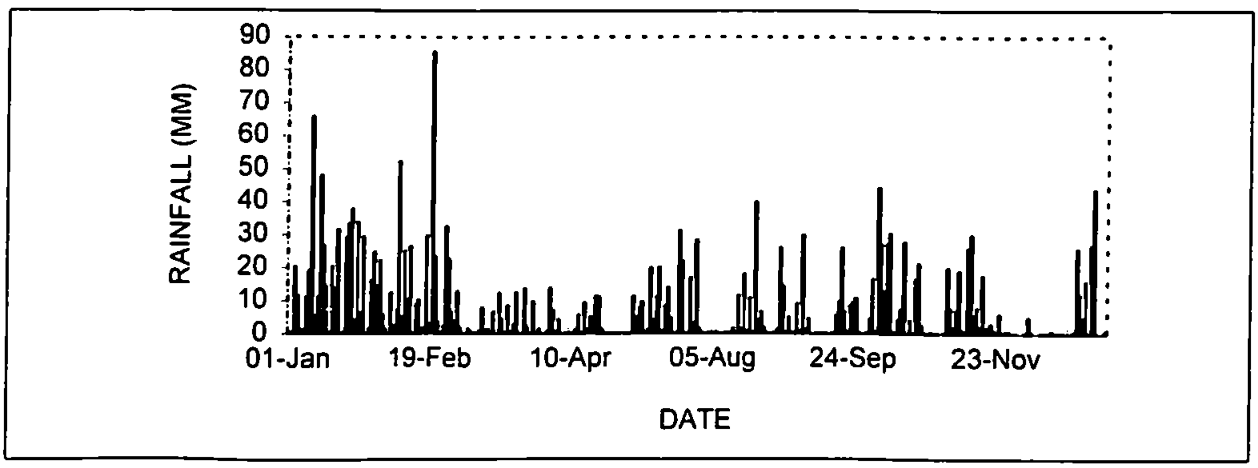


Figure 4.2 Daily rainfall at Beddgelert during 1990

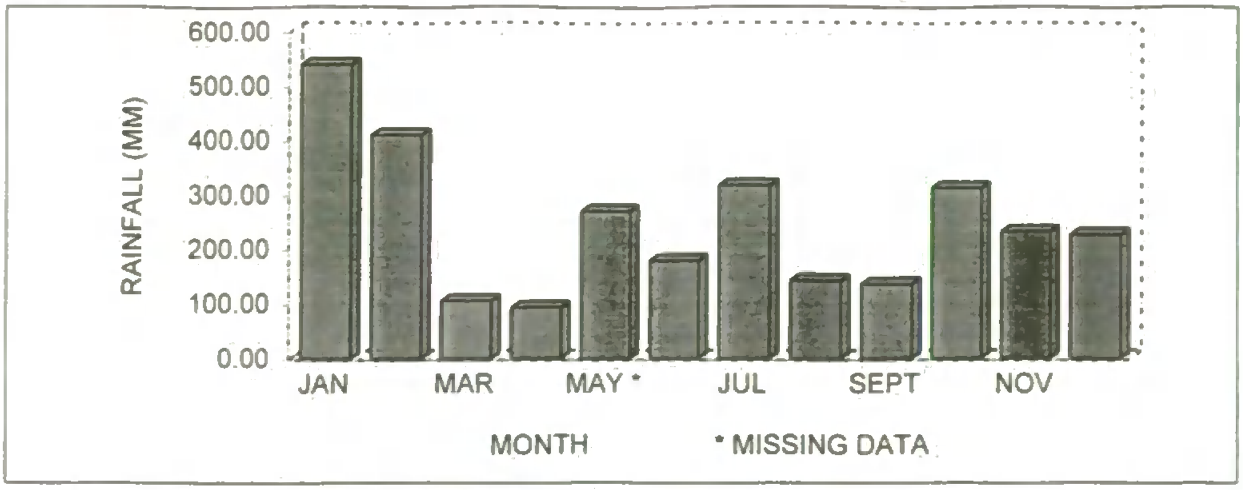


Figure 4.3 Monthly rainfall at Beddgelert

The rainfall for January and February represents 34 % of the annual rainfall. This result has important implications for the hillslope hydrology in terms of antecedent conditions and hillslope soil water flux (Chapter 5). Conversely March, April and May had the lowest levels of rainfall with just 105.92 mm, 92.79 mm and 108.97 mm respectively (Table 4.1 & Figure 4.3). The total of which (307.68 mm) represents only 11% of the annual rainfall. June, August and September were also low in rainfall with 178.43 and 135.8 mm respectively (Table 4.1 & Figure 4.3). July and October were very wet, with just over 300 mm of rainfall each. November and December had average rainfall for this site with just in excess of 200 mm each. The annual pattern of rainfall therefore suggests large scale water flow and particularly saturated flow only has the potential to occur during January and February. During the other months of the study year flow will occur. However it is unlikely to be of the same magnitude and will almost definitely be unsaturated apart from high impulses occurring during storms.

4.4.2 Rainfall Intensity

Of the 280 rain days, only 31 days during 1990 had an intensity in excess of 1 mm hr^{-1} and these were all in autumn and winter months (Figure 4.4).

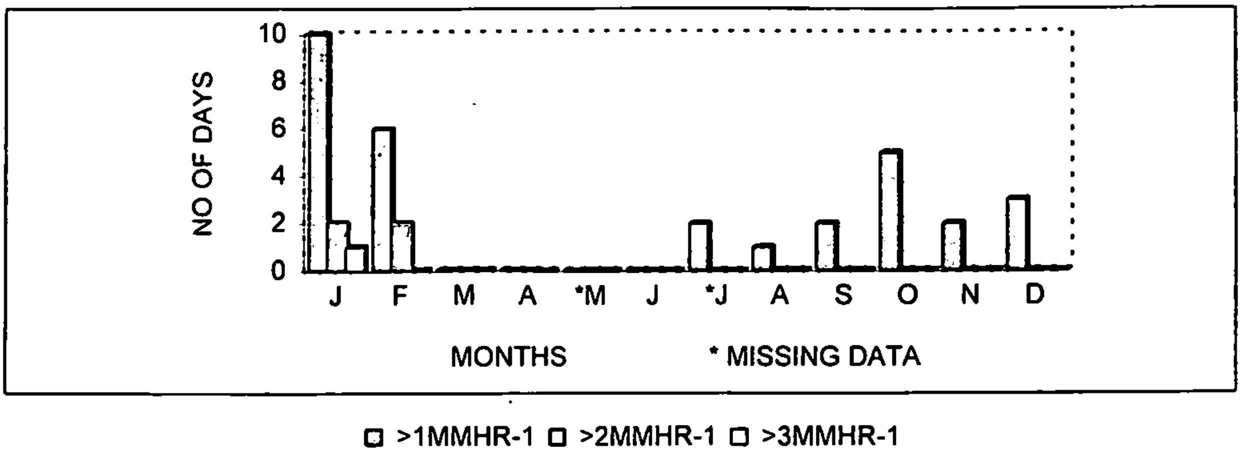


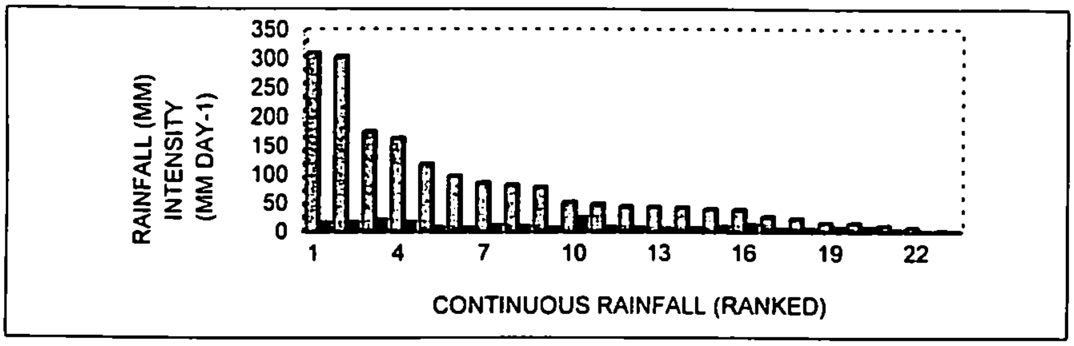
Figure 4.4 Average rainfall intensity at Beddgelert

Rainfall occurring at 1 mm hr^{-1} is of relatively low intensity and for this water to drain into and through the soil there only needs to be a K value of $\leq$ 1 mm hr^{-1}. The greatest intensity of rainfall occurred on 20 th February with an average of 3.58 mm hr^{-1} when 85.8 mm of rain fell in day. These events all occurred in winter where 11% of annual rainfall occurred (Figure 4.4). These rainfall intensities are very crude and for the true rainfall intensities to be presented the 15 minutes rainfall data should be examined. Since limited temporal tensiometer data were available, it was felt that this detailed rainfall intensity data was not required and therefore data at this level of analysis was not collated and examined.

Examination of daily rainfall data showed that the greatest duration of continuous precipitation was 18 days from February 5th 1990 to February 22nd 1990, when 311 mm of rainfall fell (Table 4.6 & Figure 4.5). During this period, these large volumes of water probably create conditions where saturated flow can occur. During a two day Summer storm, from the 5th to the 7th of July, there was 54 mm of rainfall giving an intensity of 27 mm day^{-1}.

Table 4.6 Continuous periods of rainfall, ranked in volumetric order

Rank Vol	Storm Start Date	Storm End Date	Total Rainfall (mm)	Duration (days)	Intensity (mm day-1)	Annual Rainfall (%)
1	50290	230290	311.3	18	17.29	10.52
2	30190	200190	305.33	17	17.96	10.32
3	190190	270190	175.89	8	21.99	5.94
4	300990	91090	165.02	9	18.34	5.58
5	190690	30790	120	14	8.57	4.06
6	120890	250890	98.9	13	7.55	3.34
7	280190	40290	87.23	7	12.46	2.95
8	240290	40390	83.41	8	10.42	2.82
9	170990	270990	79.59	10	8	2.69
10	50790	70790	53.67	2	26.84	1.81
11	280790	20890	50.66	5	10.13	1.71
12	40990	90990	46.03	5	9.21	1.56
13	150490	220490	45.24	7	6.46	1.53
14	260890	310890	44.61	5	7.55	1.51
15	161090	201090	40.8	4	10.2	1.38
16	101090	131090	39.8	3	13.27	1.35
17	20490	251090	27.34	5	5.47	0.92
18	190390	230390	25.12	4	6.28	0.85
19	160390	180390	16.88	2	8.44	0.57
20	250390	270390	16.28	2	8.14	0.55
21	90390	130390	12.06	4	3.02	0.41
22	100490	140490	7.84	4	1.96	0.26
23	50390	70390	2.21	2	1.1	0.08



TOTAL RF (MM) INTENSITY (MM DAY-1)

Ranks refer to dates presented in Table 4.6

Figure 4.5 Periods of continuous rainfall during 1990 at Beddgelert

4.4.3 Rainfall

In summary, many storms of low intensity caused the input of large volumes of precipitation throughout the study period. The majority of rainfall occurred during long periods of rainfall, up to 18 days, and these were mainly in the winter with slightly higher intensity. The precipitation was frontal, (i.e. cyclonic rainfall) and there were large volumes of rainfall. The majority of rainfall occurred in winter, particularly in January and February, where there were very few days without rainfall. The greatest number of dry days occurred during the summer.

4.5 NET PRECIPITATION BENEATH THE FOREST CANOPY

Stemflow is that component of precipitation which is funnelled from the canopy to and down the tree stem. Many studies have ignored the spatial component of stemflow and throughfall variability. However, it is an important part of the hydrological balance (Durocher, 1990). For example, Voigt (1960) found that stemflow accounted for between 0.1 % and 15 % of gross precipitation, while Ford and Deans (1978) recorded stemflow as 27 % of gross precipitation, (Table 4.7).

Table 4.7 Throughfall and stemflow percentages of gross precipitation within Beddgelert Forest and other pine forests in the U.K.

Study	Species	Stand	Thin- Age	Tf Thinning	Sf	I
Hodgkins (this study) Beddgelert	S/S	50	T	65	3.5	29.5
Stevens *et al.* (1989) Beddgelert	S/S	49	T	65	6	25.4
Soulsby (1992) Llyn Brianne	S/S	25	T	73	9.5	17.6
Chappell (1990) Plynlimon	S/S	45	T	56	5	39
Gash & Stewart (1977)	S/P	45	T	67	1.6	-
Law (1956) S/S	-	T	60	7	-	
Ford & Deans (1978)	S/S	14	UT	43	27	-
Gash *et al.* (1980) Plynlimon	S/S	43	UT	56	28	26.7
Rutter (1963)	S/P	18	UT	48	16	-

KEY
S/S Sitka Spruce (*Picea sitchensis*)
S/P Scots Pine (*Pinus sylvestris*)
Tf Throughfall
Sf Stemflow
I Interception
T Thinned
UT Unthinned

Meteorological, morphological and physiological factors all influence stemflow volume. Significant meteorological factors include rainfall intensity, duration and its timing. The pattern of rainfall is important because the storage capacity of the canopy and stems must be exhausted before stemflow can occur. Morphological factors include tree height, diameter, breast height, basal area, projected crown area, branching patterns and number of branches per unit area. The relative position of a tree in the canopy can also influence stemflow. For example, if the tree is taller than its neighbours, then it has the potential to collect more water, since it may be covering the canopies of other smaller trees. In this scenario, stemflow would readily occur on the taller tree. Where a tree is intermediate in height or relatively small, stemflow may only occur infrequently. Navar (1993) suggests that the number of branches and position of canopy rather than total projected branch area controls stemflow. Branching pattern or habit is also important and trees with branches at an acute angle to the tree trunk produce larger volumes of stemflow due to funnelling (Herwitz, 1986), than those with flat or obtuse angled branches.

Significant physiological factors affecting low volumes of stemflow particularly include, smoothness of the bark, (the smoother it is the more conductive it is for stemflow to flow) and capacity for absorption of stemflow by bark, (the least absorbent bark allows greater stemflow). Consequently, measurable stemflow occurs most often with large-crowned, relatively tall trees that have smooth bark and inclined branches.

Spatial patterns of stemflow wetting the soil are highly variable, the highest inputs of water are closest to the tree trunk itself. The movement of water at the base of trees is transported into the soil either by Darcian flow through the bulk of the soil or by macropore flow, through large channels or pores. Downward flow is encouraged by the root surfaces, dead root channels and fractures in the soil induced by the presence of roots. This pathway will have implications for macropore flow due to the high input of water around the tree trunks.

4.5.1 Stemflow

Stemflow was measured at 6 sites (Section 3.2.1). Total volume of stemflow was monitored from January 1st 1990 to December 31st 1990. Stemflow was calculated for a 3 x 4 m plot which contained 11 Sitka Spruce (*Picea sitchensis*, Bong Carr.) trees (Table 4.8).

Table 4.8 Mean depth of stemflow

Total Sf volume down 6 representative trees	= 6248666 cm^3
Total number of trees in plot	= 11
Total area of plot 300 x 400 cm	= 120,000 cm^3
Mean depth of Sf	= 6248666 cm^3 (11/6)
	120000
	= 9.373 cm = 93.73 mm

The total of 93.73 mm represents 3.5 % of gross precipitation (2800 mm), (Section 4.4.1). This method of calculating depth of stemflow is very area sensitive and any inaccuracies in this measurement will greatly change mean stemflow. The crucial factor is deciding the sphere of influence of the tree. For the purposes of this experiment, the sphere of influence was taken to be mid-way between two trees, since the tree canopies were touching. However, the calculation detailed above does allow good comparisons to be made between precipitation, throughfall and stemflow (Section 4.5.2). Figure 4.6 presents the cumulative gross precipitation and constituent parts of net precipitation, throughfall and stemflow.

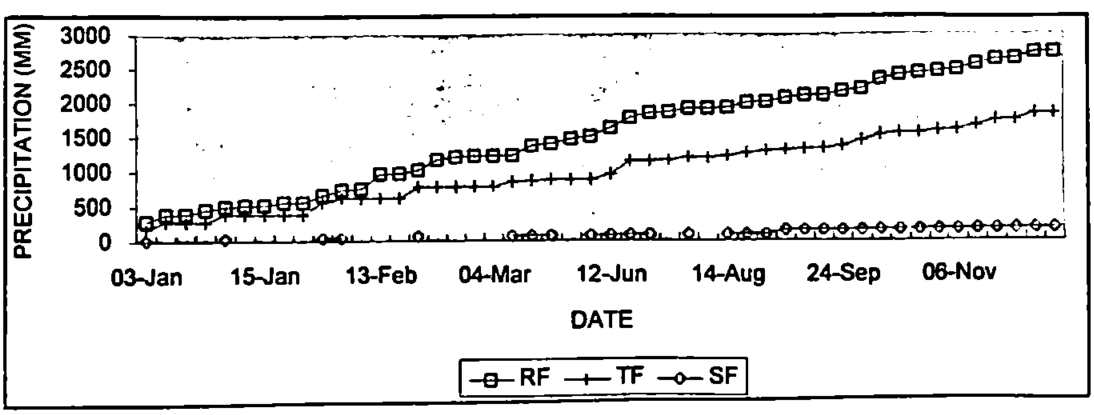


Figure 4.6 Cumulative gross precipitation, throughfall and stemflow at Beddgelert

Figure 4.6 shows that throughout the year there is close similarity in precipitation and throughfall inputs, although stemflow is less apparent due to the low mean depth of stemflow.

Table 4.7 shows the similarity with other pine forest sites. It appears that thinning reduces stemflow by an average of 77 %. If stemflow has important implications on macropore flow at the base of trees, thinning and spacing of trees will be an important factor governing soil water pathways and soil water flux.

4.5.2 Stemflow Variability

Table 4.9 shows the individual annual stemflow figures, ranging from 93 litres to 2514 litres. The annual range in stemflow for individual trees was 36.3 mm, which represented 38.7 % of annual stemflow. Despite this large range in annual stemflow, there were significant correlations at 0.01% between all the fortnightly recorded stemflow data (Table 4.10). These data not only highlights the variability in stemflow between the different trees, but also that the degree of variability is consistent between individual trees and therefore related to tree physiology and morphology (Figure 4.7).

Table 4.9 Individual Stemflow values

Gauge No	Volume (l)	Mean Depth (mm)	Individual Sf as a % of total Sf	Tree Diameter (cm)
SF1	1594.4	23.4	25.9	69
SF2	1360.3	20.4	21.8	67
SF3	93.4	1.4	1.5	42
SF4	362.1	5.43	5.8	54
SF5	330.2	5	5.3	52
SF6	2513.7	37.7	40.2	77

Table 4.10 Stemflow gauge correlation matrix

	SF1	SF2	SF3	SF4	SF5	SF6
SF1	———	0.956	0.545	0.851	0.823	0.962
SF2		———	0.508	0.922	0.809	0.99
SF3			———	0.566	0.606	0.54
SF4				———	0.789	0.926
SF5					———	0.829
SF6						

Table 4.9 and 4.10 shows that there is a perfect correlation between individual stemflow mean depth (mm) and diameter at breast height (cm). The greatest stemflow volumes occurred down the trees with the largest breast diameter, a finding also observed in other studies at similar sites, Soulsby (1992a). Stemflow can therefore be a considerable amount of water entering a small point around the tree. On several occasions during an intense period of rainfall, localised ponding occurred upslope of the widest tree trunks, demonstrating that the water input was exceeding the infiltration rate. This observation implies the potential for macropore flow to occur in these areas of localised saturation.

The range of stemflow between the 6 stemflow collectors was greatest from January 29 th to February 20th 1990 during the winter when rainfall and stemflow were highest. Stemflow ranged from 1.6 litres at gauge 3 to 500.7 litres at gauge 6 (Table 4.11) representing 37.8 % of the total for that period, which is a large proportion. During the summer, seven days from April 18th to April 25th stemflow ranged from 0.1 litres at gauge 3 to 38.4 litres at gauge 6 representing 61.7 % of the total stemflow for this period, which is higher than during the winter (Table 4.11).

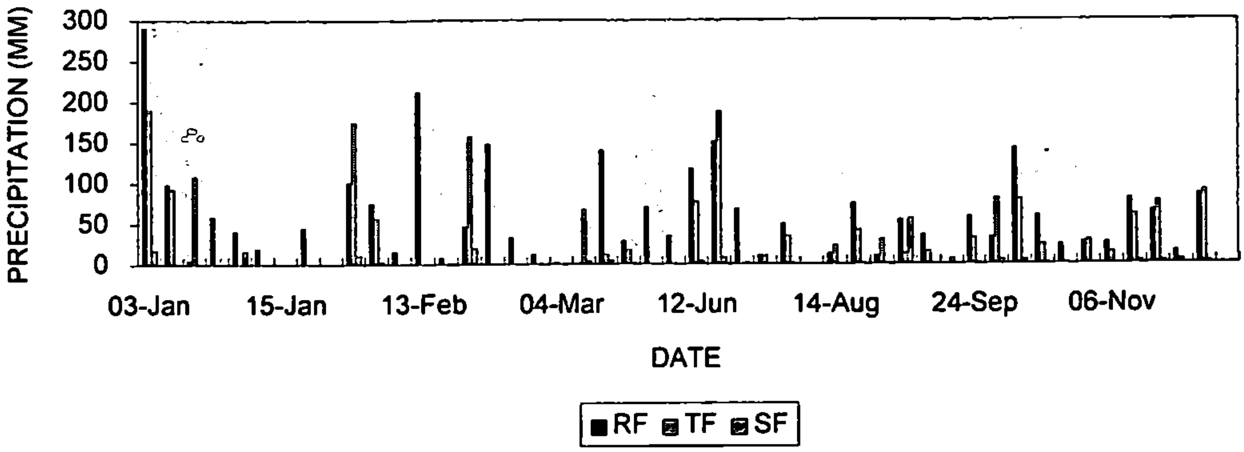


Figure 4.7 Rainfall, Throughfall and Stemflow at Beddgelert

Table 4.11 Individual stemflow values during a winter and summer period

	Stemflow (l)	
Stemflow to Gauge	Winter Example 29th January to 20th February (22 days)	Summer Ex. 18 th April 25 th April (7 days)
1	333.5	1.4
2	297.4	13.3
3	1.6	0.1
4	72.4	4.8
5	114	4.1
6	500.7	38.4
Total Sf	1319.6	62.1
Range	499.1	38.3
%	37.8	61.7

Table 4.12 Correlations between P, Tf and Sf

-	P/Tf	P/Sf	Tf/Sf	Significant at
Seasons	1	1	1	0.01
Annual	0.79	0.89	0.87	0.01

KEY
P = Precipitation
Tf = Throughfall
Sf = Stemflow

4.5.3 Stemflow Pattern

The seasonal stemflow volumes are comparable with the rainfall volumes, and the similarities are clearly seen in Figure 4.8. There was a perfect correlation of Rs = 1 between seasonal rainfall and stemflow (Table 4.12 & Figure 4.8). There is also a very significant correlation at 0.01 % of Rs = 0.89 for all the rainfall and stemflow data.

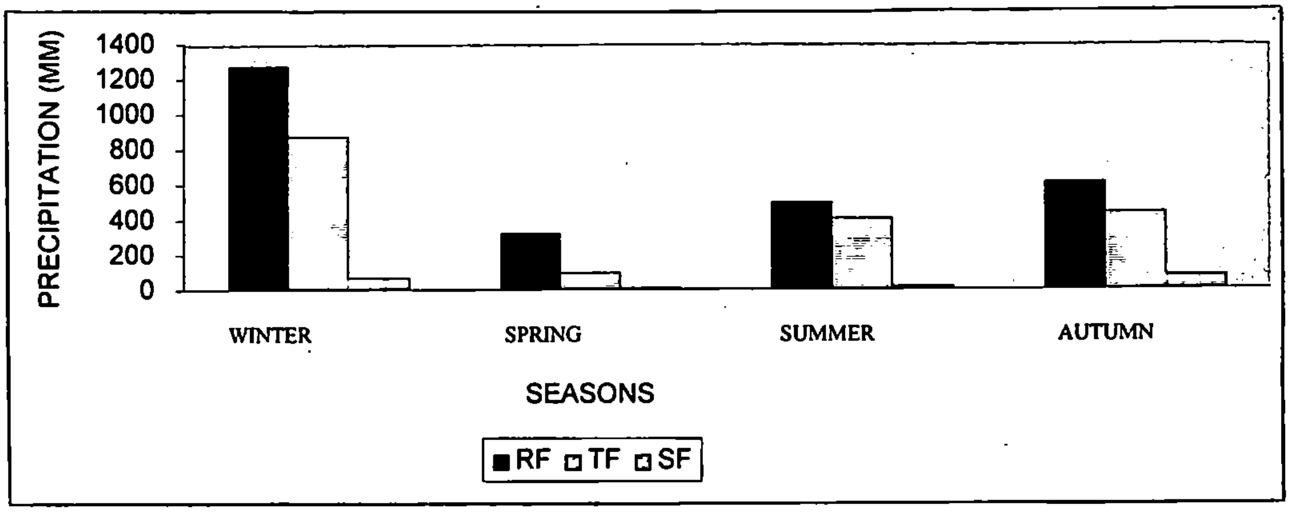


Figure 4.8 Seasonal rainfall, throughfall and stemflow at Beddgelert

<u>Summary</u>

Loustau *et al.* (1992) found that the stemflow coefficient of variance has a tendency to decrease asymptotically with an increase in gross rainfall and that the same occurs with throughfall. He also found that, although the effect of individual trees on stemflow was significant, the amount of stemflow per tree was not related to tree size. Although the stemflow data in this study are crude on comparison with Loustau *et al.* (1992), they do not support his theory: as gross precipitation decreases, so too did the variability between the 6 stemflow collectors. However, contrary to his findings, but supporting the work of Soulsby (1992), there was a relationship between individual stemflow mean depth and mean breast diameter.

The data generated during the stemflow experiments are similar to that for other upland forest sites in Britain. The significance of stemflow was noted by Durocher (1990) and Dowd *et al.* (pers. comm.). At the forest site, the stemflow element of net precipitation is funnelled and concentrated into a localised point of entry into the soil, although it only represents a mean depth of 3.5 % of gross precipitation. Stemflow of such magnitude constitutes a large volume of water in such a small point of entry into the soil and thus causes localised saturation.

The implication of localised point of saturation is that they provide conducive conditions for macropore flow and therefore preferential flow through the soil profile. Due to the route taken by the water (i.e. through the canopy and down the branches and trunk) there has been an ideal opportunity for dry deposition to be collected and concentrated and thus have implications for acidification of groundwater. One of the ways further research could be carried out to find out more about the importance of rootflow is to apply a tracer using appropriate stemflow volumes to the stemflow collar. Monitoring could then be achieved using a series of suction cup lysimeters surrounding the trunk with increasing distance, both laterally and vertically from the trunk. This array would allow any complex soil water pathways to be identified.

4.5.4 Throughfall

Throughfall is the component of precipitation that drips from the canopy, originating from either dripping leaves and branches or direct fall from the atmosphere. Loustau *et al.* (1992) found that the spatial distribution of tree trunks had a negligible effect on the throughfall partitioning beneath the canopy. The sensitivity of throughfall to canopy structure parameters is related to the amount of gross rainfall per storm (Gash, 1979). Loustau *et al.* (1992) found this spatial variability of throughfall was higher for light storms and decreased asymptotically as gross rainfall increased.

Throughfall was measured at 5 sites which was sufficient to represent the true distribution of net precipitation (Section 3.2.1). Total depth of throughfall over a 12 month period, from December 14th 1989 to 19th December 1990, was 1824 mm. Over this same period, 2717 mm of precipitation fell at the WTH site and therefore throughfall is equivalent to 67.1% of the gross precipitation (Figure 4.8). Over the same period as gross precipitation and stemflow (January 1st 1990 to December 31st 1990), 1973 mm of throughfall occurred. The pattern of throughfall throughout the year is similar to stemflow and gross precipitation (Figure 4.7).

4.5.5 Throughfall Variability

During the winter when rainfall was at its highest (22 days, from January 29th to February 20th 1990), the range in throughfall was only 29.3 mm representing 3.7 % of total throughfall for this period (Table 4.13). During the summer, when rainfall was at its lowest (7 days, from April 18th to 25th 1990) the range in throughfall was 3.3 mm, representing 3.6 % of the total throughfall for this period. In summary, there was very little variability between the individual throughfall collectors and individual throughfall totals (Table 4.13). The annual range in throughfall totals was only 207.46 mm or 2.3 % of annual throughfall.

Table 4.13 Individual throughfall values during a winter and summer period

	Throughfall (mm)	
Throughfall Gauge	Winter Example 29th January to 20th February (22 days)	Summer Ex. 18 th April to 25 th April (7 days)
1	164.1	19.9
2	169.6	17.4
3	160.2	17.7
4	140.3	16.6
5	151.9	19.3
Total Tf	786.1	90.9
Range	29.3	3.3
%	3.73	3.63

Summary

There was very little variability between the throughfall totals at each gauge. Therefore within this large plot, throughfall can be considered as a uniform input. As throughfall increased (i.e. winter compared to summer), there was a negligible decrease in throughfall variability. This finding does not support Loustau's findings as the differences were too small to amount to any correlation. The throughfall element of net precipitation was therefore similar to gross precipitation at the whole tree harvested site. Net precipitation represented 69 % of gross precipitation, which was similar to that measured by Stevens *et al.* (1989) on the opposite side of the Cwm. The annual pattern of net and gross precipitation was similar.

4.5.6 Interception

Interception losses for 1990 were calculated using the canopy water balance equation:

$$P = I + TF + SF \tag{4.1}$$

where P = Precipitation

I = Interception

TF = Throughfall

SF = Stemflow

Total interception at the forest site for 1990 was 827 mm, which represents 29.5 % of gross precipitation. This result compares well with 25.4 % interception measured by Stevens *et al.* (1989) at Beddgelert and other studies at similar sites supporting the credibility of the data collected (Table 4.7 and Section 4.6.1). Interception at the whole tree harvested site will be lower.

4.6 CLIMATIC CONDITIONS

Temperature

Mean monthly air temperatures ranged from 3.76 ^{o}C in December to 14.95 ^{o}C in August (Table 4.1). January, February and March were very mild being above 5 ^{o}C and consequently snowfall was uncommon with lying snow only occurring once. The summer months were not exceptional, with the hottest day being in August when air temperatures reached 24.04 °C. Throughout the year, mean soil temperatures at 10 cm depth were warmer than the air temperatures, ranging from 6.14 °C in January to 21 °C in August (Table 4.1). The soil remained much warmer during Autumn than air temperature, and when it did cool down in winter, it was on average 1°C warmer than corresponding air temperatures.

<u>Wind</u>

Winds were generally between NW and N, with 72% of all days experiencing winds with a Northerly component. Due to the orientation of the cwm (Figure 1.1), the study site was fairly sheltered compared to the rest of the cwm. However, this site still remained windy, with a mean wind speed of 3.3 $m.s^{-1}$. The remaining 28 % of days had a stronger Westerly component. Most of these days were in January and February, when frontal systems from the Atlantic were most frequent. The highest mean daily wind speeds were also recorded during this time.

4.6.1 Evapotranspiration

Beddgelert annual PEt loss for 1990 was 600.69 mm, which was 22 % of gross precipitation. As expected, PEt was at its highest in the summer months and lowest in winter (Table 4.1 & Figure 4.9). The highest PEt was in July with 99.54 mm of water loss representing 16.56 % of total PEt, and the lowest PEt was in December with 12.72 mm of water loss, representing 2.18 % of total PEt. However, the latter is probably an over-estimate, Et would have been lower because evaporation would have been closer to zero due to the low temperatures. During the summer months of May through to September, 400.39 mm of water were potentially lost through evapotranspiration, which is 67.32 % over 5 months, leaving just 32.68 % water loss over the remaining 7 months of the year.

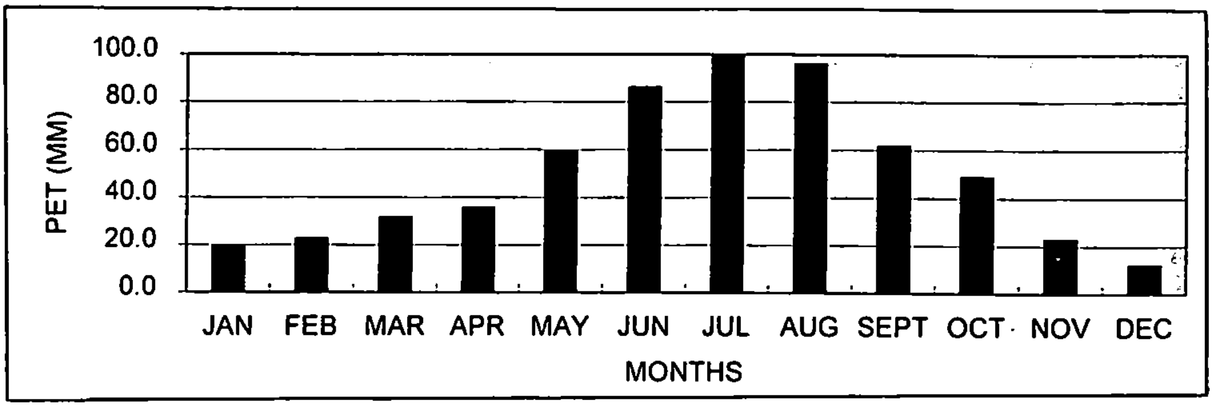


Figure 4.9 Monthly evapotranspiration at Beddgelert

Chappell (1990) found on his hillslope within the Tir Gywn catchment, Plynlimon that 22.5 % of water was lost through evapotranspiration during 1987/88. From this figure it can be seen that a value of 22 % for evapotranspiration was realistic and can therefore be used with confidence.

Interception

At Plynlimon, Reynolds *et al.* (1988) found that the forest site lost 21.6 % of water through interception during 1984/85. The grassland Cyff catchment lost 18.2 % of water through evapotranspiration. At Kershop, Anderson *et al.* (1990) found that their site lost between 37 % and 42 % of water through interception between 1981 and 1985 representing only a small difference between the two sites. Work by Gilman (1994) found there was little difference in interception between forest and grassland sites. Using their findings it can be seen that a value of 29.5 % for interception was a realistic value and can therefore be used with confidence.

Whilst estimated Et at the whole tree harvested site will have taken into account some interception, at the forest site, net precipitation will have included an element of Et. For the purposes of this water balance calculation, duplication of recordings were assumed to be similar at both sites, since these measurements were secondary to the investigation.

4.7 SOIL WATER RECHARGE

Using the straightforward black box approach for soil water recharge, which was described at the start of this chapter, monthly and annual soil water recharge figures were calculated and are presented in Tables 4.14 & 4.15. Once PEt has been taken into consideration, the effective precipitation can be looked at in terms of soil water infiltration and movement through the soil. Changes in soil water storage were negligible from the beginning to the end of this investigation (Section 5.3 & 5.6), and were therefore treated as zero for the purposes of the water balance equation.

Table 4.14 Beddgelert monthly water balance

MONTH	TOTAL P (mm)	TOTAL PEt (mm)	TOTAL Q(mm)
JAN	538.7	19.7	519
FEB	409.4	23.1	386.3
MAR	105.9	32.1	73.8
APR	92.8	36.1	56.7
MAY	108.9	59.8	49.1
JUN	178.4	86.5	92.0
JUL	317.3	99.5	217.7
AUG	141.9	96.4	45.5
SEPT	135.9	62.2	73.7
0CT	312.2	49.3	263.0
NOV	231.8	23.4	208.4
DEC	226.1	12.7	213.4

Table 4.15 Annual water balance

INPUTS/OUTPUTS (mm)	FOREST	WTH
Gross Precipitation		2800
Stemflow	94	
Throughfall	1879	
Net Precipitation	1973	
Interception	827	
Evapotranspiration		601
Soil Water Recharge	1973	2199

Soil water recharge was greatest in the months of January and February. Soil water recharge was calculated at 1973 mm for the forest site and 2199 mm per annum for the whole tree harvested site representing a difference of 226 mm between the two sites (Table 4.16).

Table 4.16 Water balance error

Gross Precipitation	2800 ± (10 %) 280 mm
Evapotranspiration	601 ± (20 %) 120 mm
Soil Water Recharge	1803 to 2603 mm

The seasons of autumn and winter (October through to February) were very wet with in excess of 200 mm of potential soil water recharge per month. Spring and Summer (March to September) are dry with less than 93 mm of potential soil water recharge (excluding of July, which had an exceptional 217 mm of potential soil water recharge).

4.8 SUMMARY

The rainfall data from the AWS gauge compares well with that collected at the nearby Warren Springs site, and was also similar to previous and subsequent rainfall at that site (Stevens *et al.*, 1989). Stemflow and throughfall data also compare well with other upland studies (Chappell, 1990; Gash & Stewart, 1977; Soulsby, 1992 and Stevens *et al.*, 1989). Like other upland sites rainfall was highest during the winter months, when PEt was at its lowest resulting in the greatest potential for soil water recharge in January and February.

Values for stemflow, throughfall and interception from this investigation fell midway between data collected on these variables for this site during 1982/83 and 1983/4 (Stevens *et al.*, 1989) which correspond to a dry and wet year. From these results, it can confidently be assumed that this study year was a typical year in terms of net precipitation inputs at the forest site. Being conducted during a typical year makes the data collected during this study valuable for comparison to other upland studies. The uniformity and quantity of precipitation was supported by similarities between precipitation collected by the AWS and nearby Warren Springs raingauge for the study year. Other upland sites in Britain have similar values for net precipitation and interception Anderson *et al.* (1990) at Kershope; Chappell (1990), Reynolds *et al.* (1988) and Soulsby (1992) at Plynlimon.

Volume of inputs were similar at the forest and WTH sites. The majority of net precipitation at the forest site occurred in the form of throughfall and this was almost as uniform as the rainfall at the whole tree harvest site. However, there are three important factors concerning stemflow. First, precipitation is funnelled down the tree concentrating the volume of precipitation in a small area around the base of the tree trunk. Second, variability of stemflow occurred between the trees measured with the greatest volume of stemflow occurring at the tree with the largest breadth diameter. Third, the range of stemflow variability was greatest in the summer, when rainfall was lowest. Differences in throughfall variability were negligible and therefore, throughfall variability and rainfall volume showed no correlation.

Ponding of water was only observed upslope of the largest tree on a few occasions. At these times, saturated flow would have occurred. Analysis of other stemflow data (Table 4.7) showed that tree thinning reduced stemflow and therefore the spacing of trees is an important factor for the degree of variability of stemflow. Depending on the effect this had on soil water movement, the spacing of trees and lack of trees (i.e. at the WTH site), could be an important consideration on forest management.

Trees change the pattern of precipitation input and have potential implications for soil water movement and soil water chemistry. Differences in soil water mechanisms operate when localised saturation of water occurs and the path length is shorter, (i.e. by-pass flow), (Luxmoore *et al.*, 1990), allowing minimal chemical changes to occur. However, due to the route precipitation took prior to reaching the soil, the accumulation of dry and wet deposition could have management implications. Chemically loaded water will quickly enter the streamflow and will have disastrous consequences for aquatic habitats.

The water balance was not sufficiently accurate to quantify soil water recharge at both sites. However, the data are of reasonable accuracy to say both sites had similar soil water recharge.

To conclude, gross and net precipitation were very high and the volume of potential soil water recharge were similar at both sites, with this being greatest in January and February. The nature of gross precipitation was usually low intensity and over long periods of time. The seasonal pattern of gross and net precipitation were similar at both sites. Precipitation at the WTH site and the majority of net precipitation at the forest site (throughfall) were spatially uniform. However, a small but potentially significant quantity of stemflow was spatially variable.

CHAPTER 5

SOIL WATER

5.1 INTRODUCTION

In this chapter, a comparison of a forest and whole tree harvest site is made on the basis of an analysis of soil water pathways, soil moisture content, soil suction and water movement. Attention must be given to the scales at which soil properties in the field are measured. The overall objective of this chapter is to present the results on soil water content and water status of forested and whole tree harvested sites in Beddgelert forest in order to understand the hydrology. The objectives are as follows:

1. To measure the changes in volumetric moisture content at both sites throughout 1990.
2. To describe the soil water status at selected points at each site and to explain any movement in terms of the soil physical characteristics, such as hydraulic conductivity and water content.
3. To ascertain whether lateral or vertical water flow predominates, and to see whether matric or gravitation potential has the most significant effect.
4. To elucidate and study mechanisms responsible for flow.
5. To model vertical water movement.

The structure of Chapter 5 follows the objectives as set out above. First, the change in soil moisture content, and therefore change in storage, is considered through time. (Moisture content is a function of inputs/outputs and physical properties and is expressed in the soil moisture characteristic curve (Section 2.7.1)). Second, a discussion of the soil water potentials leads to an analysis of both the type and direction of the major water pathways. Finally, modelling will identify important soil parameters which may govern soil water movement at this site. (The aims of the investigation will be explored in three sections:

soil moisture content, suction and modelling). Background theory will be described on each subject prior to the results being discussed.

5.2 VOLUMETRIC SOIL MOISTURE CONTENT AND SOIL WATER MOVEMENT

Volumetric soil moisture content was determined in the field using a neutron probe (Section 3.2.3). Soil moisture depends on the balance between inputs and outputs to the soil system. Changes within the soil profile are influenced by inputs from the atmosphere (rain/throughfall/stemflow) and infiltration from upslope as well as loss of water via evapotranspiration (Et) and downslope flow. Upslope contributions and downslope losses are dependent on soil moisture potential and are described in Section 5.5 & 5.7. Soil moisture content is a term describing the volume of water held in the soil, whereas suction is a pressure term describing the force applied to the soil water. The relationship between soil moisture content and suction was illustrated by the soil moisture characteristic curve in Figure 2.4 & 2.5. Hydraulic conductivity (K) is a function of volumetric moisture content (θ_V). and will be calculated from saturated hydraulic conductivity (K_S) (Campbell, 1974).

The nature of slopes have been shown to affect moisture conditions (Anderson and Burt, 1978; Dunne and Black, 1970; Kirkby and Chorley, 1967 and Miyazaki, 1993). Miyazaki (1993) found that vertical infiltration dominates on slopes less than 30^o. However, slopes above 30^o and indeed those with relatively impermeable horizons lead to lateral downslope movement of water (Miyazaki, 1993; Redinger *et al.*, 1984). Since the slopes at Beddgelert Forest were around 30^o (Section 2.4.2), this theory would suggest that there is a significant lateral flow component.

5.3 CHANGES IN FIELD SOIL MOISTURE AT THE FOREST SITE

At the outset of this discussion, it should be noted that there are errors with neutron probe readings in the surface soil (due to the atmospheric interference). Hence the soil moisture content at 15 cm will be treated cautiously.

Soil moisture content at the start of the experiment in September 1989 was 24 % and at the end was 26 %. This 2 % increase in soil moisture content is very small, considering the large input to this site in winter. There was no evidence to suggest that the site saturates. Therefore the soil is able to transmit the abundant rainfall very quickly. There was very little change in average soil moisture content throughout the study year (Table 5.1).

Table 5.1 Volumetric soil moisture content of a 150 cm vertical soil profile at the forest site

depth	18/9/89	3/10/89	13/12/89	16/1/90	23/1/90	30/1/90	16/5/90	25/7/90	22/8/90	29/8/90	25/9/90
cms	261	276	347	381	388	395	501	571	599	606	633
15	0.56	0.49	0.35	0.62	0.54	0.37	0.53	0.56	0.57	0.51	0.17
20	0.46	0.49	0.55	0.56	0.56	0.55	0.49	0.48	0.51	0.57	0.40
30	0.35	0.42	0.47	0.46	0.45	0.44	0.38	0.39	0.42	0.49	0.56
40	0.27	0.30	0.29	0.35	0.35	0.35	0.29	0.44	0.32	0.40	0.49
50	0.22	0.24	0.19	0.27	0.27	0.27	0.23	0.23	0.25	0.28	0.36
60	0.17	0.19	0.11	0.21	0.21	0.21	0.18	0.19	0.20	0.24	0.30
70	0.13	0.15	0.11	0.16	0.17	0.17	0.14	0.15	0.16	0.20	0.23
80	0.13	0.12	0.12	0.13	0.13	0.12	0.12	0.13	0.14	0.15	0.18
90	0.13	0.12	0.15	0.12	0.12	0.11	0.12	0.13	0.13	0.14	0.13
100	0.16	0.13	0.21	0.13	0.13	0.13	0.14	0.15	0.14	0.15	0.14
110	0.20	0.16	0.16	0.17	0.15	0.15	0.16	0.18	0.17	0.18	0.15
120	0.24	0.22	0.13	0.22	0.20	0.19	0.21	0.22	0.22		0.17
130	0.19	0.21		0.22	0.23	0.24	0.20	0.21	0.23		0.23
140	0.16	0.16		0.16	0.19	0.19	0.15	0.16	0.18		0.25
150	0.17	0.15		0.16	0.15	0.15	0.14	0.15	0.15	0.17	0.19

From September 1989 to April 1990, there was no net change in average soil moisture content. Over one month, from December 13th to January 16th, the average soil moisture content increased by 2 %. During the summer, May was the driest month, with an average soil moisture content of 23 % and this figure gradually increased by 3 % to 26 % in September.

In the upper soil (0-40 cm depth), the wettest period was from December 13th to April 18th. In these upper soil layers the driest period was from May 15th to August 22nd. An exception in this period was July 25th when moisture content at 40 cm increased sharply. One way the soil moisture content can increase at depth, without the upper soil layers being affected, is if water moves through the upper layers without allowing moisture to filter into the soil matrix, such as when preferential/macropore flow occurs. Alternatively, it could increase if water had moved down the outside of the neutron probe access tube. This was likely during dry summer conditions when the tight seal surrounding the tube could break. However, there was no other evidence of this phenomenon during the year, which would be likely if macropore flow was common.

The soil moisture content at 15 cm fluctuates more than any other band of soil (Figure 5.1a), and throughout the year this band is generally wetter than the soil at 20 cm, which suggests erroneous results due to atmospheric interference. From a depth of 20 cm to 90 cm the soil matrix gradually decreases in soil moisture content, with the exception of December 13th, where the soil at 90 cm and 100 cm sharply increased in soil moisture content by approximately 2 % and 6 %, respectively (Figure 5.1a, b).

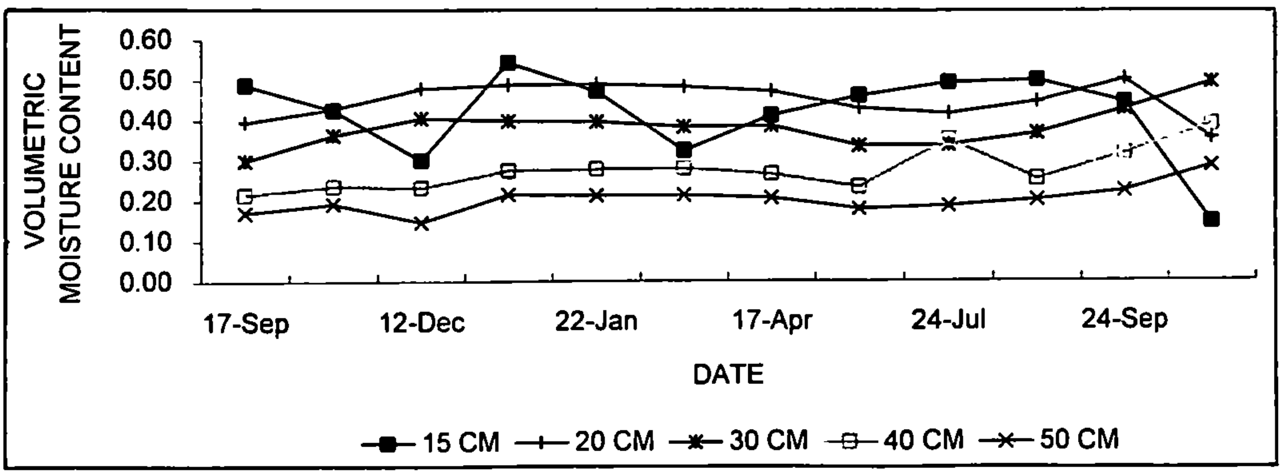


Figure 5.1a Forest soil moisture content from 15 cm to 50 cm: September 1989 to September 1990

This finding suggests that there was localised wetting at 90 cm and 100 cm that did not occur directly above this point. Throughout the year, the soil at 100 cm is slightly wetter than the soil at 80 and 90 cm. These data suggest that around 90 cm there was a slightly more impermeable band. Between a depth of 80 and 110 cm, depending on overall soil profile wetness, the soil became wetter with depth, and from 110 to 150 cm it became drier again (Table 5.1 & Figure 5.1b & c).

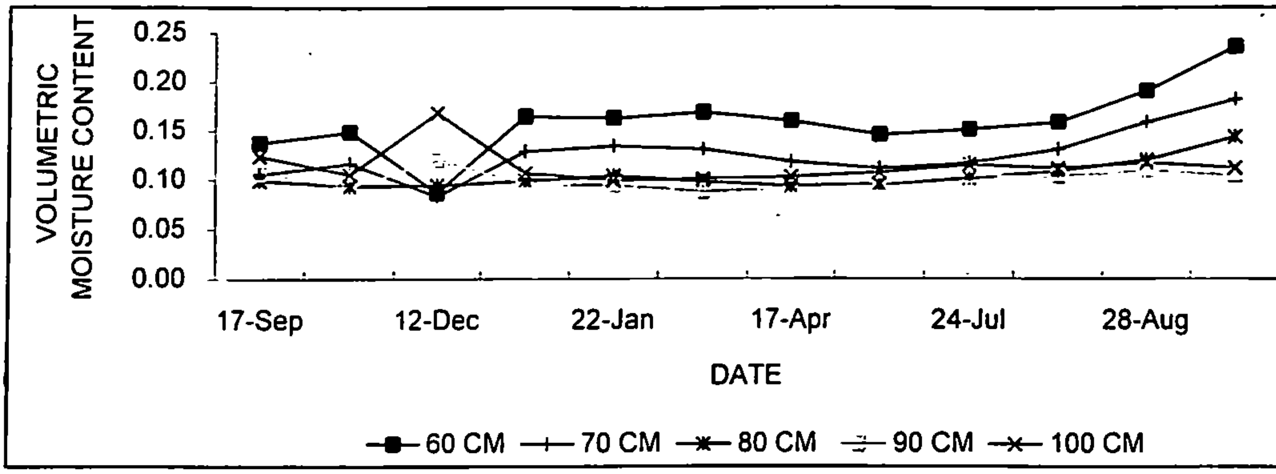


Figure 5.1b Forest soil moisture content from 60 cm to 100 cm: September 1989 to September 1990

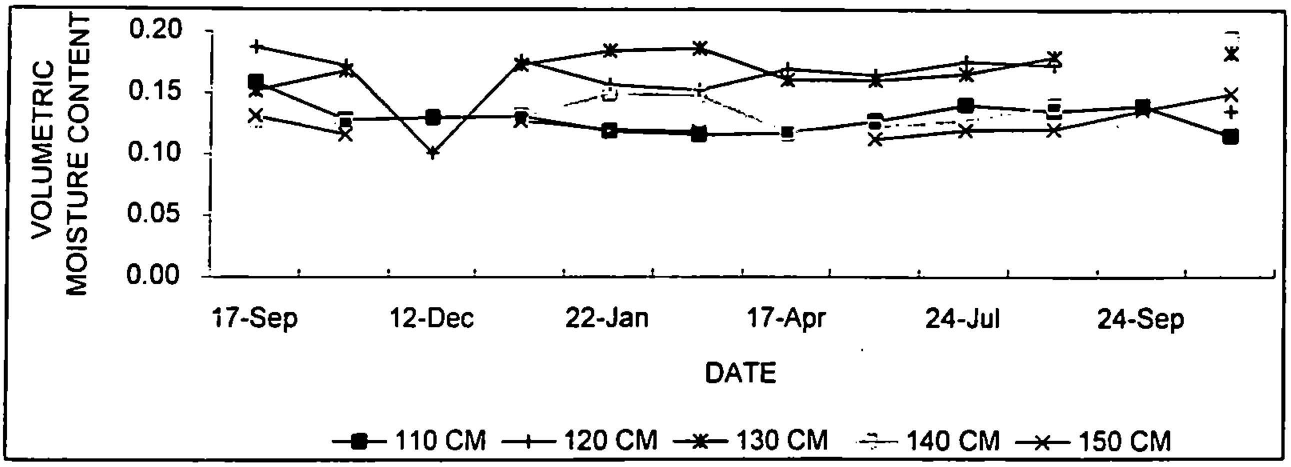


Figure 5.1c Forest soil moisture content from 110 cm to 150 cm: September 1989 to September 1990

This pattern of soil moisture content throughout the soil profile is highlighted in Figure 5.2.

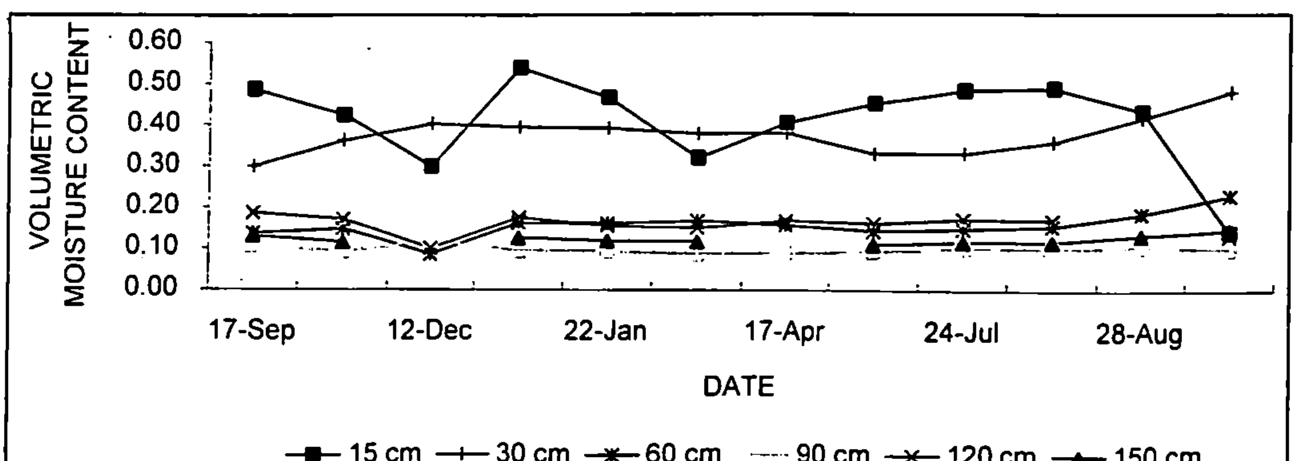


Figure 5.2 Forest soil moisture content throughout the soil profile: September 1989 to September 1990

In summary, the soil is very close to saturation (-10 cm H_2O to -20 cm H_2O cm) but not sufficiently close for true macropore flow to occur. However, mesopores conduct water rapidly and it is these that must be transmitting the large volumes of water measured during the course of the study year. It is also likely that mesopore flow is variable, due to the variability in soil suction that existed at both sites. Areas of connected mesopores that are saturated (but without saturation in the macropores) may feed other areas of like soil characteristics so that a network of saturated mesopore flow is created in soil of near total saturation. Further research is required to confirm and identify the structure of this preferential mesopore flow network.

5.4 QUANTITY OF SOIL WATER MOVEMENT AND DARCY'S LAW

Using the definition that potential is a measure of a body of waters energy, water moves from an area of high potential to one of low potential. Total potential is made up of matric potential (tension due to air/water interface), elevation (position) and osmotic potential (solute concentration). Matric and elevation or gravitational potentials combine to control the direction of water movement. For a large volume of soil, the amount of water movement is governed by the relationship between hydraulic conductivity and water content.

Darcy's law is used to calculate water fluxes between two points in the soil, given the hydraulic gradient.

$$q = K(\theta)\partial h/\partial x \qquad (5.1)$$

Where q is the rate of soil water flux in $m.s^{-1}$, $K(\theta)$ is the hydraulic conductivity of the porous media in $m.s^{-1}$ and $\partial h/\partial x$ is the hydraulic gradient in the direction of x. Darcy's Law assumes that there is steady state flow or that the flux rate is constant over time. Darcy's Law is usually applied to saturated conditions: calculations are more complicated in unsaturated conditions because conductivity is a function of soil moisture content and therefore depends on water flux itself.

Flux calculations based on Darcy's Law can be determined from soil water pressure potentials to quantify direction and quantity of flow. Hydraulic gradient was determined from two tensiometers as follows:

$$i = \frac{(p1+z1) - (p2+z2)}{l}$$

where i = Hydraulic Gradient

p = Pressure Head

z = Elevation Head

l = Distance between two points on streamline where p is measured (5.2)

Stratifications caused by changes in bulk density, texture, structure, and indeed a fragipan, cause water movement to be diverted laterally along the interface of a soil layer. Assuming that each layer is parallel with the slope, Miyazaki (1993) showed that, by sandwiching a very coarse grained layer in between a sandy loam textured horizon, the soil's porosity is reduced considerably in the very coarse grained layer.

During this experiment, within each plot a vertical bank or nest of tensiometers provided data to calculate the vertical flux, whilst the tensiometers at the same depth lower down the slope were used to calculate the horizontal or lateral flux element (Atkinson, 1978) following Harr, (1977). These vertical and lateral fluxes can then be used to resolve the resultant flux vector given by:

$$q_R = [(q_D + q_V \sin \propto)^2 + (q_V \sin \propto)^2]^{0.5} \qquad (5.3)$$

where q_R is the water flux; $_R$, $_D$ and $_V$ are the resultant, downslope and vertical fluxes respectively; and $\propto$ is the slope angle (Harr, 1977). This allows the calculation of the angle (Y) of the resultant flux (q_R) which is given by:

$$Y = \sin^{-1} (q_D \cos \propto / q_R) \qquad (5.4)$$

The direction of the resultant vector indicates the relative importance of lateral flow and vertical percolation (Harr, 1977; Nortcliff and Thornes, 1981).

The results from this will determine the influence of soil characteristics and slope angle. Since the effect of gravity potential is constant, changes in direction can be studied through time as the influence of matric potential.

5.4.1 Soil Water Matric Potentials (Suction)

Temporal variations in soil water matric potentials facilitated the study of water pathways together with an understanding of a redistribution of rainfall and subsequent uptake (Hodnett and Bell, 1986; Pyatt and Smith, 1983).

5.5 FOREST SOIL WATER PRESSURE POTENTIALS

Lower Plot

The average soil water tension varied from -25 cm H_2O in January to -20 cm H_2O in December. This result suggests firstly that the soil is just below saturation and secondly there was less suction in the forest soil at the end of the study year than at the beginning (Section 5.3). On average, the potential at the surface was -30 cm H_2O in winter, rising slightly in spring to reach an average of -130 cm H_2O in summer. It then decreases more gently in autumn to an average of - 50 cm H_2O. Unlike soil moisture content, there was a substantial change in potential between summer and winter.

At the lower plot at the forested site, (Figure 5.3a) all the peaks in soil water pressure potentials were marked with the corresponding date. Soil at 15 cm had the sharpest peaks and troughs, indicating its receptiveness to atmospheric controls such as evapotranspiration and rainfall.

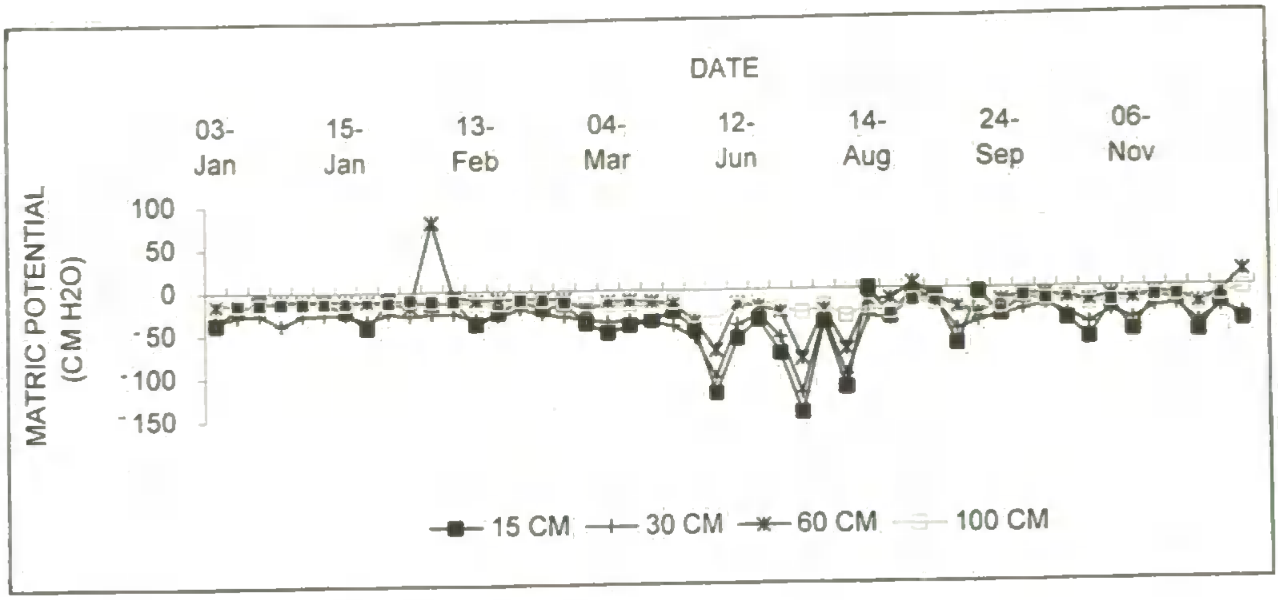


Figure 5.3a Forest matric potential at the lower plot during 1990

During the very dry periods, shown by the peaks on Figure 5.3a, it was always the soil at 15 cm that was the driest, with the exception of January 12th 1990, when only the 30 cm tensiometer peaks. This pattern indicates the strong influence of evapotranspiration (Et), thus supporting earlier findings that Et drives the soil water system in summer (Section 4.6.1).

Two moisture content regimes were noted firstly, September to mid May and secondly, June to August. During September to mid May, the soil at 30 cm was drier in relation to the soil at 15 cm. This demonstrates the sensitivity of the surface horizons to rainfall. However, during the summer, from June to August, the reverse is apparent and the soil at 30 cm is always wetter than the soil at 15 cm. The behaviour of the soil at 30 cm although wetter, follows the pattern of peaks and troughs of the soil at 15 cm for most of the year. The soil generally becomes wetter with depth, approximately -40 cm H_2O at the surface to -10 cm H_2O at depth in winter and -150 cm H_2O at the surface to -25 cm H_2O at depth in summer. A small gradient of soil water suction occurred in winter, whereas a much greater gradient occurred in summer. The matric potentials at 60 and 100 cm depth are very similar which suggests similar soil water properties at these depths and also vertical flow. The medium/long term fluctuation in matric potential is very slight, with the exception of May 23rd, July 25th and August 8th when the soil is very dry. These small changes in matric potential show that the soil becomes less responsive with depth to the rainfall and that there is a marked difference between 30 and 60 cm depth. Although the matric potential fluctuations in the 60 cm and 100 cm depth are dampened after a dry period, the soil does fluctuate more than in the winter/spring period. Throughout the soil profile, soil matric potential remains relatively constant during three distinct periods, winter and spring (January to mid May), summer (June to early August) and autumn (mid August to December).

Upper Plot

In the upslope plot, there is a striking similarity in the pattern of soil water matric potentials to those in the lower plot, Figure 5.3a & b.

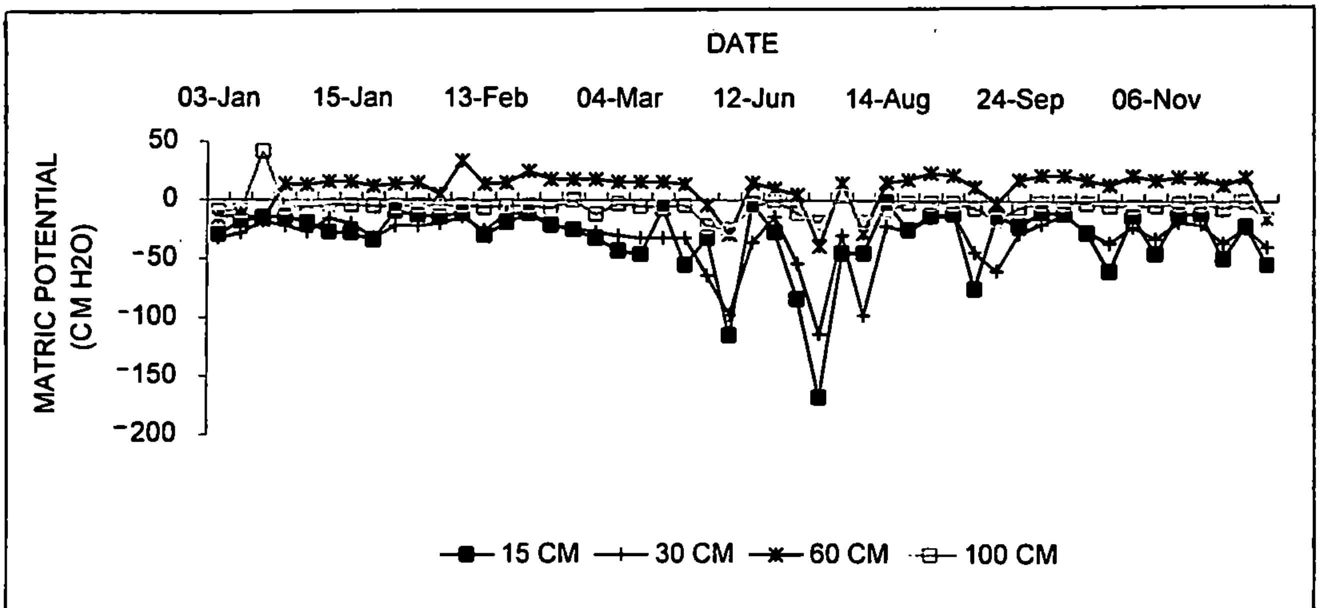


Figure 5.3b Forest matric potential at the upper plot during 1990

The main differences between the two plots are the greater range in matric potentials between the tensiometers at different depths and that saturation occurs at 60 cm and 100 cm. Despite this, the tensiometer readings still demonstrate a decrease in soil water pressure potentials in the same order, i.e. 15, 30, 100 and 60 cm depth, which is identical to the readings obtained at the lower plot. The range in soil water pressure potential between 15 cm and 100 cm is far greater, in both the summer and winter months at the upper plot compared to the lower plot. For example, on July 25th the matric potential for the upslope plot recorded at 15 cm was -168 cm and at 100 cm was -19 cm. However, at the lower plot it was -144 cm and -28 cm at 15 cm and 100 cm respectively. In the upper plot on February 20 th, the matric potential recorded at 15 cm was -11 cm and at 100 cm was -4 cm, whereas in plot A (the lower plot) was -11 and -11, respectively. Both these days are described in more detail in Figure 5.3a & b. This wider range in matric potential at the upslope plot was most apparent during the summer period when there was less rainfall. During the wetter period, it was more noticeable that the soil at 60 and 100 cm was wetter at the upslope plot compared to the downslope plot. These data sets show that there was variability in soil matric potentials between the two plots which was either due to variability in inputs to the system or to the physical soil properties. As this phenomenon cannot be explained by the location of the two plots relative to each other, canopy funnelling resulting in stemflow may be responsible (Price, 1994). This theory suggests that there are localised areas of saturation due to variations in horizon thickness. As there is so much slate at this site, it is also possible that the 60 cm and 100 cm tensiometer was augered into slate and the ceramic cup is located in an unrepresentative area of saturation.

There was a distinct seasonal pattern at both plots which closely followed that exhibited by the rainfall. At the upslope plot from January 4th to April 25th the soil was not saturated but still very wet with matric potentials around -15 cm H_2O at 60 cm and 100 cm depths, and around -35 cm H_2O at 15 cm depth. The soil was very dry during the summer (May 16th to August 8th). On August 29th, the soil became very wet, saturation occurred at 60 cm depth. From September 5th to December 19th, it was similar to the earlier part of the year, but with more fluctuations of a more extreme variety. The soil changes in all the horizons, but more so at 15 cm and 30 cm depth possibly due to greater evapotranspiration in autumn compared to winter. At the upslope plot, the same pattern was repeated, but with a wider range of matric potentials throughout the year.

In summary, the main difference between the two plots was the variations in matric potential at the same depths. Localised saturation is likely to be a result of funnelling caused by horizonal differences in soil (Price, 1994). In the lower plot, at all the soil depths the soil is below saturation for the majority of the time, whereas in the upslope plot the soil at 60 cm is saturated for most of the year, with few exceptions. The soil at 100 cm depth is also close to or at saturation for most of the year. Other similarities exist between the two plots with respect to the pattern of soil pressure potential throughout the year and so the soils respond in similar ways. There are large changes in soil pressure potential between summer and winter in the soil of 15 cm and 30 cm depth and much less change at 60 cm and 100 cm, which therefore demonstrates the responsiveness of these horizons to inputs and outputs.

5.5.1 Direction and Quantity of Soil Water Movement at the forest site

Flux was calculated as discussed in Section 5.4, assuming K_S was 50 mm day^{-1}. (K_S had to be higher than the highest rainfall intensity recorded at Beddgelert (27 mm day^{-1}), since no overland flow occurred, indicating that the soil could always cope with the rate and volume of precipitation). A wet day (winter) and a dry day (summer) were selected as typical precipitation extremes in order to highlight seasonal differences in soil water movement. During the wet period, K_S was used and during the dry period $K\theta$ was calculated using Campbell's equation (1974). Lateral flux was calculated between the upslope plot's 100 cm tensiometer and the downslope plot's 100 cm tensiometer (Table 5.2), using Harr's resultant vector equation (Section 5.4). Vertical flux was calculated between tensiometers within a nested bank (i.e. between the 15 cm and 30 cm tensiometers), at both plots (Table 5.2).

During both February 20th (high precipitation) and May 23rd (low precipitation), the predominant direction of flow was vertically at both sites, the former having greater flux. The lateral component was less than the vertical component on both these dates at both sites. At both sites, the greatest vertical flux on the wet day was between the 60 cm and 100 cm tensiometer in the C horizon. During the dry day, the greatest vertical flux at the forest site was between the 30 and 60 cm tensiometers in the B_S horizon, whereas at the whole tree harvested site vertical flux was greatest in the C horizon. This pattern was the same during the winter period.

Table 5.2 Soil water flux calculations

Depth (cm)	Forest Site	Whole Tree Harvest Site
	VERTICAL FLUX (CM SEC^{-1})	
Winter Example:		
15 - 30	$7.3E^{-5}$	$9.3E^{-5}$
30 - 60	$5.5E^{-5}$	$4.2E^{-5}$
60 - 100	$1.2E^{-4}$	$2.3E^{-4}$
Summer Example:		
15 - 30	$4.4E^{-5}$	$3.6E^{-5}$
30 - 60	$1.3E^{-4}$	$6.6E^{-5}$
60 - 100	$5.5E^{-5}$	$2.3E^{-4}$

Depth (cm)	Forest Site	Whole Tree Harvest Site
	LATERAL FLUX (CM SEC^{-1})	
Winter Example:		
15	$1.6E^{-6}$	$1.4E^{-6}$
30	$1.8E^{-6}$	$1.0E^{-6}$
60	$2.2E^{-6}$	$1.1E^{-6}$
100	$1.8E^{-6}$	$1.5E^{-6}$
Summer Example:		
15	$5.0E^{-7}$	$9.0E^{-7}$
30	$1.7E^{-6}$	$1.9E^{-6}$
60	$2.3E^{-6}$	$1.0E^{-6}$
100	$1.8E^{-6}$	$1.6E^{-6}$

The average vertical and lateral flux during both the winter and summer day were similar at both sites. Although these data are just one example, and the same assumed $K\theta$ value was used at both sites for all depths, it is interesting to see that they were similar. This similarity supports the theory that the differences in forest management do not affect soil water movement.

The flux calculations indicate a vertical flux at the soil surface. However, at depth vertical flux is extremely unlikely on a 30° slope. The steep gradient of the slope would dominate the direction of water movement. Water will also always take the easiest route, which in a layered horizonal soil with no active macropores is laterally. Whatever the combination of soil hydraulic conductivities, the easiest route for water will ultimately be laterally. If water is initially moving vertically and is restricted by an impeding layer, the easiest route is for it to move laterally through similarly conductive soil.

Vertical flux has dominated in these calculations because only one value for K_S has been used and the soil was isotropic for the purposes of these calculations. In the field, the soil would be anisotropic, so that K would be different in the horizontal and vertical planes. This demonstrates that a more complex simulation is required to model field conditions for this study.

5.6 CHANGES IN FIELD SOIL MOISTURE AT THE WHOLE TREE HARVESTED SITE

Throughout the course of the year, the long term change in soil moisture content was negligible and was similar to the forest site (Figure 5.4). From the beginning to the end of the study period there was a net increase in soil water content of 2 % (Table 5.3).

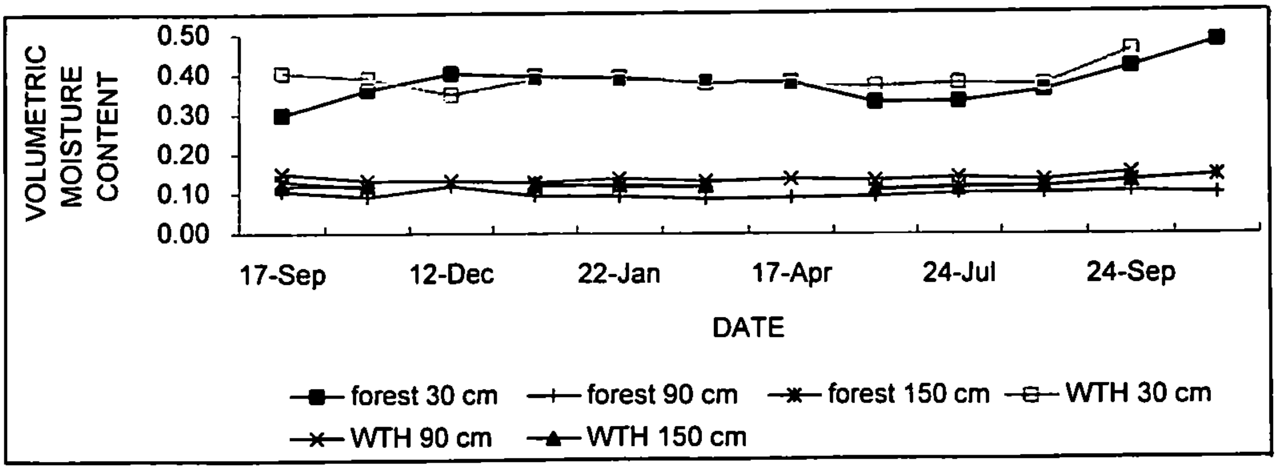


Figure 5.4 Forest and whole tree harvested soil moisture content profile: September 1989 to September 1990

During the winter, the average soil water content was 20 % from October to April, and during the summer it was 21 %. One percent change constitutes very little difference between the water content during the summer and that during the winter. The fact that the summer water content is higher could be due to the timing of the readings (i.e. during periods of extreme moisture content or due to the overall moisture content of the site increasing from the beginning to the end of the study year). This hypothesis could only be confirmed by further monitoring of the soil moisture content over an extended period of

Table 5.3 Volumetric soil moisture content of a 150 cm vertical soil profile at the WTH site

N/P depth	18/9/89	3/10/89	13/12/89	16/1/90	23/1/90	30/1/90	18/4/90	16/5/90	25/7/90	22/8/90	29/8/90	25/9/90
cms	261	276	347	381	388	395	473	501	571	599	606	63
15	0.49	0.43	0.30	0.54	0.47	0.32	0.41	0.46	0.49	0.50	0.44	0.1
20	0.40	0.43	0.48	0.49	0.49	0.48	0.47	0.43	0.41	0.44	0.50	0.3
30	0.30	0.36	0.40	0.40	0.39	0.38	0.38	0.33	0.34	0.36	0.42	0.4
40	0.22	0.24	0.23	0.27	0.28	0.28	0.26	0.23	0.35	0.25	0.31	0.3
50	0.17	0.19	0.15	0.22	0.21	0.21	0.21	0.18	0.19	0.20	0.22	0.2
60	0.14	0.15	0.09	0.16	0.16	0.17	0.16	0.15	0.15	0.16	0.19	0.2
70	0.11	0.12	0.08	0.13	0.13	0.13	0.12	0.11	0.12	0.13	0.16	0.1
80	0.10	0.09	0.09	0.10	0.10	0.10	0.09	0.10	0.10	0.11	0.12	0.1
90	0.11	0.09	0.12	0.10	0.09	0.09	0.09	0.10	0.10	0.10	0.11	0.1
100	0.12	0.11	0.17	0.11	0.10	0.10	0.10	0.11	0.11	0.11	0.12	0.1
110	0.16	0.13	0.13	0.13	0.12	0.12	0.12	0.13	0.14	0.14	0.14	0.1
120	0.19	0.17	0.10	0.18	0.16	0.15	0.17	0.16	0.18	0.17		0.1
130	0.15	0.17		0.17	0.18	0.19	0.16	0.16	0.17	0.18		0.1
140	0.13	0.13		0.13	0.15	0.15	0.12	0.12	0.13	0.14		0.1
150	0.13	0.12		0.13	0.12	0.12		0.11	0.12	0.12	0.14	0.1

time. At the forest site, the first dry period and the wet period were the same as at the WTH site, but this wet period continues up to September 25th 1990. One difference exists between the two sites. The whole tree harvested site is on average 5 % drier than the forest site, suggesting that more water is lost from the whole tree harvest site compared to the forest site.

Figure 5.4 shows the soil moisture content at 30, 90 and 150 cm for both the forest and WTH site. The largest differences between the WTH and forested sites occurred at 30 cm depth during September 1989, when the WTH site was 10 % wetter than the forest site and during the summer of 1990,(May 16th to August 22nd) when the WTH site was 5 % wetter. Both these periods occur during the summer when evaporation and transpiration were high, and so these differences are probably due to the presence and absence of trees. However, for the remainder of the year, there was very little difference between the 30 cm soil moisture content of the two sites. At 90 cm, although the WTH site was approximately 5 % wetter than the forest site, any changes in soil moisture content were similar at the two sites. The soil moisture content at 150 cm depth is almost identical at the two sites.

In a similar manner to the forest site, the moisture content decreases with depth down to approximately 80 cm. There was approximately a 2 % increase in moisture content between 80 cm and 120 cm. Thereafter SMC decreases again (Figure 5.5a, b and c).

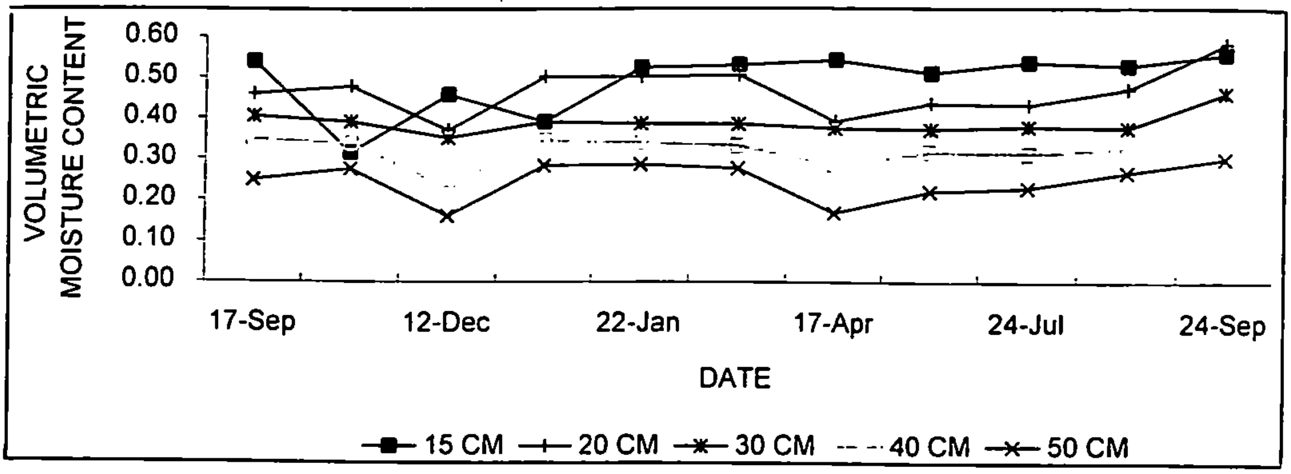


Figure 5.5a Whole tree harvested soil moisture content from 15 cm to 50 cm: September 1989 to September 1990

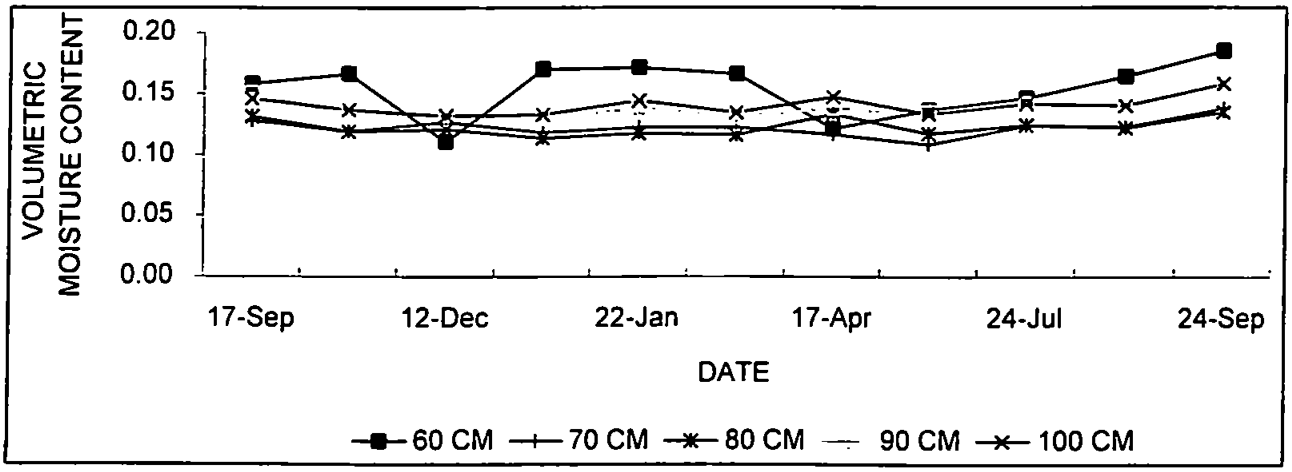


Figure 5.5b Whole tree harvested soil moisture content from 60 cm to 100 cm: September 1989 to September 1990

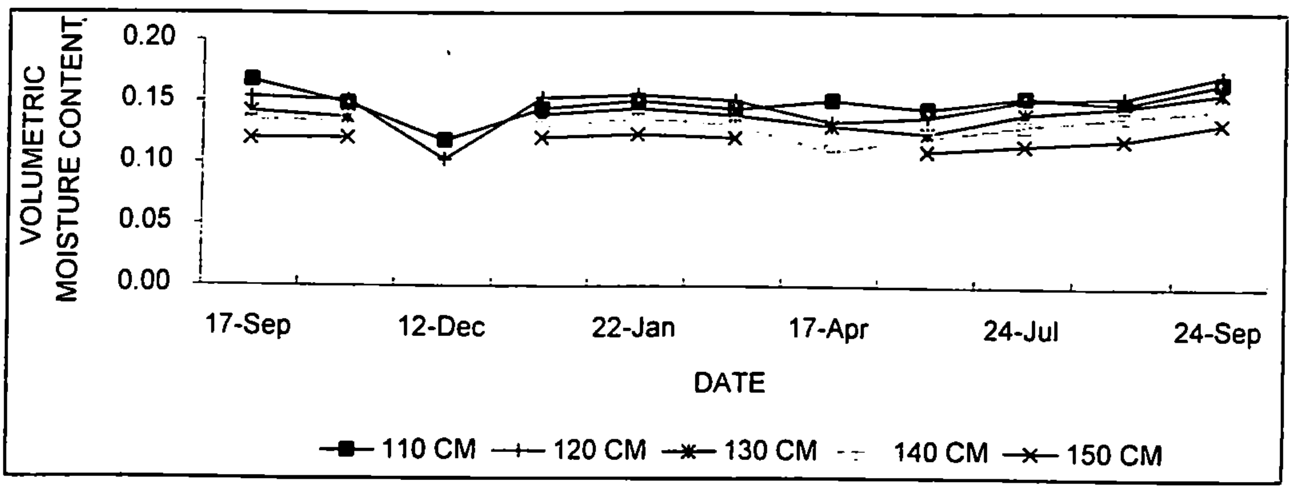


Figure 5.5c Whole tree harvested soil moisture content from 110 cm to 150 cm: September 1989 to September 1990

An increase in SMC between 80 and 120 cm suggests that here there is a relatively impermeable layer which restricts water movement. The pattern of profile soil moisture content changes at the WTH site was similar to that found at the forest site.

There was a considerable drop in moisture content on December 13th 1989 in the majority of horizons, which was similar to the forest site. However, the soil at 15 cm depth increased in soil moisture content, possibly due to the soil at the Whole Tree Harvested site responding much quicker to the infiltrating rainfall. At both sites throughout the year, there was a more marked decrease in soil moisture content between the surface and 70 cm (which relates to the mineral soil), than from 70 cm to 150 cm, which mainly consists of slate surrounded by a sand matrix.

5.7 WHOLE TREE HARVESTED SOIL WATER PRESSURE POTENTIALS

Lower Plot

The average soil water tension varied from -8 cm H_2O (wet) in January to -12 cm H_2O (relatively dry) in December suggesting there was less water held in the WTH soil at the end of the study year than at the beginning. The opposite occurs at the forest site where the mean potential at the surface was -25 cm H_2O (relatively wet) in winter, rose slightly in spring to reach an average of -160 cm H_2O (dry) in summer, then decreased more gently in autumn to an average of - 40 cm H_2O (relatively wet).

There was a strong similarity in the seasonal pattern of all the peaks and troughs between both the lower and upper plots, and those at the forest site (Figures 5.6a, & 5.6b).

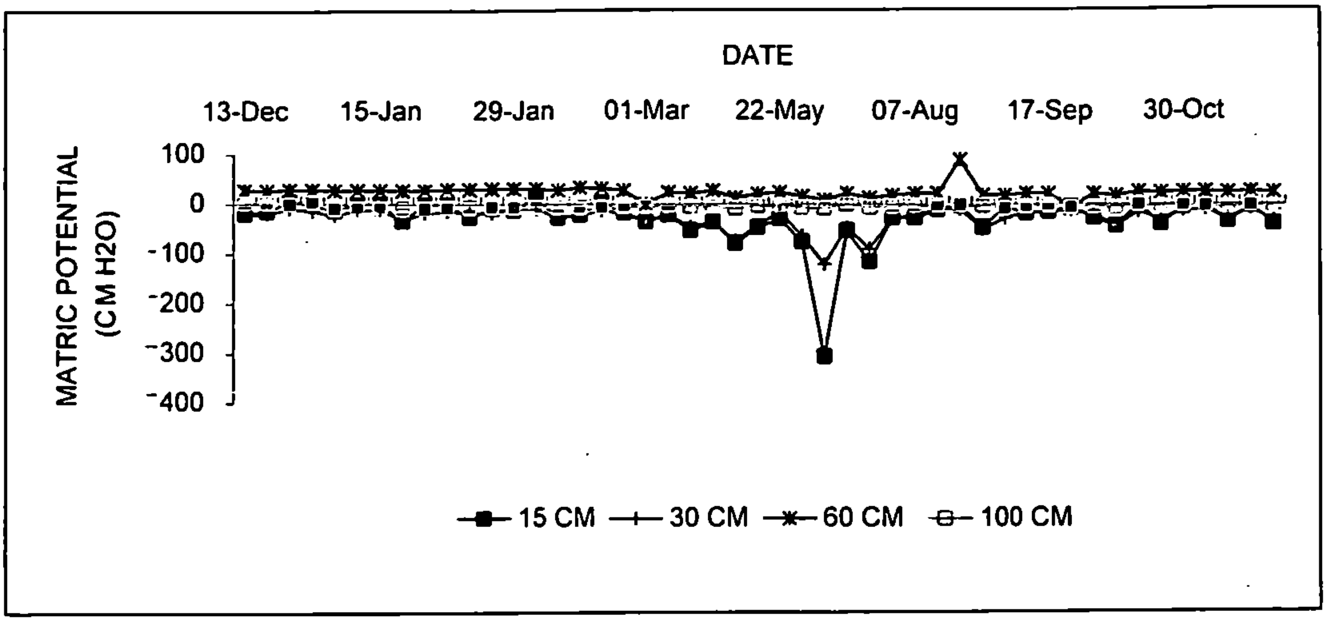


Figure 5.6a Whole tree harvested matric potential at the lower plot during 1990

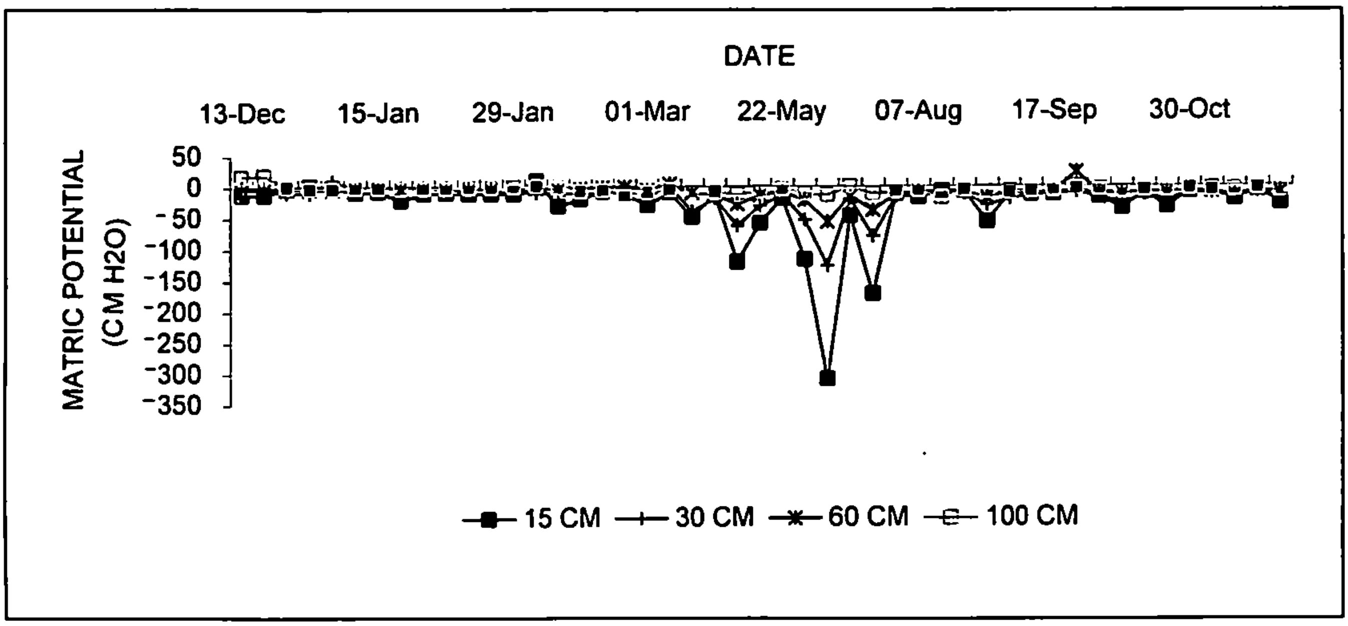


Figure 5.6b Whole tree harvested matric potential at the upper plot during 1990

At the lower plot, the sequence of matric potential superiority throughout the profile demonstrated by each tensiometer was the same as at the forest site, (i.e. 15, 30 100 and then 60 cm). The soil around 100 cm depth changed very little throughout the year. Soil matric potential around 60 cm depth varied very little before February 14th and after October 24th, which were the wettest times of the year. On September 5th, there was apparently a significant drop in soil water pressure potential at 60 cm depth, however, this reading was erroneous due to a dry tensiometer. The upper plot was similar with regard to peaks, with the highest positive potentials in the summer months and pressure potentials decreasing in the order of 15, 30 100 and then 60 cm depth.

5.7.1 Direction and Quantity of Soil Water Movement at the Whole Tree Harvested Site

The predominant direction of flow was vertical as at the forest site, both during the winter and summer (Table 5.2). Unfortunately, as discussed towards the end of Section 5.5.1, these calculations are too simplistic and therefore inaccurate. Future hydrological calculations at this site would require a mathematical model which allows for changes in K over time and space. Despite the unsophisticated method used in this study, soil water flux was also similar at both sites.

5.8 MODELLING THE HILLSLOPE

There are a number of different models which can be used to investigate hillslope flow, ranging from complex three dimensional, to more simplistic one dimensional, Germann and Beven, 1981). Quasi-three dimensional models such as Modflow are mainly used for groundwater flow (US Geological Survey Model). Two dimensional models such as SUTRA have been used to model forest hydrology, (Chappell, 1990) but require a large amount of computing resources. LEACHM is a one dimensional (vertical flow) deterministic research model. It is straightforward to use and relies on few parameters. LEACHM has evolved over twenty years, and has been successfully used to describe pesticide movement in field soil (Wagenet and Hutson, 1987; Wagenet *et al.* 1989). Other research investigations have provided feedback which has been regularly used to change and improve the model. Changing soil water conditions in terms of depth and time are solved numerically using Finite difference to solve the Richard's Equation (Section 3.3).

LEACHM has four components, LEACHW concerns the water regime and was used in this study. The main program initialises variables, calls upon subroutines and performs mass balancing. Subroutines deal with data input and output, time step calculation, evapotranspiration and water flow. The model is organised using modules, these are represented using segments (100 mm) each having a central node. The boundary conditions are defined using additional nodes one above the surface and one below the lowest depth. Choice of lower boundary condition include: drainage, water table or rock, the former was chosen. Mass balancing occurs between the second and second to last node. Simulations begin on day one with a pre-determined set of initial conditions (Wagenet and Hutson 1989).

Modelling was used as an exploratory tool to ask "what if" questions. The model used included a sub-routine which provided the opportunity to calculate the relationship between saturated hydraulic conductivity (K_S) and volumetric soil moisture content (θ_V). This was vitally important in a study such as this, which measured K_S rather than K_{unsat}. Section 6.1 will explain why K_S has been measured. However, Chapter 5 has essentially said that the soil does not saturate at either site, nor on any occasion when hydrological measurements were taken. Therefore, the relationship between K_S and θ_V is essential for meaningful interpretation of these results.

As discussed in Section 3.4 LEACHM was used to model water movement at one tensiometer nested site. The modelling approach will serve two purposes. It allows the relationship between K_S and θ_V to be identified, and by quantifying the other hydrological variables it will help to identify their significance. The first step was to characterise the soil properties - texture, bulk density and conductivity. For this, the field and laboratory measured data were used. The second step was to analyse the field soil moisture content data from the surface to 150 cm depth in order to compare field results to those modelled. The soil profile was characterised in a straight forward manner by noting the key changes in the soil profile. The 0 - 30 cm region represented the Eag horizon, 30 - 40 cm represented the more permeable Bs horizon and remaining 80 - 150 cm represented the densely packed slate. Field bulk density values were deemed erroneous because the standard way of calculating this uses sampling tins that have a diameter of 5.0 cm and a depth of 3.0 cm, which could not accommodate the large pieces of slate that were common in this soil. Therefore, a range of bulk density values corresponding to the different horizons was used accordingly.

5.8.1 Parameterisation

Input data were required on the following soil parameters:

1. hydraulic conductivity,
2. soil moisture release characteristics,
3. air entry,
4. bulk density,
5. initial soil moisture content.

Within the LEACHM model, a subroutine called RETFIT, which uses Campbell's (1974) equation to calculate the relationship between hydraulic conductivity (K) and volumetric moisture content (θ_V) from the soil moisture characteristic curve was used. The two horizons (Eag and B_S) were used to check the validity of the RETFIT results.

In the top 10 cm of soil, saturated hydraulic conductivity (K_S) ranged from 6048 mm day^{-1} to 416400 mm day^{-1} at the forest site and 86 mm day^{-1} to 19543 mm day^{-1} at the WTH site. For the purpose of the modelling, no prior knowledge of K_S was assumed. A very low K_S value of 50 mm day^{-1}, an average K_S value of 100 mm day^{-1}, and a high K_S value of 600 mm day^{-1} were used in the top soil. For the B_S horizon where soil water moved much quicker due to the well structured, porous nature of the soil a contrasting higher K_S value was used, 100 mm day^{-1} or 3000 mm day^{-1}.

Modelling was used to determine how soil hydrology behaves. By considering the summer and winter conditions using rainfall and transpiration data collected for the periods February 16th to February 27th, and June 18th to July 14th, and using different K_S values it was possible to determine the effect conductivity had on soil moisture content, matric potential and flux. To reduce the complexity of response, the effect of a summer storm during this same period was modelled using just one of the days with rainfall, the remainder of days were changed to zero. This allowed the effects of this impulse of rain to be identified on the soil moisture status. With this simplified rainfall input, soil hydraulic properties, air entry or the point at which the soil becomes unsaturated measured in cm H_2O and the gradient of the relationship between soil moisture content and soil pressure potential (Campbell's A and B parameters) were varied to see how sensitive soil moisture movement was to these. The next stage was to introduce the complex array of rainfall for the summer and winter period with the different A and B parameters. The results were then compared to those measured in the field.

5.9 RESULTS OF MODELLING

Effects of K_S

Within the sub-routine RETFIT, three profile scenarios of K_S were used to determine the relationship between K and θ (Table 5.4). The change in the K/Q relationship is linear and therefore it is straightforward to model. A soil with a high K value will allow a substantial volume of water to move per unit time, whereas one with a low K value facilitates slower water movement. For the purposes of modelling soil water movement, the lowest values of K_S were used (Table 5.4), since the others drained too quickly.

Table 5.4 K_S Soil Profile Scenarios

Scenario N°	Depth (cm)	Ks (mm day $^{-1}$)
1	10 to 30	100
	40 to 70	1000
	80 to 150	100
2	10 to 30	600
	40 to 70	3000
	80 to 150	600
3	10 to 30	50
	40 to 70	100
	80 to 150	50

Effects of Campbell's A and B parameters on a simple impulse of rainfall

To begin modelling, only one value of rainfall was used to follow a wetting front through the soil and a single rainfall pulse to be traced.

The following combinations of Campbell's parameters A and B were modelled to consider all the possibilities:

i) High B and low A (Steep gradient, low air entry point)

ii) Low B and low A (Shallow gradient, low air entry point)

iii) High B and high A (Steep gradient, high air entry point)

The combination of low B and high A could not be modelled since one parameter contradicts the other, i.e. if the air entry value is high then the gradient has also got to be fairly steep so it passes through the high A value.

5.9.1 A Single Input of Rainfall.

High B and Low A (Steep gradient, low air entry point)

The soil at 15 cm depth wetted up in one day and drained very quickly into the lower horizons (Figure 5.7). Flux increased substantially in the top 45 cm on the day of rainfall only. The 31.6 mm of rainfall was redistributed within the soil profile and did not increase the immediate drainage flux. This indicated that the soil profile is retentive. Prior to the rainfall, the soil lost a lot of water in the top 5 cm to evaporation and small amounts were lost 45 cm below the surface due to vertical drainage.

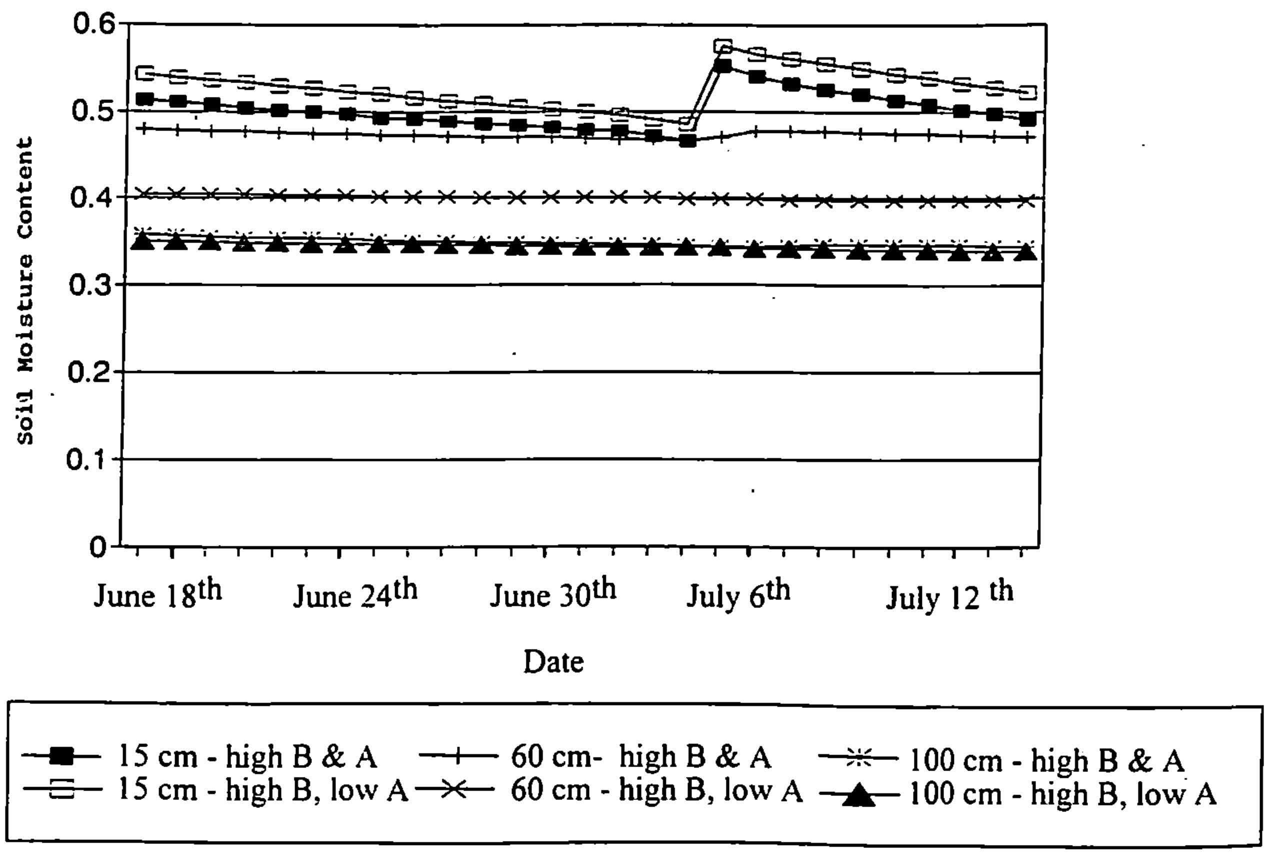


Figure 5.7 Single rainfall input and modelled soil moisture content (High B and Low A): June 18th to July 14 th

Low B and Low A (Shallow gradient, low air entry point)

By lowering B the effect of the rainfall was that the soil at 15 cm wetted up slower than with a high B value, i.e. over 5 days instead of one, and held the water better than the high B soil (steep gradient, low air entry point), (Figure 5.8). A noticeable increase in flux was only seen in the top 15 cm of soil. At 60 and 100 cm, with both the low and high B values (steep and shallow gradient), the effect of this single rainfall input was not yet apparent. Prior to the rainfall, the soil with the low B (shallow gradient) drained more in the lower horizons compared to the soil with a high B parameter (steep gradient), and losses due to transpiration are low. The other striking difference is that in the low B soil (shallow gradient), the soil below 65 cm was always wetter than the equivalent soil within the high B soil (steep gradient). Overall, there was more drainage flux from this soil type than the first or third soil type.

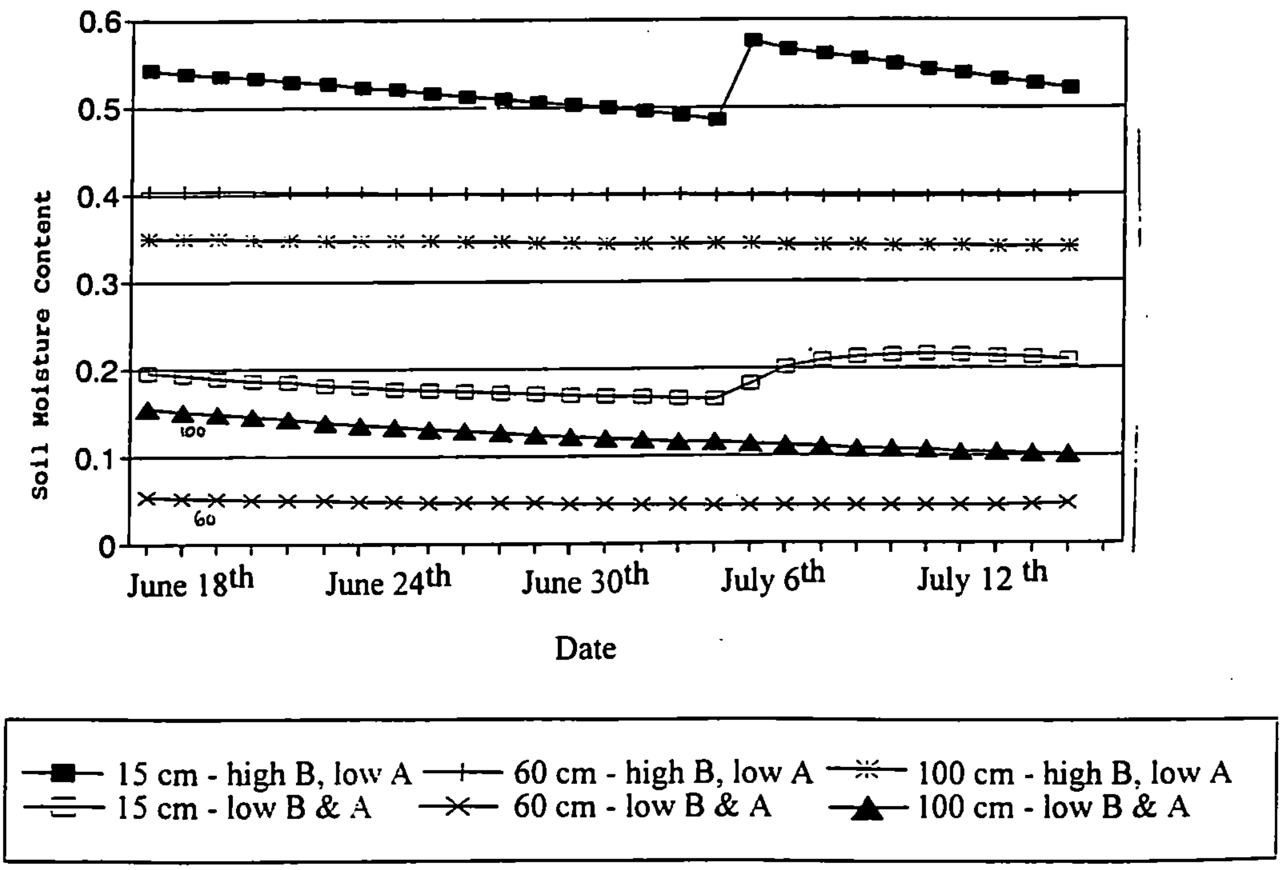


Figure 5.8 Single rainfall input and modelled soil moisture content (Low A and Low B): June 18th to July 14 th

High B and High A (Steep gradient, high air entry point)

At 15 cm, the first scenario of high B and low A retained slightly more water than a high A and B value after a single input of rainfall (Figure 5.7 & 5.9), and overall, high B, low A held more water than high A and B. At 60 cm depth, it was noted that with high B, low A, the effect of the single input of rainfall was not detected, whereas with high A and B there was a slight increase in soil moisture content over two days, therefore the soil is more responsive at depth, (providing the bulk density and K_S are high enough) with a higher air entry value. The difference in soil moisture content between these two soils at 60 cm depth was much greater than the difference at 15 cm and 100 cm depth. Again the response to the rainfall is minimal at 100 cm depth in the soil with a high A and B value, whereas there was no change in the high B and low A soil. Prior to the rainfall, the soil lost a lot of water to evaporation in the top 15 cm and small amounts from 95 cm below the surface. Overall, the drainage flux from this soil type is similar to the first soil type.

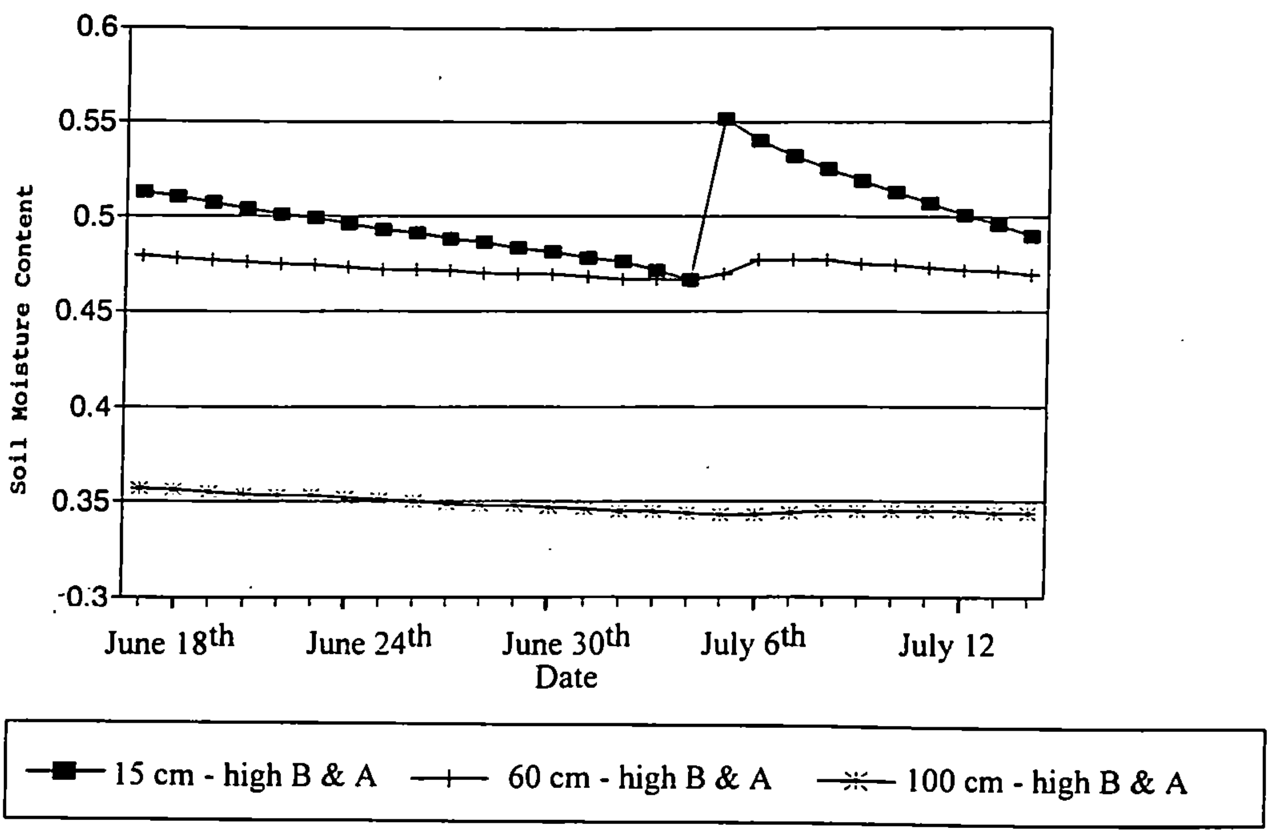


Figure 5.9 Single rainfall input and modelled soil moisture content (High A and High B): June 18th to July 14 th

5.9.2 Effects of Campbell's A and B Parameters on a Summer and Winter Rainfall Event

<u>Summer Rainfall</u>

The effect of rainfall during a typical summer month was modelled for two different soil profiles, in which the slope of the moisture characteristic curve was high in the first run, and low in the second i.e. (one high B, low A, and (shallow gradient, low air entry point) one low B, low A), the effect on soil moisture content was, as expected, far more complex. The impulse of water can be clearly seen at the 60 and 100 cm depths (Figure 5.10) in both soil profiles, because the impulse of water took so long to reach these layers, it suggests that a substantial amount of water was held in the soil between 15 and 60 cm in both soil profiles. In the high B, low A soil profile, it took at least 17 days for a noticeable increase in soil moisture content at 60 cm, and 19 days at 100 cm. This speed of water movement at depth shows that there was more rapid vertical movement of water between 60 and 100 cm than between 15 and 60 cm.

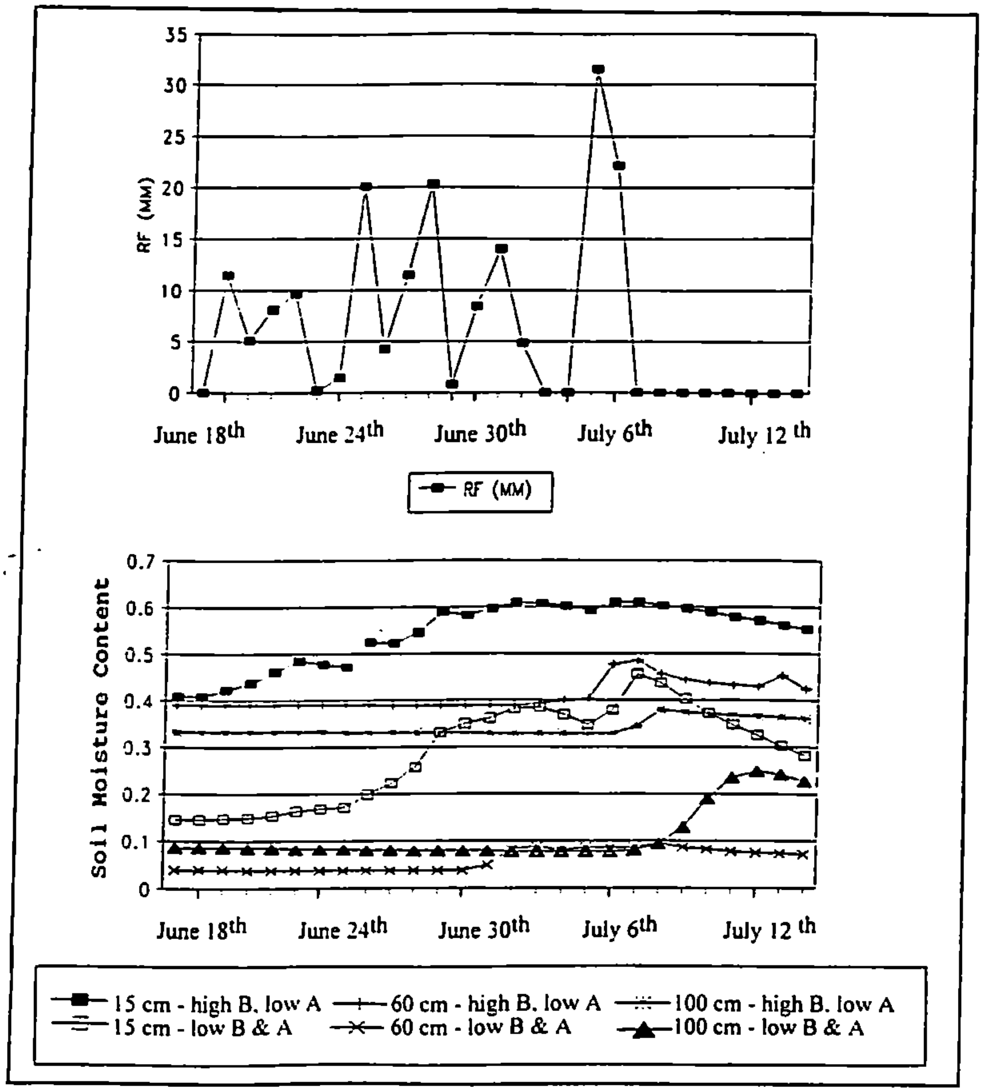


Figure 5.10 Summer rainfall event and modelled soil moisture content

In the low B, low A soil profile (shallow gradient, low air entry point), it took 14 days for the soil at 60 cm to wet up, which was quicker than the high B, low A soil, however there was less water than in the high B, low A soil. The 100 cm layer took 20 days, which was the longest to wet up, but it was far wetter than any other layer, showing considerable vertical movement, when there was sufficient water.

Winter Rainfall

As expected in the winter, all soil layers were wetter, in the low B low A soil profile (shallow gradient, low air entry point), the lag time between the 15 cm layer wetting up on 20th February and the 100 cm layer wetting up on 22nd February was much shorter than in the summer when it was drier (Figure 5.11 & 5.10). The increase in soil moisture content was also just over 10 % which was considerable. In the high B, low A soil profile, the wetting up in any layer is very slow and no clear pattern emerges.

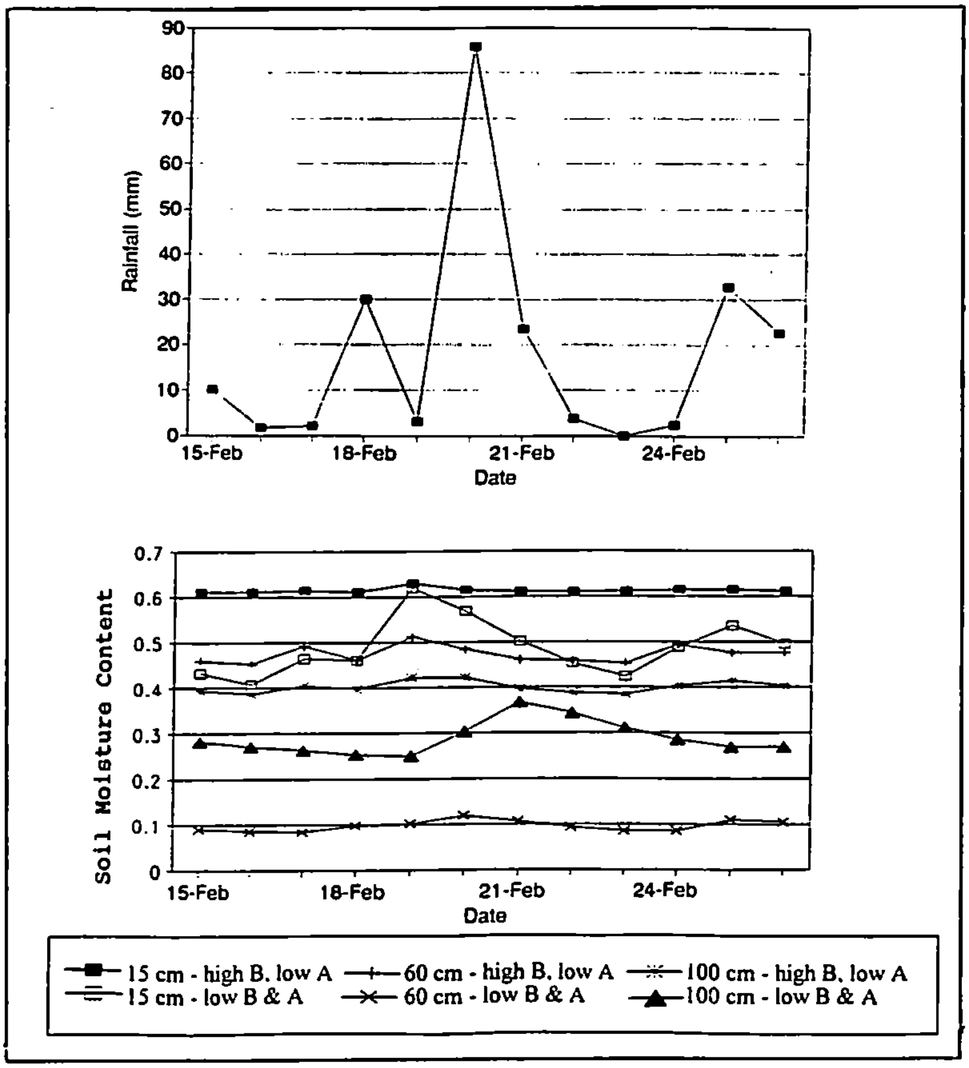


Figure 5.11 Winter rainfall event and modelled soil moisture content

5.9.3 Modelling Summary

The three differently modelled soil profiles were compared to the field-measured soil moisture content and matric potential values during the summer and winter periods. The high A and B soil profile was the closest match to both the field soil moisture content and matric potential values (Figure 5.9).

<u>Low B and low A (Shallow gradient, low air entry point)</u>

This scenario is unlike the research site soil because the 15 cm layer is far too dry, although the lower layers are a fairly good match (Figure 5.8).

<u>High B and low A (Steep gradient, low air entry point)</u>

This scenario is unlike the research site soil because the matric potentials are too low. Although, the soil moisture content in the 15 cm layer is very similar to the high B and A soil (Steep gradient, high air entry point) (Figure 5.7).

<u>High B and high A (Steep gradient, high air entry point)</u>

This scenario is the closest match to the research site soil in terms of the soil moisture content, matric potential and the responsiveness of the soil (Figure 5.9).

The gradient of the soil moisture content curve as expressed by Campbell's B parameter is crucial to soil water movement. A high B produces a large change in soil moisture content results in a very small change in matric potential, whereas a low B produces the reverse. The implications for the latter are considerable, since if a soil has a high B value then only a slight increase in soil moisture content will be needed for a large increase in matric potential, which is the driving force for water movement. This would imply that it is more important to measure and/or accurately model the A and B parameters than K. Also, if the soil is more sensitive to changes in matric potential i.e. a low B soil, then it is more important to measure matric potential than soil moisture content, whereas for the reverse scenario it would be more important to measure soil moisture content. It is already well established that soil with a low bulk density will restrict water movement and soil with a high bulk density will allow water to drain freely through its matrix.

From this modelling exercise, it has become apparent that the hydraulic conductivity, soil structure and their respective variability are the most important factors governing soil water movement. Chapter 6 will look at the variability of saturated hydraulic conductivity and soil properties and Chapter 7 soil structure in terms of the micro and macro morphology. The field and laboratory work posed problems of variability, size of sample and limitation of methods which modelling provided an opportunity to overcome.

5.10 CONCLUSIONS

At both sites, the soil moisture content does not reach saturation, despite the high proportion of soil water recharge available. This input was similar at both sites and was particularly high in January and February. However, there was little change in soil moisture content from summer to winter, despite the seasonal nature of rainfall at this site. This demonstrates that the soil can transmit large quantities of rainfall in the winter and retain the small volume of water in the summer to maintain a constant soil moisture content. For the soil to do this, there must be an array of pore sizes from small to medium/large. Since the small pores would retain water in times of low rainfall and the medium/large pores would transmit water in times of high rainfall, different pores are important at different times. This may result in different soil water mechanisms operating in the summer compared to the winter. This may have implications on forest management and will be discussed in Chapter 9. There was a negligible increase in moisture storage over the study year at both sites.

At both sites, soil water content decreased with depth, yet soil matric potential increased with depth, demonstrating increased water content. This contradiction is most likely a result of poor soil calibration when determining the soil moisture content. Soil moisture content was calculated using the appropriate IH calibrations curves. In this instance, they may have led to an over simplification of their application. For example, below 60 cm the soil was very compact with a large constituent of slate leaving little room for water. When calculating soil moisture content, this change in bulk density has not been correctly characterised, and therefore cannot be applied to the IH calibration curves. This inaccuracy could have been easily corrected if the neutron probe used had an attached density probe. In this type of study, it is therefore important to use a dual density and moisture probe. This information would also help understand more about whether the soil had large macropores in it or not.

The patterns of matric potential throughout the year and soil profile were similar within both the upper and lower plots and at both sites. Although more data would be required to confirm this, this study demonstrates that the relationship between horizons at the two sites behaves similarly despite the vegetation differences. Within each site, there was an element of variability between the matric potentials of the two plots, and the most likely cause was variability in the soil's physical properties.

There was a greater degree of change with matric potential compared to soil moisture content (indicating greater sensitivity in pressure potentials compared to the changes in soil moisture content). This means a small input of precipitation results in a much greater corresponding energy gradient, thereby quickly activating soil water movement. It was therefore of greater importance at this study site to have a more comprehensive data set concerning matric potential than soil moisture content, since the former provides information of greater detail regarding soil moisture status with depth.

Within one of the plots at both sites, there was localised saturation at 60 cm. This area is unlikely to connect to other saturated areas because of the surrounding unsaturated soil matrix and therefore will have a minimum effect on soil water movement. However, more detailed temporal and spatial tension data would be required to confirm this.

During the winter and summer, the predominant direction of water flow was vertically at both sites using simple calculations. However, this is extremely unlikely and must be deemed erroneous. It is most likely that lateral soil water flow dominates, with some degree of vertical soil water movement. This is because of the steep nature of the slope and due to a layered soil (Miyazaki, 1993). Water will always take the easiest route and any changes in K with depth will mean it is easier for water to move laterally. The soil water flux was similar at both sites during the winter and summer. Again, with these simple calculations, this must be treated with extreme caution.

Modelling has enabled the gap between K_s and K_{unsat} to be bridged. Using this vital information the section of hillslope at Beddgelert could be more realistically modelled to gain insight to how it behaves. Field values of soil moisture content and soil water pressure potential were used to act as a check against the modelled values. Modelling demonstrated the importance of air entry and the relationship between θ and ψ. These are important aspects of soil structure which influence soil water movement.

The lowest K_s value (Scenario 3) was used, since it was found to produce more realistic flux values. Using K_s as a starting point LEACHM calculated the appropriate K_{unsat} value from the soil moisture content data. This enables a more realistic flux calculation to be modelled. Three soil profiles were modelled using different air entry values and different relationships between soil moisture content and soil water pressure (Campbell's A and B parameters). From these three modelling runs, the predicted response of soil moisture content and soil water pressure was most similar to field data at Beddgelert in the third run. The similarity occurred when Campbell's A and B parameters where high, which means a high air entry point and a steep gradient between soil moisture content and soil water pressure. This scenario means that the soil is reasonably retentive, yet sufficiently permeable for vertical soil water movement to occur to a depth of 60 cm. soils of this type have both small and medium to large sized pores. The smaller pores retain water and the medium/large pores transmit water.

Although further refinement of the modelling process and also more field data would be required to match predicted soil water movement to actual field soil water movement, this was not the aim of this project. To model flux at this site, a two-dimensional model would be required, since both lateral and vertical flow occur.

CHAPTER 6

SPATIAL VARIABILITY OF SATURATED HYDRAULIC CONDUCTIVITY (K_S) AND SOIL PROPERTIES

6.1 INTRODUCTION

This chapter will attempt to elucidate upon the variability of K_S, soil properties and their implications for soil water pathways. Saturated hydraulic conductivity (K_S), a component of Darcy's law, describes the soil's maximum potential to transmit water. Due to the inherent spatial variability of K_S (Anderson and Rogers, 1987: Nielsen *et al.*, 1973 and Russo and Bresler, 1981), the values used to model discharge represent K_S in the field too simplistically.

The previous chapter presented data which indicated that the section of hillslope at Beddgelert did not achieve full saturation. Campbell's equation to calculate K_{unsat} was therefore used in the theoretical modelling section. It would be most appropriate to measure K_{unsat} for soil water movement calculations. However, due to the difficulties of sampling caused by the need to apply a vacuum to the sample area, K_S was measured instead. K_S is easier to measure in the field as it can be measured directly. With the type of soil present at the research site it would have been difficult to remove a block of soil to measure the K_{unsat}. In terms of soil water movement, the relationship between soil moisture content and K can be calculated using Campbell's equation. Since one of the main objectives of this thesis was to compare the forest and whole tree harvested sites, a relative comparison using K_S, rather than K_{unsat}, was sufficient in this study, as it is the comparison that is most important not the way in which it is executed.

In chapter 5, like many other studies (Chappell, 1990; Soulsby, 1992), an average or lumped value for K_S was used in Darcy's equation to calculate soil water flux. K_S can be expressed in a probability-distributed model, where the data are not related in space or by a geometrically-distributed model which expresses spatial variability in terms of orientation of the network points to one another and their distance apart (Clark, 1972). By distributing $K_{S,}$ the model has the ability to include a measure of population variability, but this does not necessarily mean that the model represents spatial variation. Theoretically, K_S can be incorporated deterministically for distributed models, but there are problems associated with measurement and representing K_S dimensionally which restrict this (Anderson and Rogers, 1987). Other methods have been used to incorporate a 'representative' value of K_S into the model. For example, Freeze (1980) used the mean value, standard deviation and distribution to describe the variability of K_S. An alternative approach used for distributed models is to utilise a single value to describe the variability of a parameter and to overcome the restrictions to the model structure (Anderson and Rogers, 1987). Despite the research undertaken, K_S remains a difficult variable to represent in modelling. Other problems exist with modelling, such as the type of model to be used, (i.e. one, two or three dimensional model) and whether it is steady-state or non steady-state (see Beven (1989)).

K_S data were measured in the field using a nested hierarchical sampling strategy (Webster, 1977, See Section 3.5 & 3.5.1). This method was used because it allowed both the spatial variability of K_S and the hierarchical effects of scale on spatial variability of K_S to be addressed. On the hillslope K_S was sampled at a number of different "lag" distances, starting at 50 m apart, continuously subdividing the distance between points and finishing at sample points 71 cm apart (Section 3.5.1). The main sampling point in each plot was also used for measuring bulk density, particle size analysis, porosity, soil moisture characteristic curve (Chapter 2), micro and macro-morphology (Chapter 7). As individual K_S values are described from these main sample points the corresponding values of bulk density, particle size analysis, fine root density and profile description will be discussed. In Chapter 7, the micro-morphology of these same sample points will be described in detail.

Large soil samples (30 cm diameter and 10 cm depth) were used in the field to measure K_S because they are likely to be more representative of the soil mass (Lauren *et al.*, 1988 and

Skinner *et al.*, 1978). Horizons can be sampled individually but, where conditions permit, a large soil sample could encompass anything from one to four soil horizons. In thin mountain soils, the technique of examining several horizons is useful since the result integrates the influence of bordering horizons. This technique is satisfactory whether the soil is isotropic or flow occurs vertically. However, it must be highlighted that although K_S was measured in the field, soil samples were removed from the profile and therefore pathways were disconnected resulting in higher values for K_S data than if it were measured *in situ.* The disturbance incurred whilst sampling will be considered in the final conclusions drawn from these data.

The aim of the first part of Chapter 6 was to quantify K_S and its variability at the forested and WTH sites and to represent this variability in a model. The aim of the second part is to explain the spatial variability of K_S at both sites. The content of this chapter includes:-

i) Statistical analysis of K_S at both sites.

ii) Analysis of the spatial variability of K_S at both sites to determine the population distribution for use in the calculation of water movement.

iii) The effects of scale on the spatial variability of K_S will be examined to give a guide to the scale of structural examination and future sampling of K_S.

iv) The Quantifying of K_S values for the forest and WTH, relating the values to both a profile description and explaining the differences in terms of soil physical characteristics to determine the importance of macropores.

There have been no studies carried out on K_S and its spatial variability at Beddgelert and, with the exception of Chappell (1990), very little work has been conducted on similar upland sites in the UK.

6.1.1 Chapter Structure

The theory and background relating to K_S variability will be presented initially, followed by the experimental results. The results will be presented in detail for comparable plots at the whole tree harvested site (Plot 1) and at the forest site (Plot 5). Then variability within the WTH site will be discussed using all four plots at that site and finally, the discussion will include the differences and/or similarities between the two sites.

6.2 SATURATED HYDRAULIC CONDUCTIVITY (K_S)

Forest Saturated Hydraulic Conductivity

The mean saturated hydraulic conductivity (K_S) for the first 10 cm of soil was 1.56 E^{-1} cm sec^{-1} (Table 6.1) which indicates a very permeable soil. From 10 to 20 cm, K_S was 1.34 E^{-3} cm sec^{-1}, which is much less permeable.

Table 6.1 Saturated hydraulic conductivity at both sites

	K_S (cm sec^{-1})				
Plot No	Ave Log	Ave	Min Log	Max	S Dev
WTH (0-10 cm)					
1	$6.58E^{-3}$	-2.18	$2.77E^{-4}$	$2.26E^{-2}$	-2.11
2	$3.52E^{-3}$	-2.45	$1.53E^{-3}$	$9.79E^{-3}$	-2.54
3	$3.84E^{-3}$	-2.42	$3.73E^{-4}$	$6.95E^{-3}$	-2.56
4	$1.24E^{-3}$	-2.91	$1.00E^{-4}$	$3.08E^{-3}$	-2.95
1-4	$3.80E^{-2}$	-1.42	$1.00E^{-4}$	$2.26E^{-2}$	-2.32
1-4 (10-20 cm)	$1.31E^{-2}$	-1.88	$4.27E^{-4}$	$3.80E^{-2}$	-1.90
Forest (0-10 cm)					
5	$1.56E^{-1}$	-0.81	$1.00E^{-4}$	$4.82E^{-1}$	-0.78
WTH & Forest					
1-5 (0-10 cm)	$3.42E^{-2}$	-1.47	$3.01E^{-3}$	$4.82E^{-1}$	-1.02

In the top 10 cm, there was a considerable range in the K_S values, from 3.01 E^{-1} cm sec^{-1} to 4.82 E^{-1} cm sec^{-1} (Table 6.1). The frequency distribution of K_S log was positively skewed (Figure 6.1) with a high standard deviation (Table 6.1), suggesting high variability.

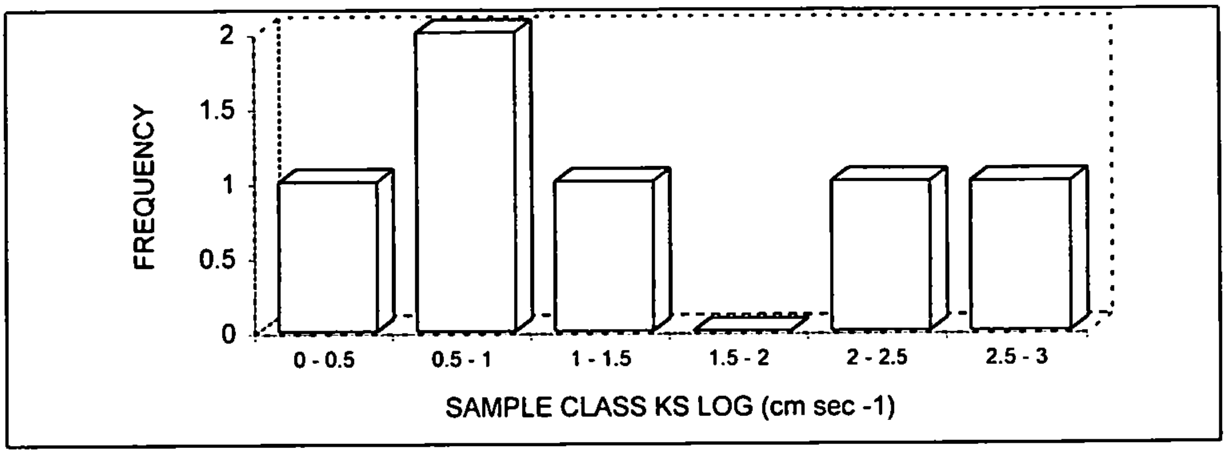


Figure 6.1 Frequency distribution of K_S at the forest site

The large amount of variability that is spatially dependant makes it difficult to statistically represent K_S in a flux model. The forest K_S findings are tentative due to the limited number of samples at this site.

<u>WTH Saturated Hydraulic Conductivity</u>

Mean K_S in the first 10 cm of the WTH soil was much lower than the forest soil, 3.08 E^{-3} cm sec^{-1} compared to 1.56 E^{-1} cm sec^{-1} (Table 6.1). From 10 to 20 cm, K_S was 1.31 E^{-2} cm sec^{-1} which was lower than the upper soil layer. These results are similar to the forest soil. In the top 10 cm, K_S ranged from 1.0 E^{-3} cm sec^{-1} to 4.83 E^{-1} cm sec^{-1} (Table 6.1), which are low values when compared to the forest soil (Table 6.1). There was also a smaller range in K_S values.

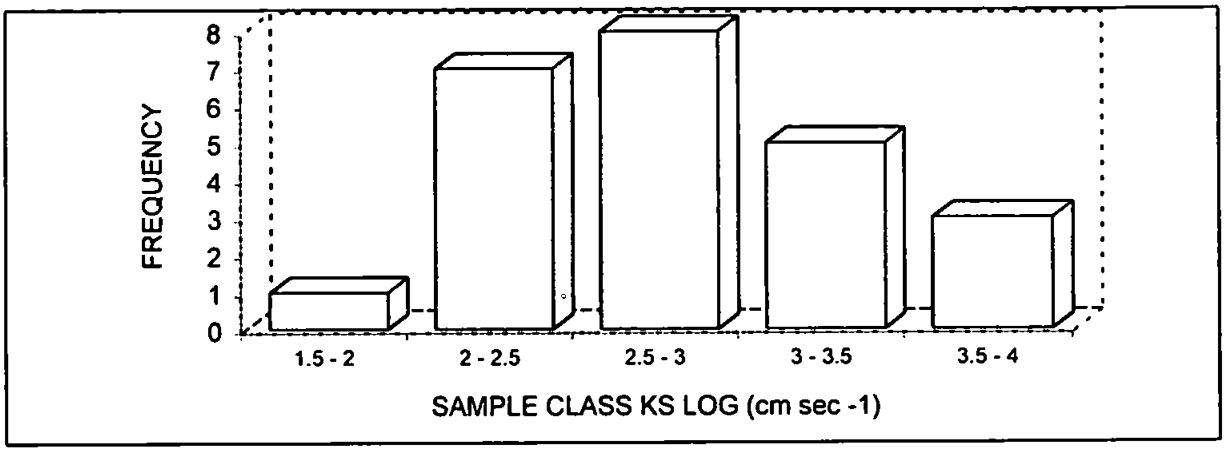


Figure 6.2 Frequency distribution of K_S at the whole tree harvest site

The frequency distribution of K_S log was normal (Figure 6.2) and the standard deviation was lower than that of the forest (Table 6.1). Both these factors suggest there was less variation at the WTH site. Within each plot, the mean and standard deviation were similar (Table 6.1), which indicates that there was little variation between the WTH plots. These data suggest K_S could be statistically represented in a computer model such as LEACHM. The average of all the K_S values was 3.40 E^{-2} cm sec^{-1} and the range of values was 4.82 E^{-1} cm sec^{-1}. These data imply that the forest K_S values dominate the overall average and range due to their very high K_S values. All of the K_S values show a normal distribution, (Figure 6.3).

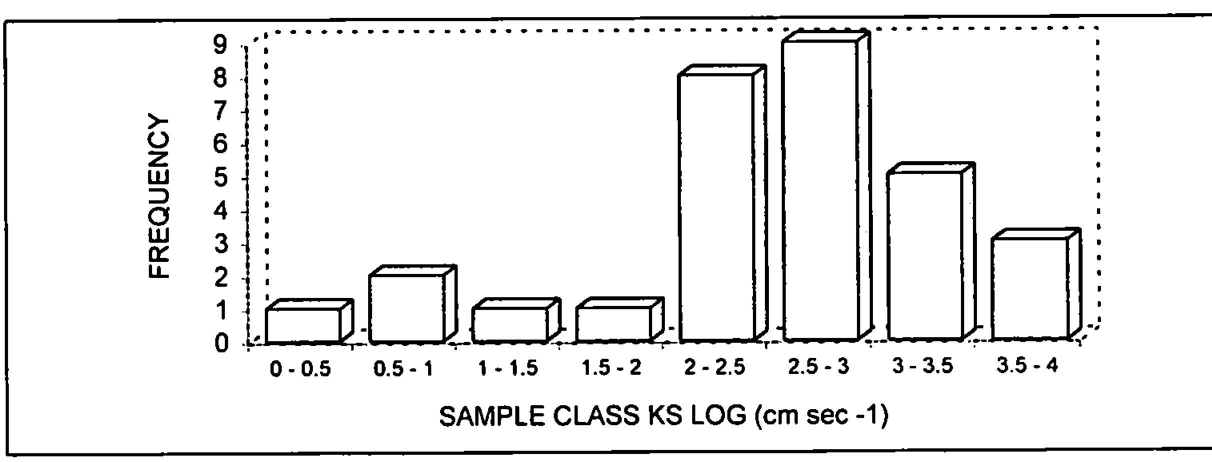


Figure 6.3 Frequency distribution of K_S at both sites

6.3 SPATIAL VARIABILITY OF K_S BETWEEN SITES

The Mann-Whitney U test is a non-parametric technique (Hammond and McCullagh, 1978). It was used to statistically test whether there was a difference between the forest and whole tree harvested K_S means and therefore to indicate whether the sites belong to different populations. The null hypothesis (H_O) was that the forest and whole tree harvested site form part of the same distribution and that differences between them were the result of chance variations and therefore not significant. The alternative hypothesis (H_1) was that the K_S distribution in the whole tree harvested site was significantly lower than at the forest site. The level of rejection of H_O was decided at $x = 0.05$. The results of the test show that $U = 13$ at a significance level of 0.002. Therefore, the null hypothesis can be rejected and the alternative hypothesis can be accepted. There was a statistical difference at a significance level of 0.002 between the K_S values from the forest and whole tree harvested sites, and therefore they both belong to different populations.

6.4 THE EFFECTS OF SCALE ON THE SPATIAL VARIABILITY OF K_S

The effects of scale on the spatial variability of K_S was analysed using a nested hierarchical sampling procedure (Webster, (1977) (Section 3.5.1). Investigations were made into the spatial variations between each plot, by comparing the analysis of variance at each level. The immediate aim of analysis of variance is to apportion the degrees of freedom properly and to calculate the sums of squares for each stage.

Spatial variation at the whole tree harvested site is apparent at different levels. The semi-variogram (Figure 6.4) shows that there is a significant difference between levels 1 and 2, with a significantly higher variation apparent on the smaller scale, (i.e. between levels three and four). From this observation, it can be seen that the greatest variability occurs at the smallest sampling scale (50 cm apart) and therefore it is factors present at this scale, possibly soil cracks, that are causing a change in $K_{S.}$

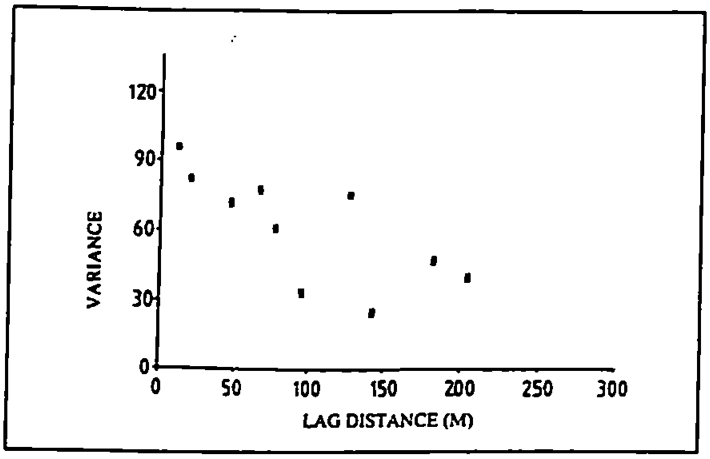


Figure 6.4 Whole tree harvest K_S semi-variogram

The second semi-variogram (Figure 6.5) presents the spatial variation for both sites together. As expected from previous analysis, the extreme K_S values from the forest site dominate these results. However, the same pattern emerges: there is greater variability at sample points closer together.

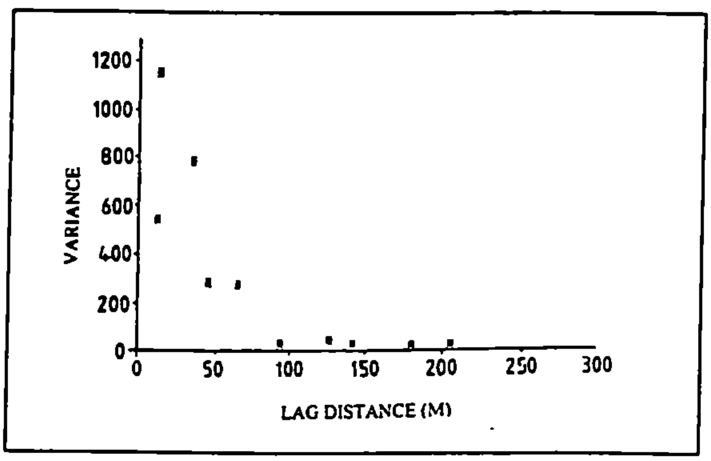


Figure 6.5 K_S Semi-variogram for both sites

These results suggest that relatively little variance is occurring in K_S at the larger scale, whilst on a smaller more detailed scale K_S is being strongly influenced by a number of local factors. The implications of this conclusion are that the smaller a study area, the more detailed the investigation has to be in order to truly represent the variability. The next Chapter (7) will consider soil structure at a more detailed scale.

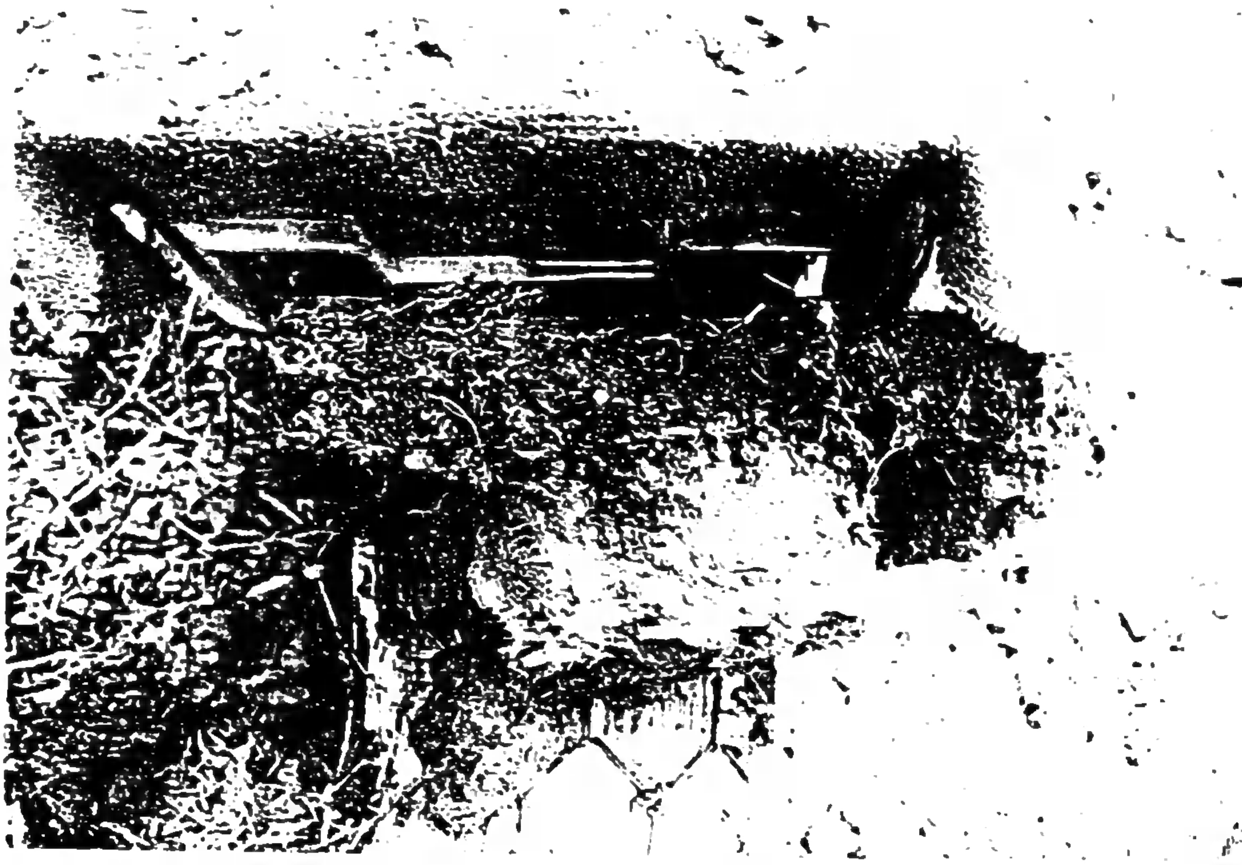
6.5 DESCRIPTIVE EXPLANATIONS OF INDIVIDUAL K_S VALUES

It is widely recognised that saturated hydraulic conductivity of a porous medium is a highly spatial variable (Anderson and Rogers, 1987; Nielsen *et al.*, 1973 and Russo and Bresler, 1981).What is not fully understood is how much, or precisely why K_S varies.

Many studies have analysed the spatial variability of certain soil hydraulic properties in the field (Baker, 1978; Baker and Bouma, 1976; Nielsen *et al.*, 1973 and Russo and Bresler, 1981). Some investigations have also tried to identify the dominant factors influencing hydraulic conductivity (K) (Bresler *et al.*, 1984 and Byers and Stephens, 1983). Saturated hydraulic conductivity is affected by the structure and texture of the soil. Conductivity is greater if the soil is highly porous, fractured or aggregated, than if it lacks structure and is tightly packed. Total porosity affects K_S, but primarily it is influenced by the size and configuration of the pores. For example, sand is very porous compared to clay, but a well structured clay soil may have larger cracks and has a higher K_S value: sandy soils are rarely well structured. Experiments have shown that variations in the K_S coefficient with porosity are roughly linear on a logarithmic scale. Cracks, worm holes and decayed root channels will affect flow in different ways, depending on the direction and condition of flow processes. Macropores are an important factor affecting K_S because macropore flow can be up to 1000 times faster than saturated matrix throughflow (German and Beven, 1981).

Individual values of K_S were measured at each sample point and then summarised. The influence of the following characteristics on K_S was examined: root density, bulk density, particle size analysis, porosity and soil moisture characteristic curves at sample point 1 and 5. The same depth of analysis was conducted at the remaining WTH plots and a summary is presented below. Figure 6.6 and 6.7 highlight the main cracks, roots and fragments of slate that influence K_S at the forest and WTH sites, respectively. A selection of these samples have been photographed (Plate 6.1 to 6.5) to demonstrate the nature of the soil at both sites.

Sample 5Ca



Sample 5Cb

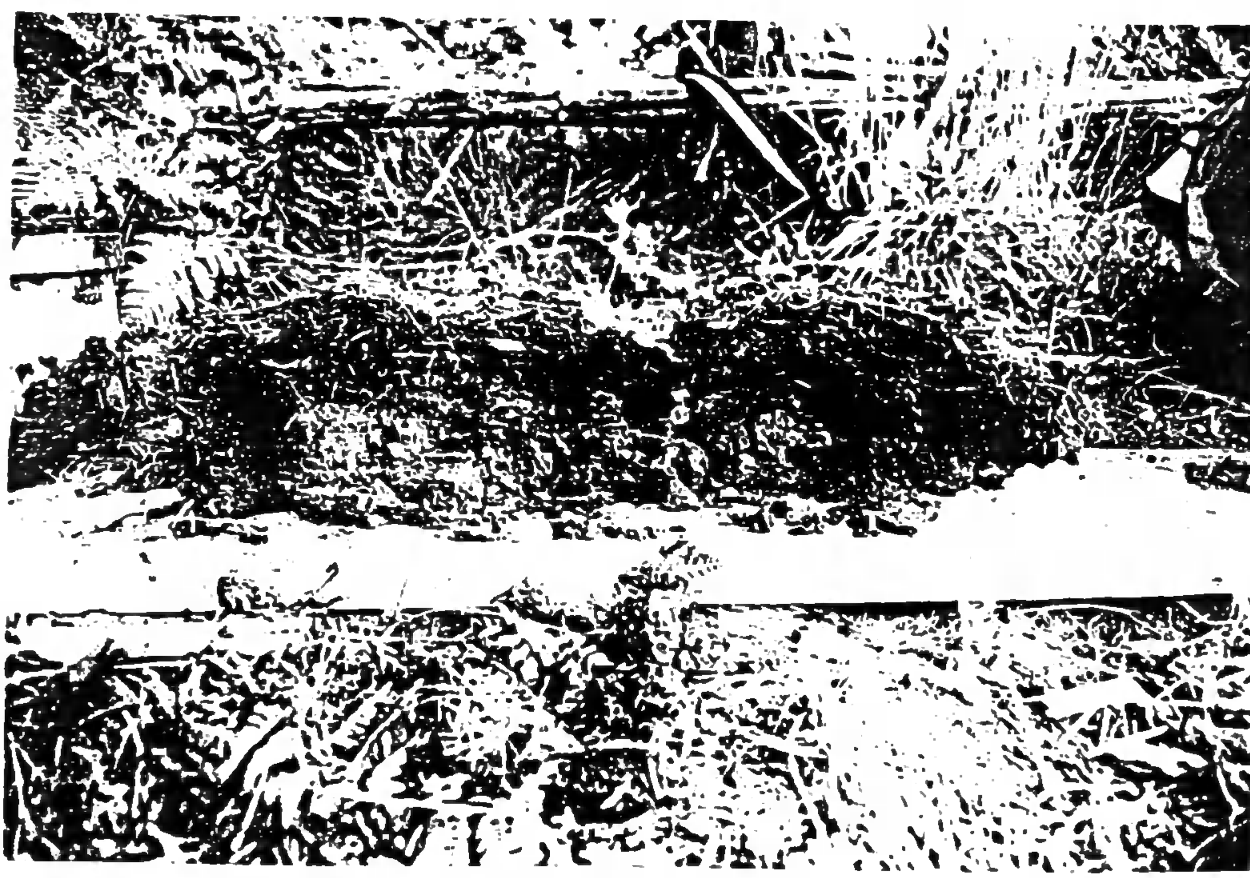
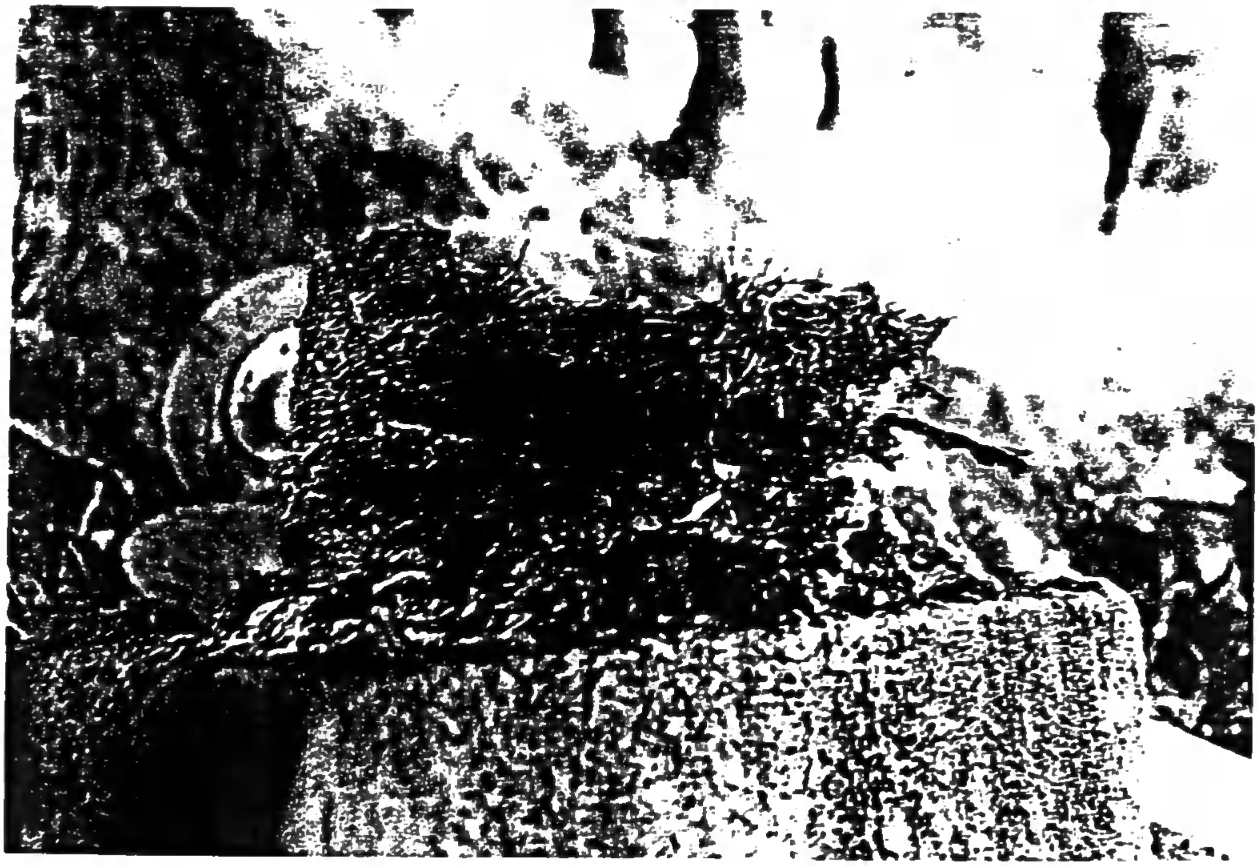


Plate 6.1 Forest sample profile of 5Ca & 5Cb

Sample 5Da



Sample 5Db

Plate 6.2 Forest sample profile of 5Da & 5Db

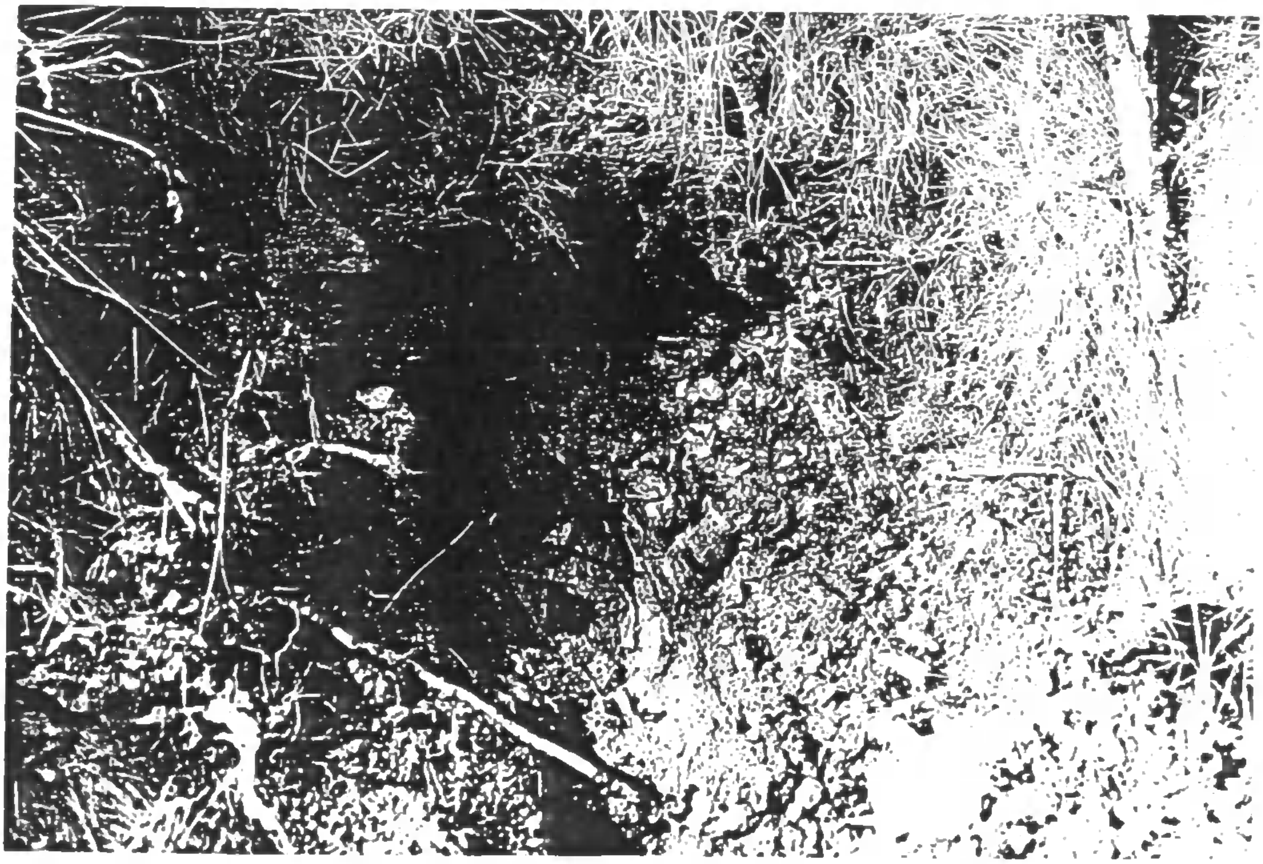
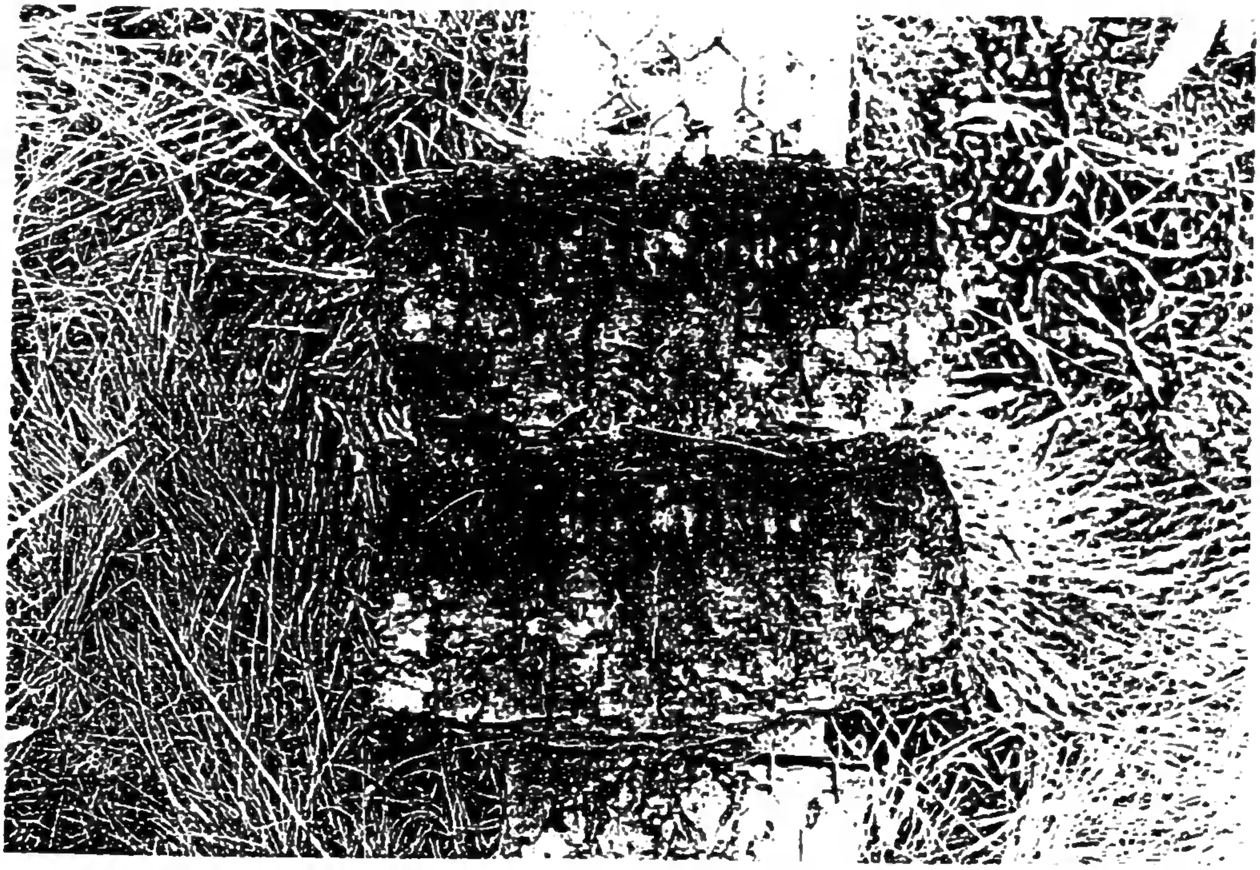


Plate 6.3 Whole Tree Harvest sample 1A - impeding layer of slate 11 cm below ground surface

Sample 1Ca



Sample 1Cb

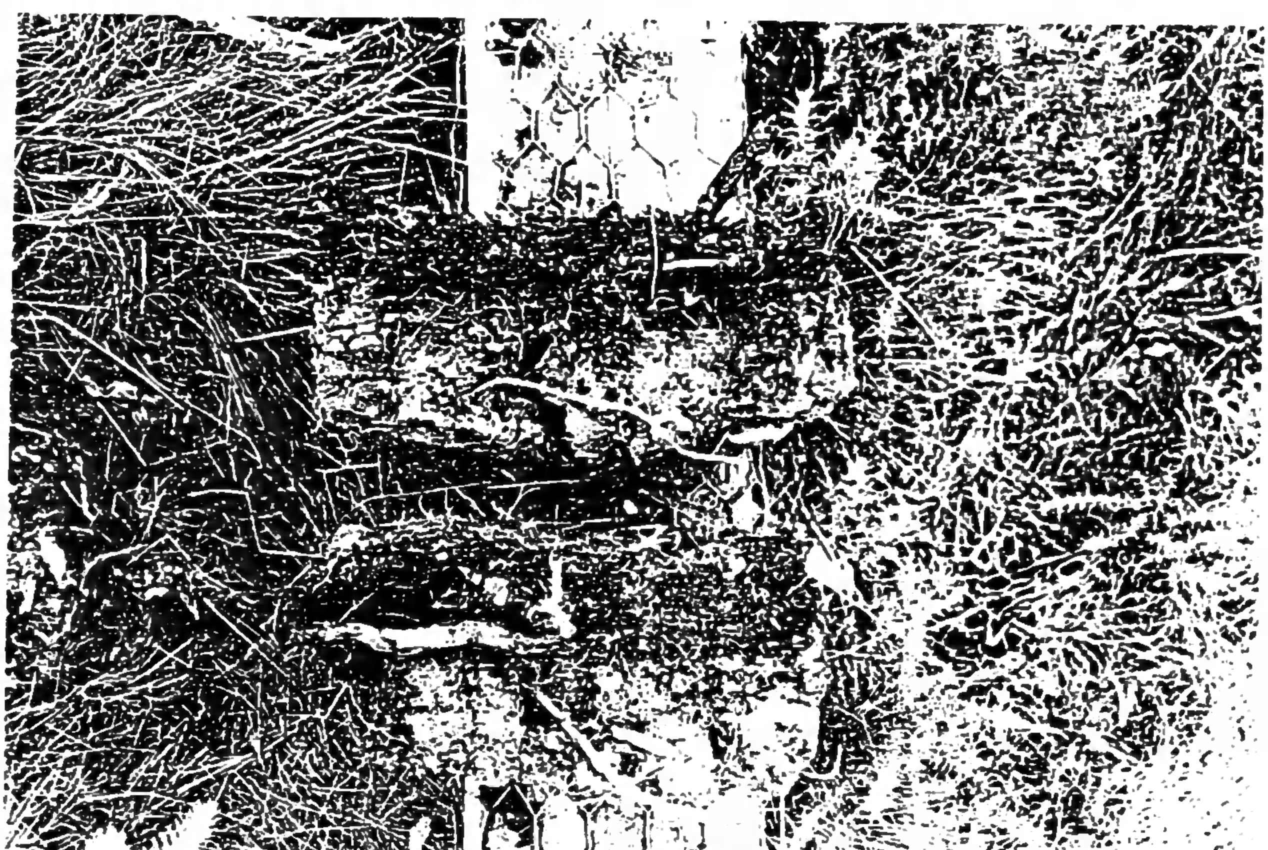
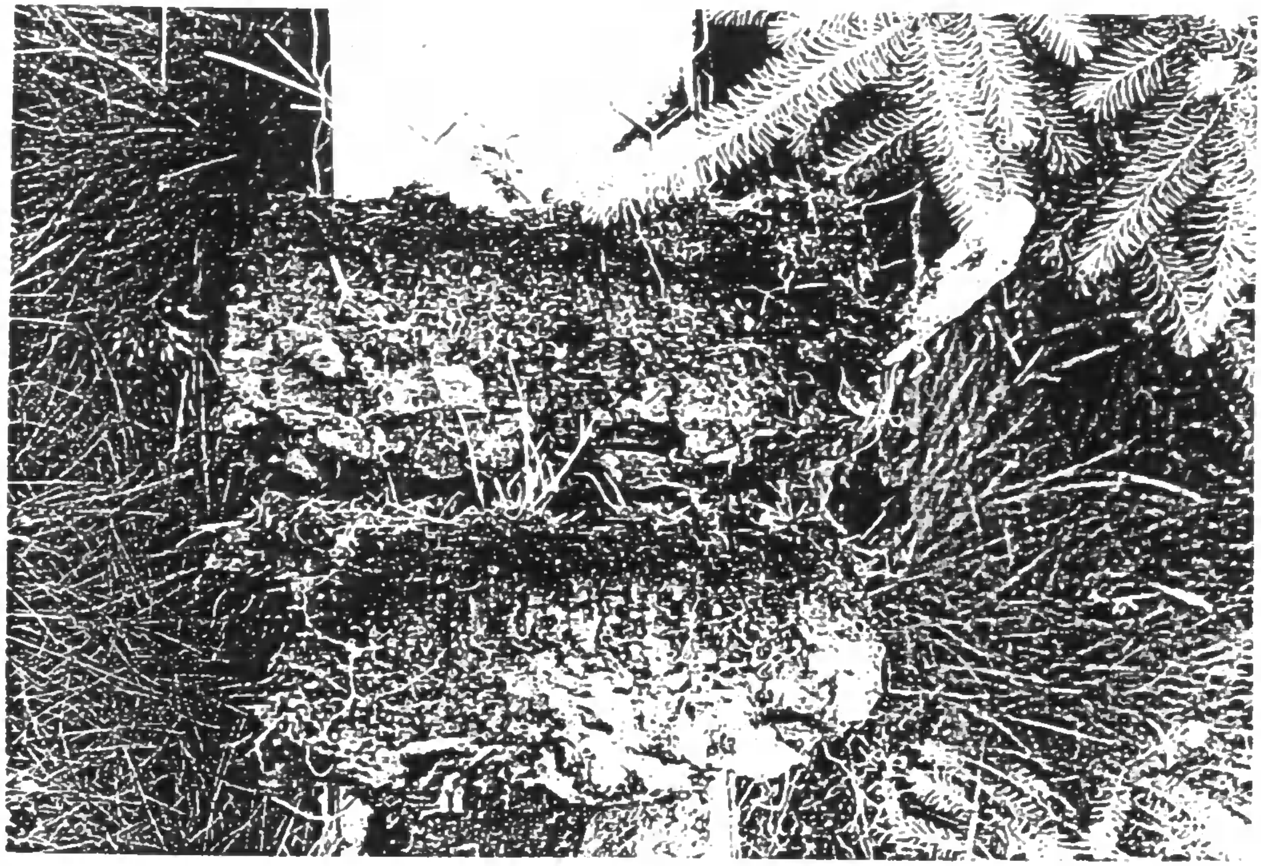


Plate 6.4 Whole Tree Harvest sample profile of 1Ca & 1Cb

Sample 1Da



Sample 1Db

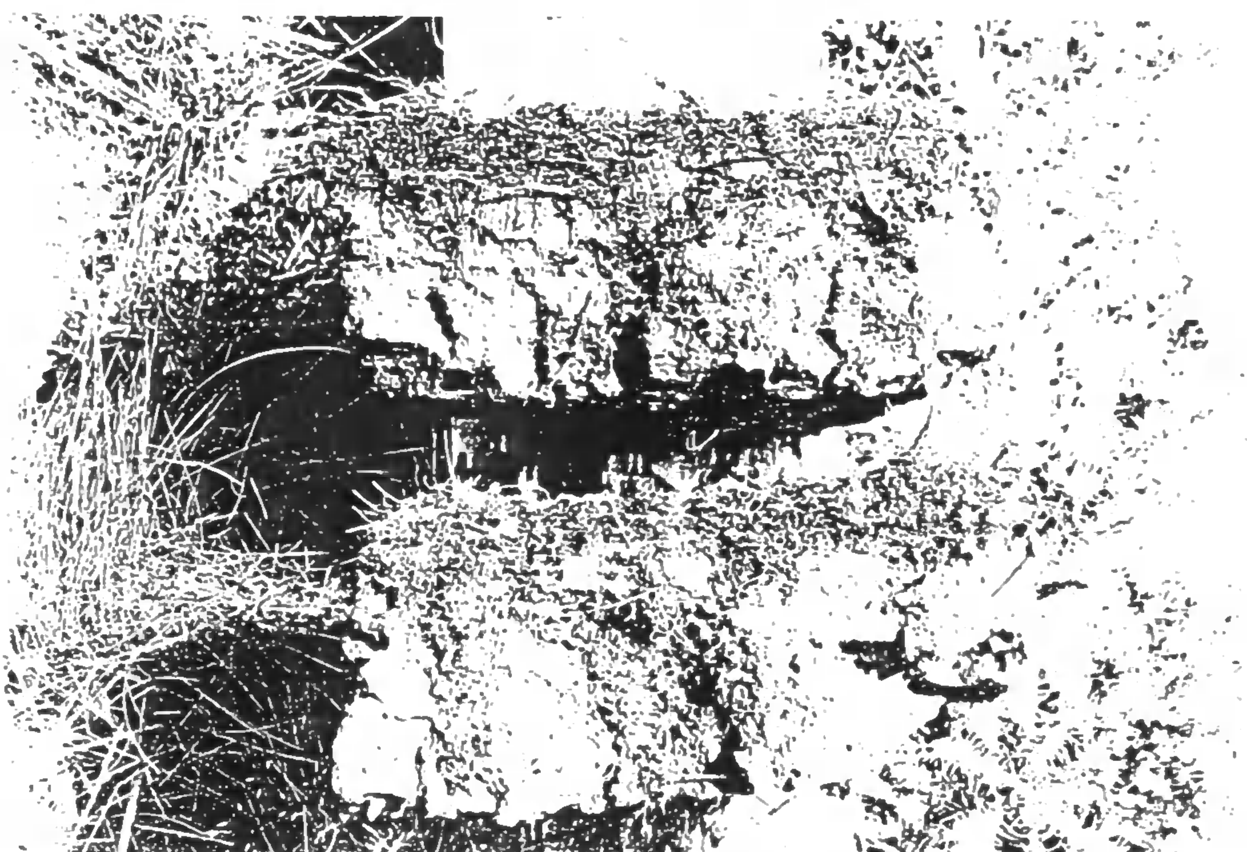


Plate 6.5 Whole Tree Harvest sample profile of 1Da & 1Db

6.5.1 Descriptive Explanation of K_S Values

The following key will be used to summarise K_S:

- E^{-1} = V. HI (very high)
- E^{-2} = HI (high)
- E^{-3} = MED (medium)
- E^{-4} = LOW

If there are any borderline K_S values, two categories will be used to denote them, for example MED/HI = 9.80 E^{-3} (Sample 2Db). Table 6.2 shows the findings from the forest soil and Table 6.3 for the WTH soil.

Table 6.2 Soil Properties

Site	Horizon (cm)	Bulk Density (gm cm^{-3})	Coarse (%)	Sand (%)	Silt & Clay (%)	Root Density (%)	K_S (cm s^{-1})
$1A_1$	0 - 10	0.55	0.5	36.5	63.0	50	$2.77E^{-4}$
$2A_1$	0 - 10	0.65	1.0	34.0	65.0	33	$1.17E^{-3}$
$3A_1$	0 - 10	0.65	0.5	32.0	67.5	68	$3.73E^{-4}$
$4A_1$	0 - 10	0.49	0.5	55.5	44.0	14	$1.00E^{-4}$
$5A_1$	0 - 10	0.57	18.5	22.5	59.0	57	$3.01E^{-3}$
$1A_2$	10 - 20	0.97	1.0	24.5	74.5	16	$2.00E^{-2}$
$2A_2$	10 - 20	0.94	3.5	8.0	88.5	50	$1.53E^{-3}$
$3A_2$	10 - 20	0.89	9.0	28.0	63.0	10	$4.27E^{-4}$
$4A_2$	10 - 20	1.06	18.0	7.0	75.0	2	$3.04E^{-2}$
$5A_2$	10 - 20	0.94	17.0	23.5	59.5	1	$1.34E^{-3}$

Table 6.3 Forest Soil K_S Explanations

Plot 5

Sample	K_S	Observations suggest
$5A_1$	MED	soil matrix properties dominate K_S
$5A_2$	MED	soil matrix properties dominate K_S
5B	MED	soil matrix properties dominate K_S
5Ca	HI	two large interpedular cracks dominate K_S
5Cb	V. HI	numerous cracks dominate K_S
5Da	V. HI	interpedular cracks dominate K_S
5Db	V. HI	numerous cracks dominate K_S

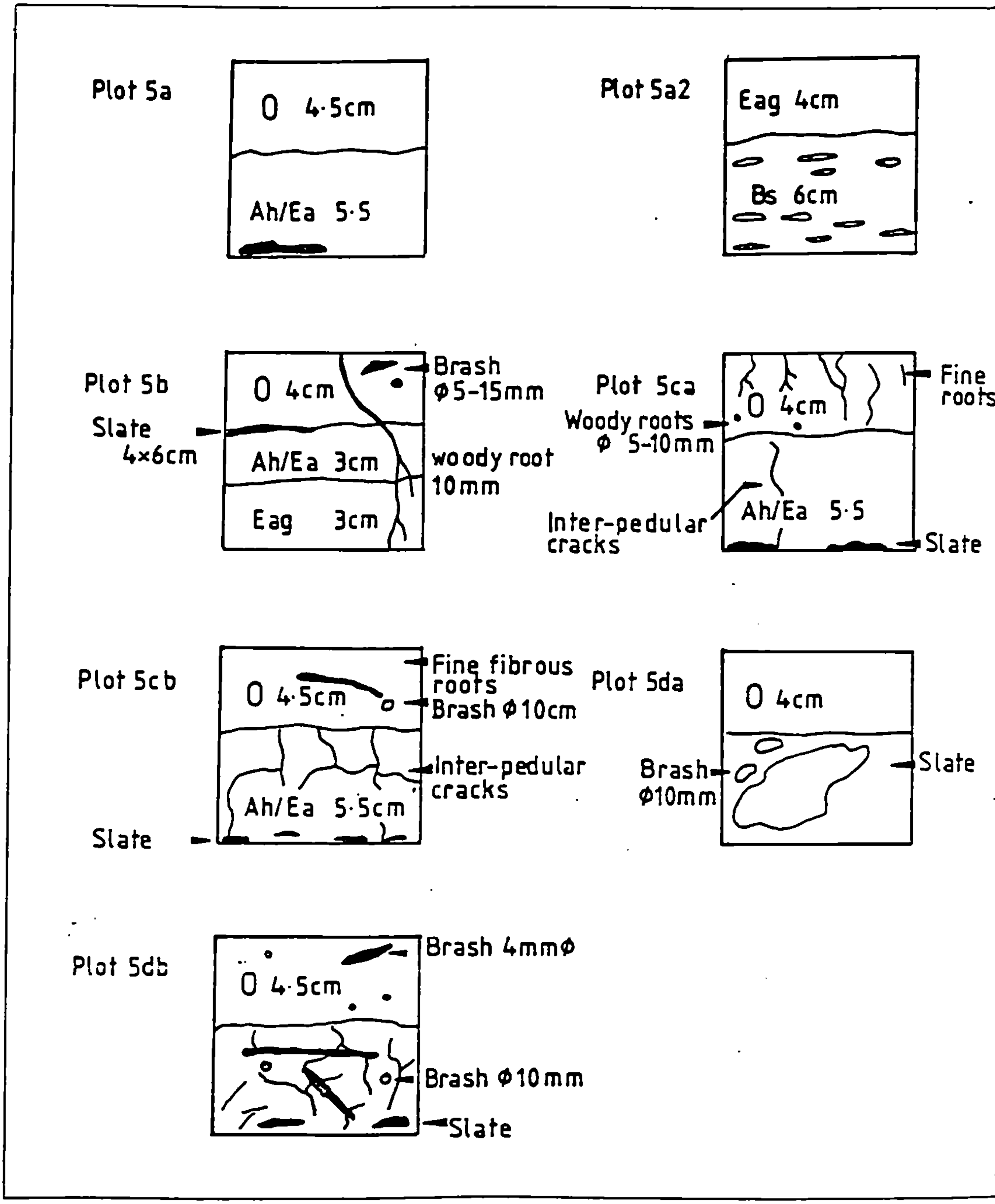


Figure 6.6 Forest K_S soil sample profiles

Table 6.4 Whole Tree Harvest Soil K_S Explanations

Plot 1		
Sample	K_S	Observations suggest
$1A_1$	LOW	soil matrix properties dominate K_S
$1A_2$	HI	one large vertical macropore dominates Ks
1B	LOW	soil matrix properties dominate K_S
1Ca	MED	interpedular cracks dominate K_S
1Cb	MED/HI	interpedular cracks and cracks caused by brash and roots dominate K_S
1Da	MED	a large horizontal dead woody root and peripheral cracking dominates K_S
1Db	HI	a small horizontal dead woody root and strong cracking pattern dominates K_S
Plot 2		
Sample	K_S	Observations suggest
$2A_1$	MED	cracks dominate K_S
$2A_2$	MED	soil matrix properties dominate K_S
2B	MED	vertical roots dominate K_S
2Ca	MED	vertical roots and numerous small fragments of slate dominate K_S
2Cb	MED	fragments of slate dominate K_S
2Da	MED	a friable and crumbly soil structure dominates K_S
2Db	MED/HI	cracks dominate K_S
Plot 3		
Sample	K_S	Observations suggest
$3A_1$	LOW	soil matrix properties dominate K_S
$3A_2$	LOW	soil structure dominate K_S
3B	LOW	soil matrix properties dominate K_S
3Ca	MED	cracks and fragments of slate dominate K_S
3Cb	MED	a large horizontal dead branch and to a minor extent cracks and slate dominates K_S
3Da	MED	a medium horizontal dead branch cracks and slate dominates K_S
3Db	MED	cracks and fragments of slate dominate K_S
Plot 4		
Sample	K_S	Observations suggest
$4A_1$	LOW	soil matrix properties dominate K_S
$4A_2$	HI	interpedular cracks dominate K_S
4B	LOW/MED	soil matrix properties dominate K_S
4Ca	LOW	soil matrix properties dominate K_S
4Cb	MED	interpedular cracks dominate K_S
4Da	MED	interpedular cracks and slate dominate K_S
4Db	LOW	soil matrix properties dominate K_S

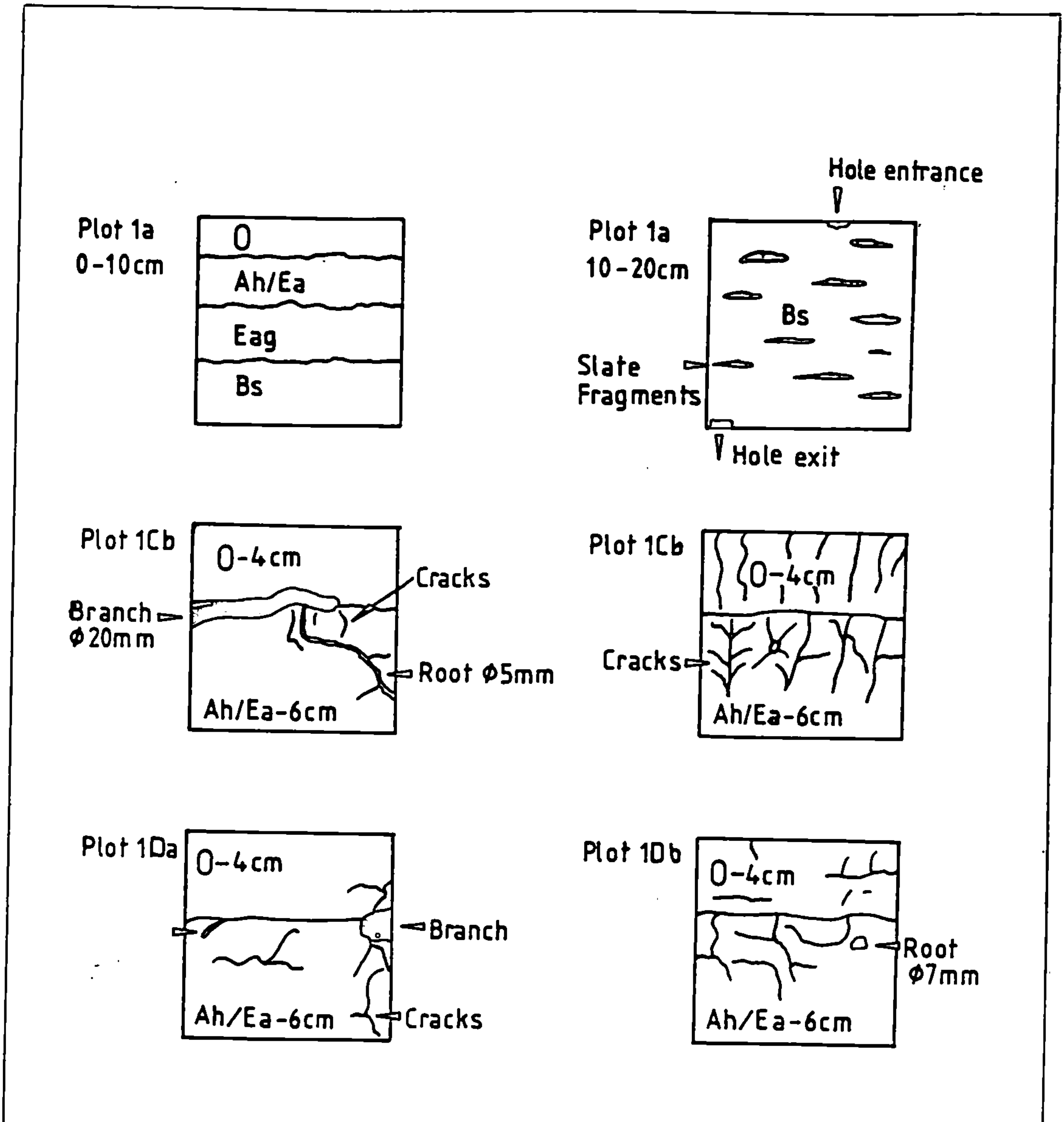


Figure 6.7 Whole tree harvested K_S soil sample profiles

The data indicate that at both sites, the presence of inter-pedular cracks increased K_S. However, it must be stressed that all these samples and data reflect infinite sinks, due to the method of measuring Ks. Therefore the cracks will still transmit the water, but water flow depends on the K_S value of the next layer. The frequency and size of slate in this underlying layer made the measurement of K_S unrealistic. From field observation and simple tests, the soil/slate transmitted water rapidly and therefore would have a high K_S value. Without an impermeable layer, there is nothing to promote the build up of water to saturation and therefore the antecedent conditions are not favourable for macropore flow. Earlier data (Chapter 5) suggested saturated conditions are uncommon. Therefore, whilst macropores exist, macropore flow is unlikely to occur under the prevailing conditions and the meso and micropores will conduct the water at both these sites.

6.6 STATISTICAL EXPLANATIONS OF K_S VALUES

A measure of the strength of relationship between K_S, bulk density, fine root density, coarse particles, sand, silt and clay content was conducted using the Product Moment correlation coefficient or Pearson's correlation coefficient (Hammond and McCullagh, 1978). Table 6.5 shows the results in a correlation matrix. Any value above 0.7 was significant at a confidence level of 95 % or above and therefore a correlation probably exists.

Table 6.5 Correlation coefficients between K_S and bulk density, percentage sand, percentage silt & clay, percentage coarse and root density

Correlation Coefficient between K_s and the following parameters	
Bulk Density	0.69
% Sand	0.74
% Silt & Clay	0.57
% Coarse	0.45
Root Density	0.29

Percentage Bulk Density

There was a significant correlation (R = 0.69) between bulk density and K_S at confidence limits of about 94% (Table 6.5, Figure 6.8) therefore there is 94 % probability of a correlation between bulk density and K_S.

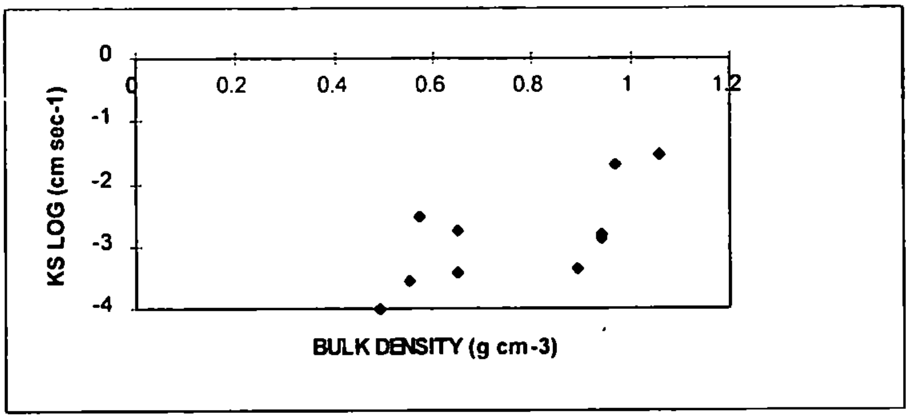


Figure 6.8 Scattergraph of K_S and bulk density

The above scattergraph (Figure 6.8) shows two distinct clusters: the lower bulk densities for the upper soil cores and the higher bulk densities for the lower soil cores. As bulk density increases, so does the saturated hydraulic conductivity. This situation is unusual, because higher bulk densities usually mean the soil is more compact. Therefore for these soil samples, an average value for bulk density was not a good indicator of soil structure because of the dominance of macropores. Bulk density was only a partial indicator of soil structure and therefore a thorough investigation of soil structure could explain more fully the variations in K_S.

Percentage Sand

There was a significant correlation (R = 0.74) between percentage sand and K_S at confidence limits of 95 % (Table 6.5). The scattergraph (Figure 6.9) shows a fairly close scatter of points indicating an inverse relationship between the percentage of sand and saturated hydraulic conductivity.

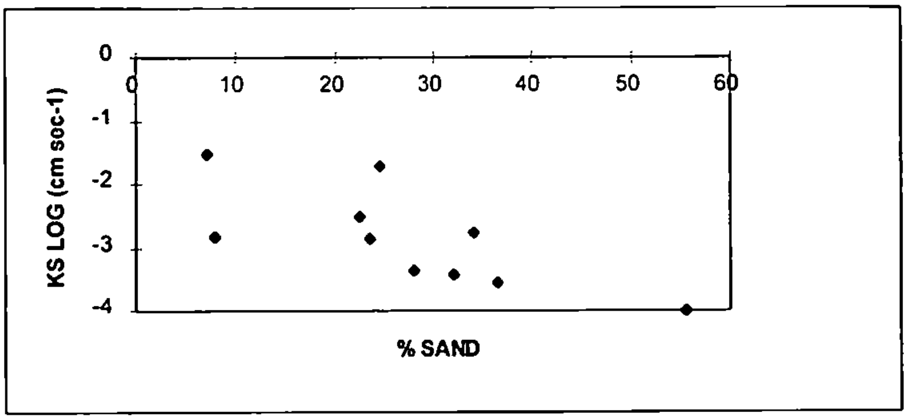


Figure 6.9 Scattergraph of K_S and percentage sand

These data suggest that higher saturated hydraulic conductivities occur where there was less sand present which is unusual. Normally higher percentages of sand indicate higher saturated hydraulic conductivities. Therefore another factor, that had not been correlated, influences K_S and has a direct relationship with sand.

<u>Percentage Silt & Clay</u>

There was no significant correlation between K_S and percentage silt and clay. However, there was a relationship between the two (Rs = 0.57). The relationship to K_S was again the opposite to what normally occurs (Figure 6.10). The highest saturated hydraulic conductivities are found where the percentage of silt and clay were highest. Certainly, with a clay soil one would expect a low K_S value. This result supports the theory that another factor is correlated to K_S.

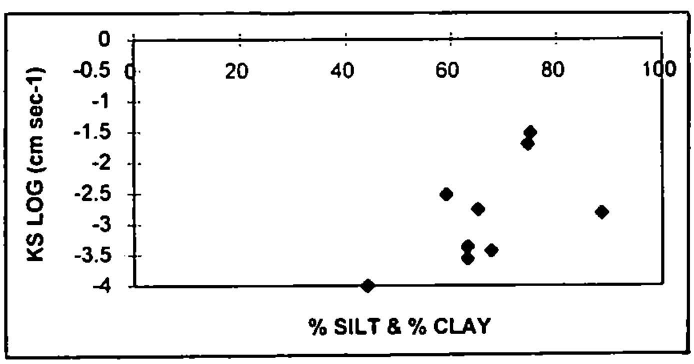


Figure 6.10 Scattergraph of K_S and percentage silt and clay

Percentage Coarse particle & Root Density

There was no significant correlation between K_S and percentage coarse particle or root density (Table 6.5). The scattergraphs (Figure 6.11, 6.12) were completely random, r = 0.45 and r = 0.29 respectively (Table 6.5). There was very little relationship between these variables. However, at a few sites these factors are responsible for permeability (Table 6.3).

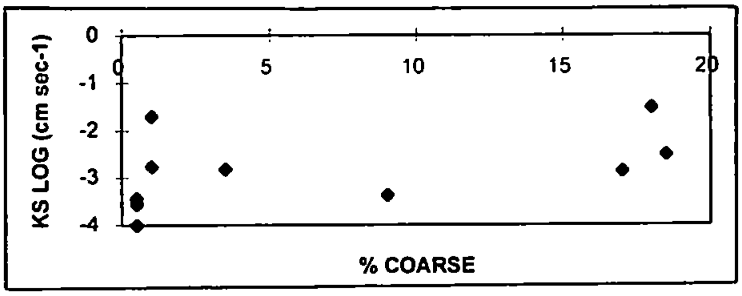


Figure 6.11 Scattergraph of K_S and percentage coarse particle

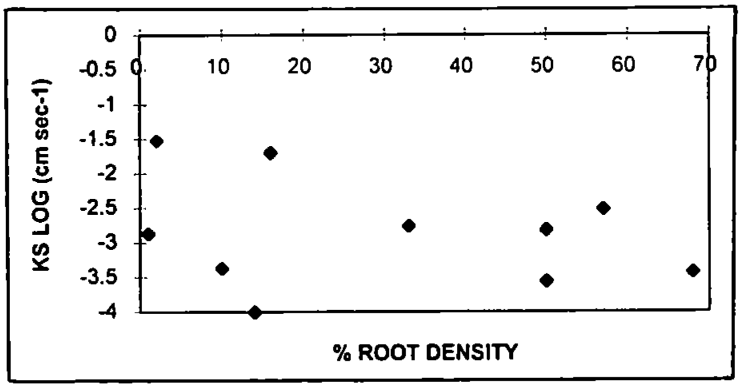


Figure 6.12 Scattergraph of K_S and percentage root density

This experiment produced evidence to suggest that it could be cracks, woody roots and slate, and therefore macropores that provided the missing correlation that influences the saturated hydraulic conductivity. High percentages of silt and clay are a prerequisite to cracking, and hence their positive relationship with K_S. This relationship will be quantified and addressed in more detail in chapter 7 and 8.

6.7 SUMMARY

There was a significant difference in saturated hydraulic conductivity (K_S) between the soil at the forest and whole tree harvested sites at 0 - 10 cm. Saturated hydraulic conductivity (K_S) was on average two orders of magnitude higher at the forest site compared to the whole tree harvested site. The implications of this result are that K_S must be defined and represented separately for both sites. Also, within each site there was a lot of variability of K_S, the greatest variability being at the forest site. At the forest site, K_S was positively skewed, which makes it difficult to represent statistically in a flux model such as LEACHM. However, more data are required to confirm this distribution. Whereas, at the whole tree harvest site, there was a normal distribution of K_S, which, if not spatially dependent, allows it to be represented statistically.

The variability of saturated hydraulic conductivity (K_S) occurred at different scales, and in line with current theory of Representative Elementary Volumes (REVs), variability does increase with a decrease in scale. Therefore, samples taken at the largest scale, those taken at 50 m lag distance (Points A), will be more representative of the hillslope study area. Whereas at smaller scales much more variability occurred, so more samples are required to represent this variability accurately.

At the more detailed scale, there was no significant relationship between K_S and silt, clay, course fragments or fine root density, probably because of the overriding influence of singular cracks and networks of cracks. This would suggest that it is the inter-pedular scale which is more significant than the particle size scale at saturation. However, this hypothesis needs to be investigated further at the relevant degree of unsaturation, to establish if there is a critical point where the importance of cracks may give way to another controlling factor. There was an inverse relationship between K_S and sand or bulk density, which was the opposite to what should occur, suggesting there was another factor controlling K_S and that a scale greater than particle size is more influential. Bulk density is greater than particle size scale yet there was still no direct relationship between bulk density and K_S. Cracks and inter-pedular gaps may dominate over the influence of particle size and bulk density where K_S is concerned.

At this detailed scale, the data suggest that cracks in the soil are the most influential factor governing saturated hydraulic conductivity. Cracks appear to increase K_S, the size of cracks seems more important than frequency of cracks at the whole tree harvested site, whereas the reverse is true at the forest site making K_S spatially dependant. Both sites have predominantly unsaturated flow, although the soil is close to saturation, it is not fully saturated. Although saturated flow is likely to occur in the Ah/Ea horizon, the soil moisture content and matric potential data suggests that the underlying Eag and B_S horizons prevent further by-pass flow occurring. These cracks just allow preferential flow into the soil rather than through it. These conclusions highlights the need for a range of K_S/K_{unsat} values throughout the entire soil profile. The differences in cracks did not cause differences in soil moisture content and matric potential and therefore the data suggests that WTH does not change soil water movement. Therefore these cracks will not influence soil water movement on the study hillslope, allowing K_{unsat} to be represented statistically.

On a small scale, there was evidence of localised saturation at a depth of 60 cm. K_S data were for 0 to 20 cm only, but the implicit nature of this saturation (Section 5.3) infers these points of saturation are "internal catchments" (Van Stiphout *et al.*, 1987), and therefore saturated flow does not occur. Soil water movement at both sites is therefore through the soil matrix. These data suggest that this detail of the frequency and number of cracks produces the greater variability of K_S at sample points closer together. On a larger scale, such as the 50 m lag distance between K_S sample points that were used in this study, the semi-variogram indicates less variability. The detail regarding the influence of cracks on soil water movement is lost. Although the influence still remains in the field, it is simply averaged out and lost in the measurements. However, it is the fine level of detail that is required if there is some element of field saturation, whether it be a hydrological study at the plot, hillslope or catchment scale. Since it is this factor that has the greatest potential for water movement, this has implications on water quality and quantity studies. Water inherently moves through the easiest route. Therefore if there are inter-connecting cracks or areas of like high K_S values, then water will move preferentially through these channels.

At both sites, K_S at 10 to 20 cm indicated less permeability than the layer above it. Excluding variability and assuming matrix flow occurred, this results in an element of flux being diverted laterally when saturated conditions prevail. However, variability does occur and only near-saturated conditions prevail which make water movement far more complex.

It must also be stressed that the saturated hydraulic conductivities measured were from samples extracted from the top 10 cm of soil profile, and therefore were effectively disconnected from the lower soil profiles. This means blocked soil water pathways are opened up when the soil sample is removed, thus giving a higher saturated hydraulic conductivity than its true field value.

CHAPTER 7
SOIL STRUCTURE

7.1 INTRODUCTION

This chapter will explore the link between soil structure, hydraulic conductivity and soil moisture patterns. Many research projects have concentrated on establishing links between soil structure and K_S (Bresler *et al.*, 1984, Byers and Stephens, 1983), but no universal model for all soil types has been identified. These investigations were all carried out on lowland agricultural land. There has been very little, if any, research conducted on an upland forest site in the UK that investigates the direct effects of soil structure on soil water pathways.

This chapter will also describe soil structure at both the forest and WTH sites in terms of quantifying the size, orientation and irregularity of pores (Murphy *et al.*, 1977a) and pedal fractal dimension (Holden, 1993). These results will help to identify which characteristics or elements act to control soil water movement at both sites.

Soil structure is fundamental to the study because it governs the route and the rate at which water moves through the soil profile. Soil water pathways are very complex tortuous routes through the soil matrix. Therefore soil structural analysis is inherently very detailed and concerns individual pores, their shape, orientation and dimensions.

Chapter seven will describe and analyse soil in the following order: (i) field observations (ii) fractal dimensions of peds (iii) micromorphological analysis. For each section (as outlined above), the results for the forested site will be presented first, then the WTH site, followed by comparisons between the two. Finally, a summary of the soil structure at both sites and the effect of whole tree harvesting on soil structure will be presented.

7.2 FIELD OBSERVATIONS OF SOIL STRUCTURE

Soil profile descriptions were used in the field to represent the soil when *in situ*. These results are presented for both soil profiles in Section 2.6.1 and 2.6.2 and are illustrated in Table 2.3. Both sites have similar soils, which have been formed from head material with slate being inclined downslope. In terms of water movement, these factors and the relatively high porosities which decrease with depth would promote lateral water movement.

7.3 PEDAL STRUCTURE

Quantification of ped surface roughness allows both sites to be compared at a scale which is between the micromorphological and field scale, and gives an indication of resistance to flow. Ped surface roughness was quantified using the theory of fractal dimensions, which suggests there is self-similarity at different scales. Quantification of ped roughness can be made using callipers which are set at a range of reducing widths to measure the ped perimeter (Steinhaus, 1954). This theory was developed further by Richardson (1961), who found a relationship between the data when applying the Steinhaus paradox. The Steinhaus paradox is expressed by

$$L(E) \sim FE^{1-D}$$

where L = perimeter length estimate using steps of length E

F = the number of steps (7.1)

Mandlebrot (1977, 1982) progressed ped roughness research by suggesting that the gradient of the best-fit straight line for the data of the logarithm of step length against the logarithm of the perimeter estimate will equal the term 1 - D. He referred to D as the fractal dimension. The fractal dimension is the degree of irregularity in two dimensions of the perimeter.

The study used a scale of 1:1 for observation (Holden, 1993). The problem of three dimensional measurements is overcome by taking a series of perimeter measurements of peds that lie in random directions. Based on the theory of reducing step width to estimate perimeter length the technique "reveals" additional detail in the same manner as observation at a smaller more detailed scale (Holden, 1993). The fractal dimension technique may allow the representative elementary volume to be quantified rather than taking the rule of thumb 30 peds to be a representative area (Bouma, 1990)

7.3.1 Forest Pedal Soil Structure

Forest peds ranged in diameter from 2 cm to 5.6 cm and were blocky in shape (Plate 7.1). At the forest site, the fractal dimension was 0.0818 (Figure 7.1), representing a shallow gradient. A shallow gradient indicates that the degree of perimeter roughness was low, and by using an increasingly smaller calliper width to measure the ped perimeter little additional detail was revealed.

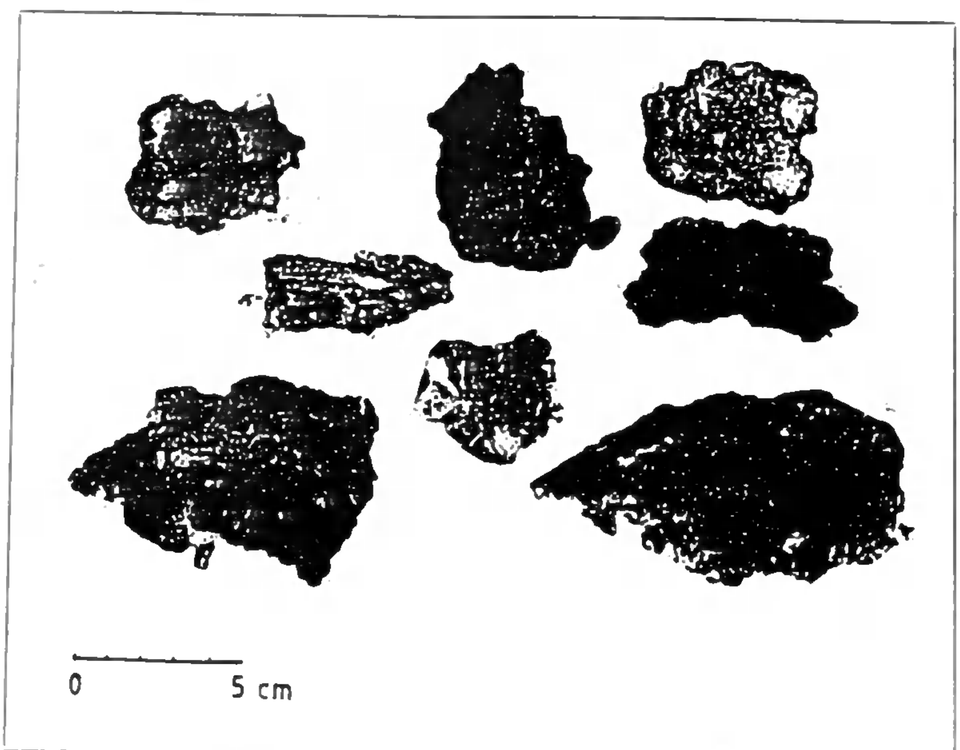


Plate 7.1 Forest peds

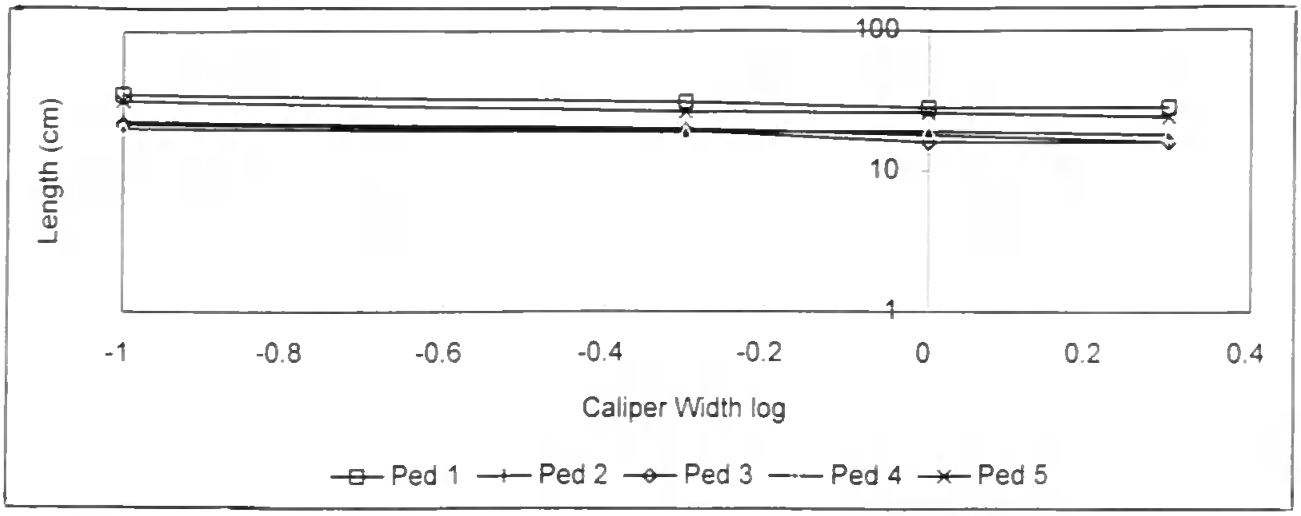


Figure 7.1 Forest fractal dimension

7.3.2 Whole Tree Harvested Pedal Soil Structure

The peds from the whole tree harvested sample ranged from 0.9 cm to 7.5 cm. (forest sample ranged 2 cm to 5.6 cm), indicating a far greater range at the whole tree harvested site (Plate 7.2). The shape of the whole tree harvest peds are blocky, the same as those at the forest site, which would suggest that the inter-pedular flow is similar at both sites.

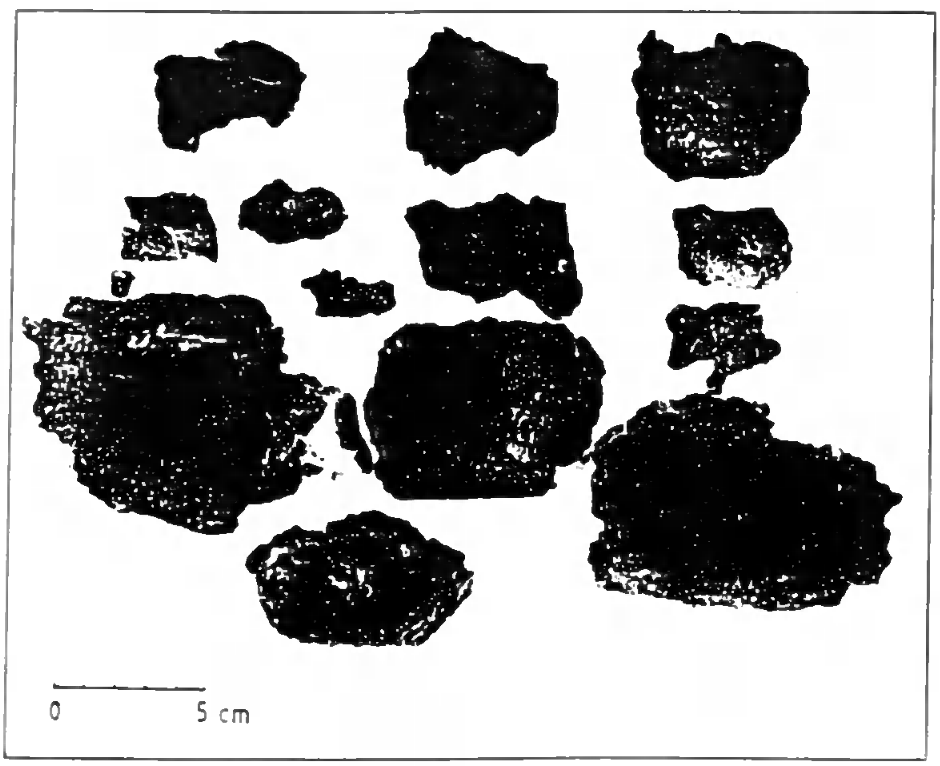


Plate 7.2 Whole tree harvested peds

At the whole tree harvest site the fractal dimension was 0.0114, which was very similar to the forest site figure of 0.0118 (Figure 7.2). Therefore the ped perimeter roughness is similar at the two sites, as both have small crenulations. However, there is a greater spread in perimeter length at the whole tree harvest site, compared to the forest site, indicating more variability in ped size.

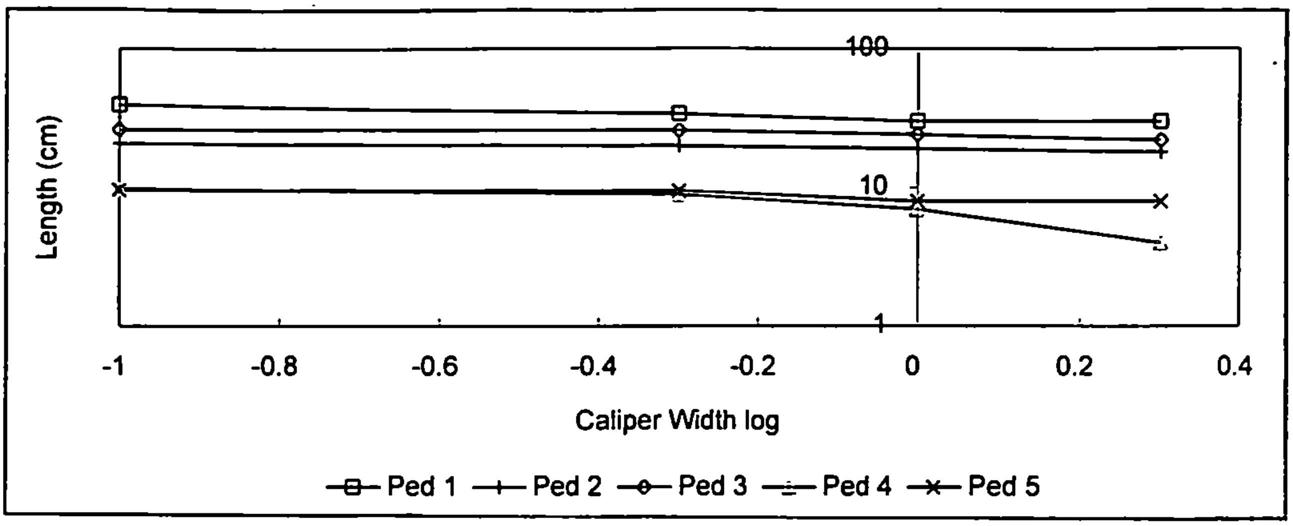


Figure 7.2 Whole tree harvested fractal dimension

7.4 MICROMORPHOLOGICAL ANALYSIS

Pore Morphology

Pore morphology can be defined in terms of shape, orientation and digitation. The shape factor used is Area/Perimeter^2 (where 0.796 is circular and 0 is elongated; Murphy *et al.*, 1977a). Anisotropy describes the alignment of individual pores,

where:

random pattern of pores = 1

pores aligned vertically = >1

pores aligned horizontally = <1.

Orientation describes the orientation of the greatest feret, which is the orthogonal distance between two parallel lines,

where:

random orientation = 0

vertical orientation = +1

horizontal orientation = -1.

Digitation or degree of irregularity expresses the length of protuberance away from the main part of the pore (Murphy *et al.*, 1977 a). Digitation will be used to quantify the smoothness or roughness of the individual pores, indicating the resistance to flow produced by the friction of the pore walls.

7.4.1 Forest Pore Morphology

Mean Pore Shape

Table 7.1 shows the depths of micromorphology samples. Pore shape at the forest site was described by a factor close to zero, with only a small range between 0.05 and 0.1 throughout the soil profile. These data suggest that the pores were elongated (Table 7.2, Figure 7.3). The extreme degree of elongation represented by these data indicates that pores have coalesced and cracks have been identified (Plate 7.3a).

Table 7.1 Soil sample depth

Slice Number	Horizon	Depth of Soil (cm)
Sample 1		
1	O	1
2	O	2
3	Ah/Ea	3
4	Ah/Ea	4
Sample 2		
1	Ah/Ea	8
2	Ah/Ea	9
3	Ah/Ea	10
4	Ah/Ea	11
Sample 3		
4	Eag	20
4	Eag	21
4	Eag	22
4	Eag	23
Sample 4		
4	B_S	40
4	B_S	41
4	B_S	42
4	B_S	43

Table 7.2 Percentage probability from T test of forest and WTH soil structures belonging to the same population structures

Soil Horizon	Pore Shape %	Mean Pore Breadth %	Total No of Pores %	No of Macro Pores %	No of Meso Pores %	No of Micro Pores %
O	81	38	17	34	25	25
Ah/Ea	27	34	1	1	2	1
Eag	22	38	78	90	70	91
B_S	42	1	27	50	18	19

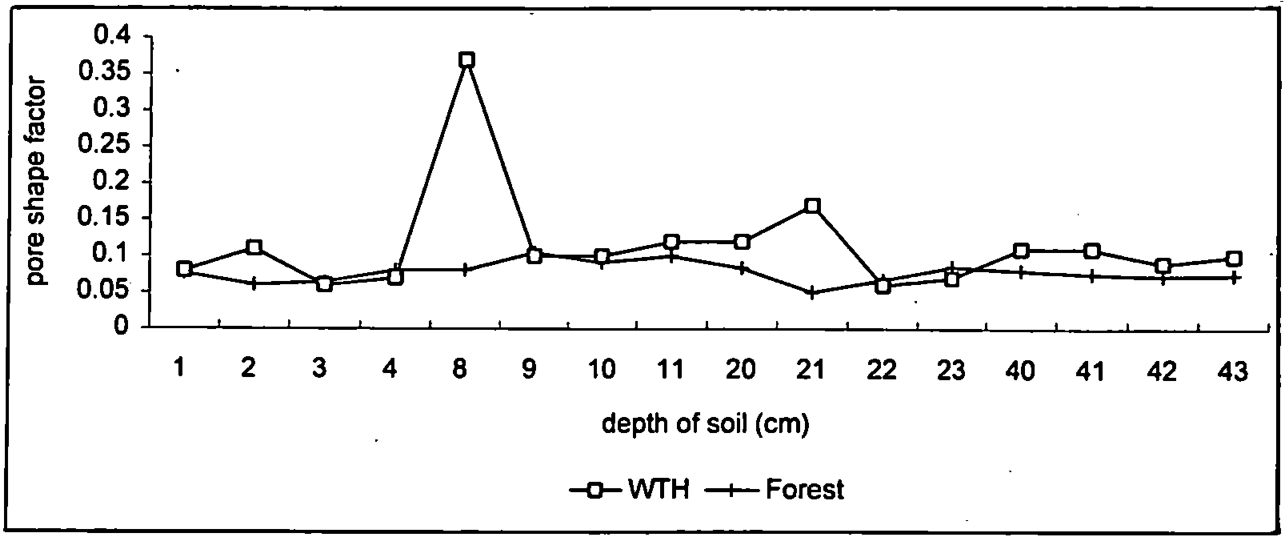


Figure 7.3 Mean pore shape throughout the soil profile at both sites

Pore Orientation

Pore orientation at the forest site was close to one throughout the soil profile, which indicates random pore orientation (Figure 7.4). Since this investigation was only in two dimensions, an anisotropic figure of one shows that there was no preferred orientation of pores, i.e. downslope.

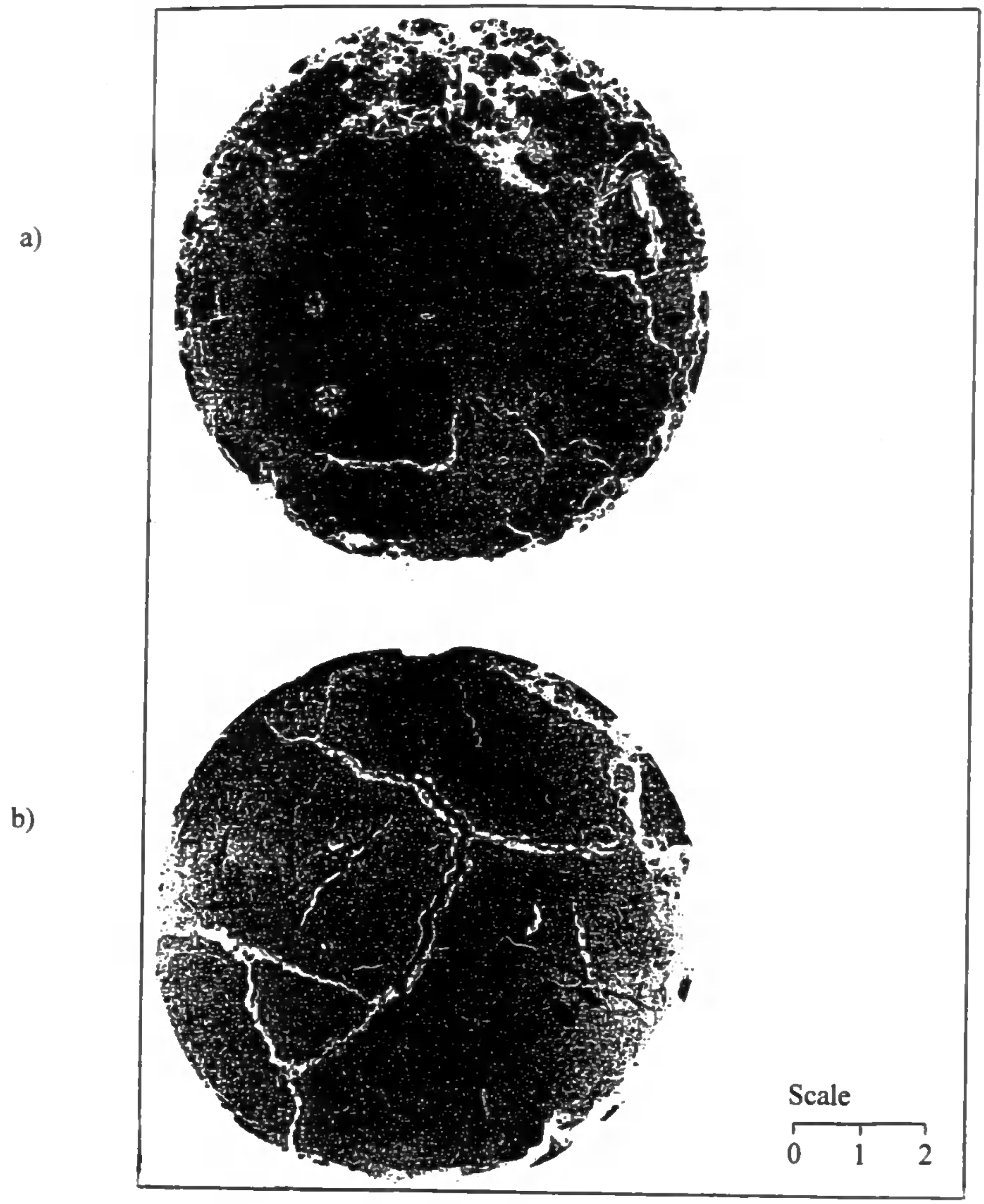


Plate 7.3 Forest Ah/Ea horizon replicate a (upper) & b (lower) at a depth of 9 cm

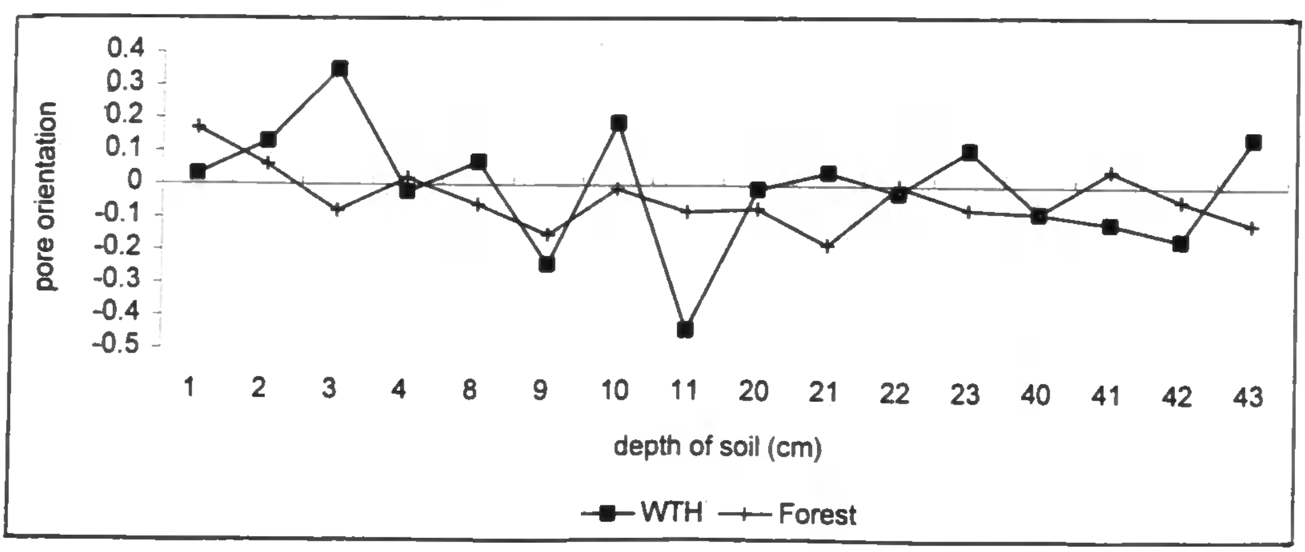


Figure 7.4 Mean pore orientation throughout the soil profile at both sites

Pore Digitation

The mean length of protuberance away from the main part of the pore varies between 0.25 mm and 1.2 mm, which indicates a large degree of pore irregularity. Plate 7.3b illustrates that these measurements are representative of void area (cracks) rather than individual pores and therefore give indication of pore/void perimeter roughness. The degree of irregularity was greatest in the O, Eag and B_S horizon, and smallest in the Ah/Ea horizon.

7.4.2 WTH Pore Morphology

Pore Shape

Throughout the whole tree harvested soil profile, the mean pore shape factor was very close to 0, (Figure 7.3), which indicated elongated pores. This figure was similar to that measured at the forest site (Figure 7.3) and is due to the coalescence of pores. At a depth of 8 cm, the Ah/Ea horizon had a much higher shape factor (0.37) which still signifies elongated pores (Figure 7.3). From observations of the soil slice photographs, the elongated pores were most striking in the Ah/Ea horizon where they could be described as planes, due to their shape and the tightly packed nature of the surrounding soil matrix (Plate 7.4). Mean pore shape differs at 21 cm indicating more elongated pores at the WTH site (Figure 7.3, Plate 7.5 & 7.6). From 22 cm depth, mean pore shape was similar to those at the forest site (Figure 7.3).

Mean pore shape at equivalent depth from both sites was very similar with the exception of the whole tree harvest site at 8 cm (Figure 7.3), where there was a much greater range of pore shapes than at the forest site at similar depth. Although similar to the WTH site, planes dominate the Ah/Ea horizon at the forested site.

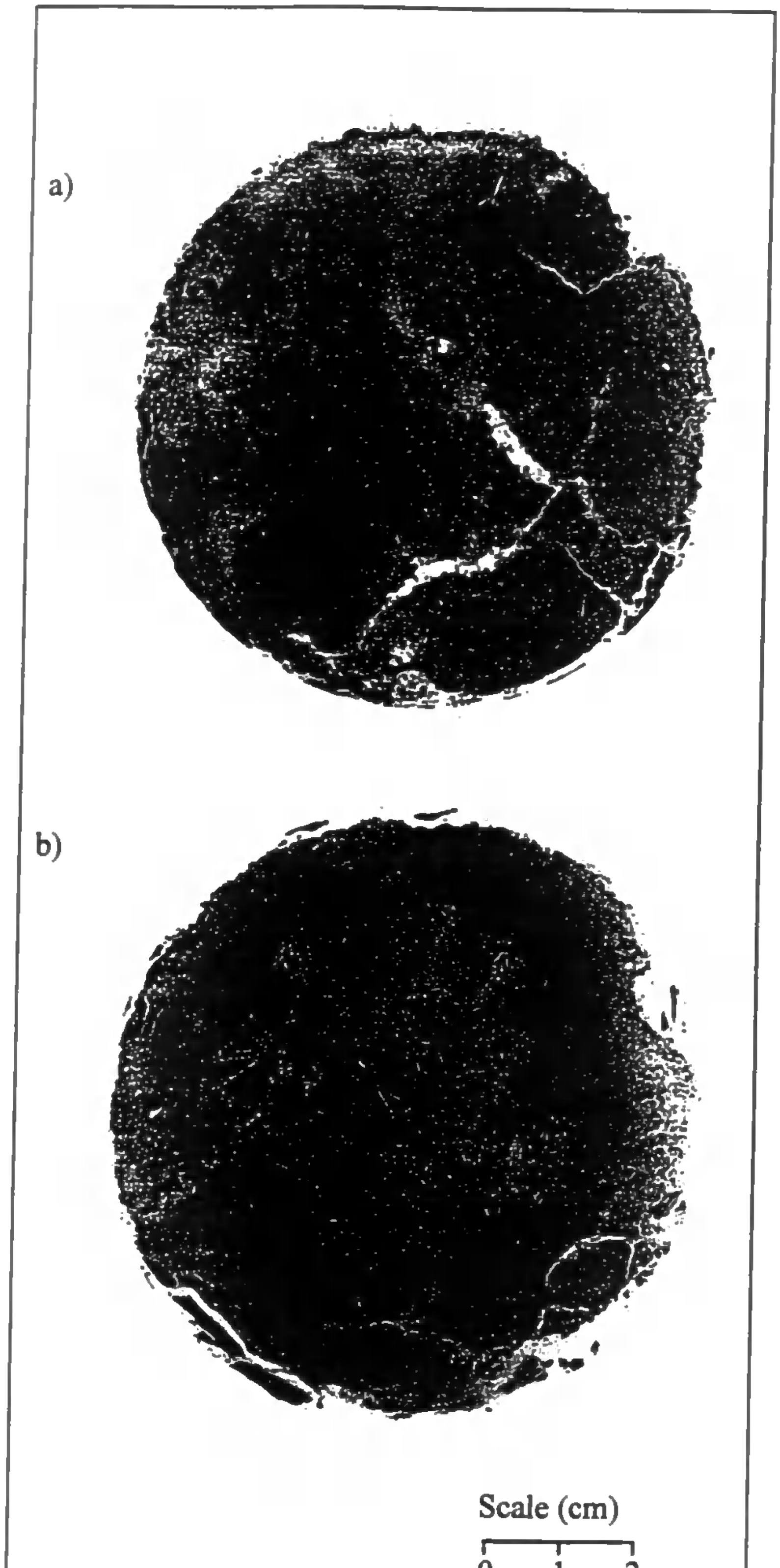


Plate 7.4 WTH Ah/Ea horizon replicate a (upper) & b (lower) at a depth of 9 cm

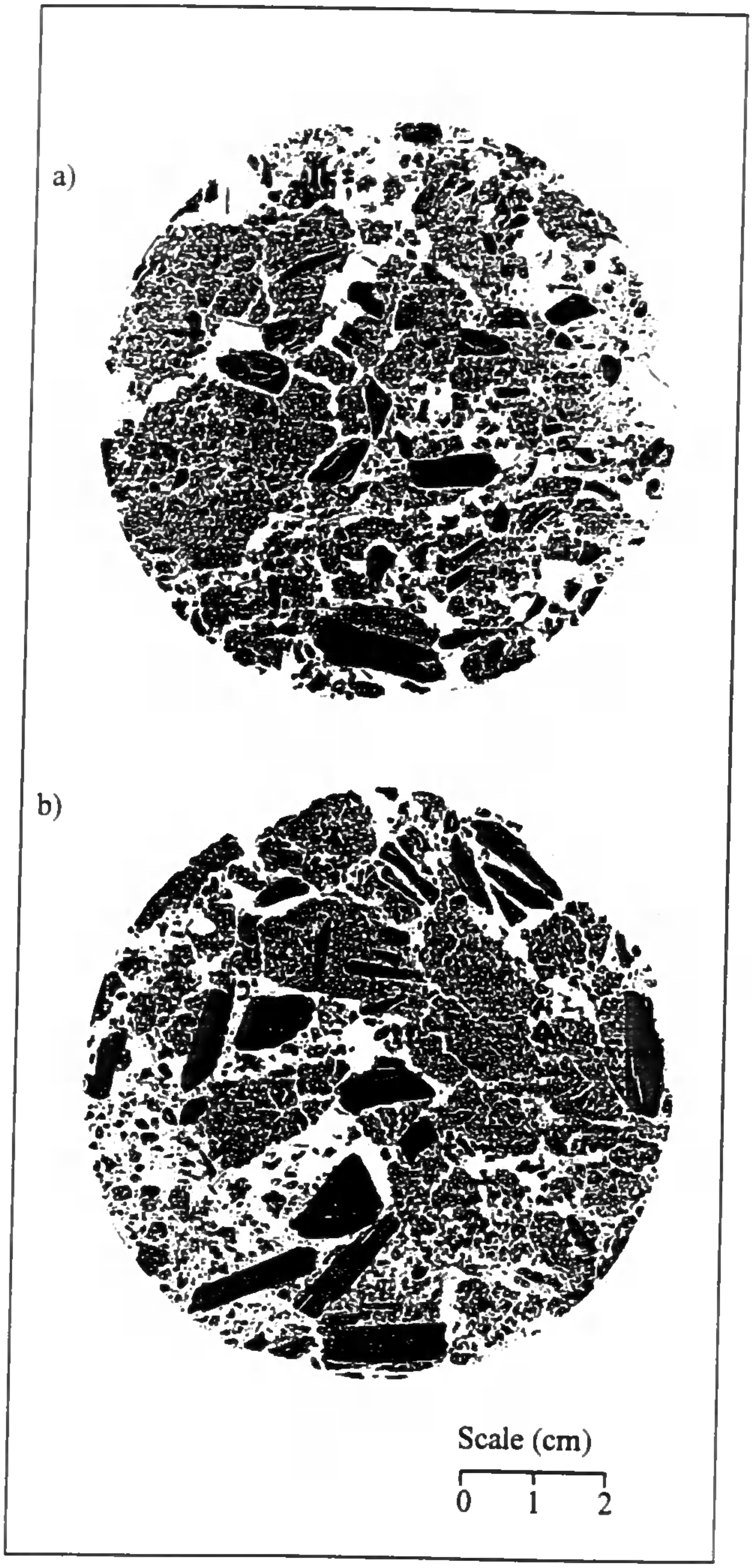


Plate 7.5 Forest Eag horizon replicate a (upper) & b (lower) at a depth of 22 cm

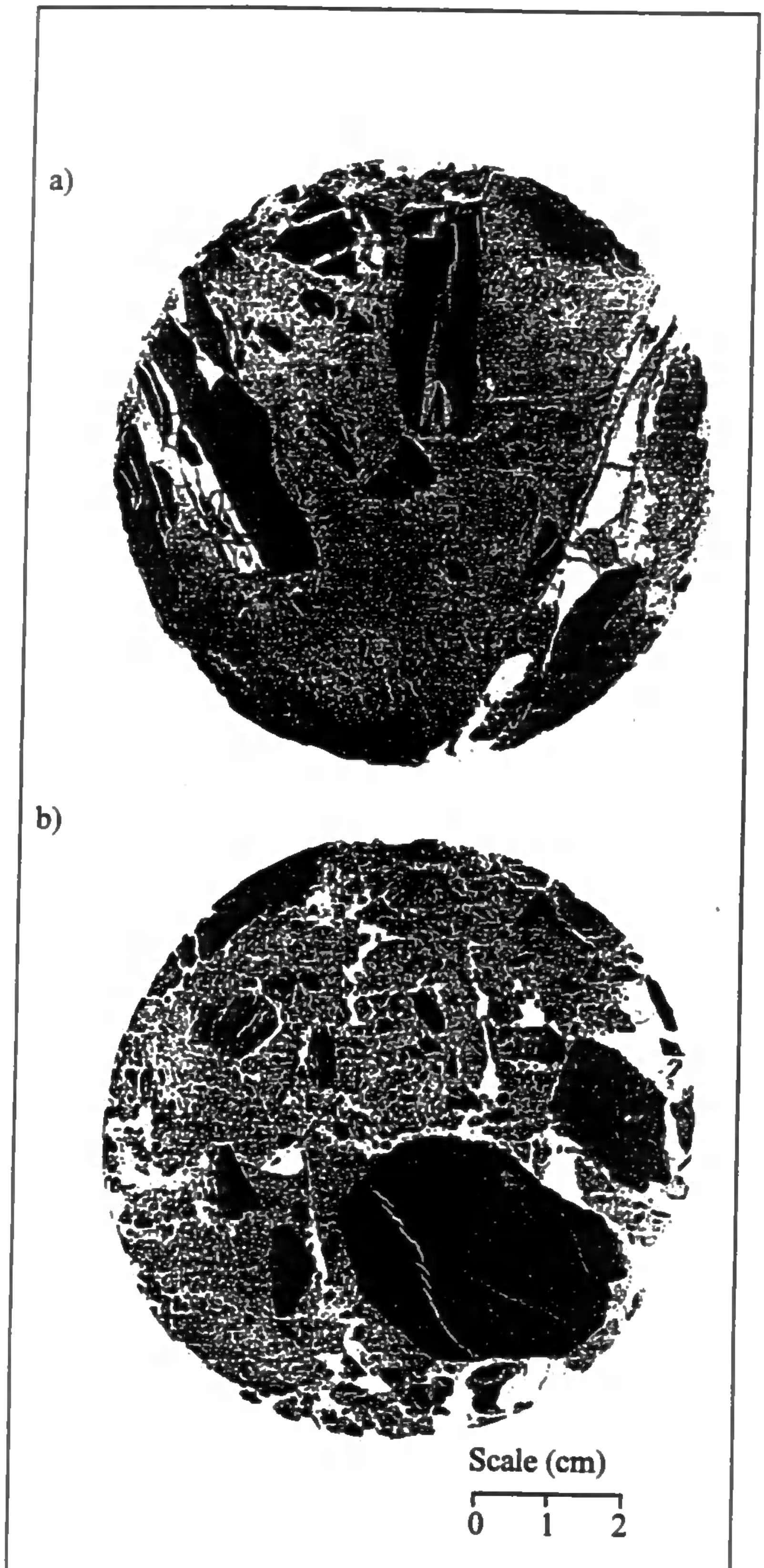


Plate 7.6 WTH horizon replicate a (upper) & b (lower) at a depth of 22 cm

Pore Orientation

Pore orientation (Figure 7.4) suggests that the pores are random, since the factor values are close to 0 which is to be expected since orientation was determined in two dimensions. In samples 3, 8, 11 and 22, there appeared to be a slight preferred orientation. Observation of Plates 7.6, 7.7 and 7.8 indicates the orientation was due to the remains of bark in sample 3 and a dominant plane in samples 8, 11 and 22. The representative elementary volume is therefore probably too small to show the full extent of the channel and macropore network.

Pore Irregularity/Digitation

The length of protuberance away from the main part of the void (digitation) varied between 0.35 mm and 1.6 mm. A range of lengths which infer a large degree of irregularity, is similar to the forest soil and was probably due to elongated voids. The degree of digitation does not appear to be linked to the different soil horizons.

The greatest variation between the two sites was within the O and Ah/Ea horizons. Generally the pores of the O horizon within the whole tree harvest soil have a large degree of irregularity with the opposite being true for the Ah/Ea and Eag horizons. The degree of irregularity was very similar within the B_S horizons of both sites.

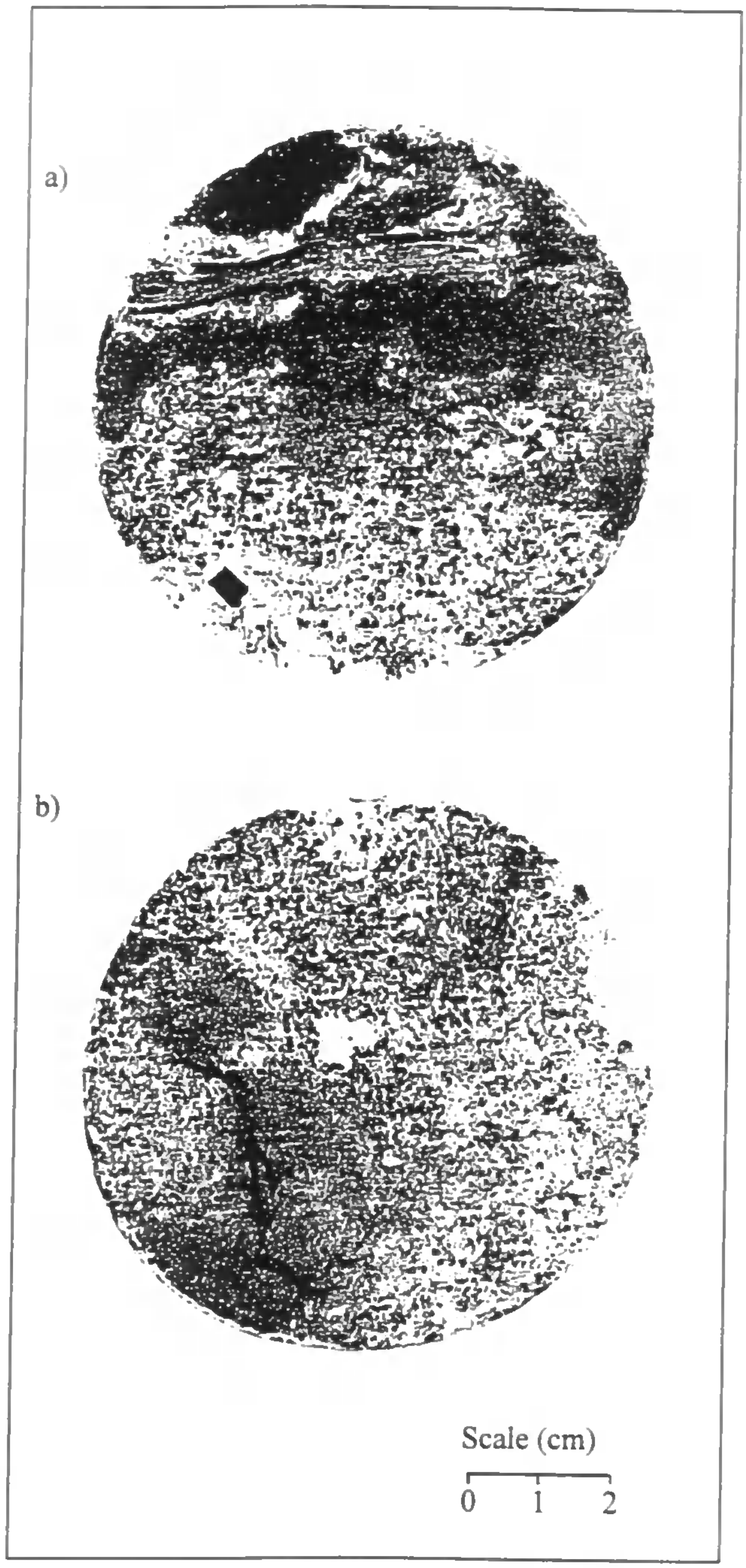


Plate 7.7 WTH O horizon replicate a (upper) & b (lower) at a depth of 1 cm

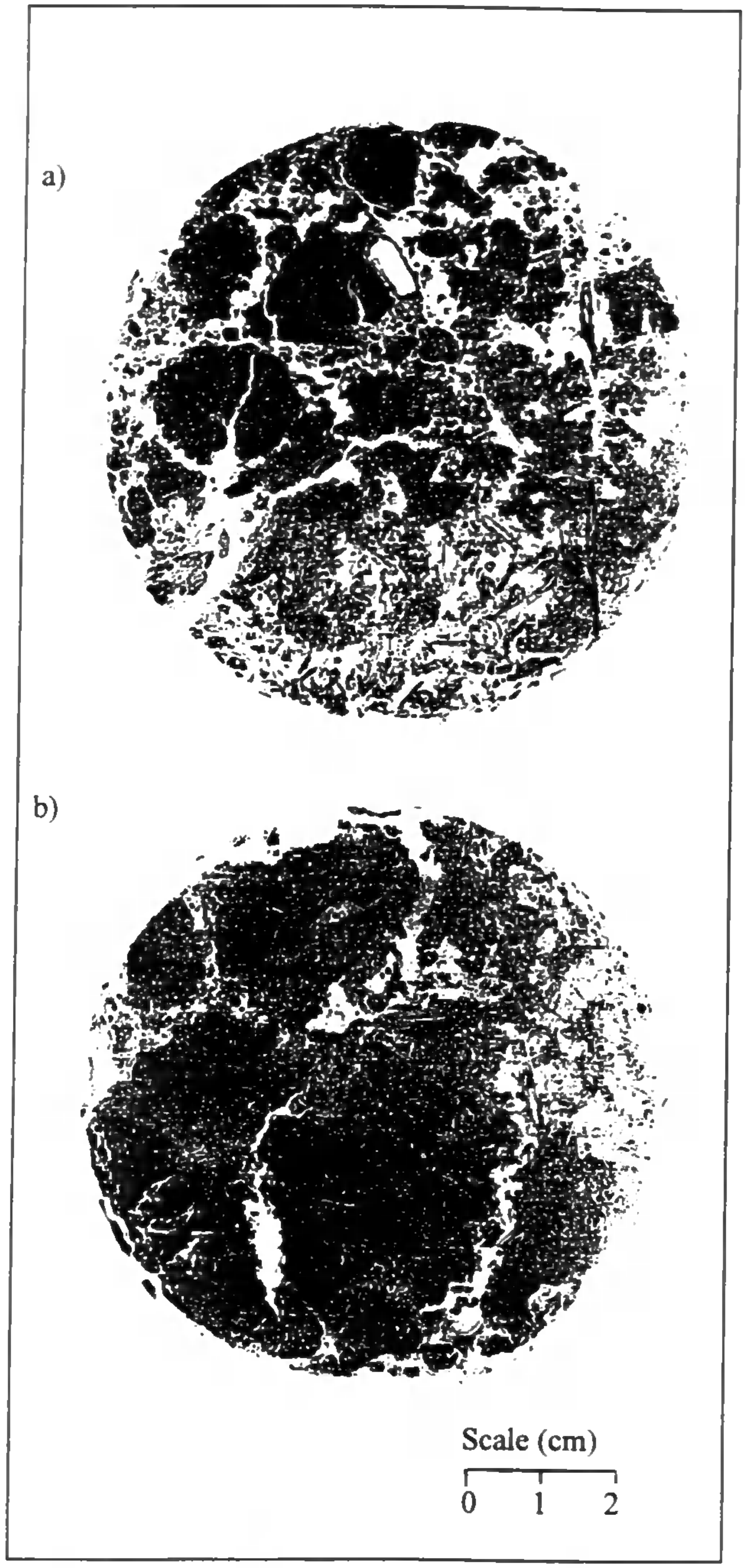


Plate 7.8 Forest O horizon replicate a (upper) & b (lower) at a depth of 1 cm

7.5 PORE DIMENSIONS AND POROSITY

Pore breadth will be used throughout this chapter as an indicator of pore size. Pore area, derived from the pore breadth (Pore area = πD), will then be used to calculate porosity:

where: D = diameter of the pore

Porosity = Pore Area / Frame Size (46 mm) x 100. (7.2)

Porosity will then be used to describe the soil structure.

7.5.1 Forest Pore Dimensions

The largest mean pore breadths at the forest site occur at 2, 4, 21 and 40 to 43 cm, which correspond to the O horizon, the border of the O & Ah/Ea horizons, and the Eag and B_S horizons respectively (Figure 7.5). Therefore, there was no direct relationship between the largest mean pore breadth and individual horizons. However, due to the technique of image analysis that was used to quantify pore breadth (Section 3.6.4), pores in very close proximity were probably being identified as coalesced (voids) rather than individual pores. The lack of extreme definition available with the image analyser without manual digitisation (an overly laborious technique given the sample numbers) therefore influenced pore breadth values. The lowest mean pore breadths at this site occurred from 8 to 11 cm which corresponds to the Ah/Ea horizon (Figure 7.5).

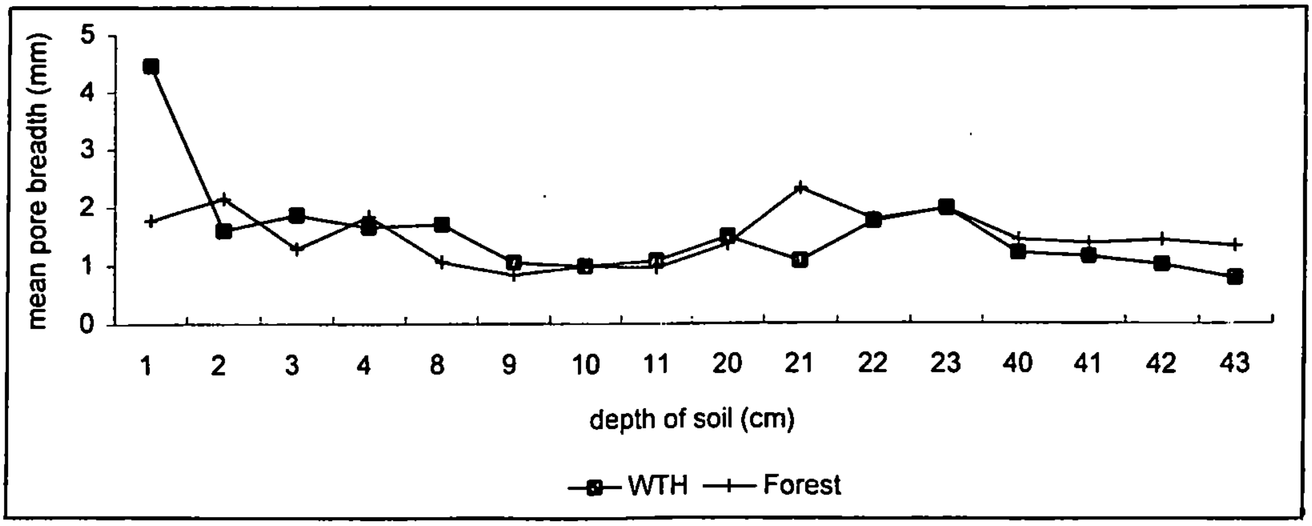


Figure 7.5 Mean pore breadth throughout the soil profile at both sites

Generally, the pores in the O horizon had a large mean pore breadth, indicating the loose structure of the organic layer (Plate 7.8). The Eag horizon (20 to 23 cm) had a much higher mean pore breadth of 1.8 mm (Plate 7.5) compared to the 1 mm breadth of the overlying Ah/Ea horizon (4 to 8 cm) (Plate 7.3a). Plate 7.3b illustrates that the higher breadth value was due to the tightly packed matrix surrounded by distinctive cracks. The B_S horizon had a mean pore breadth of 0.7 mm, which was midway between the values for the Ah/Ea and Eag horizons. A very open crumb structure (Plate 7.9) and the pore space around the slate fragments may have influenced the value for the B_S horizon.

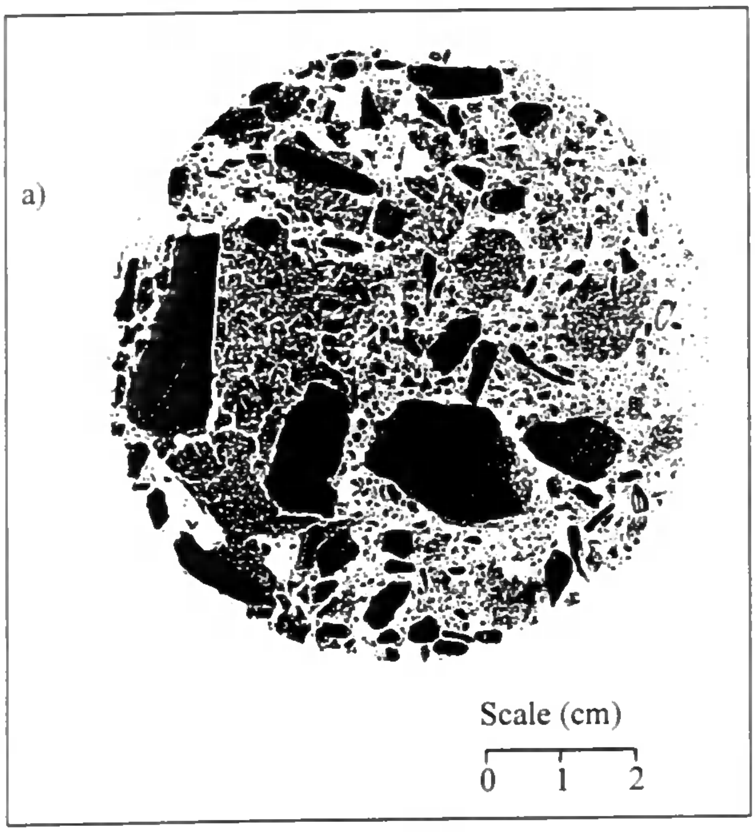


Plate 7.9 Forest B_S horizon replicate (a) at a depth of 43 cm

Mean Soil Porosity

Porosity at the forest site ranged from 6 % in the O horizon to 45 % in the Eag horizon (Table 7.3).

Table 7.3 Mean Soil Porosity at Both Sites

Soil Horizon	Porosity (%) Forest	WTH
O	6 to 44	27 to 59
Ah/Ea	7 to 21	18 to 38
Eag	22 to 45	18 to 45
B_S	25 to 33	8 to 24

The values for porosity shown in Table 7.3 are low, especially when considering the K_S value which was high at the forest site, therefore they must be treated cautiously. The small sample area (Section 3.6.4) may not be representative of the soil horizon. Porosity was high in the O horizon, declined in the Ah/Ea horizon and, from a depth of 9 cm, gradually increased to reach a peak of 45 % at 23 cm. Porosity then dropped to 25 % at 40 cm and remained constant at 32 % from 41 to 43 cm (Figure 7.6). With the exception of the organic layer, the greatest porosity was in the Eag and Bs horizons.

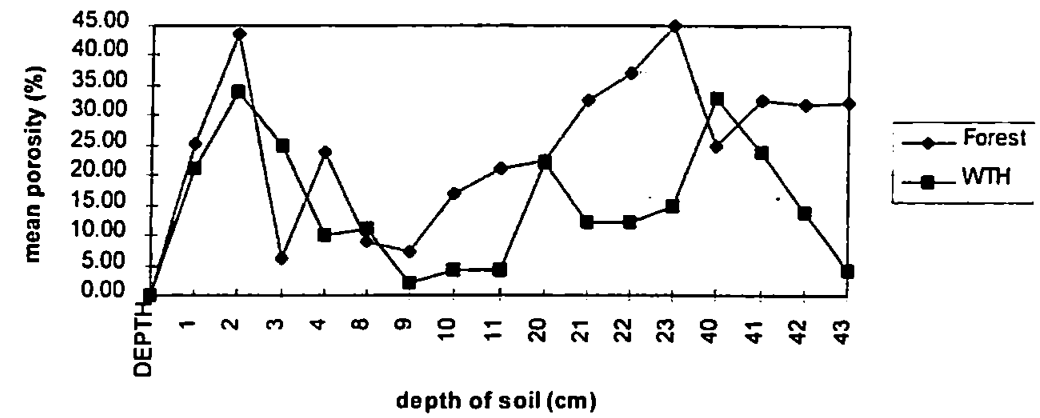


Figure 7.6 Mean porosity throughout the soil profile at both sites

In summary, the porosity was high in the O horizon, there was an impeding layer at 8 and 9 cm (Ah/Ea horizon), increased porosity of 45 % at 23 cm (Eag horizon), and a constant and lower porosity of 32 % between 41 and 43 cm (Bs horizon).

7.5.2 Whole Tree Harvested Pore Dimensions

Mean Pore Breadth

Mean pore breadth of the first resinated sample slice was 2.23 mm, which was considerably larger than the mean of any of the other slices in this soil profile (Figure 7.5). The first layer of soil was very loose and unconsolidated possibly as a result of sampling which will have influenced this value for pore breadth. The next four slices corresponding to 2, 3, 4 and 8 cm depth respectively all had a mean pore breadth of approximately 0.85 mm. At 9 cm, the mean breadth of pores dropped to approximately 0.5 mm.

The linear increase in mean pore breadth from 0.75 mm at 20 cm depth to 0.99 mm at 23 cm depth is interrupted by a decrease to 0.55 mm at 21 cm depth. This aberration could be due to the full planar structure not being represented. From 40 cm depth to 43 cm there was a steady decrease in mean pore breadth from 0.61 mm to 0.40 mm. The largest mean pore breadths, other than that of the first sample, occur in the O and surface of the Ah/Ea horizon (3, 4, and 8 cm depth) and in the Eag horizon (22 cm and 23 cm depth). The smallest pores occur at 9, 10, and 11 cm depth which correspond to the Ah/Ea horizon and in the B_S horizon (40 cm to 43 cm depth).

The pattern of change of mean pore breadth with depth at the forest site was similar to that at the whole tree harvested site. Accepting the possibly erroneous first sample at the WTH site, the greatest difference between the two sites occurred at 21 cm, where the mean pore breadth increased at the forest site to 1.2 mm and decreased at the whole tree harvested site to 0.5 mm.

Mean Soil Porosity

Porosity ranged from 8 % in the B_S horizon to 59 % in the O horizon. High porosities were also found at 22 cm (42.7 %) and 23 cm (44.5 %) depth (Figure 7.6), which corresponded to the Eag and B_S horizons. Within each horizon there was a considerable range in porosity (Table 7.3). The B_S horizons (Plate 7.10) had the lowest porosity value at

43 cm, where the soil was compact and the voids occurred as cracks around the slate particles.

Similar to the whole tree harvested site, there was a peak in forested site porosity data at 2 cm (Figure 7.6). The remainder of the forest soil profile was different in terms of porosity compared to that of the whole tree harvested site. The forest soil had lower porosities and less range within each horizon. The mean soil porosity data, derived from pore breadth measurement, is different when compared to that derived from gravimetric testing (Table 2.5 and Table 2.7). This difference could be due to the small scale of pore breadth investigation used in this study not producing the true values of porosity. If the same technique were to be used, but more samples of a greater size analysed, a more accurate and representative result may be achieved.

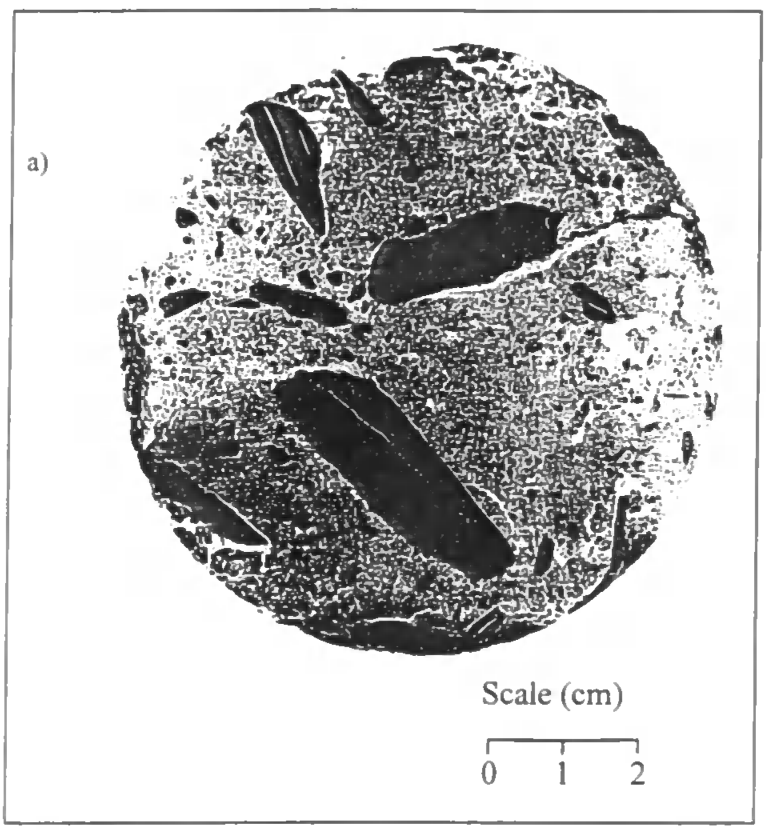


Plate 7.10 WTH B_S horizon replicate (a) at a depth of 43 cm

7.6 TYPES OF PORES

For this study, four main types of pores have been classified:

Very small (<0.01 mm)

Micropores (0.01-0.05 mm)

Mesopores (0.05-2 mm)

Macropores (>2 mm)

In terms of water movement the latter three are of prime importance. This chapter will use these definitions of pore size. Luxmoore *et al.* (1990) researched the detailed functions of pore size and his findings were taken into account during the classification of the pore types present at the study sites.

7.6.1 Type of Forest Pores

Total Number of Pores

The total number of pores ranged from 36 per 46 mm x 46 mm frame (1.7 pores/cm^2) in the O horizon to 126/frame (6.0 pores/cm^2) in the Ah/Ea horizon (Table 7.4).

Table 7.4 Range in Total Number of Pores at Both Sites

Total Number of Pores				
Soil Horizon	Forest Per 46 mm^2	Per cm^2	Per 46 mm^2	WTH Per cm^2
O	36 to 48	1.7 to 2.3	8 to 30	1.4 to 0.4
Ah/Ea	46 to 126	2.2 to 6.0	12 to 20	0.6 to 0.9
Eag	34 to 56	1.6 to 2.7	30 to 70	1.4 to 3.3
Bs	72 to 94	3.4 to 4.4	60 to 145	2.8 to 6.9

The greatest variability occurred in the Ah/Ea horizon where the number of pores increased sharply from 46 pores/frame (2.4 pores/cm^2) at 8 cm to 126 pores/frame (6.0 pores/cm^2) at 11 cm depth. Within the Eag horizon, the total number of pores reduced to an average of 50 pores/frame (2.4 pores/cm^2), then the number of pores increased again in the B_S horizon to an average of 82 pores/frame (3.9 pores/cm^2), which was lower than the maximum in the

Ah/Ea (Figure 7.7). In summary, the total number of pores reduced in the following order: Ah/Ea, B_S, Eag and O horizon.

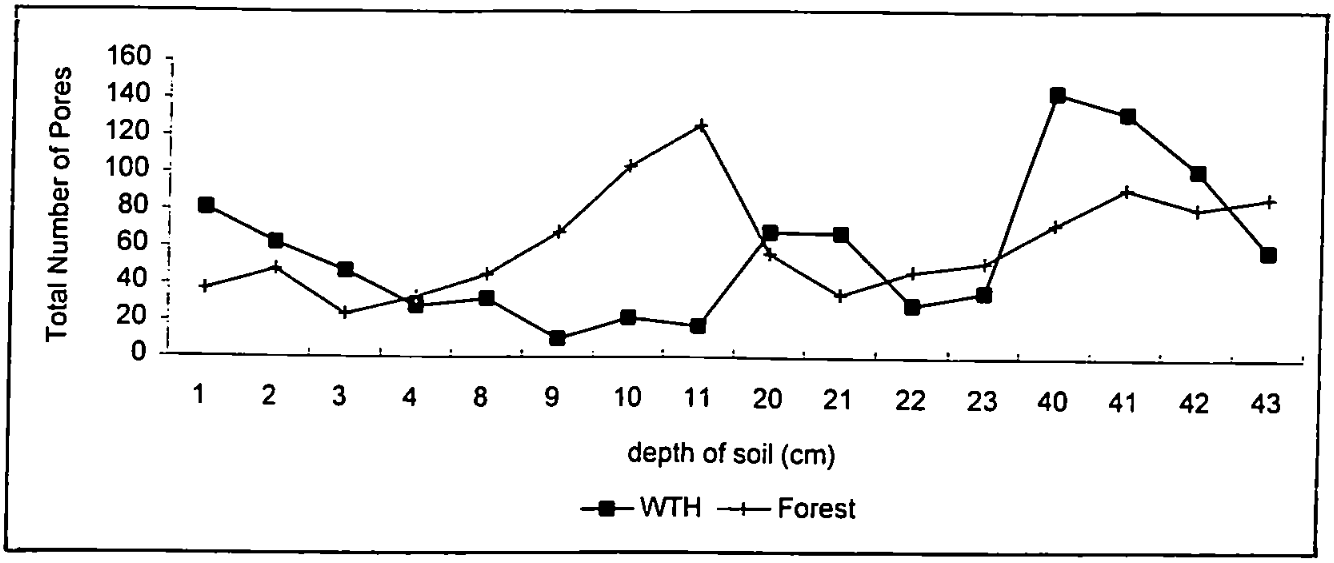


Figure 7.7 Total number of pores throughout the soil profile at both sites

Macropores

The percentage of macropores at the forest site fluctuated between 6 % in the Ah/Ea horizon and 38 % in the Eag horizon (Figure 7.8). The B_S horizon contained 16 % macropores, and the O horizon contained 20 % macropores.

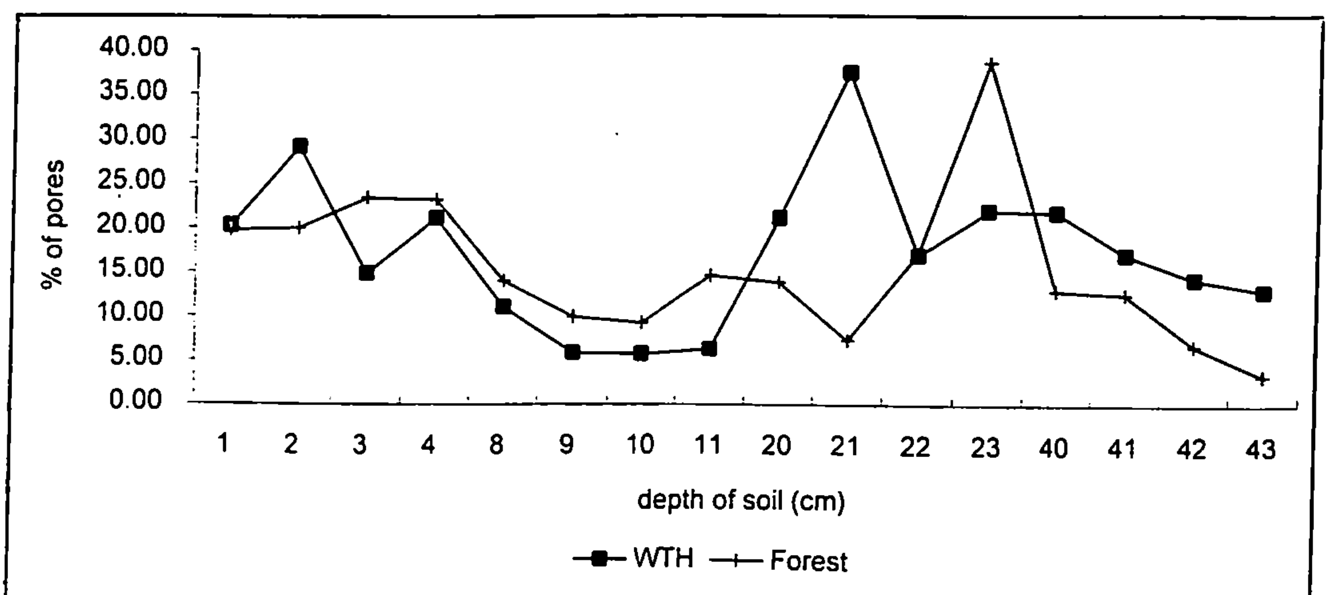


Figure 7.8 Percentage of macropores throughout the soil profile at both sites

Meso and Micro Pores

The majority of pores throughout the forest soil profile were mesopores. The presence of mesopores was greatest in the low porosity impeding layer at 11 cm, in the Ah/Ea horizon, with 93 pores/frame (Figure 7.9).

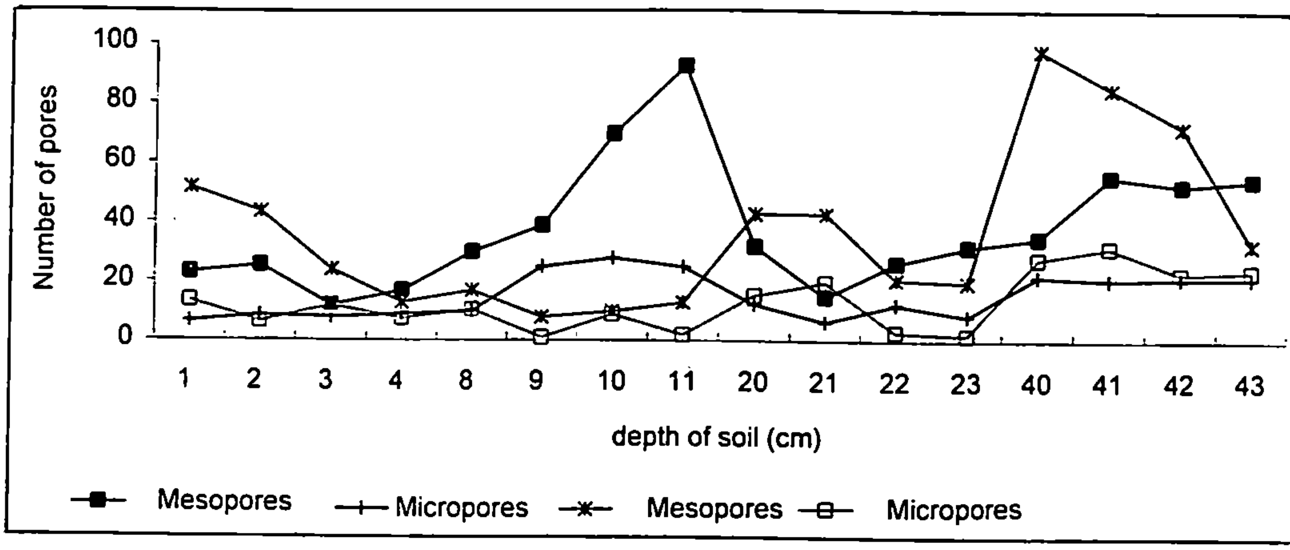


Figure 7.9 Number of meso and micropores throughout the soil profile at both sites

7.6.2 Type of Whole Tree Harvested Pores

Total Number of Pores

The number of pores varies considerably throughout the soil profile from 8 pores/frame (0.4 pores/cm^2) in the O horizon to 145 pores/frame (6.9 pores/cm^2) in the B_S horizon (Table 7.4 and Figure 7.7). There was a reduction in the number of pores from 81 pores/frame at 1 cm soil depth to 17 pores/frame at 11 cm, which corresponded to the O and Ah/Ea horizons. At 20 cm, in the Eag horizon, there was a sharp increase in the number of pores to 69 pores/frame, and then a sharp decrease at 22 cm. A substantial increase to 145 pores/frame occurred at 40 cm depth in the B_S horizon. There was a distinct difference between the total number of pores within the Ah/Ea and B_S horizons at the forest site compared to the whole tree harvested site (Figure 7.7).

Macropores

The percentage of macropores fluctuated throughout the soil profile in a similar manner to that in the forest soil. There were a high number of macropores (22 %) in the first 4 cm of soil (O horizon), which indicated the loose organic structure similar to the forest soil. At 21 cm within the Eag horizon, there was a sharp increase to 39 % macropores. The lowest percentage of macropores occurred at 43 cm in the B_S horizon.

Throughout the soil profile, the number of macropores reflected a similar pattern to the total number of pores. This similarity infers that there was a direct relationship and therefore it would be straightforward to model.

It can be clearly seen that there were similarities in pattern between sites at 4 and 11 cm and also 40 and 43 cm. There were slightly more macropores in the whole tree harvest soil compared to the forest soil. However, there were distinct differences between the two sites in the numbers of macropores from the surface to 4 cm and again between 11 and 23 cm depth. This could be due to different horizon thickness. Within the B_S horizon there were an average of 8 % more macropores in the forest soil compared to the whole tree harvested soil.

Meso and Micro Pores

The majority of the pores throughout the soil profile were mesopores. Figure 7.9 shows that the pattern of meso and micropores were very similar to the pattern of the total number of pores. The percentage of micro pores was reciprocal to the mesopores. The data for percentage of mesopore and micropore occurrence showed no pattern across the soil horizons. Although the data for number of meso and micropores produced peaks in different soil horizons, there was no statistically significant difference between the two populations.

7.7 SOIL STRUCTURE SUMMARY

Whole Tree Harvest Soil Structure

Pore Morphology

The pore shape is primarily elongated rather than round throughout the soil profile. Between a depth of 3 and 11 cm (Ah/Ea horizon), these pores could be described as planes due to their size and the surrounding densely packed soil matrix. Within two dimensions, the majority of soil pores were random in orientation. However, samples 3, 8, 11 and 22 had a slight preferred orientation. This result is due to the sample not being a representative elementary area (REA). The pores are irregular in their circumference, and the irregularity is random with depth.

Pore Dimensions

The largest mean pore breadths occur in the O and Ah/Ea horizons (1, 2, 3, 4 and 8 cm depth) and also in the Eag horizon (22 and 23 cm). The lowest mean pore breadths also occur in the Ah/Ea horizon (9 and 11 cm) and the B_S horizon (40 - 43 cm). The highest porosities occur in the O, Eag and B_S horizons, and the lowest porosities occur in the Ah/Ea horizon.

Table 7.5 Range of Transmission Pores at Both Sites

Horizon	Range of Transmission Pores Forest Soil	WTH
	%	%
O	51 to 62	46 to 70
Ah/Ea	57 to 74	47 to 80
Eag	43 to 62	56 to 72
B_S	48 to 63	56 to 71

Types of Pores

The total number of pores reduces from the surface with 81 pores to just 17 pores at 11 cm depth at the base of the Ah/Ea horizon. There is a slight increase in pores in the Eag horizon, but the biggest increase occurs in the B_S horizon at 40 cm, where there are 145 pores. Thereafter the number of pores decreases with depth. The number of macropores with depth follows a similar pattern with the greatest number of macropores occurring in the Eag and B_S horizons. Macropores represent between 6.8 % and 38.9 % of total pores, which is a wide range. Transmission pores dominate the majority of the soil profile. However, transmission pores exist in the lowest numbers in the O, borderline Ah/Ea, and Ah/Ea horizon. For the majority of the soil profile, there are more storage pores than macropores, the highest numbers being present at 11 and 43 cm, which is the Ah/Ea and Bs horizons.

7.8 SUMMARY

The forest and WTH sites have the same soil type, but the Ah/Ea to B_S horizons at the forest site have slightly higher porosities than those at the whole tree harvest site. The lower porosity of the Ah/Ea horizon at the whole tree harvest site was explained by soil texture differences, but the Eag and B_S horizons have the same texture at both sites. Pedal structure (in terms of ped roughness) of the Ah/Ea horizon was the same at both sites. Limited sampling found smaller peds within the Ah/Ea horizon of the forest soil compared to the whole tree harvest Ah/Ea horizon. Interpedular cracking, inferred by smaller peds, would promote water movement if saturated conditions were to occur. In terms of water movement, more interpedular cracks at the forest site would result in a higher K_S value than at the whole tree harvest site. This conclusion supports the findings of Chapter 6 where K_S was greatest at the forest site. Since there were no significant differences in soil type or pore morphology, these differences in the number of inter-pedular cracks must be a result of the differences in roots. At the forest site there were more cracks and also live tree roots exist, whereas at the WTH site there were fewer cracks (inferred by larger peds) and decaying roots which were no longer active. Further research is required to establish the exact effect dying and decaying roots have on soil structure. Research which must include the lower Eag and B_S horizons.

Work by Deeks (1995) using Pouiseille's Law utilised the number and size of pores per cm^2 to calculate flux. Further research may investigate the viability of using Pouiseille's Law to predict flux at the Beddgelert site. If this research were to be successful it would be crucial to establish whether any soil saturation occurs spatially (i.e. root flow) or temporally (i.e. peak storm flow). During these scenarios, inter-pedular cracks or macropores would be active. To fully characterised the soil structure, a sampling strategy would be required to represent any variations in inter-pedular cracks throughout the soil profile.

Throughout the soil profile, pore shape, orientation and mean pore breadth were similar at both sites. The removal of trees and therefore the decaying root systems have not changed the pore shape, orientation or mean pore breadth. Although the degree of pore irregularity was similar at both sites in the B_S horizon, the irregularity was greater in the forest Ah/Ea and Eag horizons compared to the whole tree harvest site. The only difference between these two sites are trees which therefore may be responsible for the varying pore irregularity. It is unlikely that pore irregularity has had any influence over the differences in K_S because a greater irregularity in pore perimeter would cause greater resistance to flow and therefore a lower forest K_S, which is the opposite to what was measured.

Throughout the soil profile, the total number of pores was similar at both sites. Macropores, intermediate and micropores were similar at both sites. However, large voids surrounding tree roots would not have been identified at this small detailed scale.

This chapter has identified that research which includes measurements of peds provides a greater understanding of saturated soil water movement than that which concentrates on the more detailed micromorphological scale. Measurements at this detailed scale provided quantitative pore morphology data for comparative purposes which established that there were no significant differences between the forest and WTH site. However, this research has not been able to relate this information to soil water mechanisms operating under unsaturated flow. Further research must focus on quantifying the range of pore sizes that do saturate at different times of the year and at different times during a storm.

This investigation has also identified that an appropriate scale must be used otherwise important data is lost. The use of semi-variograms in Chapter 6 illustrated the usefulness and appropriateness of that technique for identifying the scale at which greatest variability occurs. Different variables have different scales of variability and therefore require different scales of investigation for them to be deemed appropriate.

If a link could be found between these different scales it would enable soil characteristic data at one scale, i.e. a section of hillslope, to provide predictions on another scale, i.e. the catchment scale. Fractal dimensioning is a technique that allows the comparison in self similarity of features between different scales. These data have shown that the fractal dimension of peds was the same at both sites, and it was the frequency of interpedular cracks which was important. Therefore, to investigate the frequency of interpedular cracks, the distance between these cracks should be measured, which means sampling at a larger scale to encompass the REA. However, these cracks are only important when saturated conditions exist and this research did not identify saturated conditions. Therefore the scale of investigation needs to be reduced rather than increased, and another feature analysed for self similarity. A range of smaller scales is required to identify the point at which self similarity of the soil can be established which would allow soil water prediction at a larger scale of self similarity. If a feature could be identified that displays self similarity at a range of scales, for example, topography, aggregate, ped and pore. Then it is possible to use this easily definable and quantifiable ped or pore scale, where few variables exist to define, quantify and produce predictions at the topographic scale. For example, if a ped of size/fractal dimension z exists predominantly at a site, is it reasonable to assume that the catchment will behave in a certain way, or is the interference from the infinite number of variables going to stop the prediction?

CHAPTER 8

DYE STAINING AND SOIL WATER MOVEMENT

8.1 INTRODUCTION

The aim of this Chapter is to describe the flow route through the upper three soil horizons at both sites using a staining dye, Methylene Blue (C16H18CLN3S.2H2O). As staining techniques are essential in establishing continuity patterns in soil water pathways, the following two experiments will facilitate an understanding of the flow mechanisms operating at the research site. Section 1.7 includes further information about dye tracers.

Three fundamental assumptions must be appreciated concerning dye staining experimentation. First, it must be stressed that all the dye staining experiments were carried out under saturated or near saturated conditions. Although the experiments only represent one aspect of the water content regime, they are comparable with K_S measurements in that the results are accurate only under near saturated and saturated conditions. Second, it is impossible to distinguish travel rates (i.e. whether the dye has been moving quickly, slowly, or has ceased movement altogether). The third problem is it is uncertain whether Methylene Blue is preferentially adsorbed by organic matter and clay particles, (see Bouma *et al.* (1979) for further discussion).

This Chapter will identify whether vertical or lateral flow exists in the upper three horizons and establish whether preferential flow exists, where and how important it is. These points will be discussed for the forest site and the whole tree harvested site separately.

8.2 SOIL WATER MOVEMENT

The experiment was carried out at the WTH site on an area of soil where the grass had been removed to reduce the dilution effects of the vegetation cover. Following infiltration of the dye, the site was excavated in stages to reveal the dye pathways. Three vertical sections were made within the infiltrated area of soil and three downslope from this area each excavated to a progressively greater depth.

8.2.1 Forest Soil Water Movement

The litter layer was gradually removed to reveal a fairly densely stained organic horizon, with a few bare patches (Plate 8.1). Vertical digging was prevented by a very large root network. The core of this root network was subsequently removed from the Ah/Ea horizon (Plate 8.2). Blue dye was mainly concentrated around the root itself, suggesting water flow along and down the root network. Plate 8.3 shows that where the core of the root was situated, there was very little blue dye in the surrounding Ah/Ea soil matrix.

Plate 8.1 Forest O horizon

Plate 8.2 Large root system from within the forest Ah/Ea horizon

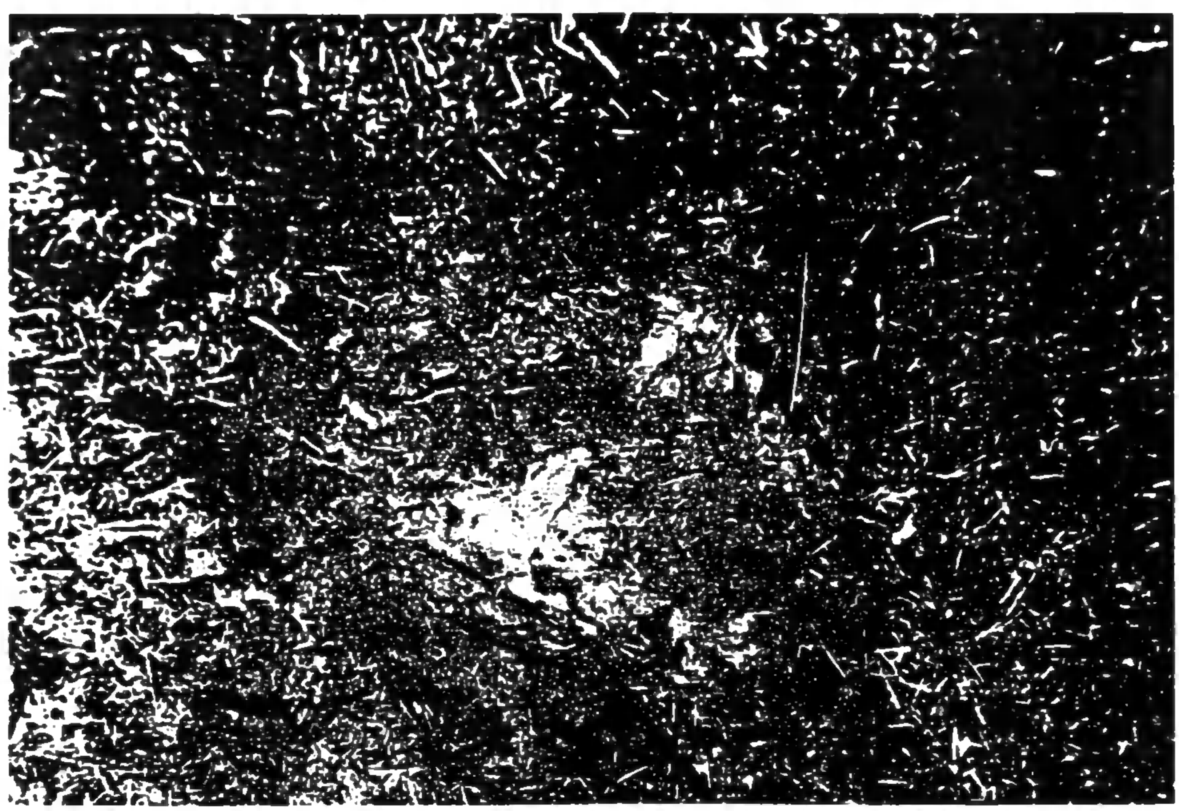


Plate 8.3 Soil immediately below the extracted root system at the forest site

Within the Ah/Ea horizon, there was a distinct hexagonal cracking pattern, which was enhanced by blue dye. Blue dye has flowed into the cracks and seeped into the immediate surrounding soil matrix (Plate 8.4). Each hexagonal ped was approximately 3 cm in diameter. There was a thin horizontal piece of slate 10 cm x 12 cm, which was removed along with a 1 cm of soil across the plot to reveal that no dye had penetrated to below the slate (Plate 8.5). However, the dye around the cracks had intensified in the area surrounding the slate suggesting a preferential pathway using the network of cracks. Therefore, the impervious slate has probably deflected the flow of dye into the cracks surrounding the slate. At the base of the Ah/Ea horizon, the hexagonal cracks were much larger, approximately 9 cm in diameter, but still they were stained by blue dye (Plate 8.6). An element of soil water was therefore moving preferentially vertically through the Ah/Ea and Eag horizons to the B_S horizon via the crack network.

Plate 8.7 revealed the top of the Eag horizon and a root system which was intensely stained blue. This result confirms that the dye loaded water had travelled along the root system.

Plate 8.4 Slate in forest Ah/Ea horizon

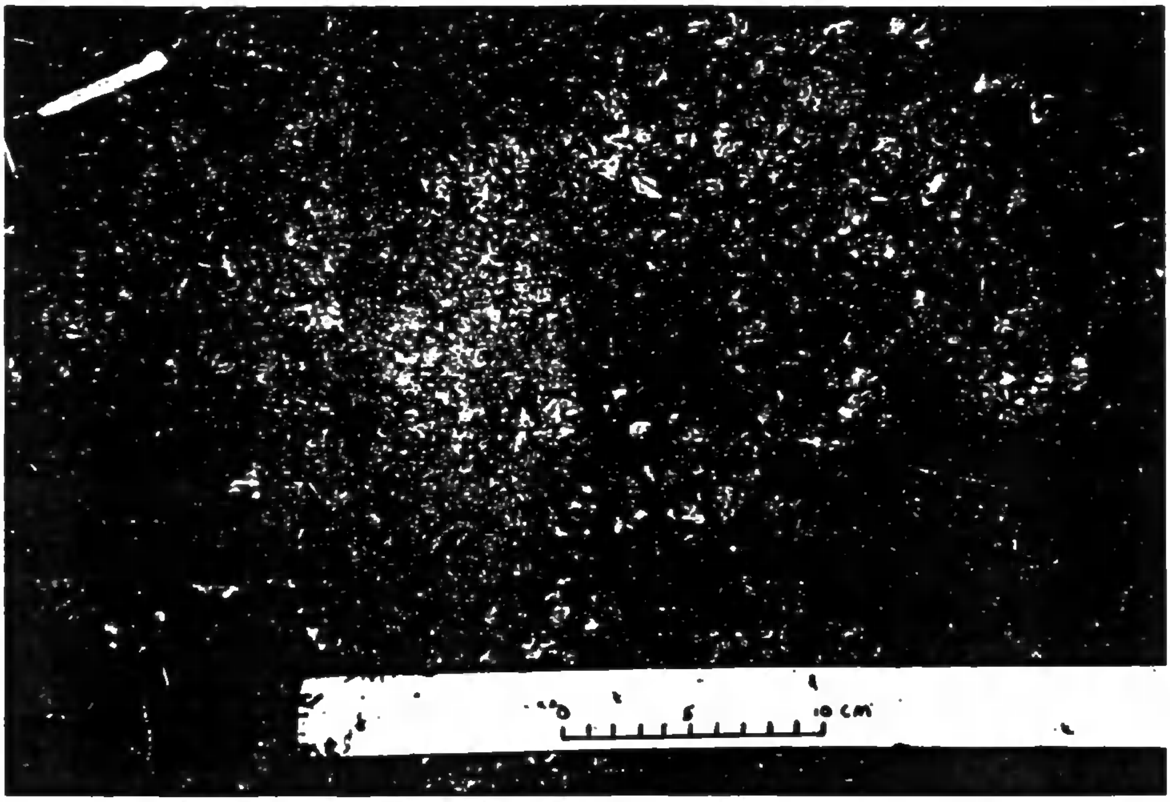


Plate 8.5 Forest Ah/Ea horizon below the slate

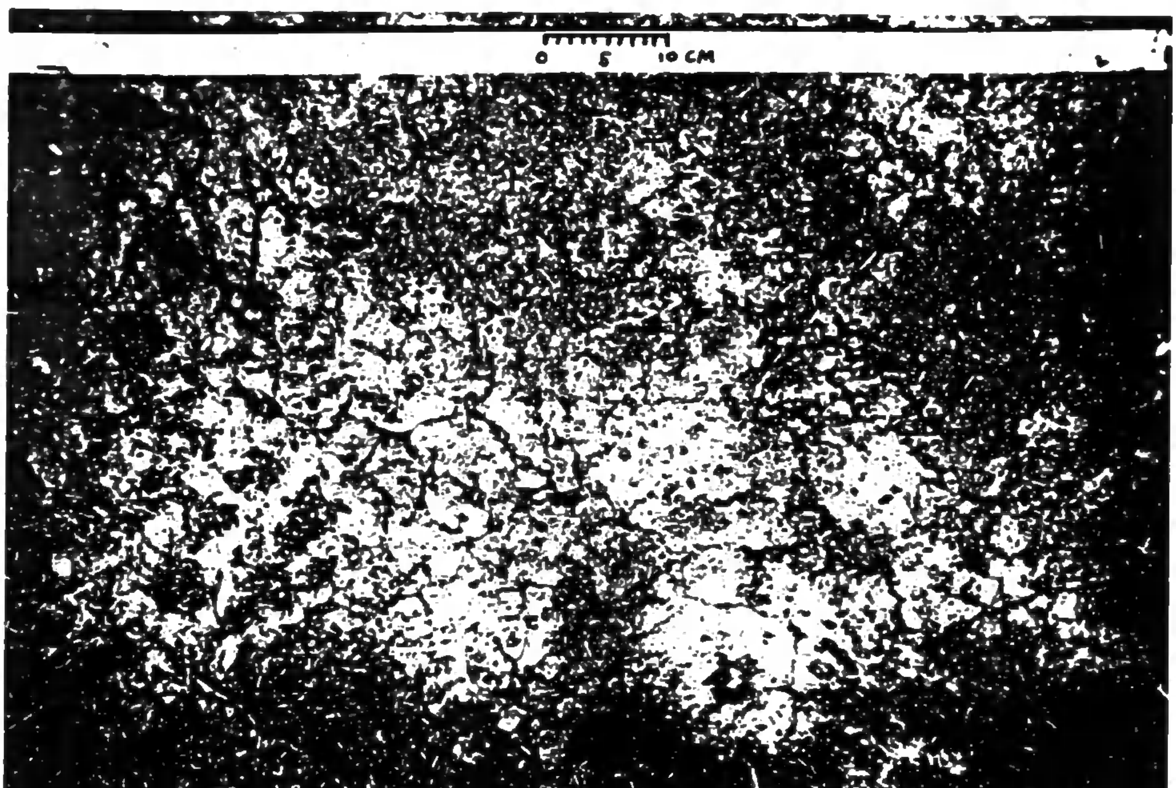


Plate 8.6 Forest lower Ah/Ea horizon

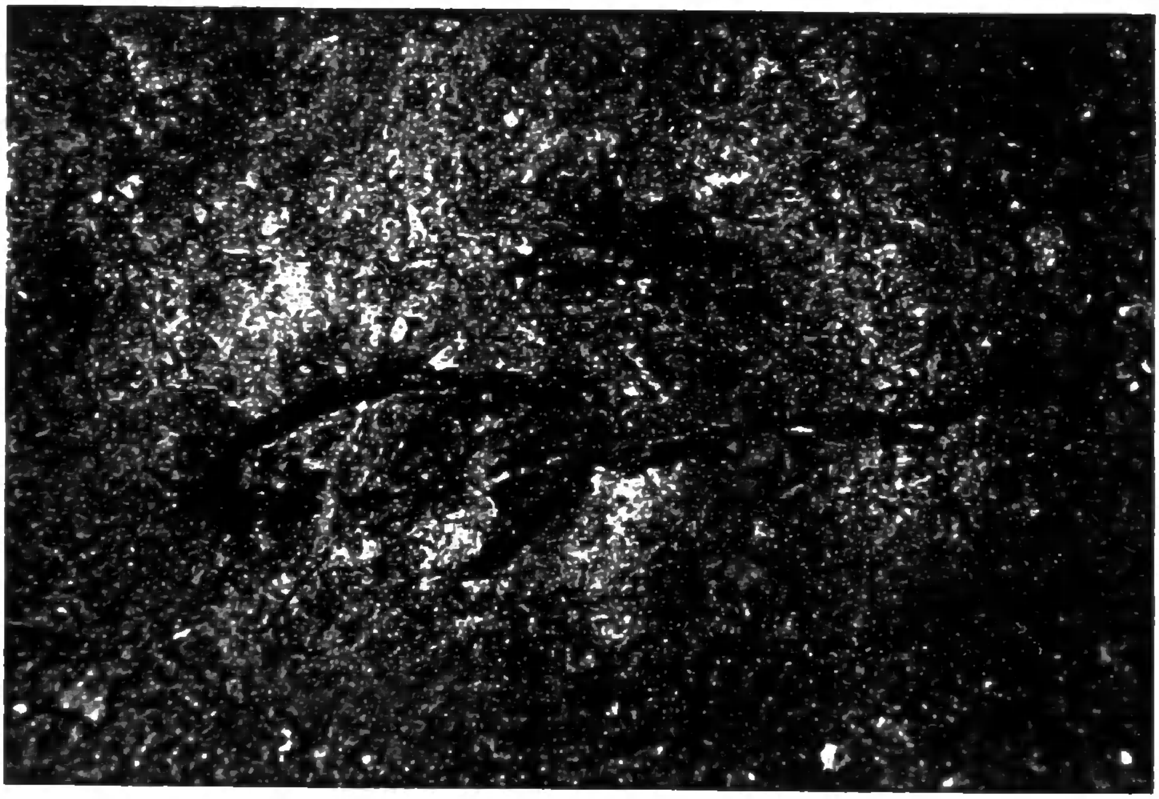


Plate 8.7 Forest Eag horizon

8.2.2 Whole Tree Harvested Soil Water Movement

The soil organic layer (top 2.5 cm) was saturated by the dye. The uniformity of blue dye was clearly shown at the top of the Ah/Ea horizon in Plate 8.8. Therefore the diluted dye flowed uniformly through the O horizon's pore structure without following any preferential pathways until it reached the relatively impeding Ah/Ea Horizon surface (Plate 8.9). At 5 cm depth, because the dye was weaker in colour and appeared in patches but of a more regular nature vertical cracks may exist in the Ah/Ea horizon. All the protruding roots had blue stains on them, particularly a large horizontal root to the left of Plate 8.9.

At 6 cm, there was a break in excavation caused by a piece of 10 cm x 5 cm quartz (Plate 8.10). The obstruction was carefully removed to a depth of 14 cm. Plate 8.10 shows dye had apparently accumulated on the upper horizontal face of the rock, which was confirmed when removing the rock (Plate 8.11). Immediately above this rock, there was a layer of dye in the soil. However, it was not uniformly distributed (Plate 8.11). The line formed the base of the Ah/Ea horizon. A soil segment, situated above the cavity formed when the rock was removed, (Plate 8.11), was separated from the main soil body due to cracks. This soil fragment was saturated with blue dye. The dye had travelled through the cracks, allowing the surrounding soil matrix to be stained by the dye. When the rock was removed, patches of dye were revealed in the soil to the bottom of, and near the front of the rock, which was in the Eag horizon. These patches produce a curved pattern, with the left side appearing to join up to the previously mentioned isolated fragment of soil (Plate 8.12).

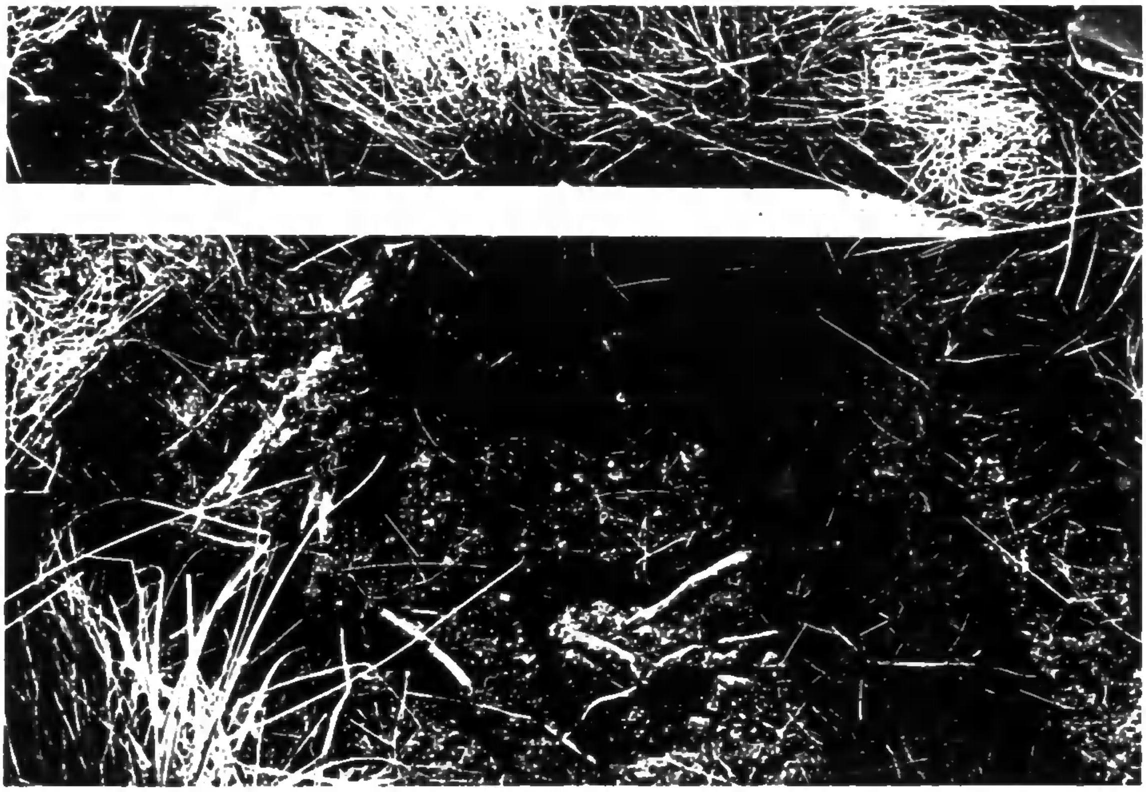


Plate 8.8 Base of whole tree harvested O horizon

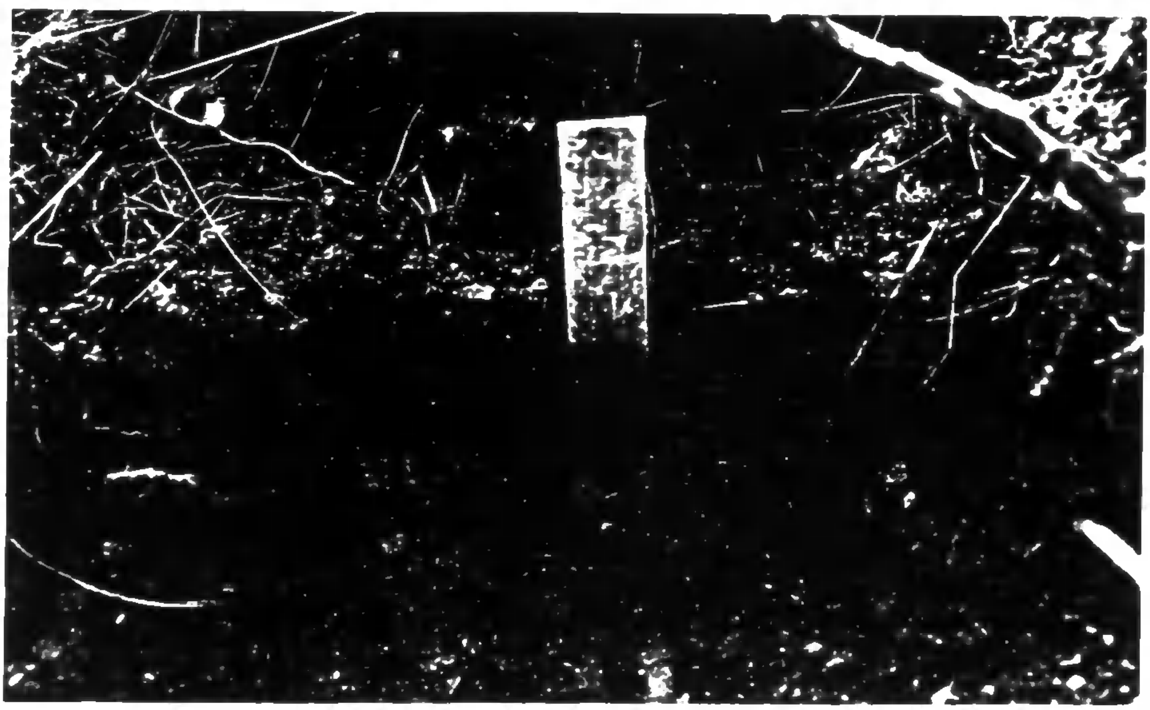


Plate 8.9 Whole tree harvested Ah/Ea horizon

Plate 8.10 Quartz in the whole tree harvest Ah/Ea horizon

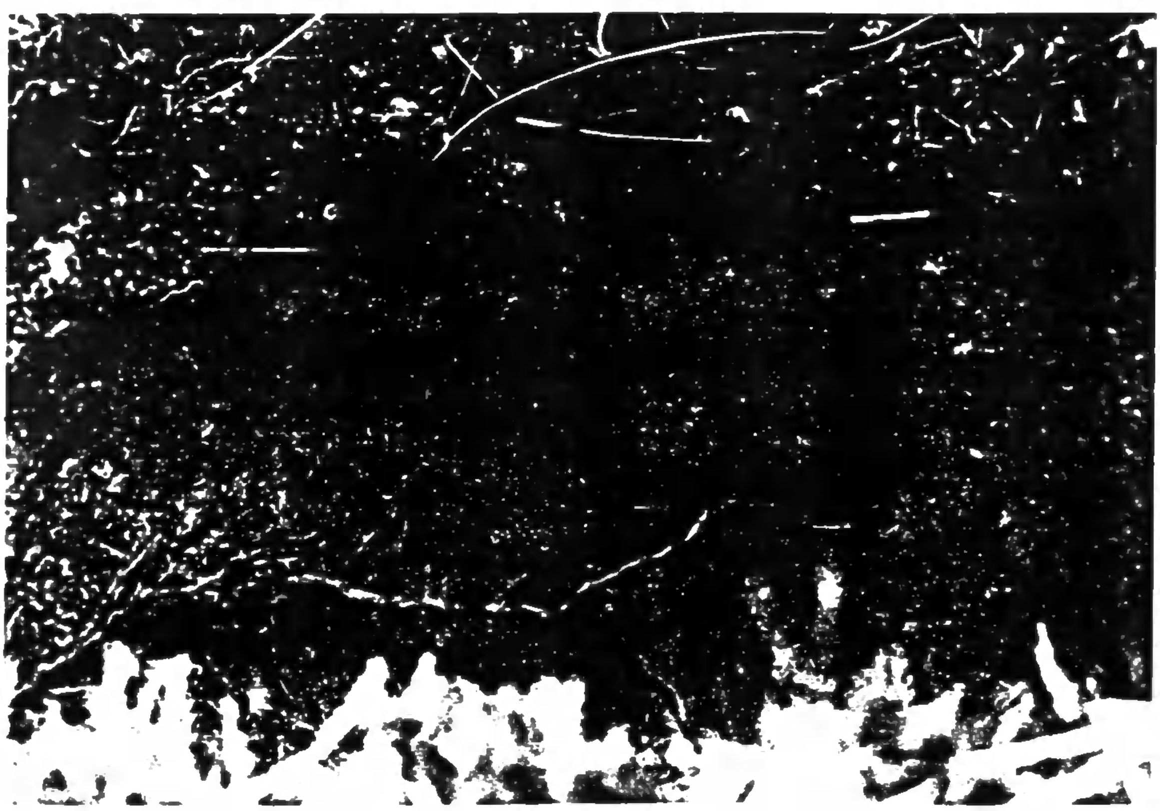


Plate 8.11 Quartz void in the whole tree harvest Ah/Ea and Eag horizons

At the bottom of the elluviated horizon (the division between the Ah/Ea and Eag horizons), to the right of the rock, there was a faint blue horizontal line (Plate 8.11). Also apparent from Plate 8.11 are two tree roots covered in dye, these have a diameter of 1 cm (previously discussed root) and 0.5 cm. There were many smaller roots, with a diameter of about 0.2 cm, which have no dye or only very small amounts of dye on them. The absence of dye on these roots does not necessarily suggest less preferential flow compared to the larger roots as reduced concentration of dye also shows this effect.

At the interception of the Ah/Ea and Eag horizon, a block of soil was carefully removed (Plate 8.12). The block that was removed also had large cracks within it, one horizontal and one vertical (Plate 8.13) Both cracks were intensely covered in dye again supporting the theory of preferential flow via cracks in this region. Excavation was continued vertically, until a depth of 19 cm was reached. A patch of dye 12 cm below the surface and scattered patches between 14 and 19 cm depth were revealed. At this depth (B_S horizon), a band of dye 20 cm x 15 cm existed in the middle of the pit floor which was fairly diffuse in nature suggesting matric flow (Plate 8.14).

Plate 8.12 Division between whole tree harvest Ah/Ea horizon and Eag horizon

Plate 8.13 Vertical cracks in the whole tree harvest Ah/Ea horizon and horizonal crack between the Ah/Ea and Eag horizon

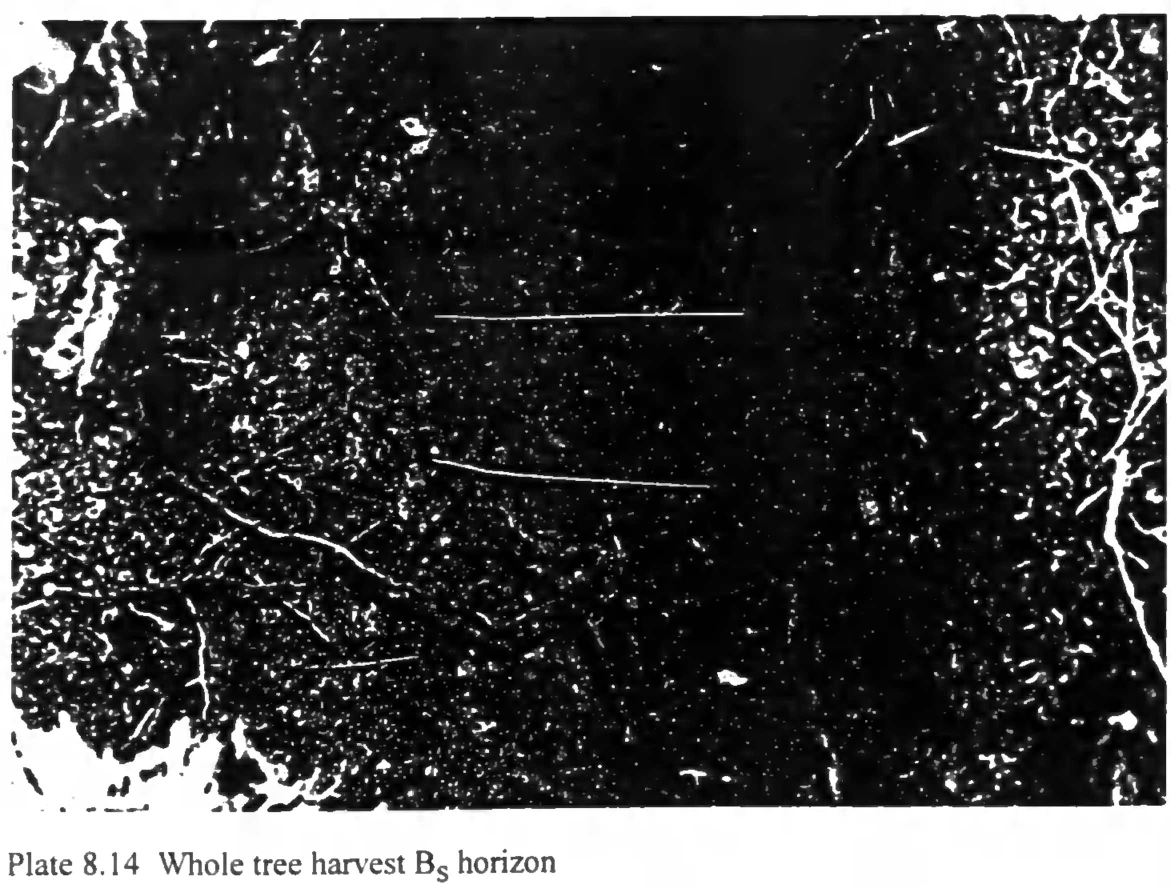


Plate 8.14 Whole tree harvest B_S horizon

8.3 WATER DISPLACEMENT

The experiment was carried out on an area 50 cm^2 with vegetation removed, 20 cm upslope from a cleaned vertical face. The area was defined on the ground with a quadrat and dye was sprayed onto the plot at an intensity of 20 ml per minute for 40 minutes.

Due to the difficulty of digging the soil any deeper than 30 cm, this second experiment was designed to see what happened at a greater depth and indicate whether existing soil water was displaced.

8.3.1 Results

Ponding occurred on the surface approximately 10 minutes after applying the dye and therefore surface saturation existed. Six minutes after spraying, seepage of clear water was observed at the vertical face. However, the seepage was not spatially or temporally uniform (Plate 8.15). Water was seeping out of a band 15 cm deep 2 cm above the shale (Ah/Ea, Eag and B_S horizons), within the band there was still heterogeneous flow. Flow started earlier in some areas and as time elapsed these areas had a greater volume seeping from them than other areas within this band. The blue dye also emerged first in the same areas which first experienced seepage. As time elapsed, the colour intensity of the blue water increased. These results support earlier findings that a range of pore sizes were operating, i.e. the larger pores drained first followed by medium and smaller pores.

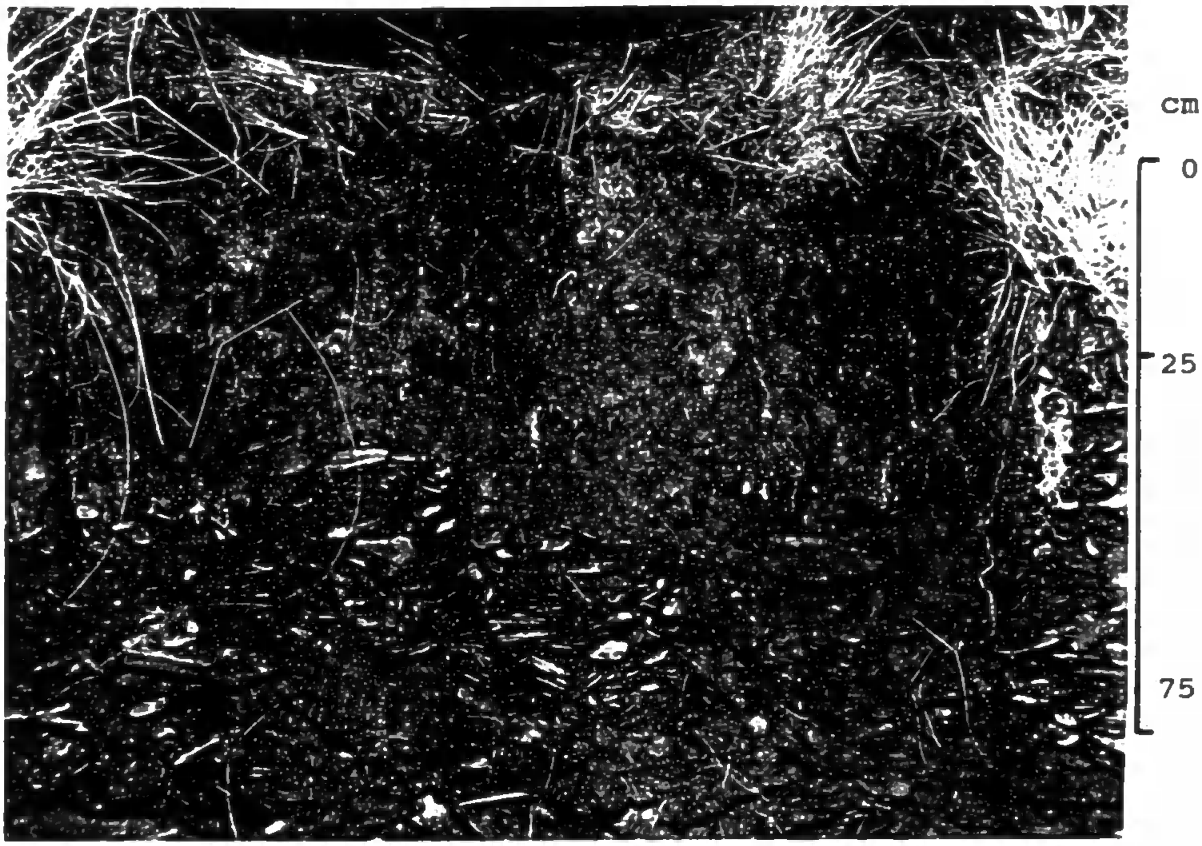


Plate 8.15 Whole tree harvest soil profile

8.4 SUMMARY

Water moved uniformly through the organic horizon at both sites. However, water did not move uniformly throughout the Ah/Ea and Eag horizons, but rather moved preferentially through various pathways. At both sites in the Ah/Ea horizon, soil water has moved through cracks, and along tree roots and tree branches. Water travelled along these cracks, roots and branches regardless of the angle they lay in.

At the whole tree harvested site, there was a distinct division in the form of a crack between the Ah/Ea and Eag horizons. This horizontal boundary crack joined regular vertical cracks in the Eag horizon, which were formed in a hexagonal pattern when viewed in cross-section. From a flat view, these vertical cracks form a hexagonal pattern. A hexagonal crack network was also found at the forest site in the Ah/Ea and Eag horizons.

Table 8.1 Summary

Whole Tree Harvested Site	Forest site
O Horizon Dye has moved uniformly	O Horizon Dye has moved uniformly
Ah/Ea Horizon Dye has moved preferentially along tree roots/brash and cracks	Ah/Ea Horizon Dye has moved preferentially along tree roots
Division Between Ah/Ea & Eag Horizons The division between these horizons formed a horizontal crack with blue staining	Not Observed
Eag Horizon Dye has moved vertically through a network of hexagonal cracks	Eag Horizon Dye has moved vertically through a network of hexagonal cracks, which increase from 2 cm to 9 cm with depth
	Upper Bs Horizon Dye has moved roots
Bs Horizon Patchy dye band suggesting soil matrix flow	Bs Horizon Patchy dye suggesting soil matrix flow

Within the B_S horizon at the whole tree harvested site, there was a band 20 cm x 10 cm of poorly defined areas of dye which suggested that soil water had infiltrated through the soil matrix rather than flowing preferentially. There were areas of little or no dye. However this lack of indicator does not necessarily mean there was no water movement (Bouma *et al.*, 1979). The lack of dye could be explained by either earlier organic/clay particle adsorption of the dye or the old water being displaced by the new blue water and the dye having not yet reached this area.

At the forest site in the upper B_S horizon, there was some evidence for preferential flow along tree roots. However, preferential flow evidence was not found lower in this horizon. Instead, poorly defined blue stains where found which suggests soil matrix flow.

At both sites, a degree of lateral soil water movement occurred because blue dye was found 25 cm downslope of application. However, this short distance may be explained by either water draining vertically, or due to adsorption of the dye. As discussed in Sections 5.5.1 and 5.7.1, the implicit nature of soil water movement in layered soils on steep slopes means that water moves laterally.

The second experiment showed that it was likely that the old water was displaced by new water. It also showed that water flowed preferentially down small openings and laterally just above the shale layer at a depth of 1 m.

In summary, the mechanisms governing soil water movement are the same at the whole tree harvested and forest site. Soil water moves uniformly through the O horizon, then a proportion of water moves preferentially through a network of hexagonal cracks which exist in the Ah/Ea and Eag horizons. These cracks are both inter-pedular and surrounding roots. More cracks occur at the forest site compared to the WTH site. This information confirms why K_S is higher in the forest where active roots exist. Matrix flow dominates the B_S horizon at both sites. A degree of vertical flow must occur, since there was evidence of lateral flow above the densely packed slate at a depth of 1 m.

CHAPTER 9

CONCLUSION

9.1 INTRODUCTION

This study was designed to investigate the effects of whole tree harvesting on hillslope hydrology, soil water pathways and soil structure at Beddgelert Forest, North Wales. Hydrological studies were undertaken to quantify precipitation, throughfall, stemflow, potential evapotranspiration, saturated hydraulic conductivity (K_S) and soil moisture status. Soil structure was characterised for the forest and whole tree harvested site. The final chapter will synthesise both the hydrological and pedological results and integrate them within a framework that examines the importance of the various controlling factors at different scales. Individual conclusions will be drawn together and discussed in broader terms to address their application to sustainable forest management and to relate them to research from similar upland sites. The discussion will highlight the main findings of the thesis and broaden the scope of this study. Where aims have not been fulfilled and where important questions still remain, a critique will be made. Finally, further research avenues and areas of improvement will be suggested.

9.2 OVERVIEW OF AIMS AND OBJECTIVES

The aim of the research study was to identify the effects of clearfelling, specifically whole tree harvesting, on site hydrology and soil structure at Beddgelert Forest. The investigation was put into the wider context of hillslope hydrology to establish which mechanisms govern soil water movement. Differences between forest and whole tree harvested upland sites were explored. In addition, this research highlighted the importance of studying flow phenomena at an appropriate scale.

The main objectives were as follows:-

1 To quantify and investigate the pathways of the hydrological inputs, outputs and soil recharge for a hillslope in Beddgelert Forest.

2 To establish and quantify the direction of soil water movement at both sites and to establish the relative importance of soil water pathways.

3 To assess and quantify the spatial variability of K_S within and between the two sites and relate the differences to management.

4 To describe and quantify the soil structure at both sites and relate the findings to the quantity of water movement.

9.3 MAIN FINDINGS

Key results are summarised in Table 9.1 and the main findings are detailed below.

Table 9.1 Key Results

Objective	Characteristic	Forest	WTH
1. Inputs	High annual input	√	√
	Uniform Throughfall & Rainfall	√	√
	Spatially variable Stemflow	x	n/a
2. Soil Water	Soil water content decreases with depth	√	√
	Soil moisture potential increases with depth	√	√
	Very small changes in SMC throughout the year	√	√
	Seasonal changes in SMP throughout the year	√	√
	Soil water content varied between -10 and -20 cm H_2O	√	√
	Localised saturation due to slate	√	√
3. K_S Variability	K_S two orders of magnitude higher than WTH site	√	x
	K_S generally decreases with depth	√	√
	Greatest variability at 50 cm scale	√	√
	Cracks influence K_S value	√	√
4. Soil Structure			
Field scale	O horizon - uniform matric flow	√	√
	Ah/Ea - vertical macropore flow	√	√
	Eag - matic flow	√	√
	B_S - matic flow	√	√
Ped scale	Degree of ped perimeter roughness similar	√	√
	Small peds and frequent cracks	√	x
Micro scale	Large range of small and medium pores	√	√
	Soil moisture characteristic curve similar	√	√
	Texture similar	√	√
	Porosity similar	√	x

- Over the long term there were no changes in soil water status or hydrological pathways as a result of WTH. The hydrological regime was similar at both sites.

- There has however, been a change in soil structure at the WTH site because of the appearance of large cracks due to woody tree roots dying and partially decomposing.

- The soil did not saturate at either site and therefore the direct impact of trees was limited.

- Soil moisture content was the most important influence over soil water movement and pathways. This is because soil moisture content determines the conductivity of the soil.

- When a certain degree of saturation occurs a particular size of pore becomes saturated and if these pores are well connected a preferential flow network develops..

- Preferential flow mechanisms can have serious implications on solute chemistry and acid deposition by allowing the rapid transmission of soil water without the occurance of macropore flow.

- Water moved predominantly vertically through the Ah/Ea horizon via cracks and predominately laterally through the Eag and B_S horizons.

- Hierarchical sampling and the use of semi-variograms are powerful techniques to assess the scale of greatest variability, particularly for K_S.

- The theory of fractal dimensions has potential scope in hydrology as a way of comparing self-similarity of variables at different scales, and therefore may lend itself to prediction at a larger scale, such as the catchment, from analysis of small scale variables.

- In order to understand soil water mechanisms, the study highlighted the need for a small area to be intensively instrumented in terms of time and space.

9.4 CRITIQUE OF OBJECTIVES

A critique of findings in relation to the objectives will be presented to identify the strengths and weaknesses of the research.

9.4.1 Objective One

The inputs were successfully measured throughout the study year. Comparisons of the inputs was made to previous measurements taken at the study site, which identified the study year as a typical year. Stemflow and throughfall were measured every fortnight. If detailed comparisons were to be made between the rainfall at the WTH and forest sites, daily readings would have been preferable. Daily readings would have enabled the identification of any spatial or temporal storm differences between the two sites, particularly any differences between summer and winter storms due to evaporation and interception.

Rainfall intensities at Beddgelert were not sufficiently accurate to make comparisons to other research sites and only acted as a crude indicator for the purposes of this study. Although 15 minute rainfall data were collected by the AWS and would have enabled true rainfall intensity to be calculated, these data were not converted for analysis. It was felt that this level of temporal detail would not have increased the understanding of soil water mechanisms, without the 15 minute matric potential data, which were not available.

Calculation of potential evapotranspiration (PEt) was problematic due to the failure of the solar radiation sensor on the Automatic Weather Station (AWS). Instead of a daily PEt value from Penman's equation, a crude monthly value had to be calculated using Thornthwaite's equation. The annual PEt of this study site compared well with other similar upland sites, but the value of monthly data was limited. Daily data would have allowed daily water budgets to be calculated, which would have identified detailed temporal patterns.

The main problem in estimating the soil water recharge was calculating the atmospheric outputs, such as interception and evapotranspiration. Inaccuracies were introduced in this study because Et and interceptions were not quantified at both the forest and WTH sites. Interception was derived from the difference between net precipitation at the forest site and gross precipitation at the WTH site. Interception was not measured at the WTH site. Potential evapotranspiration was calculated on a monthly basis, and did not account for vegetation types. The measurement of actual evapotranspiration using lysimeters would have been far more accurate, but unfortunately there were insufficient resources to install lysimeters. Lysimeter instrumentation would be more appropriate for water balance research. Although the individual water budgets for the forest and WTH sites were not accurately quantified, the measurements of annual soil water recharge was similar for both sites.

9.4.2 Objective Two

As discussed in Section 3.3 the original sampling strategy of the tensiometer network was unsuccessful, because short-term temporal data (storms) were not collected. A long-term, broader picture of soil suction was assimilated, instead of the individual storms. A second inaccuracy was introduced because fewer tensiometers were used due to failure of the automatic tensiometer system, causing temporal and spatial data to be lost. The failure also resulted in the 'L' shape sampling design being lost, and therefore comparisons could not be made between across and downslope orientations with respect to suction and flux. Having completed the research, it would be extremely beneficial for future investigations to consider detailed temporal and spatial matric potential data. From the general picture of soil moisture status, a specific and finely tuned sampling strategy can be sought for future work. Matric potential data collected between the trees did not infer rootflow at the base of the trees. If rootflow occured, there could be two reasons why this was not identified. First, rootflow is very localised and it does not affect soil matric potential more than approximately 50 cm away from the tree trunk. Second, rootflow occurs very quickly after storm stemflow and is very transient when stemflow terminates. Further research should address both these issues and also the detailed matric potential between the trees.

Further problems in data accuracy and detail were caused by there being insufficient tensiometers throughout the soil profile to detect all the differences in suction with depth. The problem was most noticeable in the Ah/Ea horizon where, due to variations in horizon thickness, no measurements of matric potential were taken. Future studies should place tensiometers every 5 to10 cm so that any variations in matric potential are detected, rather than attempting to place them in each horizon. Preliminary tests of spatial variability could be investigated using the nested hierarchical sampling strategy and semi-variograms to identify at which scale the greatest variability occurs. There is still ambiguity surrounding tensiometer measurements. Future research into water pathways should also use other techniques, such as conservative tracers. $Oxygen_{18}$ has successfully been used as a soil water tracer to help the understanding of soil hydrological pathways (McDonnell, 1990). Soil water tracers have the benefit of determining "old" and "new" water, which indicates matrix or by-pass flow. Using the conservative tracer technique, flux can also be calculated by measuring the time "tagged" water takes to travel a particular distance.

Soil moisture status and hydraulic conductivity are required to calculate the quantity and direction of soil water movement. Soil moisture content was measured satisfactorily although, due to the absence of a density probe, it was not possible to define the correct calibration curve for accurate soil moisture determination. It is imperative that future studies have accurate soil density measurements. Techniques that involve auguring holes and inserting equipment (tensiometers and neutron probe access tube), particularly on a slatey soil, such as at this study site raise the question of soil disturbance. Extreme care was taken when installing equipment and it was felt meaningful and satisfactory readings were taken during this study. When using the neutron probe, inaccuracies in soil moisture content data occured above 20 cm depth, due to environmental interference. However, below 20 cm depth, measurements were considered accurate. Due to the importance of soil moisture content, the time domain reflectometer (TDR) technique would be more appropriate in the upper soil horizons for future work at this site.

Tensiometers were unsuccessful in determining the direction and quantity of soil water flow because of the simplistic calculations used and the uncertainty of what a tensiometer measures. Flux can only be calculated with any degree of accuracy if a mathematical computer model is used, which can take into account temporal and spatial changes in K by making thousands of calculations very quickly. Despite these problems, the soil moisture content and matric potential data were similar at the two sites. This observation fulfils one of the objectives, in that whole tree harvesting operations had not changed the soil moisture content or matric potential over the long-term at the WTH site. Further research would be required to establish whether there are any differences in SMC and matric potential over the short-term, (e.g. during a storm event). Other data, such as soil texture, porosity, staining techniques and depth to bedrock, all helped to understand the basic mechanisms and direction of soil water flow.

Soil water flux was similar at both sites during the summer and winter. Tensiometer data suggested however, that the predominant direction of water flow was vertical at both sites during both the summer and winter. The tensiometer technique was inadequate to determine soil water pathways due to the ambiguity of matric potential measurements using tensiometers and also from crude calculations of flux, which did not accurately account for changes in $K\theta$. A similar conclusion was made by Addison (1995) following an intensive tensiometric investigation.

Computer modelling allowed the relationship between saturated hydraulic conductivity and soil moisture content to be identified, which is crucial to calculating soil water flux. The modelling also identified the importance of soil structure (air entry value and relationship between soil moisture content and soil water pressure) on soil water movement within this soil. However, a one-dimensional model would be inappropriate to calculate flux at the study site because there is an element of vertical flow. Therefore flux was not calculated from LEACHM (one-dimensional model), since it would have been meaningless.

9.4.3 Objective Three

Saturated hydraulic conductivity (K_S) was quantified and analysed at both sites. The spatial variability of K_S was also successfully established and quantified. The use of semi-variograms identified the scale of greatest K_S variability at the WTH site, enabling a greater understanding of the factors governing K_S. The semi-variograms also highlighted differences in K_S between the forest and WTH sites that were most probably due to the difference between live and dead tree roots and therefore due to the effects of WTH. The smallest scale of investigation for K_S variability was 50 cm, which was the minimum sampling distance that would not cause inter-sample disturbance. This critical distance could be reduced by using smaller samples but the effects of soil structure might be lost on smaller sample sizes. Although the size of soil sampled covered a number of peds, further research would be required to establish if this was the optimum size of sample. Possibly a larger diameter sample (> 30 cm ∅) is required to be truly representative of the soil structure.

Saturated hydraulic conductivity could not be measured below 20 cm, because of slate in the soil stopping sampling. Therefore, no inferences could be made regarding the Eag and B_S horizons. Further research would be required, since determining whether flow is vertical or lateral is crucial to accurate modelling and understanding solute chemistry. Less woody roots were observed in the Eag and B_S horizons at the WTH site compared to the forest site. The soil moisture characteristic curve (SMCC) also indicated less large pores in the Eag and B_S horizons at the WTH site, confirming the low porosity measurements compared to the forested site. The micromorphology data did not support the SMCC data because the representive elementary area was too small.

Due to the physical constraints of insufficient forest adjacent to the WTH site, the largest scale of sampling (50 m apart) was omitted. Therefore the numbers of K_S samples were greater at the WTH site. The unbalanced nature of this design resulted in a lack of forest samples collected to determine the true distribution and variability. However, as the analysis progressed, this omission was realised to be unimportant, as the greatest variability of K_S was at the more detailed scale of 50 cm apart.

Changes in K_S could not be identified throughout the soil profile, due to the slaty nature of the soil. The variability with depth could only be resolved by removing a very large block of soil out of the soil profile, coating it with a protective layer and establishing K_S for the entire profile within this block, thereby increasing the size of sample to incorporate the different soil horizons. This technique would also solve the problem of retaining the connected soil water pathways.

9.4.4 Objective Four

Soil structure was successfully assessed and quantified at a number of different scales, small cores (8 cm ∅), peds and a larger *in situ* soil area. At the detailed micromorphological scale, no significant differences were found between the forest and WTH sites. This observation implies that there are no differences in matrix flow between these two sites and therefore WTH does not change this type of soil water flow. However, only limited progress was made to relate the findings to hydrological mechanisms and pathways. Further analysis would be required to find a relationship between the hydrological pathways and the quantity of soil water movement.

At the ped scale, there were no differences in pore morphology between the two sites. However at the next scale up, where the inter-pedular cracks were observed, there was a difference in the frequency of cracks. Therefore WTH was shown to affect the soil structure at the pedular scale by reducing the number of cracks, thereby reducing the K_S value. This conclusion is applicable only if saturated flow occurs. The samples used to investigate peds were too small, since only a few peds were included in the 30 cm diameter sample. Future studies should consider larger samples when investigating peds.

A staining dye technique was successfully used as a qualitative tool to compliment previous data regarding flow paths. Although these results were tentative, the dye highlighted the vertical preferential flow through the Ah/Ea horizon. The porosity of the Ah/Ea horizon was low and with no evidence of saturation above the horizon, it would seem that preferential flow occurred here, despite zero tension not being recorded. Vertical flow is an important preferential flow path because of its influence on nutrient leaching. However, vertical flow was not observed in the matric potential data, because no tensiometers were directly placed in the Ah/Ea horizon due to varying horizon depth. Further soil tension data must be collected from the Ah/Ea horizon.

9.5 DISCUSSION

9.5.1 Soil Water Pathways/Mechanisms

High annual rainfall, 2800 mm, occurred at the study site, rainfall being particularly high in January and February. There was little change in soil moisture content from summer to winter, which suggested soil water movement responded accordingly (e.g. smaller pores retained water in the summer, whereas medium and large sized pores transmitted water during the winter). Field data and supporting modelling data confirmed that changes in moisture content were not as sensitive to incoming rainfall compared to those corresponding changes in matric potential. Therefore very small changes in soil moisture content result in quite large changes in soil water pressure, thus affecting soil water flux enormously.

Despite high soil water recharge, saturated conditions were not observed. A degree of vertical saturated flow occurred in the Ah/Eg horizon, probably through soil cracks since this horizon would have otherwise been a semi-impermeable layer. Below the Ah/Eg horizon only a discrete pocket of saturation occurred 0 at 60 cm. Soil tension ranged from -10 to -25 cm (H_2O), suggesting a large proportion of water could be transmitted through the soil matrix without saturated conditions prevailing. A finding which dismisses the requirement that macropore flow needs to occur for the rapid transmission of soil water. At the study site, the soil water mechanism is similar to the theory of a "capillary fringe" (Gilham, 1984). Instead of the wetting front being at the surface, it is possible that one exists below the cracked Ah/Ea horizon. For water to move rapidly, fully saturated conditions are not required. Therefore when a certain degree of saturation occurs, a particular size of pore becomes saturated and if these pores are well connected a preferential flow network develops. It is this mechanism which allows just a small addition of water (i.e. a slight increase in soil moisture content) to cause a large change in soil suction, thus resulting in a considerable amount of flux. Therefore the "critical pore size saturation" is fundamental to rapid soil water flow. Soil structure is fundamental to critical pore size saturation and therefore any structure changes could be critical to changes in soil water pathways. Evidence from the study site suggested only the inter-pedular cracks or large macropores changed as a result of WTH. The differences in cracks between the forest and WTH site were ineffectual because they never saturated, and therefore the macropores were inactive. More research of soil water status during storms is required before the role of cracks can be confirmed, because the greatest potential for saturation to occur is during storms.

Approximately the same quantity of precipitation entered the forest site as the whole tree harvest site following interception by the forest canopy. However, water was unevenly distributed into the soil at the forest site due to the stemflow component. A relationship exists between the volume of water that is funnelled to the base of a tree and the breadth of tree trunk. Stemflow has a concentrating effect on the volume of water. During the wettest period, January and February, it was not uncommon to see water ponding in a depression immediately uphill of the largest tree. Overland flow was never observed and the ponded water infiltrated the soil within a couple of hours. It has been suggested by Durocher (1990) that, after a storm, a saturation zone builds up around the tree trunk, where stemflow enters the soil. However, no changes in matric potential were measured in the soil between trees. Study data suggest that stemflow effects are limited to soil water that is in close proximity to the tree roots. Detailed monitoring of soil moisture patterns immediately surrounding the base of trees is required to investigate stemflow driven soil saturation further. It is likely that saturation may occur only in the small gaps between the roots and the soil matrix. Soil water encapsulating roots cannot be measured by tensiometers so a conservative tracer could be used in further studies to investigate root flow. A tracer could be applied to the stemflow collars in appropriate quantities and samples taken within the soil using small suction cup lysimeters. Durocher (1990) also suggested that the spatial variability of soil water movement was solely controlled by the small scale spatial variability in water input to the soil surface, rather than variability in soil physical properties such as macropores. Strictly speaking, without saturated soil conditions, macropores cannot flow. Investigation undertaken during the study discovered that soil conditions were fundamental to controlling flow. Although large differences existed between the forest and WTH sites with regard to K_S, these differences did not influence soil water macropore flow because soil saturation, with few exceptions, never occurred.

9.5.2 Soil Structure

Soil type and texture were generally similar at the forest and WTH sites. Comparison of the soil structure at the sites found no differences between the distribution of small and medium-sized pores identified by the micromorphological analysis. Micro and mesopores are constantly filled/emptied with water despite unsaturated conditions. The lack of saturation could help to explain why there were no differences in the hydrological pathways between the two sites. Differences in soil structure were noted, however, at a larger scale, throughout the mineral soil horizon, due to the status of trees roots. A larger number of tree roots existed at the forest site, whereas less roots remained at the WTH site and they were no longer active. Decomposing roots did not seem to be as effective as live ones in influencing water transmission. If saturation were to occur below the Ah/Eg horizon (where cracks are known to be active), differences in soil structure would become apparent. These differences in soil water pathways would then have serious implications on the removal of nutrients and changes in chemistry, due to variations in flow paths as a result of WTH. Therefore, establishment of whether saturation occurs during individual storms is vital, as is whether localised saturated pockets can connect and thereby transmit preferential flow.

The Ah/Ea horizon would normally be semi-impermeable, however, because of the presence of hexagonal cracks at both sites there was the potential during saturated conditions for preferential flow to occur. Ochreous mottling within the Ah/Ea horizon indicated localised saturated stagnant water. Since there was no evidence of a perched water table above the Ah/Ea horizon or surface runoff, soil water must have been transmitted through the cracks in the form of meso/macropore flow. Since the O horizon was very porous water was freely drained into the Ah/Ea horizon. Here the hexagonal cracks allow water to move swiftly to the Eag and B_S horizon. Deeks (1995) found that, due to the turbulent nature of macropore flow, this water increases the mixing potential of the soil and allows pollutants and nutrients to be well mixed. The B_S and C horizons were very permeable due to fragments of shale and slate. However, due to a decrease in bulk density with depth, the majority of water moved laterally, whilst an element infiltrated to the impermeable layer of slate at 2.5 m and was then deflected laterally. At Beddgelert, the significance of these cracks was that they allowed water to quickly bypass the Ah/Ea horizon, and then freely move through the Eag, B_S and C horizons.

The effect of WTH is to kill existing root systems, a change that reduces the K_S of the WTH site soil and therefore reduces the potential for macropore flow, and increases matric flow, thus changing the soil water pathways. Matric soil water has greater contact with more pores of different sizes and has more of a buffering effect than macropore or by-pass flow. It is therefore important to ascertain the time taken for cracks to close after WTH and CH, because the period soon after felling is when nutrient fluxes are at their highest (Stevens *et al.*, 1995). It is also important to establish how long these cracks take to develop after planting.

Staining the soil was successful in identifying differences between the two sites in inter-pedular cracks. Cracks at the forest site were more closely spaced than at the whole tree harvest site, leading to a greater number of cracks per unit area and therefore a higher K_S value. Dye was found on crack perimeters at both sites demonstrating that they were active during saturated conditions. The horizon boundaries did vary across the hillslope and further data on depths of horizons meant the 15 cm tensiometer was in the Eag horizon, 60 cm tensiometer in the B_S horizon and the 100 cm tensiometer in the C horizon. Variations in horizon depths will add to the variability in soil water movement. Unfortunately, there were no tension data or satisfactory soil moisture content data from the Ah/Ea horizon to corroborate these ideas.

Great changes in soil structure may occur due to compaction and poaching at forest sites not as steep as at Beddgelert, where machinery such as forwarders is used instead of cablecranes for WTH. It is therefore important that any guidelines for forestry management must consider the type of machinery used for harvesting. Further research is required to assess and quantify the impact of harvesting machinery and forestry practice on soil hydrology. The effects of harvesting machinery used for conventional harvesting (CH) may be less acute because of the protection provided by the brash carpet. However, damage still occurs and so has an influence on hydrology. Therefore further research is also needed to assess the protective qualities of the brash carpet.

9.5.3 Appropriateness of Samples

Sampling of the atmospheric imputs (Section 3.2) was deemed accurate. The micromorpholgy samples (Section 3.6.4) were satisfactory for comparative purposes but not for analysis of ped structure, because the samples taken were too small to encompass more than one ped. The samples used for macromorphology, impregnated with carbowax, (Section 3.6.3) were successful in this repect as they allowed observation of numerous peds in the one sample.

There was a considerable amount of variability in K_S at the forest and WTH sites. The variability was greatest when measured at a relatively small scale. It is therefore crucial to choose an appropriate scale of sampling for hydrolgical investigation. Not only should the correct scale of investigation be used for K_S, but also the correct choice of representative elementary volume (REV) is imperative. Using a REV may result in relatively large volumes of soil being sampled to measure K_S. For this reason, excavation and analysis of a large volume of soil *in situ* would provide the most accurate data concerning K_S.

9.5.4 Appropriateness of the Techniques and Samples Used

The research documented here has demonstrated the importance of establishing the optimum scale of measurement for different variables. It has also highlighted the need to consider variables at a detailed scale, both spatially and temporally. Table 9.2 identifies the different scales of measurement and illustrates the appropriate variables for that scale.

Table 9.2 Appropriate level of investigation

Scale	Appropriate and Important Variables
Hillslope/ Section	Vegetation Topography Soil Type
Plot	Soil moisture characteristic curve - air entry values - gradient of curve Soil moisture Soil tension
Point	Soil structure - ped structure - morphology of individual pores

This study has demonstrated the variable success of some standard techniques and in particular two aspects of this study worked well. It highlighted the value of semi-variogram analysis to identify the scale of greatest variability and the calculation of fractal dimensions to develop our understanding of hydrological processes. These methods may offer answers to deterministic hydrological predictions at the catchment scale from individual variables.

9.5.5 Implications of WTH on Soil Structure and Soil Water Movement

This study has highlighted that whole tree harvesting of a site produces no textural or small micromorphological changes in the soil. Large scale differences do occur after WTH, due to the inactivity of dead tree roots. However, the effects of these differences were not observed because long-term measurements at the research site indicate saturation of the soil does not occur, despite the high annual rainfall,. Further research of soil water status is needed during storms and detailed spatial measurements are required to see if any short-term saturation occurs. If soil saturation were to occur during a storm then changes to the soil water pathways caused by WTH may become apparent. Whole tree harvesting would then have serious implications on nutrient removal and changes in chemistry. If saturation never occurs at this site, then WTH does not affect the soil structure and hydrological pathways do not change. For future hydrological studies at Beddgelert, it is more important to first determine whether localised areas of saturation can develop. If localised saturation does occur, the detailed variability of macropores should then be investigated.

9.6 FURTHER RESEARCH

Future studies at Beddgelert should concentrate on the short-term changes during storms, since the research presented in this study has only investigated the long-term changes in hydrology. Soil tension and soil moisture changes in the top 10 cm of soil must be studied to confirm the hypothesis of vertical water movement through cracks in the Ah/Ea horizon. The effect of tree roots on soil structure should also be examined, especially to determined whether the type of tree species is important. Very intensive temporal and spatial sampling is required for future data collection. No research has been conducted into the effects of CH on soil hydrology, and so no direct comparisons can be made to the effects of WTH. From limited research, it does appear that harvesting trees does change the cracks and macropores in the soil. The only physical difference between CH and WTH is the protective brash carpet that remains after harvesting, which is unlikely to alter the soil structure in the short term. Potentially, this would allow conclusions made from this research to be extended to cover CH. However, differences between WTH and CH may occur due to the effects of harvesting machinery. Therefore it is essential that research is carried out to quantify the impact of different types of machinery on the hydrology of WTH and CH sites. Slope angle and soil type usually determine the type of machinery used. Therefore it would be straightforward to establish guidelines on harvesting once the full impacts of harvest machinery have been established. Further research into the effects of harvesting on soil structure and more chemistry and nutrient data from the effects of WTH and CH will allow the Forestry Commission to provide meaningful guidelines to forestry practice.

The following list of further research would be beneficial to understanding the mechanisms governing soil water movement and their implications on forest management:

- Use conservative tracers to establish the vertical and lateral flux component and rootflow alongside a network of tensiometers.
- Look at a large soil block *in situ* to determine K over the entire soil profile.
- Establish the scale of greatest variability for soil moisture content and soil matric potential to determine the sampling strategy.
- Detailed spatial and temporal monitoring of soil moisture content.
- Detailed spatial and temporal monitoring of matric potential.
- Identification of variables of self-similarity at different scales.
- Future hydrological calculations at this site require a two dimensional mathematical computer model which allows for downslope changes in K (over time and space).
- Quantification of the range of pore sizes that saturate in the field at different times of the year (long-term) and at different times during a storm (short-term).
- Use of Pouiseille's law to predict flux at the research site.
- Inclusion of topography by understanding the detailed hydrology of both a straight, convex and concave slope.
- Investigation of the effects of harvesting techniques and machinery on site hydrology and soil structure.
- Assessment and quantification of the effects of the protective brash carpet on soil structure and soil hydrology at conventionally harvested sites.
- Quantification of the time it takes for cracks caused by root activity to develop and receed after planting and harvesting.

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