BEHAVIOUR AND PREDICTION OF WATER TABLE LEVELS IN SHALLOW FOREST SOILS, SOUTHWESTERN BRITISH COLUMBIA

by

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Behaviour And Prediction Of Water Table Levels In Shallow Forest Soils,

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ABSTRACT

Water table behaviour and the occurrence of saturation was described in a forested catchment in southwestern British Columbia. Based on collected water table data, the strength of relationships between water table depth and topographic variables was also tested. Water table levels were measured during the winter of 1992-1993 at 59 maximum-rise wells located in a small (0.07 km^2) catchment in the UBC Research Forest.

Water table levels were found to respond on the order of 15 to 50 cm over some storm events. Surface saturation was observed at 25 of the wells at least once during the study period, and primarily occurred at sites of low slope with concave surface form. Hydrologic variables having the strongest relationship with peak water table levels were maximum storm discharge and 24 hour throughfall intensity. Soil indicators of saturation (colour, presence of mottles or gleying) were not applicable to this site.

A detailed survey of the catchment was undertaken to develop a digital elevation model (DEM) with a 4 m grid size. The DEM was used to derive topographic variables (upslope contributing area, surface slope, and surface curvature) at each well location. The contribution of each variable in predicting water table levels was determined through multiple discriminant analysis. Water table levels were grouped into four classes to avoid problems of data censoring. Predictions based on the occurrence or absence of saturation ranged between 69 and 97% accuracy, and were more accurate than predictions of water table groups (41 to 90% predictive accuracy). Deviations from measured water table levels are likely due to lag times in response at some wells and differences in soil structure at each site. The results support the use of topographic variables as predictors of saturation.

The accuracy of water table predictions was also influenced by the DEM scale chosen for the derivation of topographic variables. The most accurate predictions were made using variables derived from the 4 m grid, with a loss of predictive ability at coarser grids (8 m and 16 m) as averaging of catchment topographic characteristics occurred. The prediction of water table levels decreased in accuracy by 15% in some cases at the larger grid sizes. Because many DEMs are based on a 30 m grid scale, it is expected that hydrologic modelling based on this grid size may result in significant differences in output as compared to finer grid sizes.

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CHAPTER ONE - INTRODUCTION

In forested regions of southwestern British Columbia, surface soil saturation develops when infiltrating water reaches a soil horizon of low permeability, causing a saturated zone to develop at depth. Water is diverted downslope along this barrier and when upslope contributions of lateral subsurface flow and vertical infiltration of precipitation exceed the soil's ability to transmit this flux, the perched water table will rise to intersect the soil surface, thereby generating an area of surface saturation. Zones with a high probability of saturation have been linked to characteristics based on topography, soil, and precipitation. The lack of research in describing water table behaviour and assessing the strength of the relationship between water table levels and topography represents the basis of the present study.

This chapter will first review previous hydrologic studies undertaken in forested catchments. A second section will cover variables known to influence water table behaviour, including topography, soil, and rainfall characteristics. Following this, a review of two hydrologic models which are based on runoff from zones of saturation will be covered. From these models, indices have been derived which may be used to predict water table levels and the occurrence of saturation. These indices form the basis of further analysis within this study. The problems inherent in the derivation of these indices from digital elevation models (DEMs) will be discussed in reference to the effects of varying grid size. This is followed by a section on the broader significance of water table behaviour, including slope stability, vegetation production, and soil characteristics. The purpose of this section is to review previous research to determine where limitations in current knowledge may exist. Much of the research covered deals primarily with runoff processes. This information, although not directly related to the study at hand, is included to form a more complete background. The chapter will conclude with aims of the present study.

A. Background to Forested Catchment Studies

In forested catchments, it is generally accepted that the dominant runoff processes will include subsurface stormflow and overland flow from areas of saturated soil (e.g. Bonell, 1993). Hortonian overland flow is not considered significant due to the high infiltration capacity of forest soils, which will seldom be exceeded by rainfall intensity (Cheng et al., 1975). Generalised flow processes are summarised in Figure 1.1 after Wood et al. (1990).

As rainwater infiltrates the soil, it is initially stored in soil pores, causing the soil moisture content to rise. With increasing moisture, the soil will be able to transmit water as a wave of downward percolation (Dunne and Leopold, 1978). If an impermeable layer exists at depth, the percolating water will reach the barrier and a perched water table will develop, allowing water to be transmitted downslope laterally through shallow subsurface paths to the stream channel (Hewlett and Hibbert, 1963, Dunne, 1978). This subsurface stormflow will dominate runoff in humid regions most commonly in areas of dense vegetation and permeable soils on steep hillslopes (Dunne, 1983).

Subsurface stormflow may be delivered to the stream channel more quickly through macropores, which are biological and structural channels within the soil. In bypassing the unsaturated soil matrix, this water will reach the saturated zone more quickly (Bonell, 1993). Beven and Germann (1982) have stated that the most effective

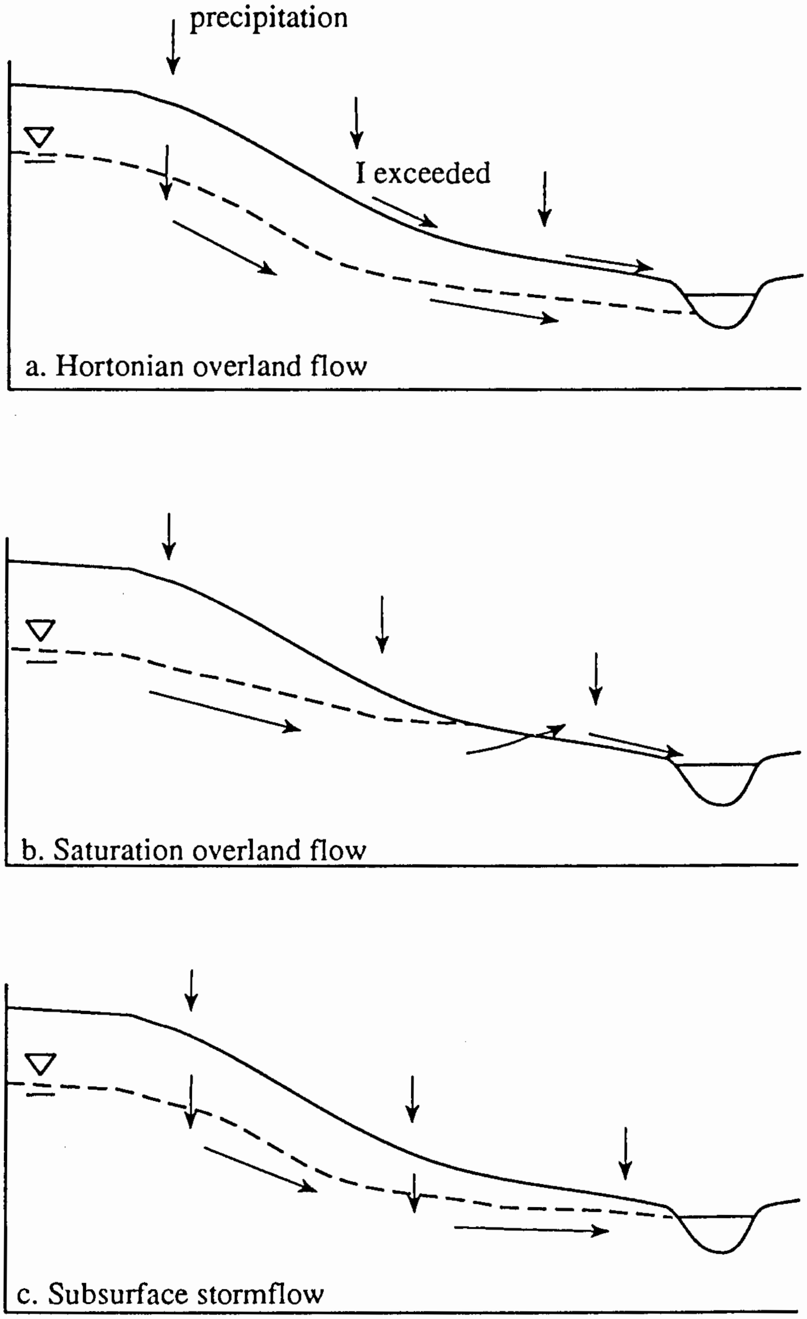


Figure 1.1. Runoff processes including (a) Hortonian overland flow, (b) saturation overland flow, and (c) subsurface stormflow. Arrows indicate precipitation, infiltration and direction of water movement. (after Wood et al., 1990).

macropore systems will develop in undisturbed forested sites. Macropores are especially dominant in surface layers due to higher root density and soil fauna activity (Bonell, 1993). The rapid rise and fall of water table levels in forested catchments has in part been attributed to the presence of macropore systems (Burch et al., 1987).

When upslope contributions of lateral subsurface flow and vertical infiltration of precipitation exceed the soil's ability to transmit this water flux, the water table will rise. In areas where the water table rises to intersect the soil surface, overland flow may be generated from zones of saturation by continued precipitation inputs or from soil return flow from upslope (Dunne and Black, 1970 a b, Ward and Robinson, 1990). This flow is called saturation overland flow. Dunne and Black (1970 a b) found that saturation overland flow developed from small portions of the watershed only. These zones were generally topographically low, with higher antecedent moisture levels than catchment averages. Potential locations of soil saturation included the base of slopes along main or ephemeral channels, in slope profile concavities (hollows), or in areas of thin or less permeable soils (Kirkby and Chorley, 1967). The development of saturated zones in these areas has been confirmed by Taylor (1982), Burt and Butcher (1985), and Cheng (1988).

In near-stream zones where the capillary fringe extends to the ground surface, water table rise may be disproportionate to the volume of infiltrating precipitation. The groundwater ridging mechanism describes the case where the rate of infiltration exceeds upslope contributions of lateral stormflow. Because the capillary fringe extends to the ground surface, soil water storage capacity is limited and the water table will respond quickly to infiltrating precipitation (Novakowski and Gillham, 1988). This will lead to a concentration of flow lines toward the stream and the rapid development of saturated zones. Gillham (1984) has stated that the groundwater ridging mechanism will have particular importance in complex topographies.

Although it is accepted that runoff in forested regions may include both subsurface stormflow and saturation overland flow, the development of soil saturation has not been investigated in southwestern British Columbia. In this region research has found the dominant stormflow process to be subsurface flow above an impermeable layer, with water flowing through macropores, the soil matrix, or a combination of the two (Cheng et al., 1975, deVries and Chow, 1978, Tischer, 1986). Plamondon et al. (1972) observed direct overland flow in the Seymour watershed, but only over short distances as microtopography prevented it from occurring over larger areas. Cheng et al. (1975) noted the development of saturated zones in the Jamieson Creek area, but no quantitative investigation of the extent of saturation was made. Heterogeneous soils, complex soil-water interactions and flow paths, and variable microtopography have been complicating factors in the study of saturation within this region (Chamberlain, 1972, Nagpal and deVries, 1976). The lack of research on water table behaviour and the development of saturation in southwestern British Columbia forms the basis of the present study.

B. Variables Influencing Water Table Behaviour

The variables which influence water table rise and the occurrence of saturation include topography, antecedent catchment conditions, soil characteristics, and rainfall intensity and duration (Dunne and Black, 1970b, Cheng et al., 1975). These variables may act alone or together in influencing water table rise at a specific point. For example, in a forested catchment in Oregon, Pierson (1980) found that over 90% of variance in piezometric response was explained by rainfall depth, catchment area, and antecedent soil moisture. Pierson's study site had soils of 2-4 m average depth and steep slopes of 30°. Although it is difficult to separate the influence of one variable from another, an attempt will be made to describe individual variables and their influence on water table rise.

1. Topography

The role of topography in influencing soil moisture levels was investigated by Dunne and Black (1970 a b) and Anderson and Burt (1978) who both revealed that water table levels were generally higher in hollows (surface concavities) than in spurs (surface convexities). Although the effect of topography on water table levels was observed, no attempt was made to correlate water table levels with topographic variables. This was first attempted by Sinai et al. (1981), who found a strong correlation between soil moisture content at a depth of 40 cm and soil surface curvature. Surface curvature, $\nabla^2 Z$, was calculated at a point i,j by measuring elevations at surrounding grid points using the equation:

$$\nabla^2 Z_{i,j} = (Z_{i+1,j} + Z_{i-1,j} + Z_{i,j+1} + Z_{i,j-1} - 4Z_{i,j}) / h^2 \qquad (1)$$

where Z = elevation at each point, and h = the distance to the neighbouring point, with neighbouring points outlined in Figure 1.2. Curvature values will be positive in concave areas and negative in convex areas.

The occurrence of higher moisture levels in concave areas was also noted by Beven (1979), Huff et al. (1982), and Petch (1988). Anderson and Kneale (1982) observed the generation of saturated zones away from topographic hollows at their pasture site of low-angle topography. They suggested that on low-angle slopes (<10%), saturation may occur downslope from concave areas, as precipitation inputs will influence soil moisture distribution more than topography. Therefore, Anderson and Kneale concluded that topographic variables should only be used in steep topographies. This finding was contradicted by Petch (1988), who found that the highest probability of saturation existed in areas of strong topographic convergence regardless of slope angle, as well as in areas of low slope close to stream channels. At this forested site, hydraulic gradients near the streams affected the distribution of soil moisture more than soil or precipitation variability as found by Anderson and Kneale (1982).

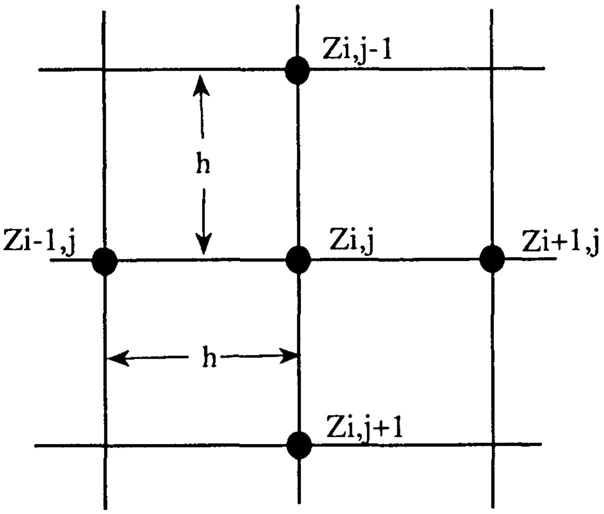


Figure 1.2. Neighbouring points used in curvature equation (after Sinai et al., 1981).

Burt and Butcher (1985) identified two topographic areas which favoured the accumulation of soil water: (1) hillslope hollows where topographic convergence lead to subsurface flow rates exceeding the transmission capacity of the soil; and (2) low-angle slopes where low hydraulic gradients accentuated water accumulation. Topographic indices based on these two areas of preferential moisture accumulation were compared to depth of saturation within a 1.4 ha steep hillslope under pasture cover. If the relationship between topographic indices and saturation depth was strong, the indices could then be used to predict wetness in ungauged catchments. The two types of indices studied were area-based and topographic-shape based.

Area-based indices are supported by the fact that the drainage flux passing through any point on a hillslope will be governed by the upslope area generating the flux (a), the gradient of the hillslope (tanB) which controls the direction of lateral flow, and soil characteristics which control the flux movement, generally defined by hydraulic conductivity (K). By assuming that soil parameters remained constant over the hillslope, depth of saturation was proportional to the topographic index: a/tanB. This index also represents the basis of Beven and Kirkby's (1979) TOPMODEL, a hydrologic model that will be discussed in the next section of this chapter.

Indices based on topographic shape reflected convergence or divergence of hillslope areas, with the highest probability of saturation occurring at points concave both in profile and plan. Topographic shape was described after Evans' (1980) method of deriving values of slope gradient, aspect, profile convexity, and plan convexity from gridded altitude data. The index based on topographic shape was PLANC.

Burt and Butcher (1985) studied a total of six indices using various combinations of the variables a, tanB, and PLANC. By correlating these indices with depth of saturation above bedrock and discharge, Burt and Butcher were able to show that the most accurate predictors were those based on both types of indices: area and topographic shape. The best predictors were (a/tanB)(PLANC) and ln(a/tanB), although both had poorer predictive ability when the soil was dry. In general, all indices proved better predictors as soil wetness increased.

In contrast to previous studies, Burt and Butcher (1985) concluded that curvature was not as important a control on soil moisture distribution as was upslope contributing area. They also suggested that soil saturation could not be predicted by topography alone, but that the general distribution of soil moisture needed to be considered to limit the effects of hysteresis and threshold change. Their study, like that of Sinai et al. (1981), was static in nature with correlations made at specific times of observation. Therefore, hysteresis affected the results in accordance to wetting and drying phases. Based on this observation, they stated that saturated zones were very dynamic and could not be accurately predicted using the quasi steady-state representation of many models.

As predictors of water table levels, topographic variables do not account for all aspects influencing water table response. Assumptions of the a/tanB index were criticised by Jones (1986) who found it particularly invalid in catchments dominated by soil piping, as surface topographic structure would not adequately describe subsurface flow through pipes. To account for this, alternative measures of upslope contributing area were proposed (Jones, 1986). Huff et al. (1982) concluded that subsurface bedding planes could also control flow to some extent, suggesting another instance in which surface topography would not describe water table response precisely. Quinn et al. (1991) suggested that topographic indices were valid predictors of flow paths and velocities only in catchments where response was dominated by surface and near surface flow processes. They developed an extension to TOPMODEL to be used in catchments with deeply weathered soil and low water table levels.

Topography is an important influence on water table behaviour and the development of saturated zones, especially in zones of flow convergence with large upslope contributing areas (Burt and Butcher, 1985, Moore et al., 1986b). Studies have shown that the most important variables in relation to water table fluctuations are surface curvature, surface slope, and upslope contributing area. However, Beven (1979) warned that the effects of soil spatial variability "may mask or reinforce the influences of topography", so other variables must be considered as well.

2. Soil

Many studies have suggested that topography and soil characteristics are intrinsically linked, which has led to the development of the catena theory. This theory states that soils derived from the same parent material and of the same age may have varying characteristics due to differences in topographic relief and drainage. The physical basis of the theory is that lateral movement of soil water in a downslope direction will carry with it soil solutes and suspensions, thereby affecting downslope soil development (McCaig, 1984). According to Birkeland (1984), "Jenny argues that topography is the primary factor in explaining soil variation". Proponents of the catena theory have found that many soil characteristics vary with topographic position, including organic matter content, A horizon thickness, degree of B horizon development, presence of soil mottles, depth to carbonates, and soil moisture distributions (e.g. King et al., 1983, Kreznor et al., 1989). However, the exact effects of catenary sequences must undergo more rigorous field verification before these characteristics can be incorporated into models or predictive indices.

With these linkages in mind, the occurrence of high moisture levels has been correlated with specific soil characteristics. Betson and Marius (1969) revealed that areas of high soil moisture were highly correlated with areas of thin A horizon soil due to the change in hydraulic conductivity at the A-B horizon interface. Burch et al. (1987)

found that surface saturation developed in soils with layers of lower permeability at or below 0.1 m depth. These layers restricted deeper infiltration into the soil, and produced widespread saturation at the surface.

Highly fluctuating water tables and the occurrence of long-term soil saturation have also been linked to soil colour and the presence of mottles and gleying. Soil scientists use these soil characteristics to determine soil drainage class and to estimate the duration of high water tables. Although used extensively, some researchers have found that these indicators do not describe saturated conditions accurately, depending on factors such as the season in which saturation occurs (Cogger and Kennedy, 1992), and the specific process leading to the development of these soil characteristics (Mokma and Sprecher, 1994).

Hydrologic models that predict the occurrence of saturated zones have generally included soil effects in a transmissivity value (O'Loughlin, 1981, Sivapalan et al., 1987). Transmissivity of the soil (T) can be obtained by integrating saturated hydraulic conductivity (K) over the soil profile with:

$$T = \int_0^L K(z)\, dz, \qquad (2)$$

where z = the vertical coordinate, with z = 0 at the soil surface, and L = the depth at which K(z) approaches zero (O'Loughlin, 1981).

The transmissivity variable has been added to topographic indices in order to increase the accuracy of water table predictions. However, Sivapalan et al. (1987) and Wood et al. (1990) found that the variability of soil characteristics was less important than topographic variability. By representing the variations of the topographic variable (a/tanB) and soil transmissivity as distribution functions, Wood et al. (1990) found that expected variations in topography were significantly larger than variations in transmissivity, and concluded that transmissivity would have a small effect on the accuracy of predictions of water table levels and size of saturated zones. Beven et al. (1988) pointed out that although the variability of soil transmissivity had little effect on the spatial distribution of saturation, it was important between storm periods at times of low antecedent soil moisture. For this reason, soil characteristics are not always included in indices which are used to predict water table levels during storm events or at times of high discharge.

Soil parameters influencing water table behaviour include saturated hydraulic conductivity, the moisture release curve, organic content, and depth to restricting layers (Moore and Foster, 1990). In predictive indices, transmissivity is usually the only incorporated soil variable. However, questions still remain regarding the use of transmissivity in predictive indices, given the possible larger influence of topography on water table response.

3. Precipitation

More immediate influences on water table behaviour and the development of saturation are hydrologic variables, including storm volume, intensity, and antecedent moisture conditions (Ragan, 1967, Dunne et al., 1975). Whereas topographic and soil characteristics influence the occurrence of water table response, hydrologic variables influence the magnitude and timing of this response. In general, water table response will be higher under high intensity storms of large volume, and response will be quicker under wet antecedent soil conditions (Pierson, 1980).

The effect of antecedent conditions on stormflow processes under identical artificial rainstorms in a forested catchment was tested by Lynch et al. (1979). It was found that high antecedent moisture conditions increased levels of quickflow, total storm runoff, maximum peakflow, time of recession, and duration of quickflow. At the study site quickflow was primarily from areas of saturated soil. It can therefore be inferred that water table response was faster under wet antecedent moisture conditions. The importance of antecedent moisture to water table behaviour has also been found by Pierson (1980) and Jordan (1994).

The influence of rainfall intensity and volume on water table response has been found in a number of studies, although a consensus on the importance of each variable has not been reached. On a Virginian coastal plain, Eshleman et al. (1993) used chemical separation techniques to conclude that high intensity rainfall enabled the production of stormflow and the occurrence of soil saturation due to high vertical flow velocities in upper soil layers. During low intensity storms, low horizontal flow velocities led to equilibration and the water table did not rise as quickly, resulting in a smaller area of surface saturation. Pierson (1980) found that catchment response was affected by rainfall intensity (as well as antecedent moisture level), while Jordan (1994) found storm volume more influential than storm intensity.

Antecedent moisture levels and the intensity, duration, and volume of precipitation will influence the magnitude of water table rise and increase the likelihood of saturation due to faster water table response and the initiation of lateral subsurface flow. If the hydrologic variables which affect water table response are known, expected water table levels under certain storm conditions may be estimated more accurately.

4. Summary

Many studies have verified the importance of topography, soil characteristics, and rainfall characteristics on water table fluctuations and the development of soil saturation. However, this review has raised the important question as to the degree of influence each variable has on water table behaviour. Can water table levels be predicted adequately by one variable or by a combination of a few? It has generally been acknowledged that topographic variables will control soil moisture distribution to the largest extent (Bonell, 1993) and that water table levels may be predicted solely by topographic variables (Sivapalan et al., 1987, Wood et al., 1990). Therefore, these topographic variables will be assessed for accuracy within this study to find their potential application in the prediction of water table levels and their relationship to hydrologic models.

C. Models Based on the Development of Saturated Zones

Two models, TOPMODEL (Beven and Kirkby, 1979) and TOPOG (O'Loughlin, 1981), have been developed to quantitatively assess catchment stormflow based on runoff generation from areas of saturated soil. The basis of the models is that complete soil saturation will occur where the drainage flux from upslope areas exceed the soil column's ability to transmit that flux. The development of saturated areas is defined and measured through knowledge of soil and topographic characteristics. Depending on these characteristics, the potential for saturation will be known according to the magnitude of the drainage flux passing through the catchment (O'Loughlin, 1986). Both models have the ability to predict the locations of zones of soil saturation, and predictions of water table levels throughout the catchment can be derived in TOPMODEL.

These models have an advantage over other hydrologic simulations because they incorporate topography into model analysis. Previously, oversimplification of flow processes in two dimensions led to the possibility of inaccurate results (Moore et al., 1991). The incorporation of terrain into these models makes this less likely to occur. It has been suggested that TOPOG can be used not only to model moisture distribution and runoff characteristics within a catchment, but also to determine effluent movement, find zones of erosion and deposition, and assess the impact of land use change (Moore et al., 1988b). The models can also be used to assess soil characteristics developing under high moisture, including areas of probable salinisation and water-logging (Moore et al., 1991).

The importance of these models in the present study is not in their hydrological representation of runoff processes, but in their ability to predict water table levels (or the occurrence or absence of saturation) at any point in the catchment. Therefore, the following discussion will focus on the components which allow predictions of water table levels and the occurrence of saturation to be made.

1. TOPMODEL

Within TOPMODEL, an equation exists which will predict the soil moisture deficit (or depth to the water table) at any point within the catchment. The derivation of this equation begins with a description of downslope flow at any point in the catchment under steady-state conditions prior to a storm as:

$$q_i = a_i r, \tag{3}$$

where q_i = net drainage flux from a point i, a_i = the upslope area drained per unit length of contour, and r = the spatially uniform recharge rate. By assuming that the water table is parallel to the soil surface, local hydraulic gradient can be approximated using surface gradient (tanB). By further assuming that local soil transmissivity (T_i) is an exponential function of depth, the downslope subsurface flow rate at any point can be calculated using

$$q_i = T_i \tan B \, e^{f z_i}, \tag{4}$$

where z_i = depth to the water table at point i, and f = the rate of decline of hydraulic conductivity with depth. This equation does not account for any flow in the unsaturated zone as downslope flow occurs almost entirely under saturated conditions (Kirkby, 1985). As well, the equation does not account for macropore flow, which may potentially limit its use in forest soils. By combining equations 3 and 4,

$$z_i = (1/f)\,[\ln (a_i / \tan B) + \ln (r / T_i)], \tag{5}$$

where ln ( ) is the Naperian logarithm. The index therefore represents a measure of water table depth scaled by f (Chairat and Delleur, 1993). This representation is the basis of the index

$$W_B = \ln (a_i / \tan B). \tag{6}$$

In this case, W_B represents an index of the likelihood of certain water table levels to be reached at any point, depending on antecedent conditions and the characteristics of the storm event. All points with similar index values will have similar water table behaviour. The index represents a simple effective way to predict the location of zones with a high probability of saturation based solely on topographic data.

In many instances, transmissivity is left in the equation to account for variations in soil characteristics throughout the catchment and the index will take the form:

$$W_{BT} = [\ln (a\, T_e) / (T_i \tan B)], \tag{7}$$

where T_e = average catchment transmissivity, and T_i = local transmissivity. However, as previously mentioned, topographic variability is usually assumed to control water table response and transmissivity is often disregarded within the index (Beven et al., 1988, Wood et al., 1990).

TOPMODEL has been tested for applicability and predictive accuracy in different environments. However, most studies have linked model capability to the accurate prediction of discharge (Beven et al., 1984, Durand et al., 1992). The studies that have used the index to predict water table levels or the occurrence of saturation will be reviewed briefly.

Phillips (1990) compared known wetland areas to predicted areas of high wetness based on the W_{BT} index. Phillips concluded that wet and dry soil groups could be delineated by W_{BT} values, and that W_{BT} could be used to identify and map wetland zones. Unlike previous studies, Phillips found that transmissivity was the most important factor contributing to variation in the wetness index throughout the catchment. Phillips' site, a wetland plain with low slope and an elevational range of 31 m, would not have great topographic variability in comparison to soil heterogeneity. From this result, the suggestion is made that the topographic parameter will better describe water table conditions in areas of greater topographic relief.

Jordan (1994) sought to find the accuracy of the W_B index by testing water table level predictions at specific points in a small Swiss catchment of mixed forest and pasture cover. Correlations between water table depth and the W_B index were primarily non-significant, with the exception of two dates which had correlation coefficients of 0.80 and 0.89. Jordan concluded that the poor predictions based on W_B were due to a complex water table response at this site, with steady-state conditions seldom being reached. However, Jordan suggested that under wet antecedent conditions and heavy rainfall the water table would reach a stable situation and the W_B index may have higher predictive accuracies.

2. TOPOG

The model of O'Loughlin (1981) also concentrates on the delineation of saturated areas and their importance as runoff contributors. The basis of TOPOG is that quickflow response, in the form of saturation overland flow, can be predicted from the relationship between soil water storage and contributing area. As in TOPMODEL, this relationship is largely derived from topography and soil characteristics within the catchment, and assumes a steady-state situation where flow direction is dominated by topographic elevation (O'Loughlin, 1986). In actual catchment studies, this steady-state assumption is only approximated during extended base flow periods, a factor that limits the model's predictive ability.

The ratio of subsurface lateral flow at any point and the soil's ability to transmit this flow is the basis of a wetness index:

$$W_i = (T_i \tan B)^{-1} \int q_i \, da. \tag{8}$$

The integral represents the accumulated drainage flux at point i. This index may be used as an indicator of soil moisture content. Where $W_i > 1$ a seepage face will exist and exfiltration will occur, while $W_i < 1$ indicates that the soil is able to transmit the flux and W_i will be a measure of the degree of saturation of the soil profile.

The two key assumptions inherent in the use of this index are (1) that all flux is derived solely from upslope drainage (no artesian sources or return flow), and (2) that topographic gradients dominate the direction of lateral subsurface flow (O'Loughlin, 1986). The assumption that lateral flow is dominated by topographic gradients is considered to be valid as gradients may drive lateral flow even where layers of lower permeability do not exist at depth (O'Loughlin et al., 1989). Because the drainage flux is a difficult component to determine locally, emphasis is placed on the relative magnitude of the integral term which should be related to the slowly varying stream baseflow (O'Loughlin, 1986). Transmissivity is important only in regions where saturation boundaries are likely to occur. Therefore, in most cases T is assumed to be constant throughout the catchment (Moore et al., 1986b).

TOPOG differs from TOPMODEL in the method of terrain division. Instead of the grid square approach, the contour-based network of TOPOG allows the terrain to be divided into small irregular polygons based on contour lines and their orthogonals (Moore et al., 1986b). These "stream tubes" represent a more natural unit within the catchment and are seen as more precise, especially in areas of divergent flow. A major drawback to this approach is that it is computationally slower and needs an order of magnitude more points to adequately describe an elevational surface than the regular grid approach (Moore et al., 1991).

TOPOG has been tested in forested catchments and accurately simulates storm hydrographs (e.g. Moore et al., 1986b). However, the stream tube method of DEM analysis is not widely used, so the W_i index has not been tested in any study with a direct comparison to water table levels. Most studies have used the W_B index to predict the size and location of saturated soil zones.

3. Model Summary

Both TOPMODEL and TOPOG have provided researchers with seemingly accurate models which determine catchment runoff without the need for intensive field monitoring. The models have been shown to accurately simulate storm hydrographs, particularly at times of high wetness. However, the models also purport to be accurate predictors of areas of saturation, a claim that has generally not been tested. Accurate representation of storm hydrographs do not mean that local processes are modelled correctly. Jordan (1994) did test the relationship between the W_B index and water table levels, but found a poor relationship between the two.

Although these models will not be investigated in the present study, the W_B index will be related to measured water table levels in order to test the strength of the relationship between the two. The results will be extrapolated to a discussion of the usefulness and potential short-comings of these hydrologic models.

4. The Effect of DEM Grid Size on Model Simulations

Model output from TOPMODEL and TOPOG will be affected by the DEM grid scale at which the topographic variables are derived. The importance of scale is seldom addressed by researchers even though it is a necessary component of hydrologic studies. If derived values are found to differ significantly at various scales, this will have serious consequences for research based on these models.

Researchers generally use a square grid cell approach as the basis of DEM generation due to its simplicity and low computer run times (Moore et al., 1991). The use of grid cells implies a homogeneous response across the entire cell, so the size of cell chosen is important to further analytical accuracy. Studies have shown that the size of grid chosen affects the derived values of variables such as slope and aspect. Coarser grids will have an averaging effect on terrain shape, resulting in more generalised terrain features and poor representation of topographic discontinuities such as narrow valleys and steep narrow slopes (e.g. Panuska et al., 1991). Within these models, commonly-used grid sizes are the 30 m grid, which is the scale of USGS digital DEM data, and the 50 m grid, which is the resolution of the U.K. national DEM database (Panuska et al., 1991, Quinn et al., 1991).

Previous scale studies can generally be grouped into those testing grid size effects on derived topographic variables, and those testing the further effects of these derived values on model output. Chang and Tsai (1989) investigated the effect of using 8, 20, 40, 60, and 80 m grids on derived topographic variables including slope and aspect. They assumed that the 8 m grid would yield the most accurate results, and found that an increase in grid size resulted in a decrease in the mean values of derived variables, with aspect being more sensitive to resolution changes than slope.

Panuska et al. (1991) studied the effect of grid size on the values of topographic variables at a 210 ha site of significant topographic variation. From DEMs of grid size 15, 30, 60, and 90 m, average slope, upslope contributing area, and maximum flow path length for each grid cell were calculated. Slope distributions did not show a large difference among the four grid sizes. However, upslope area showed great variation, revealing increasing median values with increasing resolution. Flow path length also became shorter at coarser grid scales as areas of convergence and divergence (which define flow paths) were poorly represented due to averaging of terrain features.

Similar results were found by Quinn et al. (1991), who studied changes in the W_B index over 12.5 and 50 m grids. The coarser grid had a higher percentage of high index values, although the differences between the two grid sizes were not great overall.

Quinn et al. (1991) concluded that grid size must reflect the topographic features important to hydrologic response, which may be less than the 50 m grid size available nationally to researchers in the U.K.

Derivation of gradient, upslope contributing area and the W_B index were compared at grid sizes of 2, 4, 10, 30, 90 m by Zhang and Montgomery (1994) in two small catchments of moderate to steep terrain. The sensitivity of topographic indices to varying grid size was examined by comparing the cumulative distribution functions of each topographic variable. Gradient was found to be more sensitive to changes in grid size in the steeper catchment although significant differences in distributions were found at the 90 m grid size in both catchments. Mean values of the W_B and upslope contributing area distributions increased with increasing grid size in both catchments. These derived values were then used as input to TOPOG (to predict zones of saturation) and to TOPMODEL (to simulate runoff). Model output echoed the initial results, and it was found that increases in grid size increased the size of predicted saturated areas. Zhang and Montgomery concluded that the effect of grid size on the derivation of topographic variables could significantly affect model output, and that the most accurate grid size would be somewhat finer than mean hillslope length in the study area. In their study, the optimum grid size was determined to be 10 m, representing a compromise between increased resolution accuracy and the volume of data required for analysis.

Chairat and Delleur (1993) followed a similar type of analysis, but compared runoff values predicted from TOPMODEL under three rainfall events at grid sizes of 30, 60, and 90 m on a 3.38 km^2 agricultural site. The effect of grid size on values of the W_B index was found to be significant, and larger grid sizes generally reduced the probability of saturation occurring. It was suggested that this result was probably due to the loss of convergent areas due to averaging across the grid cell. The 30 m grid showed the best predictions of simulated peak flow response.

These studies reveal that grid size will affect the derivation of variables and final model output. Panuska et al. (1991) stated that terrain variability would be characterised best by a small grid size, although DEM resolution in the horizontal and vertical directions would have to be considered. The use of coarser grids in areas of lower topographic relief would likely be a reasonable option. Zhang and Montgomery (1994) concluded that a 10 m grid would result in the most accurate hydrologic analysis. The 10 m grid, although not as accurate in predictive ability as finer grids, represented the most efficient system in terms of accuracy and data storage requirements at their site. The high accuracy at fine grid sizes will have significance to researchers using national digital data sets, such as those based on 30 and 50 m grids.

D. Broader Significance of Water Table Behaviour

The research outlined within this chapter has primarily linked water table studies to the description of runoff processes in forested catchments. However, knowledge of water table behaviour and the development of saturation may be helpful in other research areas, including slope stability, vegetation growth, and soil development. These areas will be reviewed within this section as a reminder of the broader significance of the present study.

1. Slope Stability

Slope failure, including landslides and debris flows, occurs when precipitation and/or snowmelt inputs increase soil pore water pressure. When zones of positive pore pressure develop, soil shear strength is decreased to a point where failure may occur. Failure susceptibility is heightened if these zones develop in near-surface areas where seepage forces are directed outward from the slope (Neary and Swift, 1987). Zones of failure are often associated with complete soil saturation (Buchanan et al., 1990).

Slope stability studies have generally concluded that the timing of failure depends primarily on soil antecedent conditions and rainfall intensity and duration (Caine, 1980, Sidle, 1984, Wieczorek, 1987, Johnson and Sitar, 1990). Caine (1980) developed a lower boundary or threshold condition for landslide initiation based on previous research. The condition is:

$$I = 14.82\ D^{-0.39} \tag{9}$$

where I = precipitation intensity (mm h^{-1}), and D = storm duration (h). This relationship has been used in many forecasts and predictions of landslide susceptibility (e.g. Cannon and Ellen, 1985, Keefer et al., 1987) One exception was Church and Miles (1987) who found that landslide initiation in southwestern British Columbia did not follow Caine's equation and concluded that no simple meteorological correlation existed in the region.

In determining where potential landslides may occur, researchers have studied a wide range of hydrologic, geologic, and topographic characteristics. Sidle (1984) and Buchanan et al. (1990) suggested using piezometric or water table responses to determine failure potential. Rogers and Selby (1980) included clay content, soil shrinkage, hydraulic conductivity, and shear strength in their summary of soil characteristics influencing landslide susceptibility. Soil thickness, porosity, and the presence of shallow rooted vegetation have also been linked to landslide potential (Neary and Swift, 1987, Johnson and Sitar, 1990). Reid and Iverson (1987) suggested that the underlying geologic structure influenced failure potential, particularly in hillslopes with layers of differing hydraulic conductivity. However, no variable or combination of variables has been found to accurately predict failure across differing areas. This led Johnson and Sitar (1990) to conclude that the conditions governing failure were highly site specific.

Topographic analyses are important in determining areas of potential slope failure. Topographic variables studied have included slope and surface concavities (Neary and Swift, 1987). Concave depressions are important because of their potential to accumulate soil water and become preferentially saturated. Once hollows initiate a landslide, they may fill by localised soil creep and erosion, increasing the likelihood of further failure (Sidle, 1984). Moore et al. (1988b) found that the location of ephemeral gullies was correlated both to areas of saturation and to topography, and that gully location could be described by a combination of topographic indices (upslope contributing area and surface slope).

Slope stability studies such as these have revealed the potential for further research in locating zones of saturation based on topographic indices. The presence of saturated zones increases an area's susceptibility to failure which, if delineated, could prove to be a valuable tool for landslide prediction. This has been suggested by Buchanan et al. (1990), whose landslide model showed complete saturation of all studied headscarps prior to failure. The importance of topographic variables has also been shown by the high frequency of landslides generated from concave hollows which are known to support higher soil moisture levels (Reneau and Dietrich, 1987). However, topographic influence may vary in importance at each site depending on geologic and climatic factors (Reneau and Dietrich, 1987). This suggests that indices used to predict water table levels may need to be combined with other variables to create an accurate assessment of landslide failure potential in many areas.

2. Vegetation Growth

In light of research revealing the existence of higher soil moisture levels in concave topographies, forestry studies have described vegetative growth in these areas. McNab (1989) studied the topographic factors influencing tree growth, which in the past have included variables such as aspect, gradient, landscape position, length of slope, and geometric shape of the site. McNab (1989) found tree height was highly correlated with a shape index much like the curvature index of Sinai et al. (1981). Mackey and Norton (1989) suggested that variables including slope, elevation, aspect, and catchment area could be used as indices of species diversity.

Knowledge of the location of saturated areas and/or areas of high water table fluctuation could aid foresters in site management and productivity analysis. Highly fluctuating water tables are harmful to plants and tend to restrict deep root development (Pritchett and Fisher, 1987). If large fluctuations are known to exist at a site, measures could be taken to ensure maximum growth by planting trees that respond well to these conditions, or by draining the soil to a constant level (Pritchett and Fisher, 1987). This approach has been used in agricultural areas that commonly have high water tables during the growing season. Practices such as tillage, drainage channels, and pumping have been used to lower water tables to maximise productivity (Tivy, 1993).

Linking studies of forest management to slope stability, Sidle (1992) modelled the effect of logging on slope stability. The model was developed to assess the probability of slope failure occurring after the completion of logging, based on moisture levels under certain rainfall and antecedent conditions, and the temporal changes in root cohesion and vegetation surcharge. This derived relationship could be very useful in terms of forest management and environmental protection.

3. Soil Development

Knowledge of the location of saturated areas is important to soil scientists as extensive long-term saturation of the soil will lead to the development of gleyed or mottled horizons. Such indicators of saturation are used in soil studies and classifications as a criteria of drainage condition (McCaig, 1984). Accurate predictive indices of saturation could aid in field studies and soil mapping and in the delineation of areas of poor drainage and waterlogging.

Agricultural researchers could use variables which indicate potential zones of saturation to assess areas of solutional weathering and salinisation. Crabtree and Burt (1983) found that solutional weathering occurred to the largest extent in areas of subsurface flow and prolonged saturation, which primarily were located in topographic hollows. Knowledge of areas undergoing increased solutional weathering could aid in the study of soil development and its relation to catenary sequences.

Saturation may also cause salinisation of the soil due to high water levels (Moore et al., 1988a). The concentration of salts within the soil profile occurs when areas of ponded water are subject to evapotranspiration. This process of illuviation can have a significant influence on the transfer of material within the soil. Salinised areas are particularly detrimental to agriculture as they can cause water stress and wilting in plants (Tivy, 1993). The prediction of potential zones of salinisation could therefore aid agricultural researchers and farmers in land management techniques. Although this process is unlikely to occur in forest soils due to low evapotranspiration rates under the canopy, it does outline a potential application of water table studies.

E. Aims of Research

This review has revealed the need for detailed water table studies in humid forested regions, and in southwestern British Columbia in particular. Topographic variables contributing to water table rise and the development of saturation have been identified from previous studies and include upslope contributing area, surface slope, and surface curvature. Although these topographic variables have been incorporated into hydrologic models, model predictions of water table behaviour and the occurrence of saturated zones has not been assessed adequately. Therefore, the objectives of this study are:

(1) to describe water table behaviour in a forested catchment,
(2) to test the strength of relationships between water table depth and topographic variables,
(3) to determine the effect of DEM grid scale on water table predictions, and
(4) to suggest the consequences of these results in relation to hydrologic models based on runoff generation from saturated soil zones.

The results of this study will suggest the applicability of hydrologic model use (in terms of index accuracy) in similar environments and to research incorporating water table behaviour. Knowledge of water table response may also be useful in studies of slope stability, vegetation production, and soil development.

CHAPTER TWO - METHODS

A. Study Site

The study was undertaken at the University of British Columbia Research Forest, located approximately 50 km east of Vancouver (Figure 2.1). Research was carried out in a small subcatchment (0.07 km^2), located next to a gauged catchment, where discharge is continuously measured at a V-notch weir. Discharge data were provided by Dr. M. Feller, UBC Forestry Sciences. The Research Forest headquarters, located approximately 1.5 km from the study area, also maintains a climatological station. According to Nagpal and deVries (1976), the area is typical of the forested mountainous terrain of coastal western Canada. Field work was undertaken during the peak stormflow period between October 1992 and April 1993.

1. Climate

Thirty-year normals of temperature and precipitation at the Research Forest are shown in Figures 2.2 and 2.3. These data are based on published climate data from the Atmospheric Environment Service for the Research Forest Headquarters station (Environment Canada, 1982). The climate is typical of southwestern British Columbia and is typified by mild temperatures year-round with peak precipitation occurring during the winter months. Mean monthly temperatures and total monthly precipitation at the headquarters during the study period are compared to thirty-year normals in Figures 2.4 and 2.5. Although temperatures were similar to average conditions, the study period

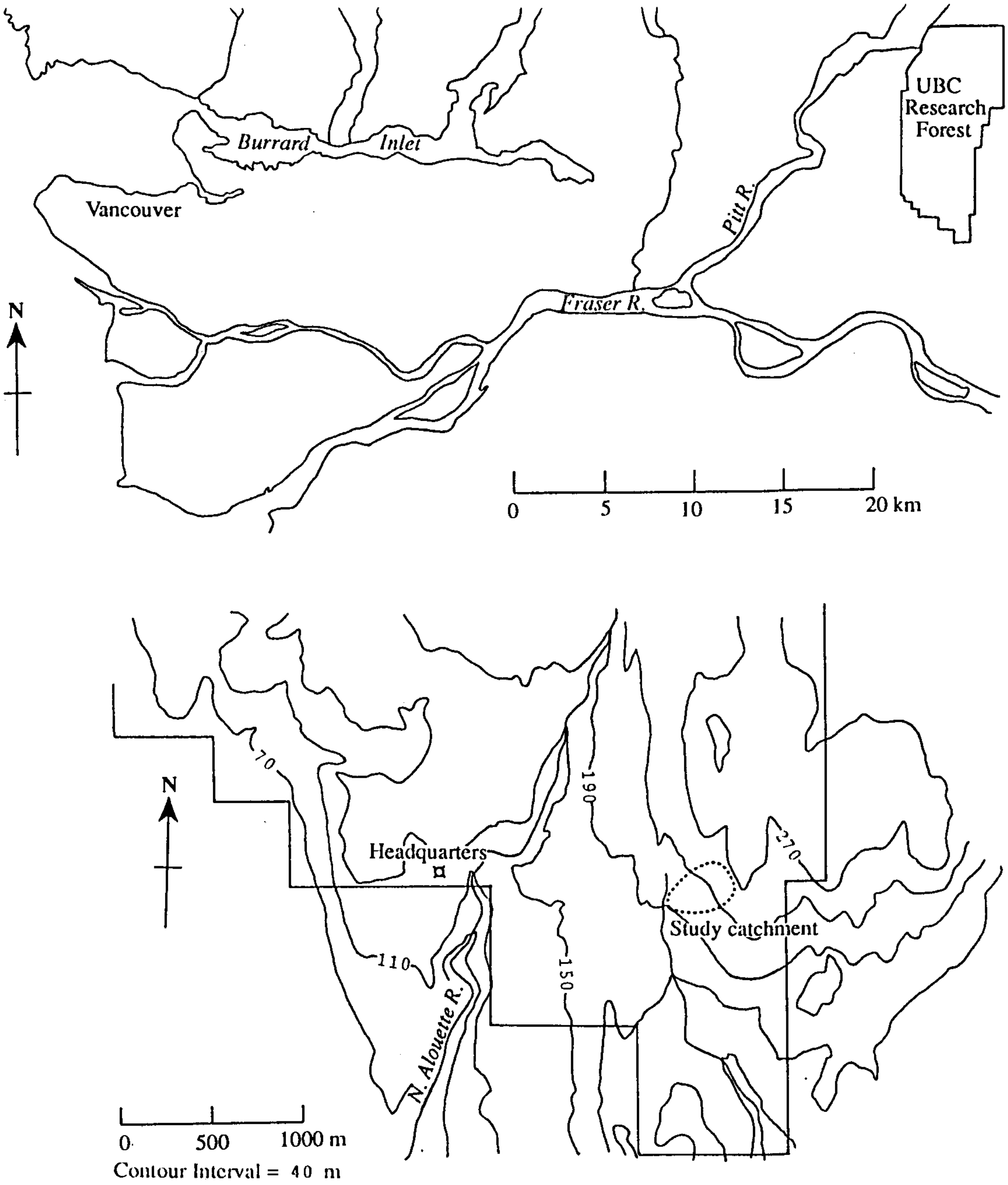


Figure 2.1. Location of study site (a) relative to Vancouver; (b) in the southern portion of the UBC Research Forest.

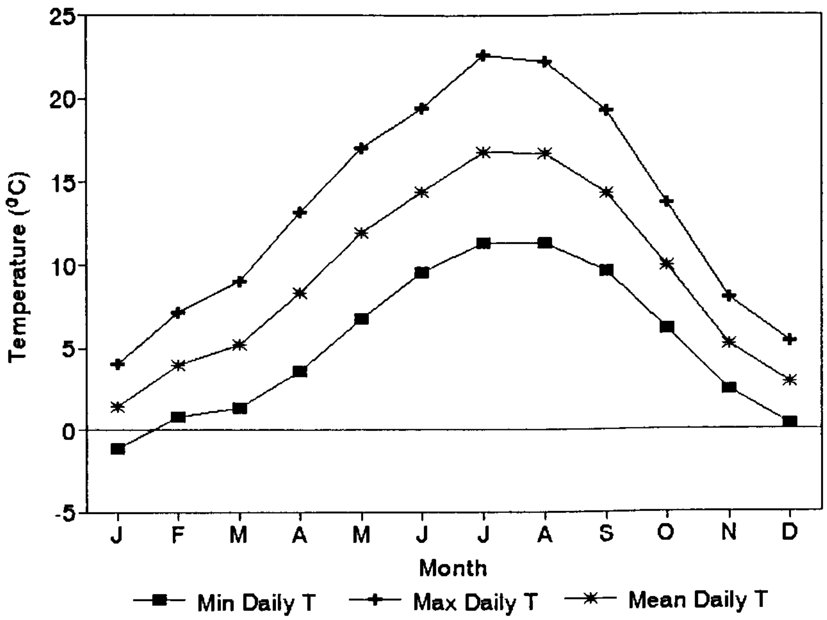


Figure 2.2. Minimum, maximum, and mean monthly temperatures for the Research Forest headquarters station, based on 30-year climate normals.

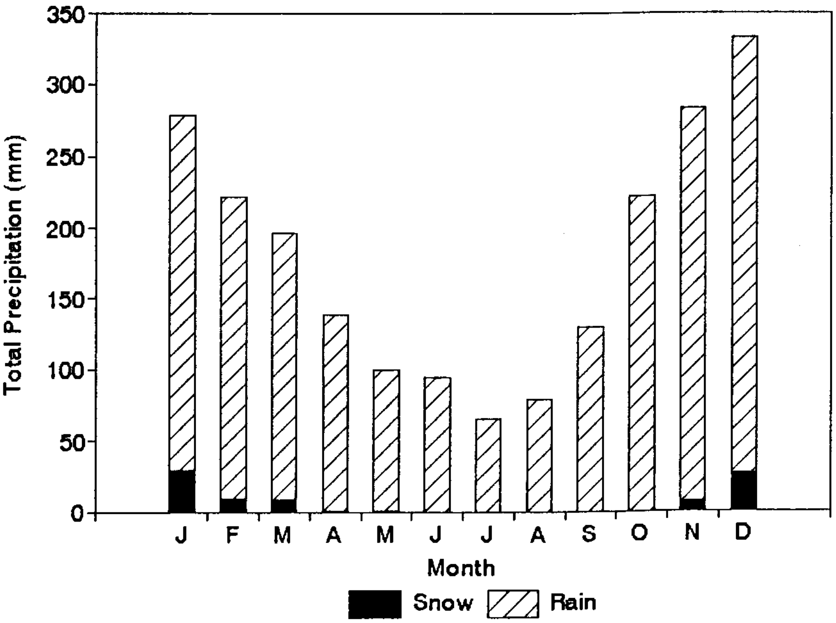


Figure 2.3. Total monthly rainfall and snowfall at the Research Forest headquarters station, based on 30-year climate normals.

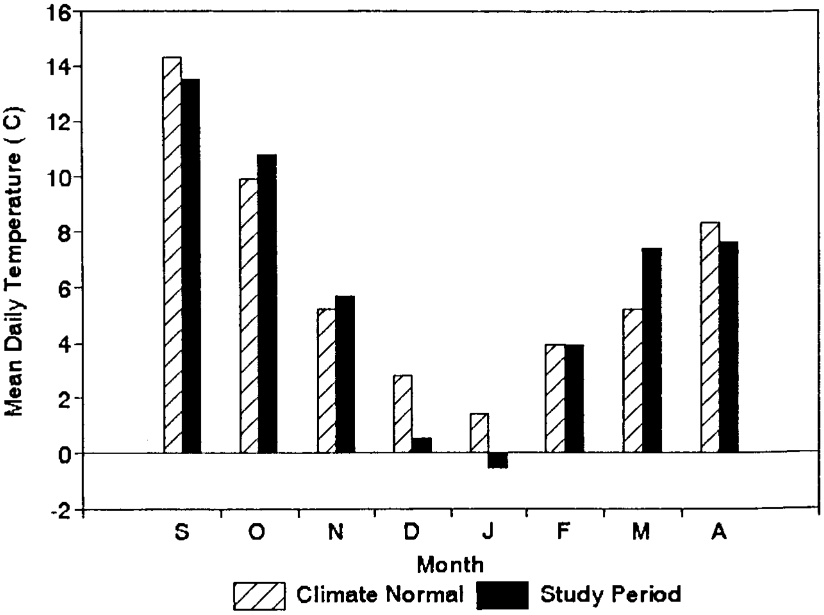


Figure 2.4. Comparison of mean monthly temperature at the Research Forest headquarters station, for the 30-year climate normal and the study period.

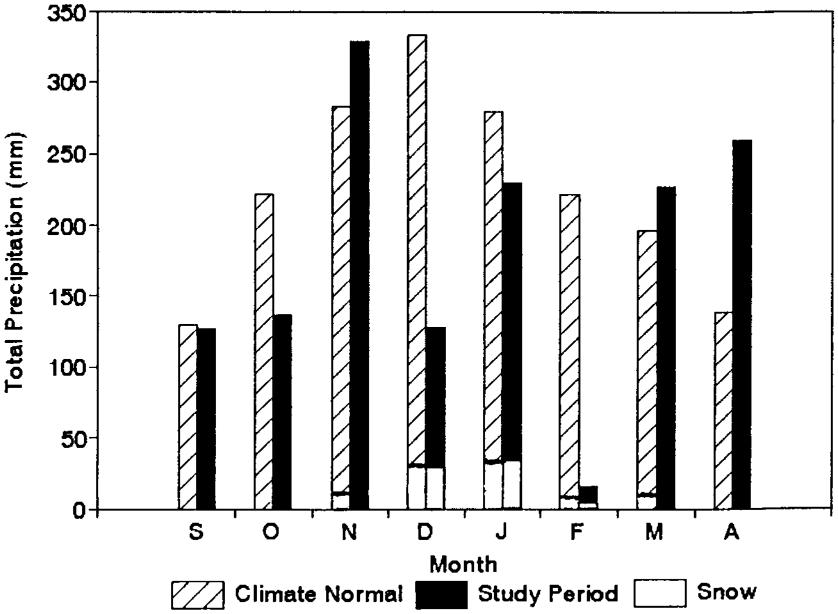


Figure 2.5. Comparison of total monthly rainfall and snowfall at the Research Forest headquarters station, for the 30-year climate normal and the study period.

received abnormally low precipitation, especially in February which received only 7% of the normal total precipitation for this period. In total, the period between October and April received only 81% of the normal expected total precipitation.

Based on the rainfall intensity-duration-frequency chart for the Research Forest (Figure 2.6), all storm events studied had return periods of less than two years. Short-duration rainfall intensities sometimes exceeded the two year return period, but when averaged over the entire storm event, these intensities did not reach the two year return period level. Maximum rainfall intensities measured at the headquarters are summarised in Table 2.1. The fact that all storm events had low return periods will have important consequences, as conclusions drawn from this study may not be valid when applied to larger storm events.

2. Hydrology

Peak stormflow occurs during the winter at the time of peak rainfall. Due to the low elevation of the study catchment (190-270 m), precipitation falls mainly as rain, although one snow event was recorded during the study period. Total annual precipitation based on the 30-year climate normals is 206 cm (Environment Canada, 1982).

As mentioned in Chapter One, runoff in humid forested catchments is generally dominated by subsurface stormflow and overland flow from areas of saturated soil. Areas of soil saturation were observed throughout the study catchment over the winter and were generally located in lower catchment areas or at sites of thinner soil. Water table response is rapid and was observed to fluctuate as much as 89 cm over a single storm event, but typically ranged between 15 and 50 cm in larger storm events.

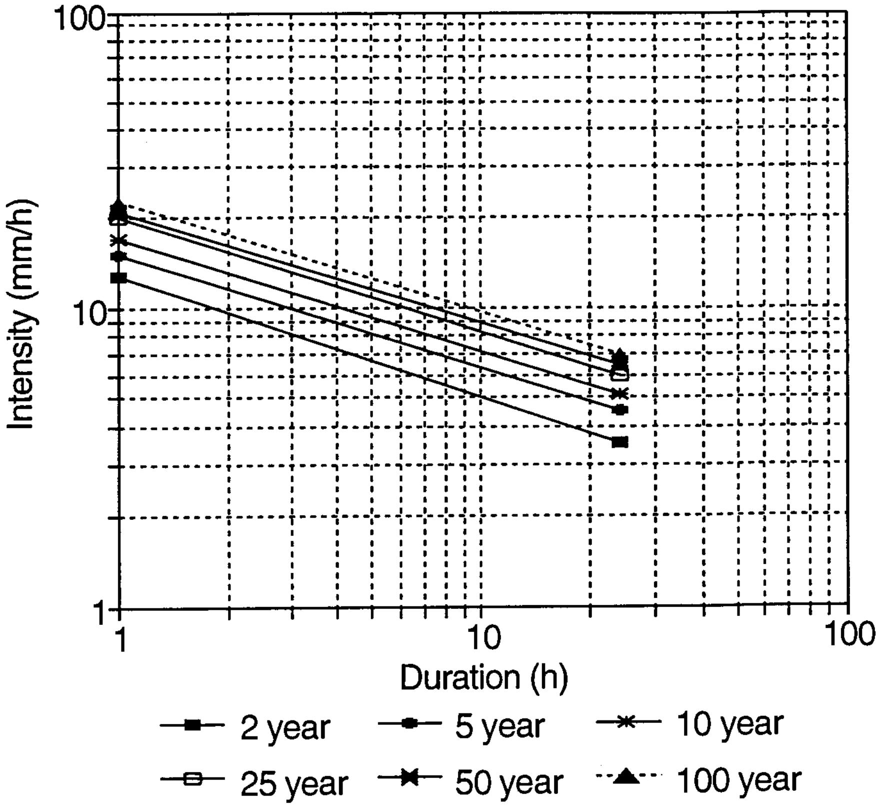


Figure 2.6. Intensity-duration-frequency curve for the Research Forest Headquarters, based on Environment Canada climatological data. Return periods for storm sizes are indicated in the legend.

There are no permanent streams within the study catchment, although ephemeral streams do carry flow during the winter months. During the winter, these streams flow continuously only at low elevations near the catchment outlet. The ephemeral streams did not begin to flow continuously until after a period of prolonged rainfall in mid-October, 1992, and no flow was observed during the summer months.

Table 2.1. Maximum rainfall intensities measured at headquarters during study compared to intensities for 2 year return period.

Date	Max I (mm/h)	Duration (h) of Intensities	I for 2 Year Ret. Period
295, 389	6.80	2	10.0
389	6.56	4	7.2
389	5.90	6	6.0
389	5.90	8	5.3
389	5.45	12	5.0
389-390	3.75	24	3.5

3. Vegetation

The study area is a relatively homogeneous stand of western redcedar *(Thuja plicata)*, Douglas fir *(Pseudotsuga menziesii)*, and western hemlock *(Tsuga heterophylla)*. The stand is between 60 and 80 years in age, having been logged and replanted in the 1920's. The average height of the stand is between 29 and 37 m, with 76-85% crown closure. The forest floor is littered with deadfall and leaf litter, and underbrush is fairly sparse, as shown in photographs of the catchment (Figures 2.7, 2.8, and 2.9).

4. Geology

Klinka (1976) summarised the geology at the Research Forest as predominantly quartz diorite, a finding supported by visible granodiorite outcrops within the study catchment (Figure 2.10). Bedrock is Mesozoic, includes granitic and associated rock types, and is generally overlain by thin and continuous deposits of glacial origin which are coarse-grained with average textural values of 57% sand, 41% silt, and 2% clay (Klinka, 1976). This glacial layer is known to be Vashon Drift, a formation of till, glaciofluvial, and glaciolacustrine sediment, deposited during the Fraser Glaciation (around 14 500 BP) at a time of maximum ice cover (Armstrong, 1980, Hicock and Armstrong, 1985). At lower elevations, Klinka (1976) found evidence of some marine reworking in post-Vashon time, which is probably of the Capilano Sediments formation (Hicock and Armstrong, 1985). This deposit is typically a thin veneer of beach gravels and littoral sand.

Figure 2.7. Photograph of study site. Area shown is looking southward down the ephemeral stream in the A well area.

Figure 2.8. Photograph of the area of B transect wells, characterised by generally steeper terrain.

Figure 2.9. Photograph of the canopy gap where well D1 is located. This site is characterised by many fallen trees and a diversity in plant species.

[redacted]

Figure 2.10. Photograph showing a granitic outcrop in the lower study site (near well B5). Field notebook for scale.

5. Soils

Soils within the Research Forest are primarily shallow, coarse-textured humo-ferric podzols (Feller and Kimmins, 1979). Soil depths range from 0.5 to 2 m, with till found on average at 1 m depth (Utting, 1979). Tischer (1986) found the forest soil to include a strongly structured B horizon due to the presence of many roots, stones, and cemented aggregates. Typical saturated hydraulic conductivity values in this type of forest soil range from 3×10^{-5} to 9×10^{-5} m s^{-1} (Cheng, 1988). Conductivity measurements at sites similar to the study area are summarised in Table 2.2. Saturated hydraulic conductivities measured within the present study ranged between 9×10^{-5} m s^{-1} for bulk depth measurements at 0.5 m depth and 3×10^{-3} m s^{-1} in surface layers. These values were found to compare closely with those from nearby catchments. Tischer (1986) found values on the order of 10^{-4} m s^{-1} in upper soil horizons, and Utting (1979) measured conductivities of 10^{-6} m s^{-1} in lower B horizons, and 10^{-7} m s^{-1} in basal till. Hydraulic conductivity derivation is discussed in more detail below.

B. Data Collection

Because this study attempts to correlate water table fluctuations and the occurrence of saturation to topographic and hydrologic variables, some measure of the depth to the water table is needed. This was accomplished by monitoring water tables at 59 maximum-rise wells within the catchment, supported by measures of throughfall and antecedent soil moisture. Topographic variables were derived through the use of a digital elevation model based on a detailed survey of the catchment, and selected soil characteristics were measured in the field. The study methodology is outlined below.

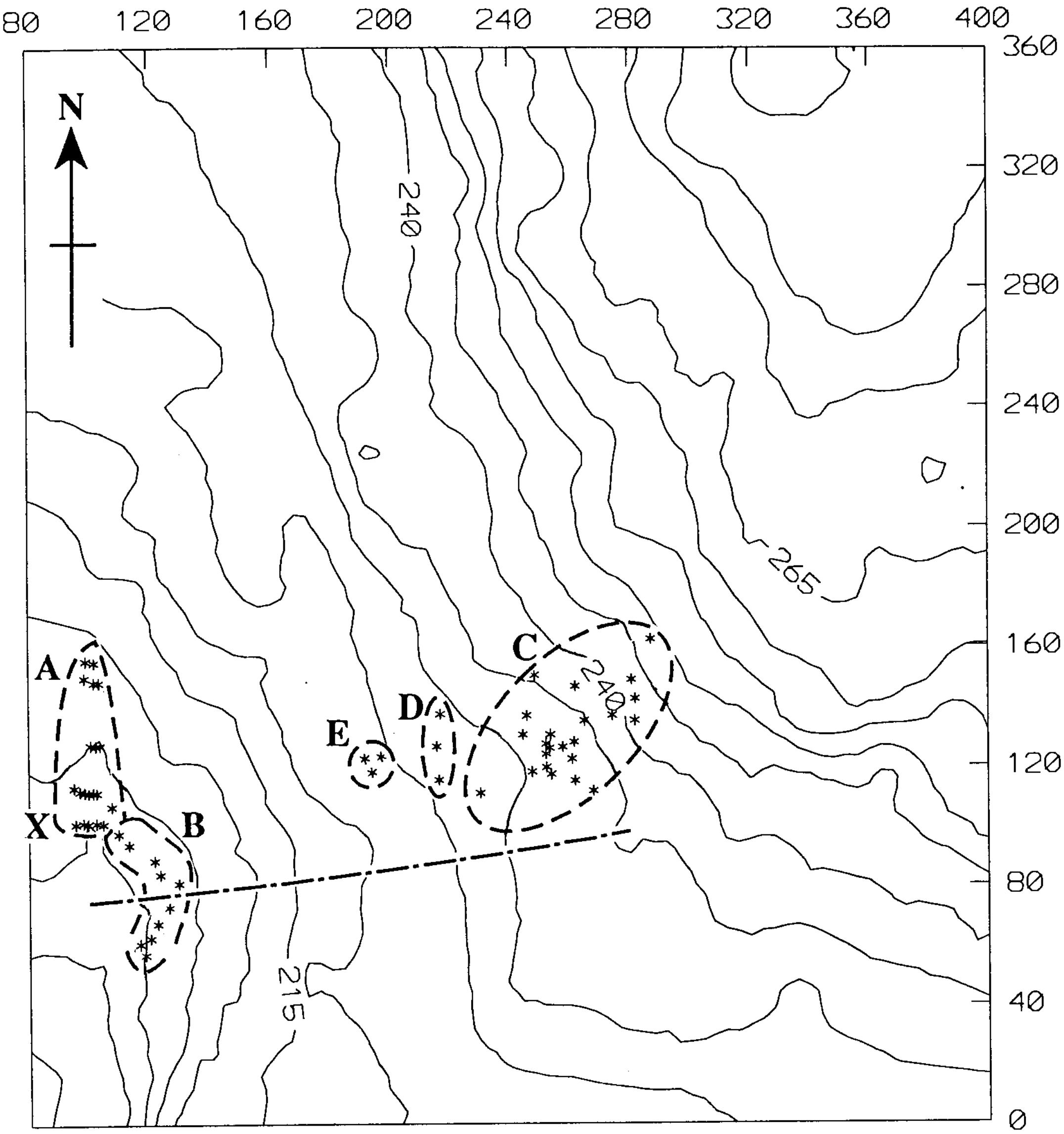
Table 2.2: Values of saturated hydraulic conductivity from Lower Mainland studies

Location	K ($m\ s^{-1}$)	Source	Method of measurement
UBC Res. Forest	$1x10^{-4}$ to $2x10^{-4}$	Willington, 1967	Infiltration capacity
Jamieson Creek	$3x10^{-5}$	Cheng et al., 1975	Estimate
Jamieson Creek	$5x10^{-5}$	Plamondon et al., 1972	Not stated
Seymour River	$3x10^{-5}$	O'Loughlin, 1972	Not stated
Jamieson Creek	$9x10^{-5}$	Chamberlin, 1972	Estimation from flux rates
UBC Res. Forest	$5x10^{-6}$	Utting, 1979	Slug tests
	$8x10^{-5}$	"	Plot outflow estimate
UBC Res. Forest	$8x10^{-4}$	Tischer, 1986	In situ soil cores
	$1.6x10^{-4}$ to $3.2x10^{-4}$	"	Kinematic wave equation
	$5x10^{-4}$ to $5x10^{-3}$	"	Soil outflow measurement
UBC Res. Forest	$9x10^{-5}$ to $3x10^{-3}$	this study	Auger-hole method

1. Water Table Data

The main variable studied was water table elevation, measured relative to local soil surface. In this study "soil surface" includes the forest litter layer and does not refer solely to the soil mineral surface. Water table levels were measured manually at 59 wells located throughout the catchment. Wells were placed according to a judgement sampling scheme to include areas of probable saturation such as near-channel zones, as well as areas with low probabilities of saturation, including steeper upslope areas. Wells were grouped into 5 areas, denoted by letters on Figure 2.11. Twenty wells were placed in the A area along 5 transects crossing an ephemeral channel in the lower part of the catchment. The ten B wells were located next to the A wells along a contour line at approximately 200 m elevation. The twenty-three C wells were in the upper catchment in a variety of topographic situations, from depressions to steep slopes. The D and E wells were both in ephemeral stream areas which connect the main drainage lines from the upper to lower catchment. Three wells each were located in areas D and E. Figure 2.12 is a location map of the wells.

Wells extended to depths between 0.6 and 1.2 m. Due to the stony nature of the soil, augering proved difficult and in some cases several holes were augered at a single site, with the well placed in the deepest hole. After fieldwork completion, a number of wells were exhumed to study the soil profile and to ensure that wells extended to parent material. None of the exhumed wells reached the parent material, although they all extended deep into the B horizon. This finding will have consequences in the calculation of the saturated hydraulic conductivity value and in interpretations of "empty" well levels, and will be discussed in more detail in the results section. Monitoring of the wells took place weekly throughout the study period, with more measurements taken during periods of high precipitation.



Legend:

X Tipping bucket
* Well locations
—·— Throughfall transect

Contour Interval = 5 m

Figure 2.11. Location of instruments in the study site. Grouping of water table wells is described in the text. Easting and Northing coordinates are in m.

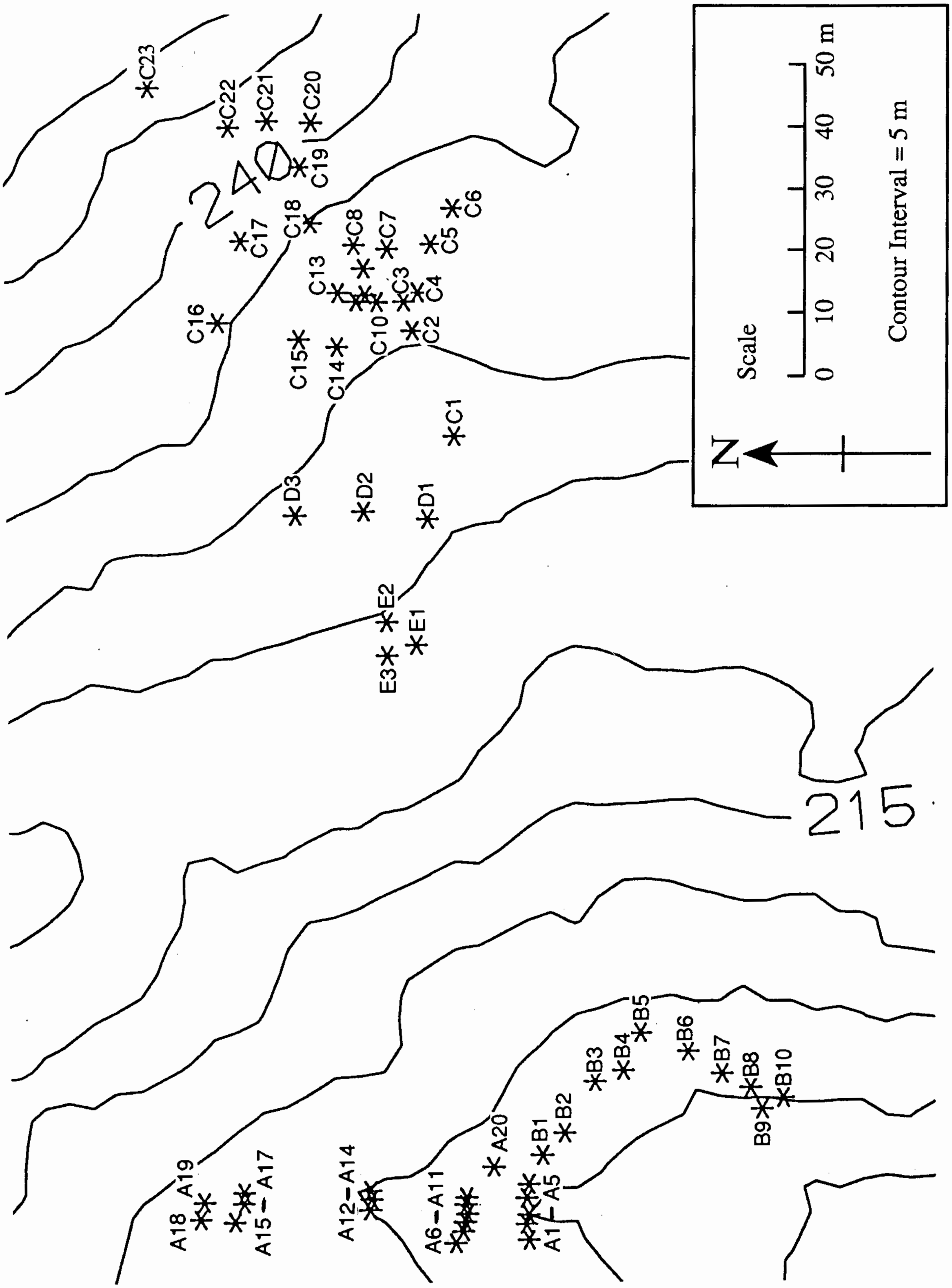


Figure 2.12. Location of wells in the study site.

Wells were constructed of ABS tubing (5 cm inside diameter) with 0.5 cm holes drilled throughout to allow water movement into the wells. They were encased in nylon netting to prevent soil from entering the tube during installation. Augered holes were backfilled with coarse sand to secure the wells in place. A styrofoam marker placed inside a smaller plastic tube in the well allowed measurements of the maximum water table height attained between successive visits (Figure 2.13). The marker would rise with the rising water table and remain at the highest level reached when the water table fell after a storm event. It was estimated that this method of measurement could underestimate peak water table levels by up to 5 cm, accounting for errors in measurement and slippage of the styrofoam pieces. Styrofoam pieces were replaced immediately if any slippage was detected. Errors in this instance could only occur in one direction, as the styrofoam marker would not rise above the level of the water table. Present water table measurements are considered accurate to ± 1 cm based on multiple measurements made at each well. All wells were capped to prevent additional water inputs from precipitation, throughfall or overland flow to enter the well.

Times of "present" water table levels were recorded at the time of measurement and it was assumed as an approximation that maximum water table levels were reached at the time of maximum weir discharge. All times are expressed in Julian Days, beginning with Day 286, which is October 13, 1992. The days follow consecutively from this point, with Day 366 equivalent to January 1, 1993.

Water table data collected in the field were entered into a spreadsheet with values of 0 indicating surface saturation and positive values indicating surface ponding or overland flow. Negative values indicate water table levels below the surface, and empty wells were given a value of -150 cm. Although both maximum and present water table levels were collected during each visit to the forest, some maximum values were deleted if they equalled present levels. This occurred depending on storm characteristics and the timing of collection, and in some instances when no throughfall was recorded between successive visits. In all, 63 water table level datasets were collected, with 35 present levels and 28 maximum levels studied.

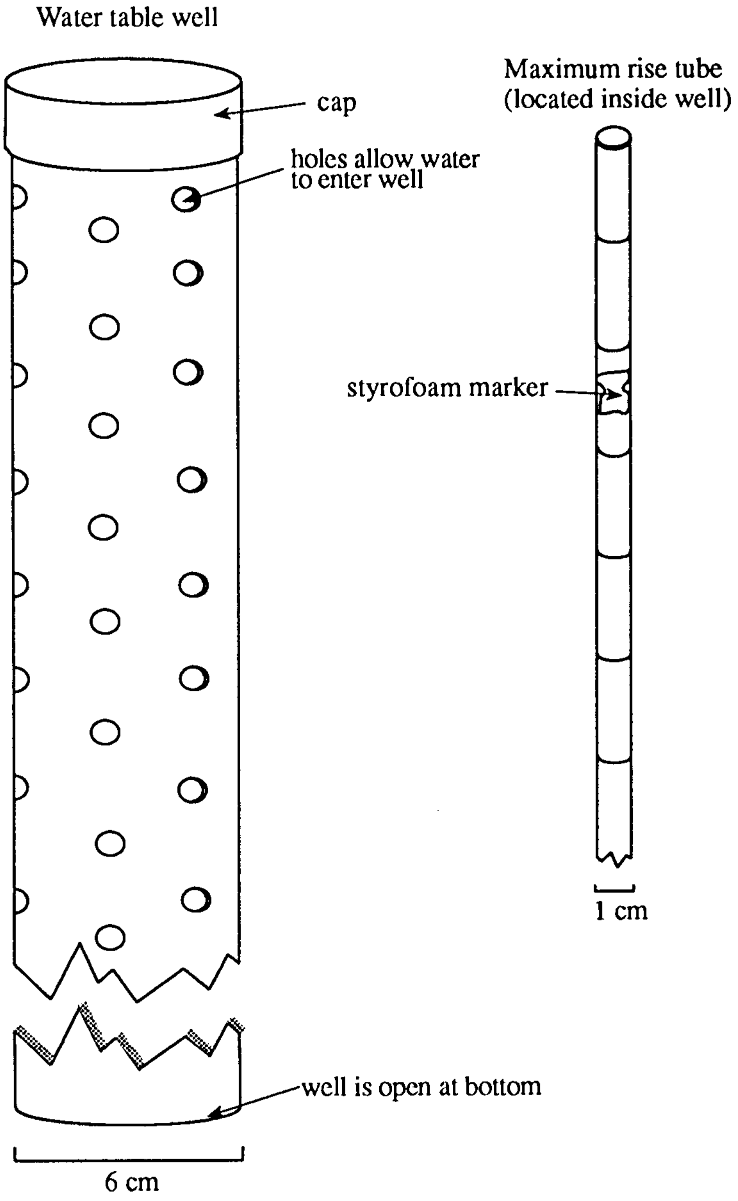


Figure 2.13. Water table well set-up, details of construction are in the text.

Overland flow collectors were used in conjunction with the wells to reveal the occurrence of saturation overland flow (Figure 2.14). These were constructed of ABS tubing similar to the wells, capped and sealed at the bottom, and drilled with holes at the top edge to allow water to enter the collector. The collector was capped and placed in the soil next to each water table well. The drilled holes were aligned with the soil surface, and a rock was placed on top to anchor the collector in place. This set-up allowed for the collection of overland flow without throughfall or soil water inputs.

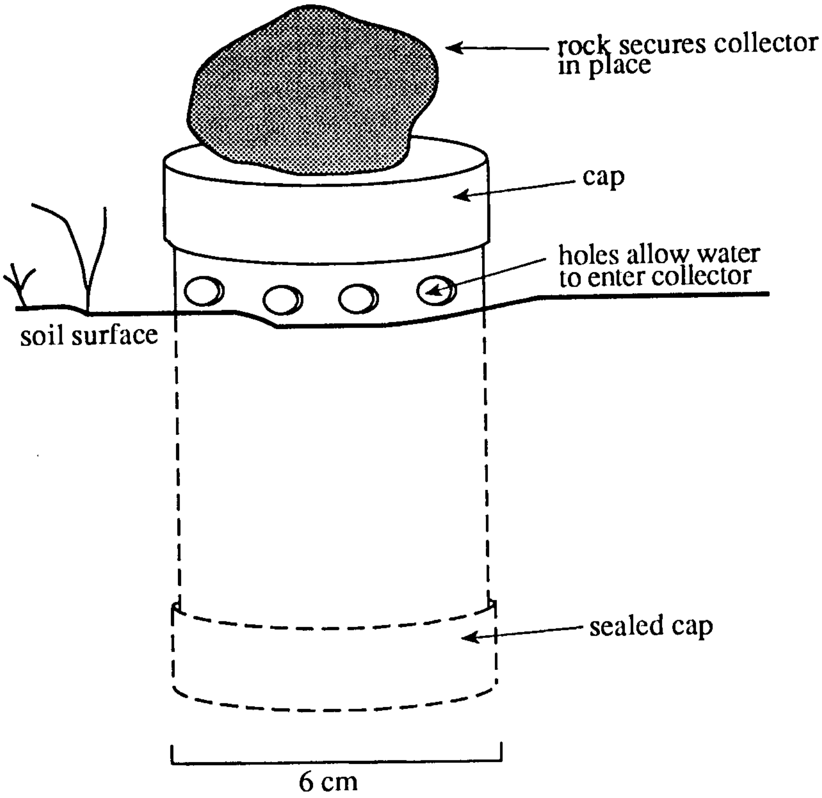


Figure 2.14. Overland flow collector construction. These were located adjacent to each water table well.

Throughfall inputs via stemflow were not measured as stemflow production is generally less than 2% of total precipitation inputs for this type of forest cover (Hutchinson and Roberts, 1981). Due to the minor influence of stemflow and the lack of observed ponding at the base of trees throughout the study period (which would indicate the potential importance of stemflow), this variable was not studied further.

2. Throughfall and Precipitation

Throughfall beneath the canopy was measured automatically using a tipping bucket rain gauge, and manually using 17 throughfall collectors. The tipping bucket rain gauge was equipped with a weekly chart recorder and was located near well A1. Throughfall collectors were constructed from 4 L plastic containers fitted with a 15.4 cm diameter funnel. Throughfall collectors were located randomly within 10 m segments along a marked transect running across the catchment, and were relocated biweekly to eliminate potential sampling bias. Data from the throughfall collectors were used solely for bulk storm volumes, while tipping bucket data were used for throughfall intensity values. The locations of the tipping bucket gauge and the throughfall transect are both marked on Figure 2.11. Two precipitation gauges were also located in a clearing outside the catchment. Average precipitation volumes from these gauges were collected and compared both to forest throughfall volumes and to precipitation volumes at the Research Forest headquarters site.

By using average values of measured throughfall depths to correct tipping bucket gauge volumes, input intensities measured by the tipping bucket are assumed representative of the study catchment. This method was used by Durand et al. (1992) who based rainfall data on two raingauges with dataloggers, corrected by five rainfall volume gauges located throughout the catchment. It was felt that this method would be of sufficient accuracy for this study. Figure 2.15 shows the collected throughfall volumes and standard deviations, which reveals the spatial variability among the 17 collectors.

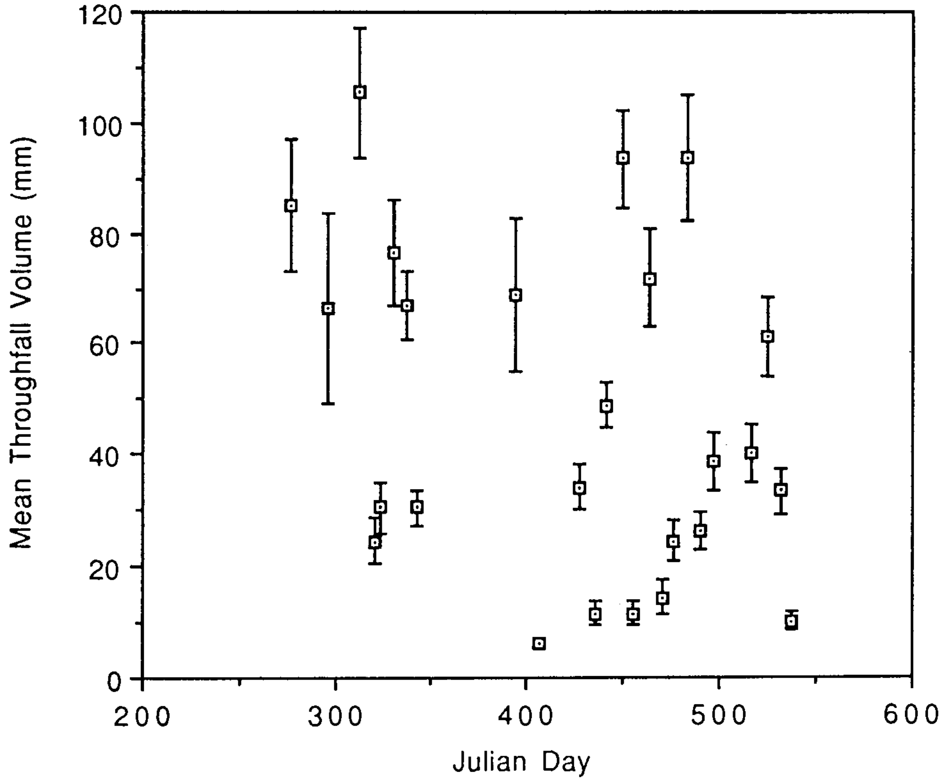


Figure 2.15. Average forest throughfall volumes and standard deviation bars for each collection time.

The use of only one tipping bucket gauge under the canopy for collecting storm intensity data may be harder to justify. Bouten et al. (1992) suggested that throughfall amounts are highly spatially variable, depending on factors such as tree density, species of tree, penetration of wind within the canopy, and the lowest height of branch interception. The study site is quite homogeneous in terms of stand size and age, and the high degree of crown closure will decrease wind velocity under the canopy. This would suggest that spatial variability at the study site should not be large. In order to test storm timing for spatial variability, tipping bucket forest throughfall data were compared to tipping bucket precipitation data collected at headquarters. Precipitation and throughfall intensities over 2 hour periods were compared over a number of storm events. The results showed a strong correspondence, with Figure 2.16 showing a typical comparison for a large storm event in April, 1993. Comparisons of other storm events were similarly of good correspondence, suggesting that tipping bucket intensities under the canopy could be assumed representative of the catchment. If there were discrepancies in storm timing, it is assumed that they would not alter throughfall timing enough to affect the results of this study. Some difference in storm timing may also be due to errors in reading event charts, although it is expected that these errors would be on the order of 20 minutes and are therefore not of great significance.

On a few occasions the tipping bucket malfunctioned and intensity data were lost. In these cases, intensity data were generated using tipping bucket precipitation data collected at headquarters. These intensity values were corrected for storm volumes, as done previously, based on average throughfall gauge volumes under the canopy. Between December 17 and January 14, throughfall volumes were not available due to ice formation in the throughfall gauges. In this instance, throughfall volumes were generated based on the relationship between storm volumes of the forest and

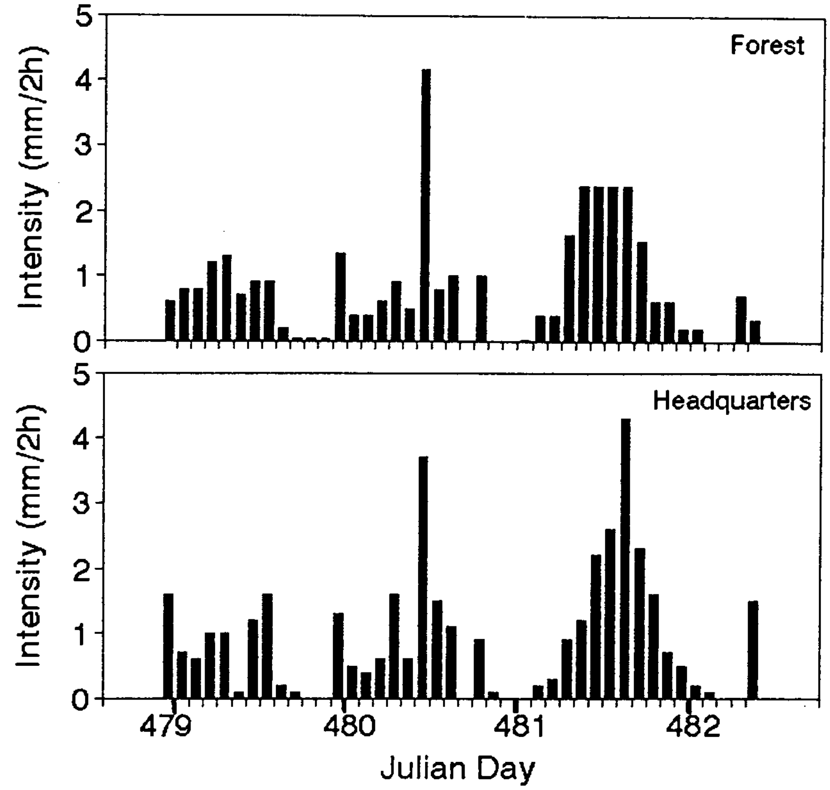


Figure 2.16. Comparison of storm intensities from tipping bucket data at the forest and headquarters over one storm, April 24 to 27, 1993.

headquarters during the study period. This relationship is revealed in Figure 2.17 and was found to be highly significant with an R^2 of 0.962. Only forest storm volumes were generated in this manner, as forest tipping bucket intensity data were still available. During the study period, two time periods (Dec. 17-18, Dec. 26-Jan.14) had both forest volume and intensity data missing. Rather than apply conversions to both variables based on headquarter data, it was decided to classify these dates as missing data. The loss of these data do not affect any further analysis because no water table measurements were taken during these times.

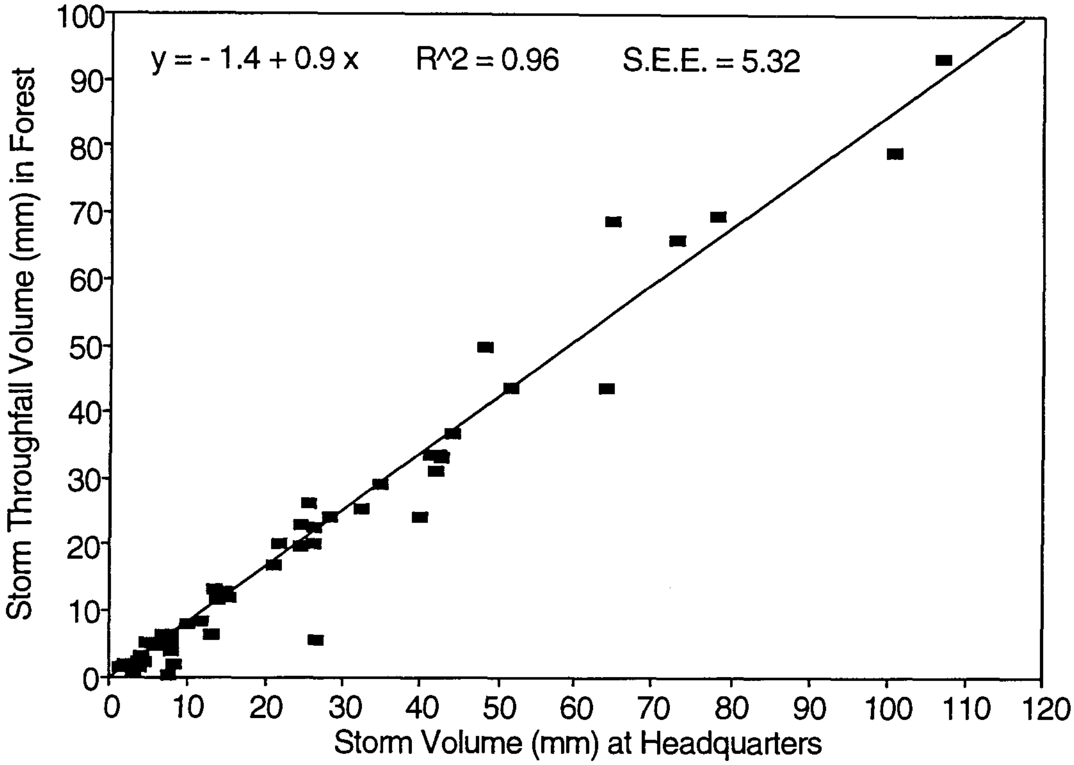


Figure 2.17. Relationship of total storm volumes from forest throughfall gauges and headquarter tipping bucket data for the study period. The standard error of the estimate (S.E.E.) is in mm, and the equation of the line is included for reference.

Throughfall intensity and volume data were discretised into individual storm events using periods of significant rainfall separated by at least 6 hours of rainfall intensities averaging less than 0.1 mm h^{-1} (Harr, 1977). Pierson (1980) used a similar delineation with a 6 hour interval because longer time intervals without rain ceased to have a combined effect on water table response. Based on these definitions, the study period was divided into 51 storm events using headquarter precipitation data. Of these, 26 had associated maximum water table readings and these were used in much of the subsequent analyses.

Precipitation volume from the two gauges located in a clearing outside the catchment was highly correlated with precipitation volume at headquarters. The relationship had an R^2 of 0.994, and the equation of the line was: $y = 0.57 + 0.90 x$, with study site data as the dependent variable. This relationship further verified the use of headquarter precipitation data to represent storm precipitation volumes at the study site. Comparisons of storm volumes from the adjacent clearing to throughfall under the canopy revealed that interception ranged from 0 to 93% of total storm volume, with an average of 26.9%. The wide range of values is due to the varied precipitation events throughout the study period. The average interception value is consistent with interception amounts from other forested catchment studies. Patric (1966) found interception under a mature stand of western hemlock and Sitka spruce in Alaska to be 25%, while Rothacher (1963) found an interception loss of 24% under a mixed forest stand of Douglas fir and western hemlock. Interception loss under pine cover was found to be 22% by Ahmad-Shah and Rieley (1989).

3. Soil Characteristics

Hydraulic conductivity estimates were assessed using the auger-hole method at various well locations following the methodology of Amoozegar and Warrick (1986). Water is pumped out of the well being tested, with the subsequent water table rise measured and timed. Hydraulic conductivity, K, is estimated using:

$$K = (\Delta y / \Delta t)\, C / 864, \qquad (10)$$

where $\Delta y/\Delta t$ is the rate of water table rise (m s^{-1}), and C is a shape factor (Boast and Kirkham, 1971). Hydraulic conductivity values derived by this method are dominated by the average value of the horizontal conductivity of the profile (Amoozegar and Warrick, 1986). Bouwer and Jackson (1974) suggested that "the auger-hole technique is among the most widely used methods for measuring hydraulic conductivity of soil for drainage design".

Conductivity measurements were made at two augered holes near the ephemeral stream in the lower catchment and at well locations A13 and D1. The two augered holes were dug specifically for the conductivity measurements and do not represent well locations. Table 2.3 summarises the measurements taken, as well as the soil layers represented at each location. Measurements were taken at two separate times during the study period with similar results found at each site both times. As mentioned previously, the results were comparable to those found by other researchers in forested Lower Mainland catchments (e.g. Utting, 1979, Tischer, 1986).

The influence of soil characteristics on surface saturation is represented using soil transmissivity (T), as defined in Equation 2. Based on the range of K values measured at the site and the soil depths estimated from the soil pits, a range of T values likely to occur within the study catchment were derived. A shallow soil (0.65 m) with a high K value would result in a high T on the order of 6×10^{-3} m^2 s^{-1}. A low T estimate would be based on a deep soil (2 m) with a low K value. Transmissivity values for the catchment were therefore estimated to fall between 6x10^{-5} m^2 s^{-1} and 6x10^{-3} m^2 s^{-1}. This estimation is based on the fact that K decreases with depth; therefore, K values for deeper soils would be lower as they are integrated over a larger depth than those of shallower soils. Shallow soils generally have higher K values, resulting in a higher T overall.

Table 2.3. Hydraulic conductivities determined by the auger-hole method

Site	Vertical Representation	Horizon Representation	Average K Derived (m s^{-1})
Site A	8 - 37 cm	LFH, A	2 x 10^{-2}
Site B	7 - 35 cm	LFH, A	3 x 10^{-3}
Well A13	15 - 80 cm	A, B	9 x 10^{-5}
Well D1	15 - 72 cm	A, B	2 x 10^{-4}

Soil transmissivity is often not included in hydrologic analyses as it has been found that topographic variability will have the highest influence on the distribution of index values. Wood et al. (1990) found that topographic variability dominated saturated zone development with comparison to soil variability at a catchment of gentle relief in Kansas. Wood et al. (1990) also summarised results from Wolock's (1988) investigation of 145 catchments in the northeastern United States, which concluded that variability in the topographic index dominated over soil transmissivity variability in all but four catchments. Since the estimated T values for this site do not vary as much as the derived topographic values, T should have a minor influence on the distribution of index values throughout the catchment, and will therefore not be studied further.

Two tensiometers were installed at 30 cm depths at midslope and bottom slope positions within the A1-A5 transect to provide an index of soil moisture content. A third tensiometer was placed at 45 cm depth in the midslope position to measure any vertical moisture variability. However, instrument failure halfway through the field season led to abandonment of this measure.

Soil pits were dug at nine well locations after completion of the field season to measure the depth of the soil above the till or bedrock layer and to assess soil characteristics. Each soil pit was analysed for horizonation, structure, texture, and any indication of long-term saturation, including soil chroma values and the presence of mottles or gleying. Pits were dug at the following well locations: A3, A8, A17, B2, B4, C2, C11, D2, E2. These were chosen to represent wells with a wide range of hydrologic response, based on water table data and topographic structure. It was found that none of the wells extended to the till or bedrock, although they did extend into the B horizon. Individual soil profiles and the location of the soil pits are included in Appendix I.

Soil samples from each horizon were collected for particle size analyses. Samples were oven dried for 48 hours at 250°C and sieved at 1 phi increments. Measurement error through sieving amounted to no more than 3% of each sample based on a comparison of total sample weights before and after sieving. No textural analysis was done on the silt/clay range, so soil textures could not be precisely determined. Particle distributions are summarised in Table 2.4.

Table 2.4. Textural analysis of soil pits

Site	Horizon	% Gravel	% Sand	% Fines
A3	Ah	9.8	79.6	9.5
	Bf	14.3	72.3	13.2
A8	Ah	10.8	75.9	12.4
	Bf	14.2	69.7	15.7
A17	Ae	11.7	68.3	18.5
	Bf	17.8	57.3	24.6
B2	Ah	7.1	85.7	6.5
	Bf	25.2	65.7	8.8
B4	Ah	20.0	75.3	4.1
	Bf	23.6	66.6	9.5
C2	Ah	24.7	68.5	5.8
	Bf	20.8	72.9	6.1
	lower Bf	24.0	68.1	7.6
C11	Ah	19.6	71.6	8.0
	Bf	35.9	57.5	10.1
D2	Ah	15.0	75.2	9.0
	Bf	33.5	54.0	12.2
E2	Ah	32.1	61.1	6.3
	Bf	38.5	53.9	7.2

4. Digital Elevation Model

A detailed survey of the study area was carried out with a theodolite and electronic distance meter at a scale suitable for the development of a detailed digital elevation model (DEM) to be used for the derivation of topographic variables. Figure 2.18 shows the detail of this survey. The density of points represents an average spacing of 4-5 m. The scarcity of data points in boundary locations is not considered significant as the drainage areas for well locations are well represented. Based on repeated measurements on known points from different instrument locations, errors are less than ± 25 cm for horizontal position and ± 10 cm for elevation. Alternative methods of DEM derivation, such as digitising topographic maps, would not have proved useful, as existing topographic maps of the area were not detailed enough to incorporate into a DEM for the purposes of this study. As well, topographic maps of the area were generated from aerial photographs based on tree-top elevations and not on ground surface measurements (compare Figure 2.19 with Figure 2.18). The survey was detailed enough to allow a 4 m grid cell for the derivation of topographic variables.

Gridded elevation data were determined by SURFER, which generates three-dimensional surfaces and contour maps from inputs of irregularly spaced x, y, z coordinates. Grid size and the interpolation method used to develop the grid can be specified by the user. In this study, the inverse distance squared method was chosen for all interpolation. The size of grid cell was altered for a study of scale effects, using 4 m, 8 m, and 16 m grids. Gridded elevation data derived at the three grid scales were based on all surveyed points, representing an average point spacing of 4 m. Since the size of grid cell is generally chosen based on the density of data points available, elevational data at the 8 m and 16 m grids represent a higher accuracy than would generally be derived. Therefore, results based on comparisons of the three grid scales

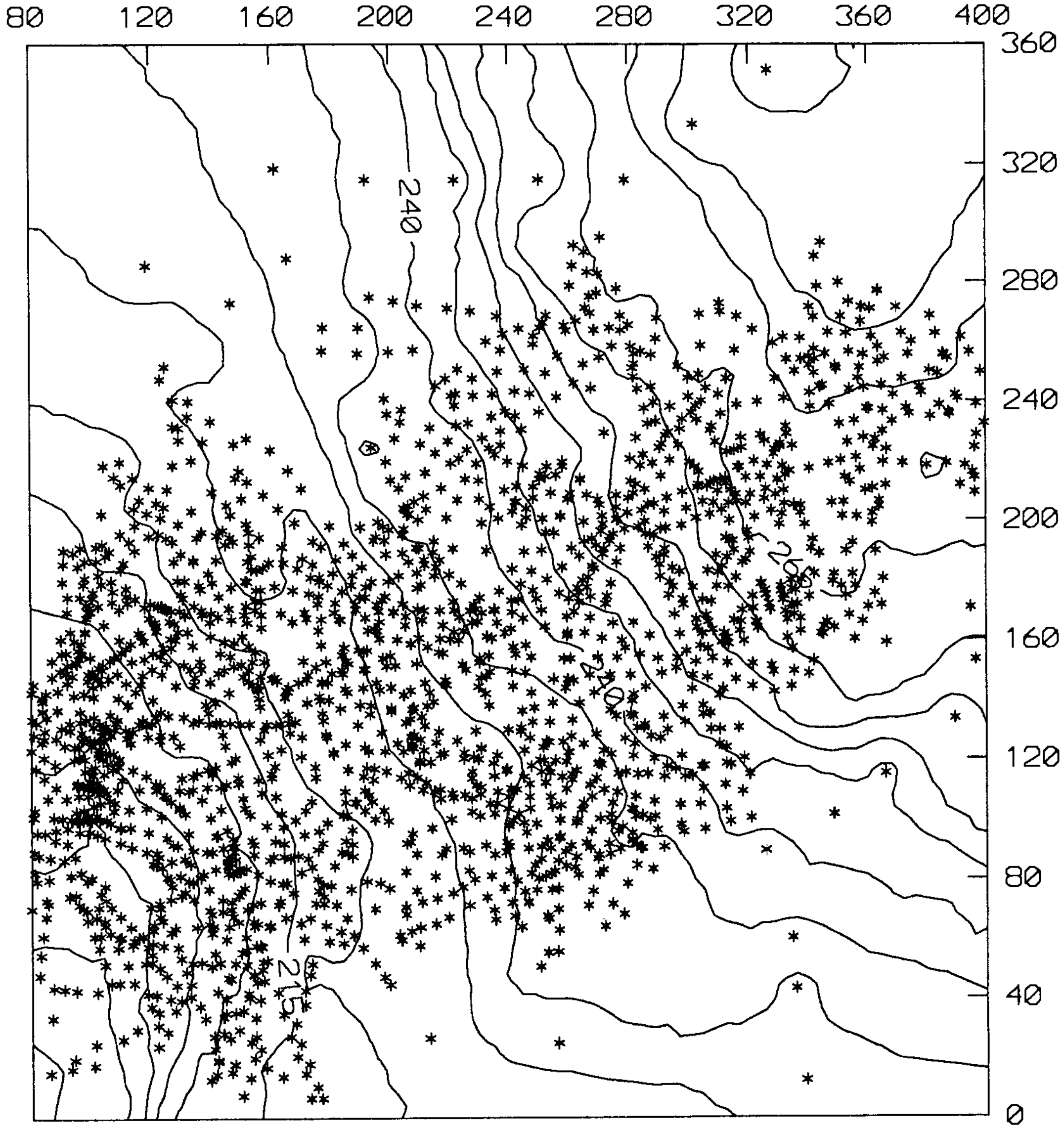


Figure 2.18. Location of surveyed data points. Easting and Northing coordinates are in metres. The concentration of surveyed points cover the drainage areas for the well sites. Contour interval is 5 m.

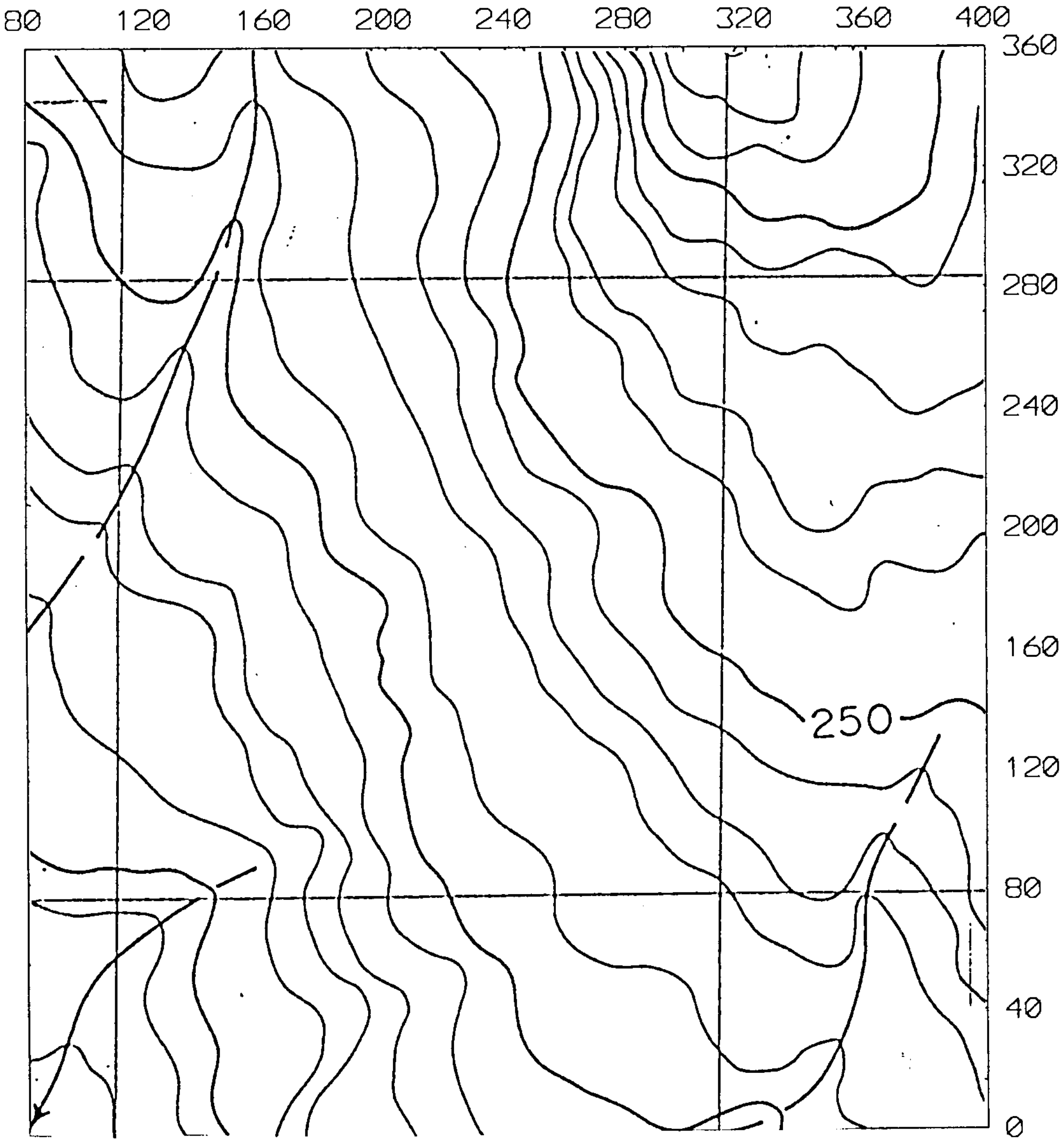


Figure 2.19. Existing topographic map of field site. Scale = 1:2500.

Easting and Northing coordinates are in m. Contour interval is 5 m.

will be conservative in nature.

Gridded elevation data were analysed by a computer program, HYTOP, developed by R.D. Moore of Simon Fraser University. As an intial step, HYTOP locates topographic depressions, or pits, as these points represent potential end points for streamlines. As Band (1986) stated, pits "may potentially cause serious errors for any algorithm that depends on mapping hydrologically connected regions". Although many DEMs treat pits as spurious information (e.g. Band, 1986, Hutchinson, 1989), within this study they are considered physical realities of the catchment. Pits are located using a landscape descriptor of "pit" or "pass", where a descriptor is given to a cell based on the elevational relationship between it and its eight neighbours (Peucker and Douglas, 1975). For a pit, all surrounding neighbours have higher elevations than the grid cell in question. For a pass, or saddle, the elevations of the neighbours shift from higher than to lower than the centre grid cell as a circuit of the eight neighbouring points is made.

The pits are processed in a further step. If a DEM contains pits, flow paths will either end at the edge of the grid or at a depression or pit. Those ending at the edge require no further processing. Flow paths ending at pits result in the program searching for all saddle locations which are connected to the pit by a flow path. The lowest saddle in elevation will be the path of flow out of the pit. Therefore, any flow reaching the pit cell will be shunted to the saddle location chosen. This method is similar to that of Martz and deJong (1988), although their method of locating neighbouring saddles was done through a 10x10 window search. Within HYTOP, comparisons of saddle elevations are not limited to a specified area of search. The algorithm also recognises and handles the problem of nested pits.

HYTOP delineates catchment flow paths following the path of steepest descent between the grid cell and one of eight neighbours. This is known as the deterministic eight neighbour single flow path algorithm (D8). Fairfield and Leymarie (1991) suggested that this approach, although used extensively, tended to produce parallel flow lines which may lead to large errors in further hydrologic analysis, especially in areas of low relief. Quinn et al. (1991) suggested that the single flow path algorithm would show inaccuracies at grid scales larger than 50 m. An alternative and perhaps more realistic approach to D8 is the multiple flow path algorithm, which divides flow proportionally among any number of lower neighbours (Freeman, 1991, Quinn et al., 1991). Although Quinn et al. (1991) claimed that the multiple flow mechanism generates more accurate and "realistic" flow paths, no study has shown this method to yield any practical improvement on actual field tests. Therefore, the single flow D8 algorithm was chosen for flow path delineation within HYTOP as it has already been used extensively in hydrologic modelling (O'Callaghan and Mark, 1984, Band, 1986, Jenson and Domingue, 1988, Martz and deJong, 1988), and as the final flow paths derived from the DEM agreed well with field observations.

For each grid point, HYTOP calculates upslope contributing area (A), contour width (w), slope (tan B), aspect (ψ), and curvature ($\nabla^2 Z$). These variables are used in further hydrologic analyses, such as delineating saturated zones, flow paths, or catchment boundaries. Detailed descriptions of the variables pertinent to the present study are included here.

Upslope contributing area (A) is calculated by summing the number of cells draining through a given cell, including the cell itself, and multiplying this by D^2, where D is the grid spacing (Martz and deJong, 1988). The derived value can be converted into upslope contributing area per unit width using

$$a = A/w, \tag{11}$$

where w = contour width. If flow path direction is in one of the four cardinal directions, w=D, and in one of the diagonal directions, $w=D\sqrt{2}$.

Slope is often calculated as the slope of the path of steepest descent between two grid cells. However, HYTOP incorporates Skidmore's (1989) method four, a third order finite difference method, which represents more of an average value based on elevations of all surrounding neighbours. In a comparison of six techniques, this method was found to be "optimal for calculating gradient and aspect from a gridded DEM" (Skidmore, 1989).

Using the calculated values of slope, contributing area, and grid cell elevations, the topographic indices W_B and $\nabla^2 Z$ were calculated for each grid cell. The indices were also calculated for each well position for further analysis of water table level predictions. Because the wells did not center on grid cells, values of a, tanB, and $\nabla^2 Z$ at each well location were interpolated, using a bi-linear scheme, from the four surrounding grid points. W_B was calculated subsequently using the interpolated values of a and tanB. Figure 2.20 shows the W_B values derived from the 4 m grid. W_B values derived from the 8 m and 16 m grids will be covered in a later section, and are shown for comparative purposes in Figures 3.16 and 3.17.

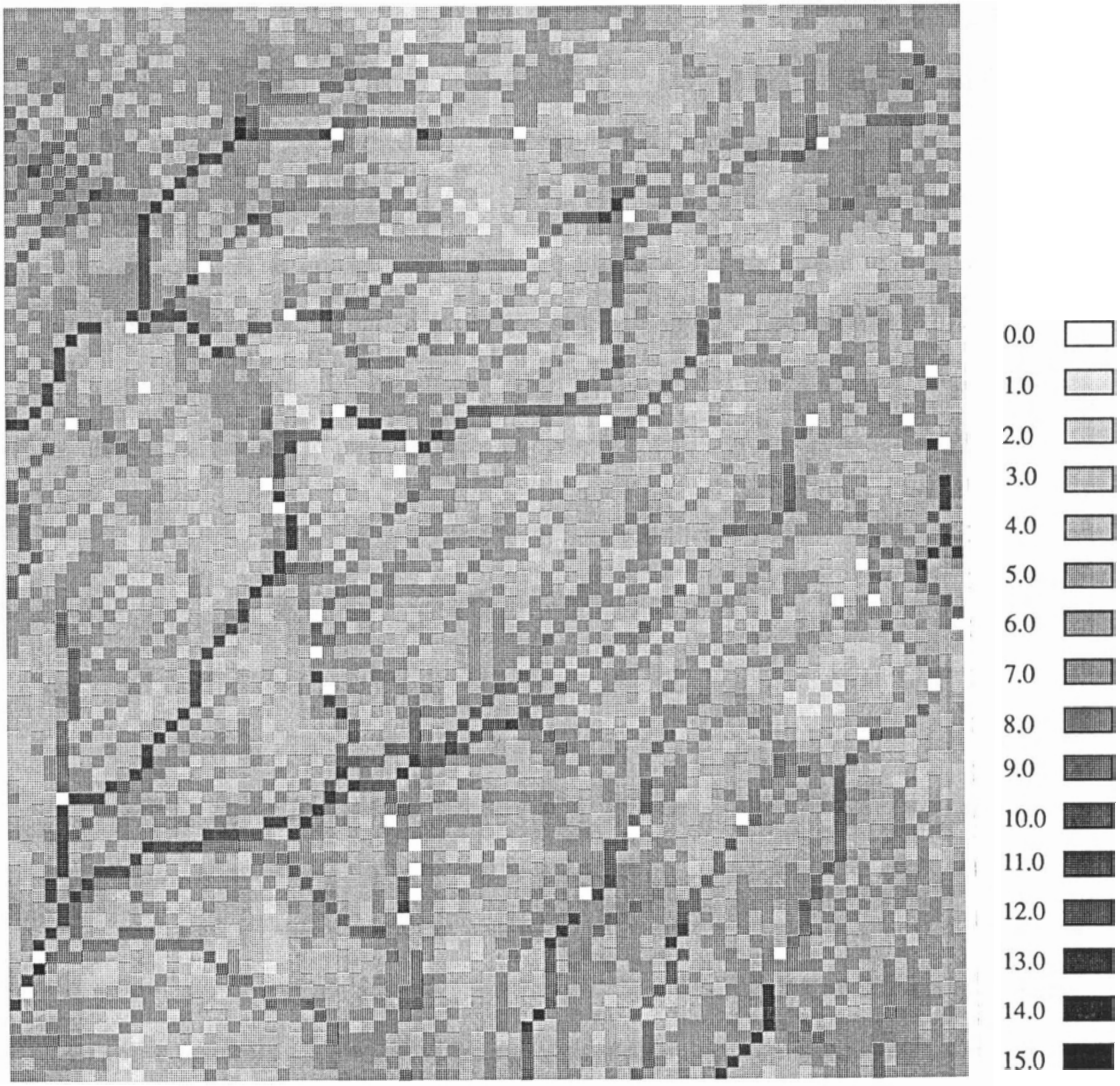


Figure 2.20. Image of W_B at the 4 m grid scale. White cells indicate "pits", while black cells show drainage paths.

CHAPTER THREE - ANALYSIS AND RESULTS

This chapter is organised into three sections based on the objectives of this study. The first section will cover water table observations, including soil indicators of high water table levels, and hydrologic influences on water table response. This section will be followed by the prediction of water table levels and the occurrence of saturation based on the topographic variables derived at each well. The main component of this investigation will be a multiple discriminant analysis. The third section involves the effect of DEM grid scale on the derivation of topographic variables and the influence grid size has on further analysis and model conclusions. In each section, methodologies of all analyses will also be covered.

A. Water Table Behaviour

1. Water Table Response

Water table fluctuations revealed a variable response throughout the catchment, with water table levels at most wells rising and falling rapidly. Water table response from storm inputs varied between 15 and 50 cm for larger storm events, with the largest response over one storm event being 89 cm for an 80 mm storm of 30 hours duration. A similar result was found by Tischer (1986) within the same Research Forest, who observed a water table response of 10 to 50 cm over storm periods. In the present study, surface saturation and overland flow were observed throughout the site even though storm return periods were less than 2 years. Of the 59 wells, 16 did not show any water table response (to the depth of the well) during the study period, and 25 revealed evidence of saturation at least once. Due to possible measurement error and the influence of the litter layer, the soil was considered saturated if water table depth was at -10 cm or higher.

Water table response showed large spatial variability as well, with saturation often occurring at wells located within a few metres of wells where response was not measurable. An example of this is shown by observations from the A1 - A5 transect (Figure 3.1). Well A1, located 4 m upslope from A3 never showed any water table response to a depth of -70 cm, while A3 became saturated quite frequently during storm events throughout the study period. This is a result of the complex microtopography at the site, which has a strong influence on subsurface flow variability. Myrabo (1986) also observed the high spatial variability of soil moisture distribution at a forested site, with variations from saturated to dry soils within centimetres of one another.

A further observation can be made from the cross-sectional water table profiles. Figures 3.1 and 3.2 show water table levels at various times across two transects in the A well area. The transects chosen both represent a series of four wells which had measurable water table levels during the study period. The cross-sections reveal that in some instances water table levels do not run parallel to surface topography, negating one of the main assumptions of TOPMODEL and TOPOG. Although in some cases water table levels do parallel surface topography, the fact that this does not always hold true may have some consequence to the accuracy of water table predictions based on topographic indices. No final conclusion can be made on the effect of this observation as cross-sectional data could only be derived from these two transects. It is suggested here that the degree of deviation will not have serious consequences on the accuracy of

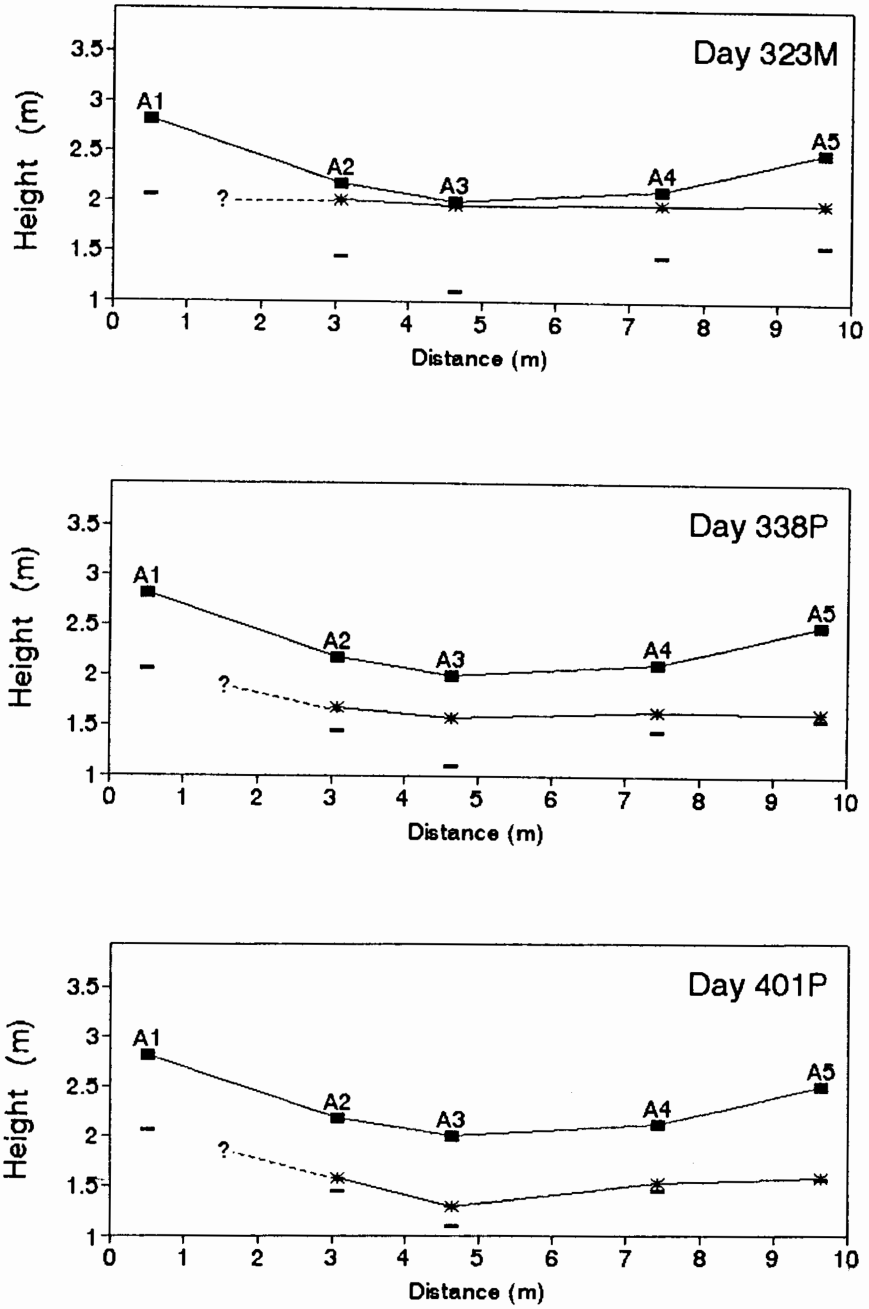


Figure 3.1. Cross-sectional profiles for wells A1 - A5 on Julian Days 323, 338, and 401, revealing the relationship of water table level and topography. The dashed lines show the depth of each well, water table measurements are marked by *. On all dates, well A1 did not show any measurable water table response.

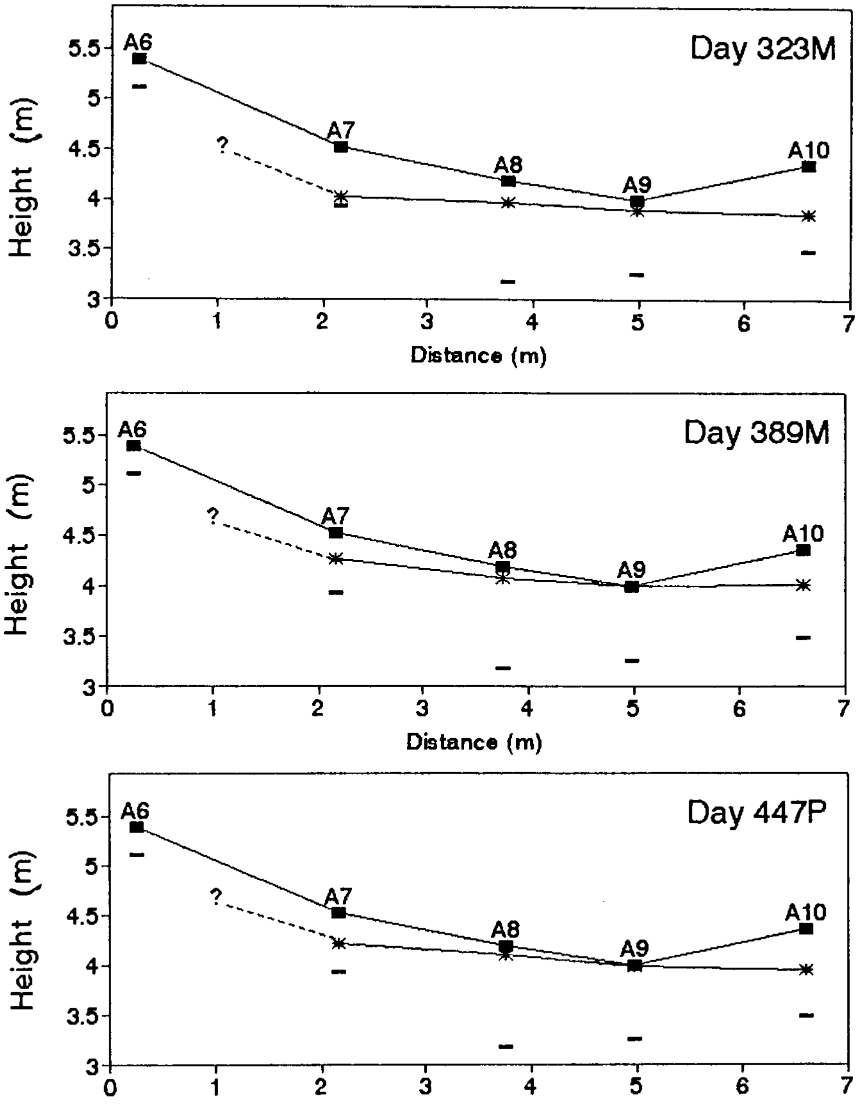


Figure 3.2. Cross-sectional profiles for wells A6 - A10 for Julian Days 323, 389, and 447P. Well A6 revealed "empty" water table levels on all dates.

predictive indices for the study site; however, this may be an important assumption to test in other catchments.

Evidence of overland flow was found using the overland flow collectors. On various occasions the collectors located adjacent to wells where saturation was observed also recorded overland flow. In total, overland flow was observed on 9 dates at 19 different wells. All dates represent times of maximum water table measurement. A summary of observations is included in Table 3.1.

Table 3.1. Summary of observations from overland flow collectors.

Date	Wells recording overland flow
323	A3 C2 C3 D1
326	A9 A18 B2 C2 C3 C10 D1
334	A3 A13 A16 A18 B2 B5 C1 C2 C3 C6 C8 C9 C10 D1 D2
343	D1
385	D1
389	A3 A16 A18 B2 B5 C1 C2 C3 C6 C9 C10 C11 D1
392	A3 A13 A16 A18 B2 B5 C1 C2 C3 C6 C10 C11 D1
447	A3 A13 A16 A18 B2 B5 C1 C2 C3 C6 C10 C11 D1
487	C2 C3

A probability analysis was carried out to determine the frequency of occurrence of water table heights. The analysis was based on the maximum water table level measured in each storm event during the study period. Maximum water table levels were then ranked at each well with the exceedance probability calculated as:

$$P_{ex} = (R - 0.5)\, n^{-1} \qquad (12)$$

where R = rank of water table level, and n = number of levels ranked. It was found that only six of the 59 wells had probabilities above 40% of becoming saturated during a storm event. Over the study period, twenty-five wells reached water table levels of -10 cm or higher, with the other thirty-four never reaching to -10 cm. Probabilities of saturation throughout the study period for all wells are summarised in Appendix II, and four probability graphs typical of overall water table response are shown in Figure 3.3.

In February 1993, three weeks without any precipitation allowed for the derivation of water table drainage graphs. In these, the dual response of the draining soil is apparent. Figure 3.4 shows water table levels from wells A13 and C2 over this period. These wells are considered representative of the drainage response, as the water table was measurable at these wells throughout the entire drainage period. The graphs reveal that drainage is initially fairly rapid, but slows considerably as lower soil moisture levels and increased suctions are reached. The effect could also be influenced by reduced K at depth. A slight rise in water table levels around day 405 (Feb. 8, 1993) represents a 5 mm storm event on this day. Continuous storm events began again on Day 426 (Mar. 3, 1993). Streamflow discharge derived from weir data is also included on the graphs. There was a continuous decrease in discharge over the period, except for a small response due to a storm event on Days 392 and 393.

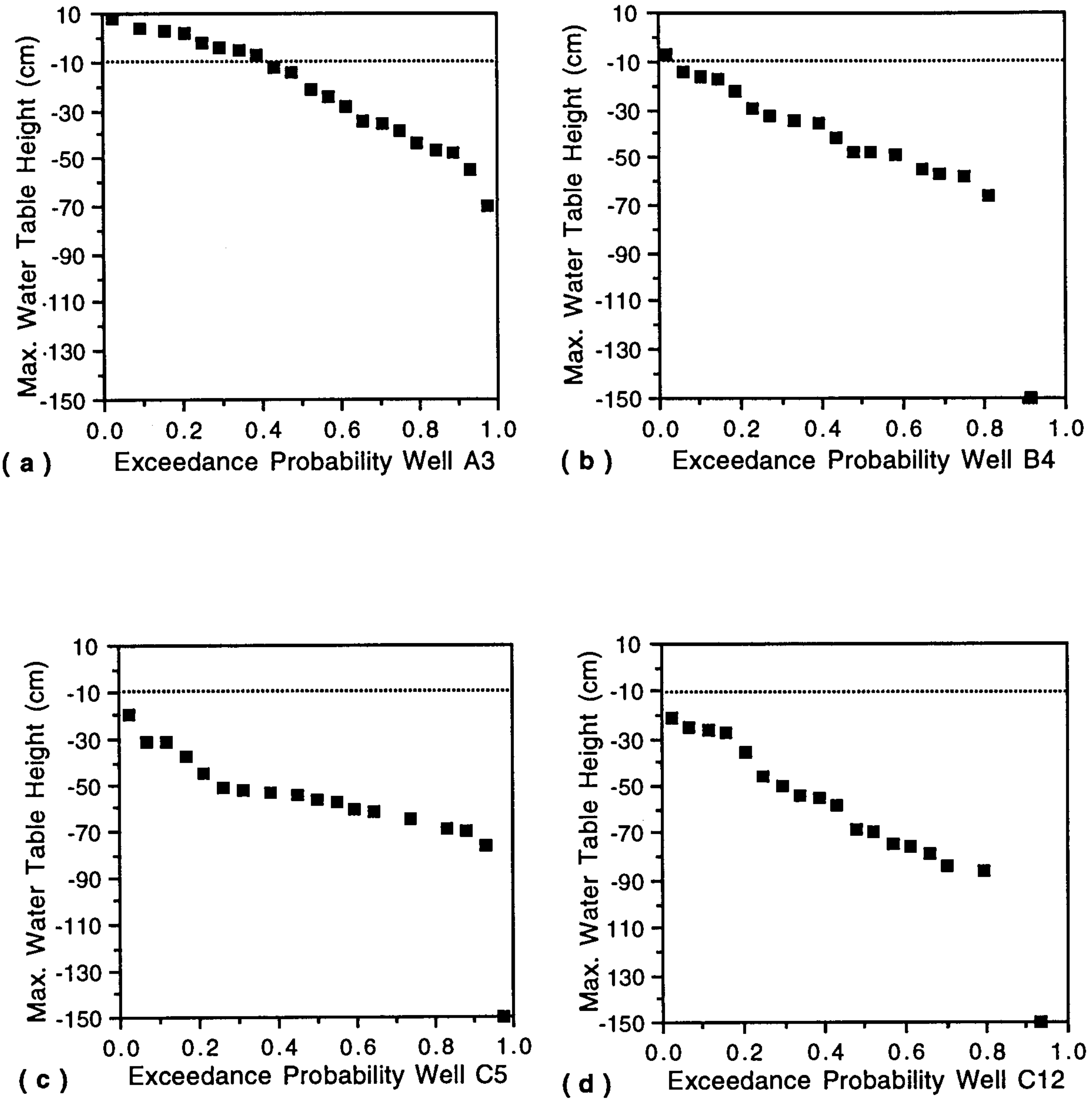
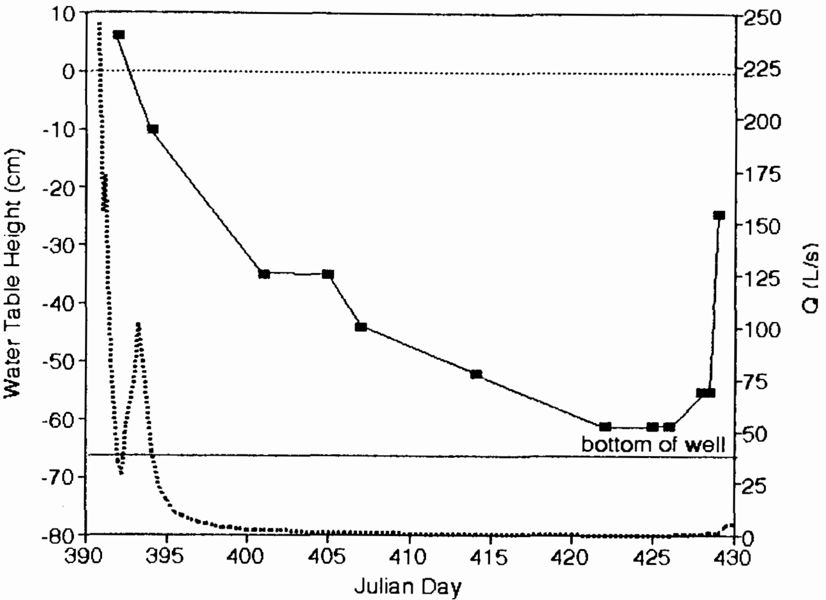
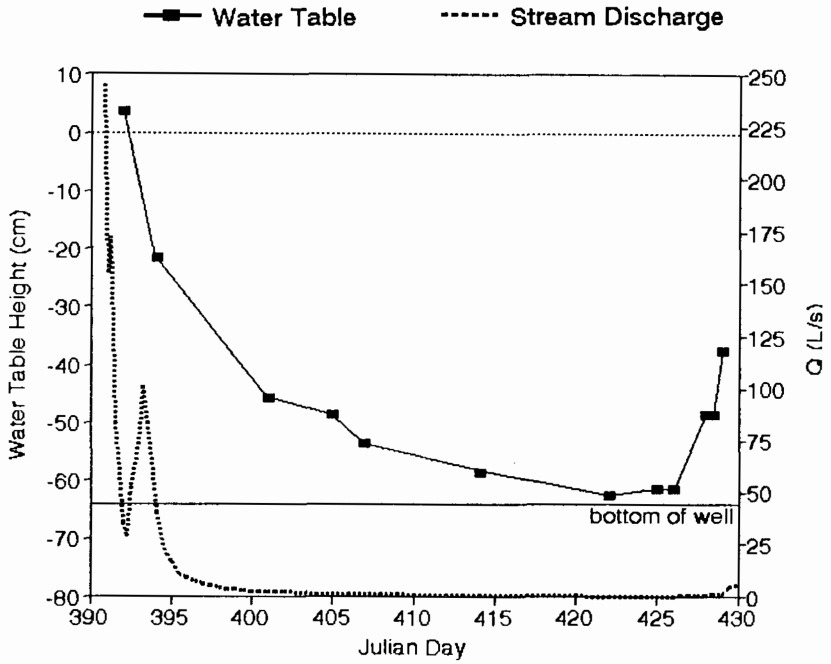


Figure 3.3. Exceedance probabilities for four wells. (a) A3 (b) B4 (c) C5 (d) C12.



(a) Well A13



(b) Well C2.

Figure 3.4. Water table heights from Jan.24 (390) to Mar. 5, 1993 (430), representing an extended period without throughfall. Note that a 5 mm storm event occurred between Feb. 8 and 9 (405-406). (a) Well A13 (b) Well C2. Streamflow discharge is included in the figures.

2. Hydrologic Variables Influencing Water Table Rise

In previous studies, researchers have linked water table levels to variables such as maximum stream discharge, baseflow level, storm volume and storm intensity. Pierson (1980) studied the factors affecting piezometric response on a steep forested slope and found the strongest relationship to exist between piezometric response and 24 hour rainfall totals (compared to 3, 6, 12, 36, 60, and 72 hour totals). Some improvement was gained by adding antecedent moisture to the regression equation. Similar variables were tested in this study to find possible relationships with maximum water table levels for each storm event.

As a preliminary investigation, the relationship between maximum discharge and maximum water table level was studied, and revealed a curvilinear relationship in most instances. Of the 35 wells which had a measurable water table response, water table elevations at 22 wells showed a tendency to level out when saturation of the soil occurred, as typified by wells A3 and C10 in Figure 3.5 (a) and (b). Saturation of the soil occurred at times of higher discharge. The curvilinear relationship was also found in six wells where saturation did not occur, as shown in Figure 3.5 (c) at well C12. This could be due to a draining effect caused by large macropores at certain soil depths in the vicinity of these wells. To test this hypothesis, shallow soil pits were dug at four of the wells which had this relationship (A5, A10, C5, and C12). It was found that extensive root systems and large rocks were found near each of these wells in the upper horizons. The root systems were more extensive than those observed at the soil pits. The soil pits are representative of wells with a curvilinear relationship reaching saturation. At wells A5 and C12, large macropores were also found in the vicinity of the wells. As shown in Figure 3.5 (c), water table levels at well C12 did not extend past

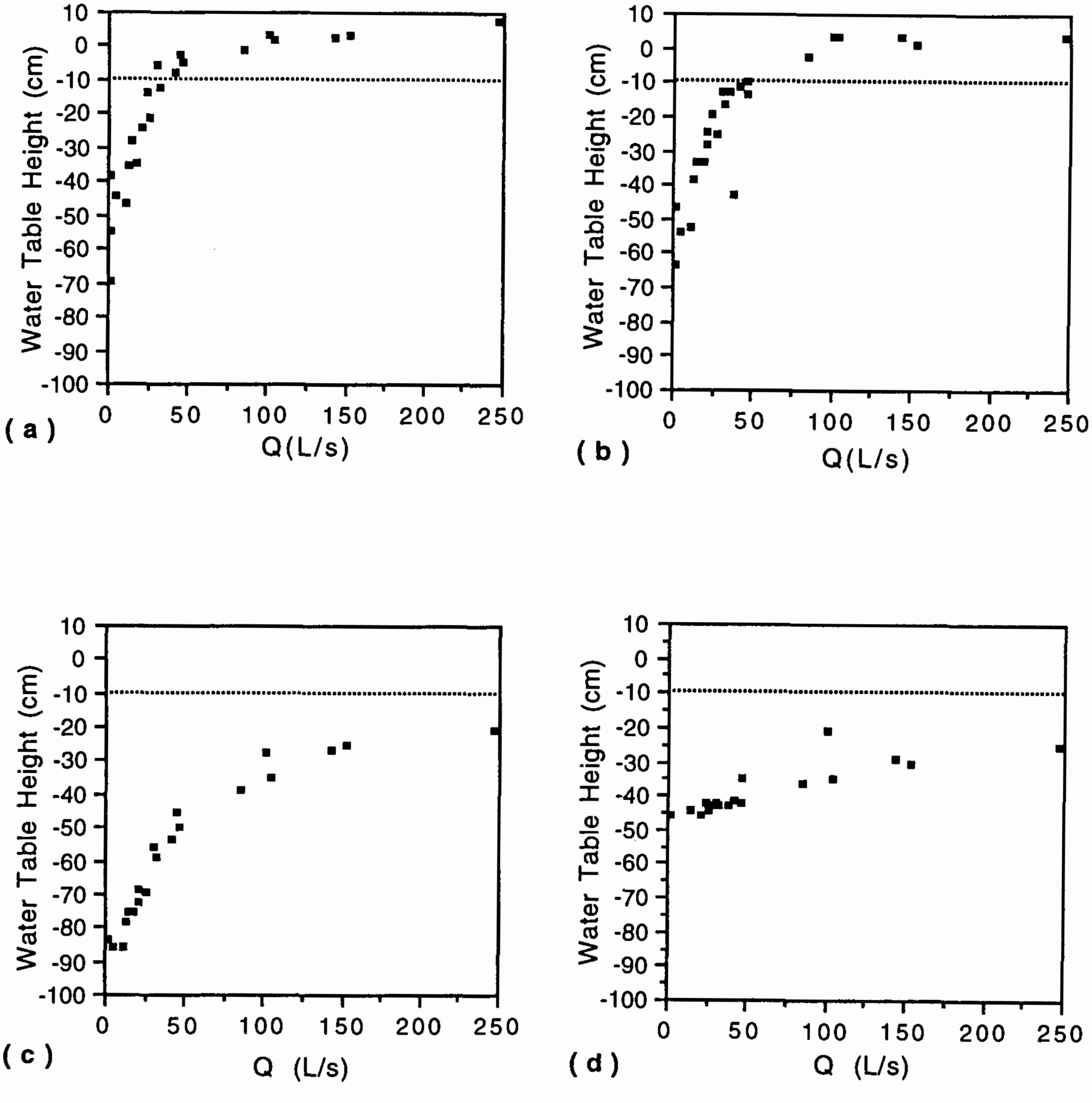


Figure 3.5. Maximum storm discharge and maximum water table levels at a number of wells. (a) A3 (b) C10 (c) C12 (d) B8.

-25 cm in any of the storm events studied. A large macropore (3 cm diameter) was found adjacent to well C12 in a downslope direction at 20 cm depth, which probably allowed infiltrating water a path of preferential flow away from the well, resulting in the maintenance of lower water table levels at this site.

The curvilinear relationship between maximum water table level and peak discharge was held by all but seven wells in the catchment. Atypical water table response occurred at wells B7, B8, C9, C13, C14, C18, and E2, and revealed a more linear relationship with discharge as shown in Figure 3.5 (d). This may have been due to data censoring at lower water table levels, thereby obscuring the existing relationship which may have been similar to those shown in Figure 3.5 (a), (b), and (c). All wells with "atypical" relationships show a certain amount of levelling off at higher water table levels and discharges.

In order to quantify the relationship between hydrologic variables and water table levels, correlations were carried out between maximum water table elevations and the following variables: maximum discharge (Q_{max}); baseflow discharge prior to the storm event (Q_{base}); 6-hour, 12-hour, and 24-hour throughfall intensities (I_n); total storm throughfall volume (V_s); and storm duration (D_s). Maximum discharge and baseflow discharge were read off weir discharge charts, with maximum discharge measured as the peak discharge reached during a storm, and baseflow measured as the lowest discharge level prior to the storm. The baseflow discharge can also be considered a surrogate measure for antecedent moisture (Eshleman et al., 1993, Jordan, 1994). Intensities at 6, 12, and 24 hour intervals were derived for each storm event by averaging storm volumes over the specified duration beginning prior to the time of maximum discharge. This was considered the most accurate method of defining intensity, as a precise measure of lag times could not be made. Total storm volume was based on forest throughfall volume, and storm duration was calculated from headquarter storm values.

In each test, only maximum water table levels with associated storm events were used. Because data censoring occurred at wells with "empty" water table levels, correlations are not valid at wells where "empty" levels were reached at times of maximum measurements. As all wells had some "empty" measures, wells were chosen for the analysis if "empty" values did not occur often (< 20% of all maximum measures). Wells included in the analysis were A4, A5, A10, A12, A14, B1, B4, B6, B8, C5, and D2. Within the analysis, "empty" levels were considered to be missing values. This method of analysis will introduce some error into the correlation coefficient values, and the strength of relationships may not be as high in actuality. Therefore, these values will be used for comparative purposes only.

Water table levels at each well were tested for linearity assumptions before correlations were carried out. Those that were not linear were tested again after logarithmic transformation. If these were still not linear, they were not included in the analysis. Results are summarised in Table 3.2 and reveal that maximum discharge had the strongest relationship with maximum water table levels, followed by 24-hour throughfall intensities. Figures 3.6 and 3.7 reveal some of the relationships found.

Table 3.2. Correlation coefficients for variables and maximum water table levels

Well	Q_{max}	I_6	I_{12}	I_{24}	Q_{base}	V_s	D_s	n
A4	0.910		0.621	0.686	0.467	0.664		24
A5			0.689	0.826	0.330	0.648		24
A10	0.900	0.585	0.657	0.798	0.430	0.578		20
A12	0.910		0.681	0.789	0.398	0.711		23
A14	0.911		0.579	0.755	0.428	0.710	0.189	22
B1	0.852		0.632	0.750	0.391	0.567		23
B4	0.901	0.704	0.763	0.825		0.685	0.195	21
B6	0.897 *	0.859	0.792	0.856	0.262			20
B8	0.783	0.664	0.606	0.767	0.365	0.657	0.106	19
C5	0.854	0.716	0.785	0.836	0.319	0.739	0.156	21
D2	0.840		0.685	0.782	0.340	0.628		20

Note: All correlations with Q_{max}, Q_{base}, and V_s were done with the logarithm of the variable in question, except for * which was correlated with Q_{max}.

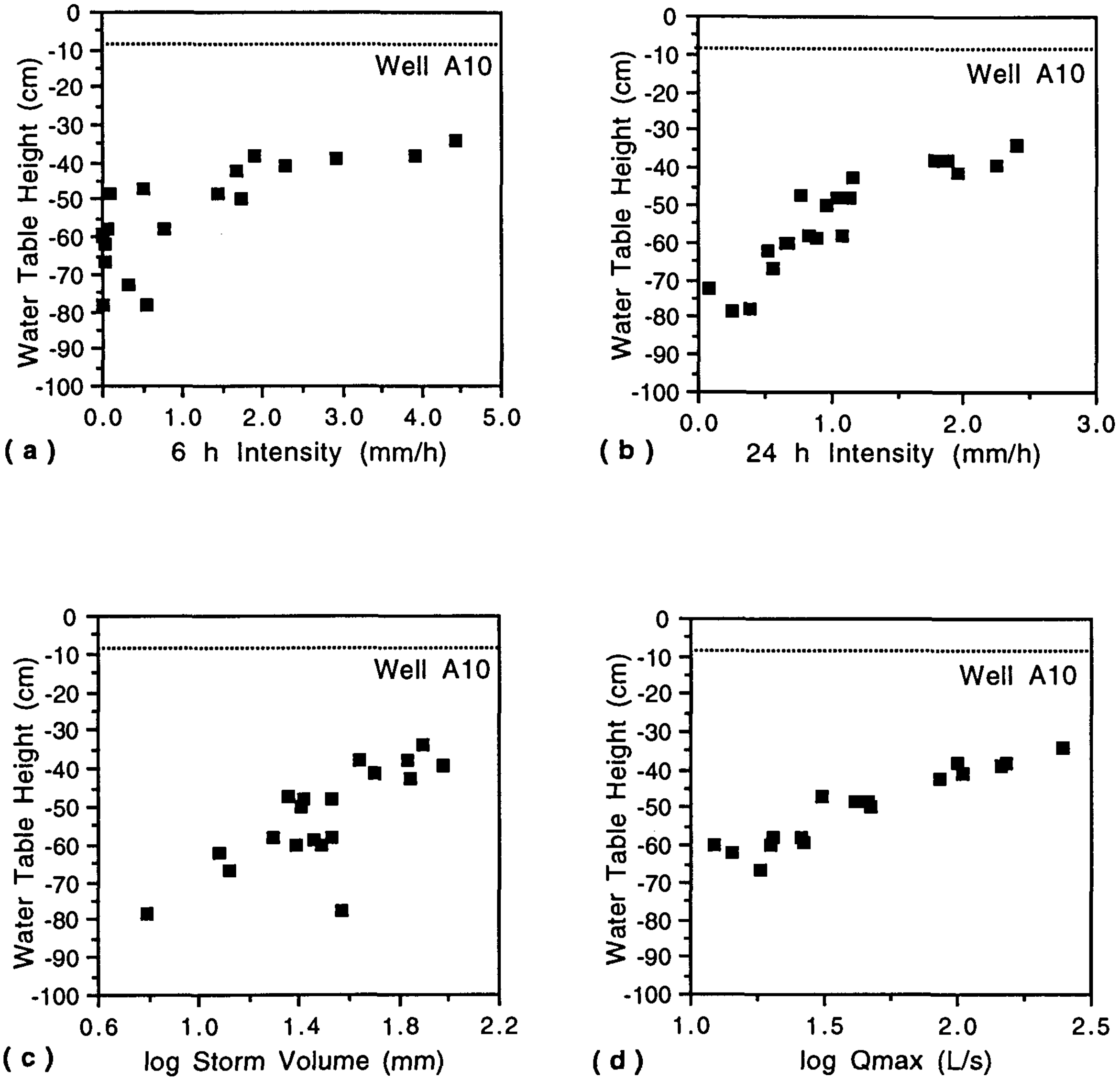


Figure 3.6. Relationships between selected variables and maximum water table levels at well A10. (a) 6 h intensity (b) 24 h intensity (c) log storm volume (d) log maximum discharge.

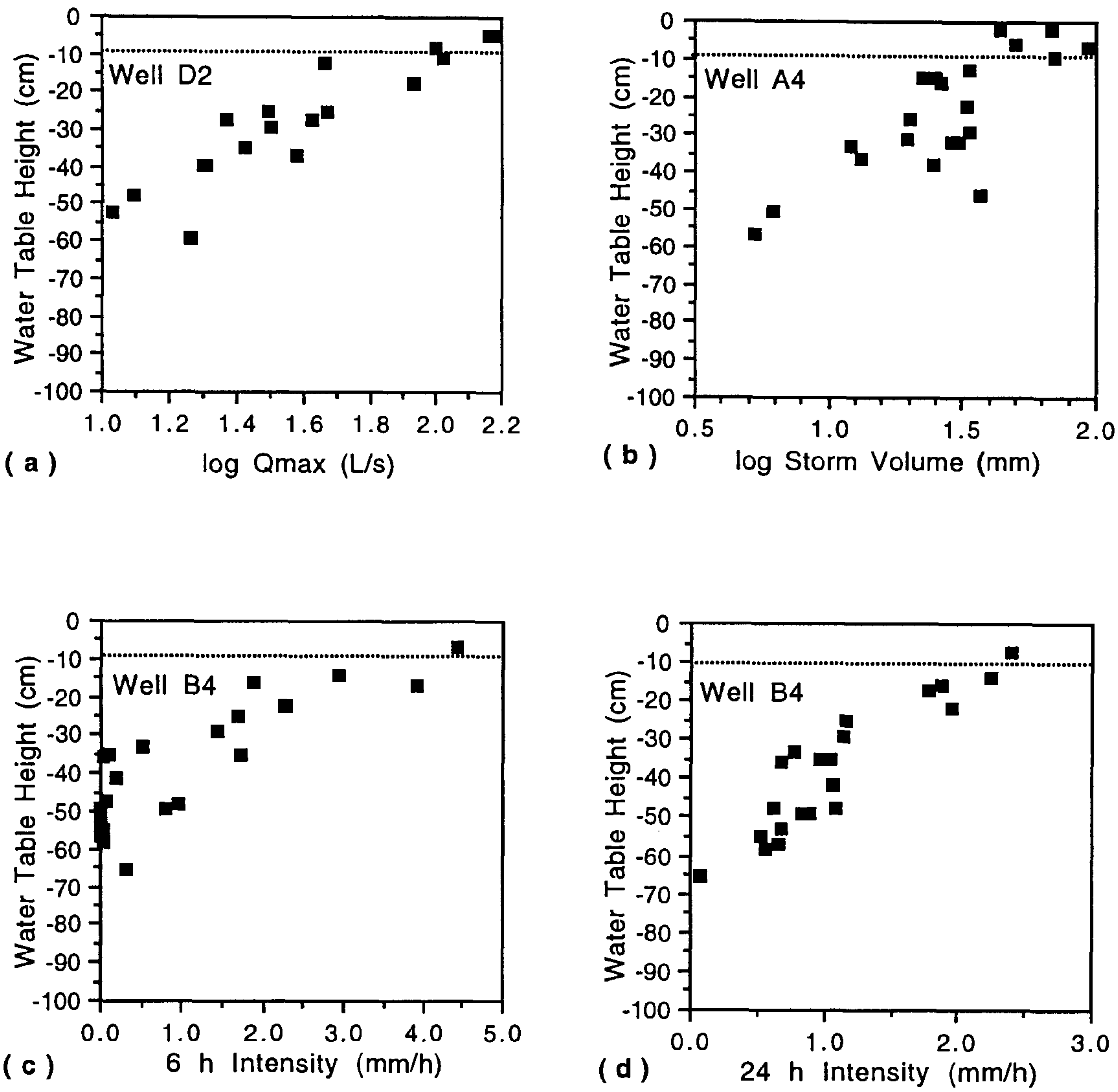


Figure 3.7. Relationships between selected variables and maximum water table levels.

(a) D2 vs. log maximum discharge (b) A4 vs. log storm volume

(c) B4 vs. 6 h intensity (d) B4 vs. 24 h intensity.

3. Soil Indicators of Water Table Behaviour

Soil pits were dug at nine sites to reveal any indication of long term soil saturation. The pits at sites A3, B2, C2, and C11 were expected to exhibit some indication of saturation, based on the occurrence of high water table levels and highly fluctuating water table levels at these sites throughout the study period. Indicators of saturation that were studied included the presence of mottling and gleying, soil colour, depth of the A horizon, and well-developed B horizons (Betson and Marius, 1969, Dunne et al., 1975).

Depth of mottling in the surface horizons may reflect the depth of the water table for two or more months during the rainy season, or the presence of a fluctuating water table (Dunne et al., 1975, Birkeland, 1984). Poorly developed mottles were only found at one site, in the Bf horizon at well A17. However, the mottles were inconsistent throughout the horizon. The lack of mottles may be explained by Cogger and Kennedy's (1992) finding that if saturation occurred during cold periods, microbial activity and Fe reduction would be lower, thereby limiting the development of mottles. Their investigations showed that reduction slowed greatly at 9°C and lower. This finding would explain the lack of mottles found in this study as saturation occurs throughout the winter when soil temperatures are low. Klinka (1976) stated that little mottling was in evidence at the UBC Research Forest, even in areas known to support high water table levels throughout much of the year. Mottles are also uncommon throughout most of southwestern British Columbia (Valentine et al., 1978).

No evidence of gleying was found in any of the soil pits. Gleying will occur under prolonged saturation of surface soil layers. Most well sites in the study catchment were too free-draining and well aerated for significant gleying to be expected. However, a few wells located in surface concavities (e.g. A3 and D1) did show continuous saturation of the upper B horizon throughout the study period, but no evidence of gleying was found at these sites.

Betson and Marius (1969) suggested that a strong correlation should exist between the location of saturated zones and zones of thinner A horizon. They hypothesised that a thin upper soil horizon would promote saturation, especially when the underlying horizon had a lower hydraulic conductivity (K). The lower K at this level would promote saturated subsurface flow to occur along the A-B horizon interface during storm events. This variable was analysed using soil pit data as well as shallow pits dug at wells A13, C1, C14, and D1. A comparison between A horizon depth and the number of times saturation was observed at times of maximum water table level was made. Figure 3.8 reveals that no relationship exists between the two variables. At this site, it is likely that subsurface flow occurs along the soil-bedrock or soil-till interface, due to the greater K difference between these two levels, so depth of the A horizon will not be as influential.

Soil colour is often used as an indicator of long-term soil saturation, although some studies have found a weak correlation between the two (e.g. Franzmeier et al., 1983, Mokma and Sprecher, 1994). Phillips (1990) outlined the problems with this measure, including using it on more recent soils where weathering would not have advanced soil colour sufficiently, or in cases where present soil colour may indicate a relict hydrologic regime. A common colour indicator is that soil chromas ≤ 2 on the Munsell chart reveal the presence of seasonal wetness (Franzmeier et al., 1983, Cogger and Kennedy, 1992). The data from the soil pits at the study site revealed that all Ah horizons had chroma values of 1 or 2, indicating a colour representing high seasonal saturation. However, all B horizons had chromas of 4 or higher, revealing that these soils are less likely to become saturated for extended periods of time. Similar results are shown by the chroma values observed by Klinka (1976) for equivalent soil types elsewhere in the Research Forest. Therefore, chroma values as indicators of saturation do not apply to the study site, as it is unlikely for the A horizon to show signs of high seasonal wetness without similar signs in the B horizon at this site. Mokma and Sprecher (1994) found that soil colour chromas < 2 in spodosols were sometimes a result of illuviation and eluviation rather than the occurrence of long-term saturation. This may be an explanation for the observation made at my site.

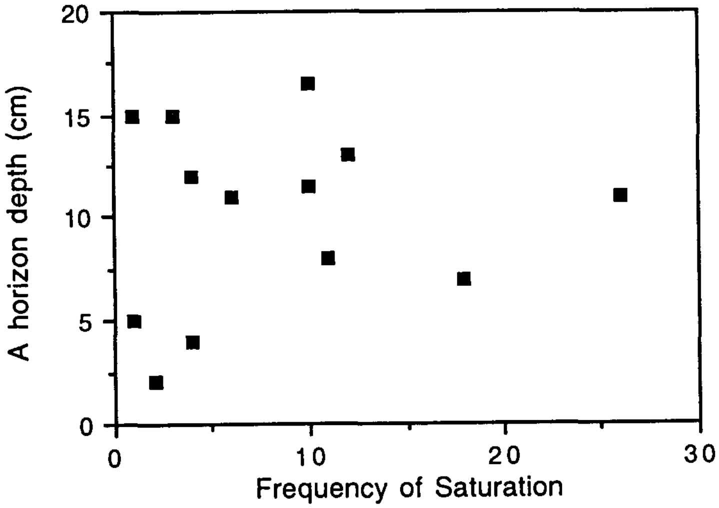


Figure 3.8. Relationship between the occurrence of soil saturation and depth of the A horizon.

In terms of topographic control on soil development, soils should be more developed in lower basin areas because these areas act as illuvial accumulation zones. These lower areas may also be rich in clay, contributing to poor drainage and thereby promoting higher seasonal wetness levels. Higher slope positions should be well drained and oxidized red (Birkeland, 1984). Within the pits studied, this was not found to be true as the well-developed podzols (with an Ae horizon) were found at both lower and upper basin areas (wells A17, C2 and C11). The textural analysis also did not show any significant increase in percent fines at downslope positions (see Table 2.4).

The topographic control on soil development may also be evident in areas of flow convergence, where it has been suggested that a thicker, more distinct B horizon may develop (Zaslavsky and Sinai, 1981). For the podzol soils at the study site, a less distinct B horizon would have a characteristic Bm signature, while more developed horizons would be closer to the podzol characteristics and described by a Bf horizon. At each soil pit Bf horizons were found, so no differentiation could be made as to the degree of soil development.

The results of this investigation reveal that the soil characteristics which are often used as indicators of both high water table levels and highly fluctuating water table levels cannot be applied at this site. These findings call into question the applicability of using these soil indicators to describe water table conditions in similar catchments.

4. Catchment Water Table Response

One of the assumptions of TOPOG and TOPMODEL is that the catchment responds to storm inputs in near steady-state conditions. This assumption can be tested by plotting pairs of well water table levels over the study period. If the resulting plot is a single-valued relationship (linear or non-linear), the steady-state assumption is valid because the water table is responding in a like manner throughout the catchment. However, if the relationship shows much spread, this reveals a non-steady response and points out the complicating effects of hysteresis. Non-steady flow and hysteresis would lead to problems in the estimation of saturated area locations from static topographic indices.

Figure 3.9 summarises some of the relationships found among the wells. Each relationship is plotted against water table levels at well A3 for comparative purposes. Since wells showed a different response once saturation occurred, the saturation level of -10 cm is also plotted on the graphs. Above this value, data should be disregarded as data are truncated. In Figure 3.9 (a) and (b), the typical relationship found at the majority of wells is shown. The spread about all relationships is as large as 20 cm, a significant amount, as it is greater than measurement error. This spread probably represents the effect of hysteresis, as the lag response of the water table to the "wave" of water moving downslope will differ due to the position of the well within the catchment.

Discrepancies from this relationship do exist, as shown in Figure 3.9 (c) and (d). The relationship shown in Figure 3.9 (c) has a greater slope than for other pairs of wells. This suggests a faster water table response at well A18 than at well A3, perhaps as a result of upslope macropore drainage to this area. Another explanation is related to TOPMODEL assumptions. If all assumptions hold, the slope of each relationship could differ as a result of variations in soil structure, which in turn causes differences in K(z) at each well. This may also explain the curvilinear relationship shown in 3.9 (d), which reveals a dual response, and suggests that at water table depths below -40 cm, response is controlled by some other characteristic (such as vertical soil structure).

Petch (1988) studied water table levels in a small forested catchment of variable topographic relief in New Zealand. Correlations of pairs of weekly peak water table levels were found to be non-significant, suggesting that water table response throughout the catchment was spatially independent. Petch further found that water table levels responded more uniformly near the stream channel where soils were more

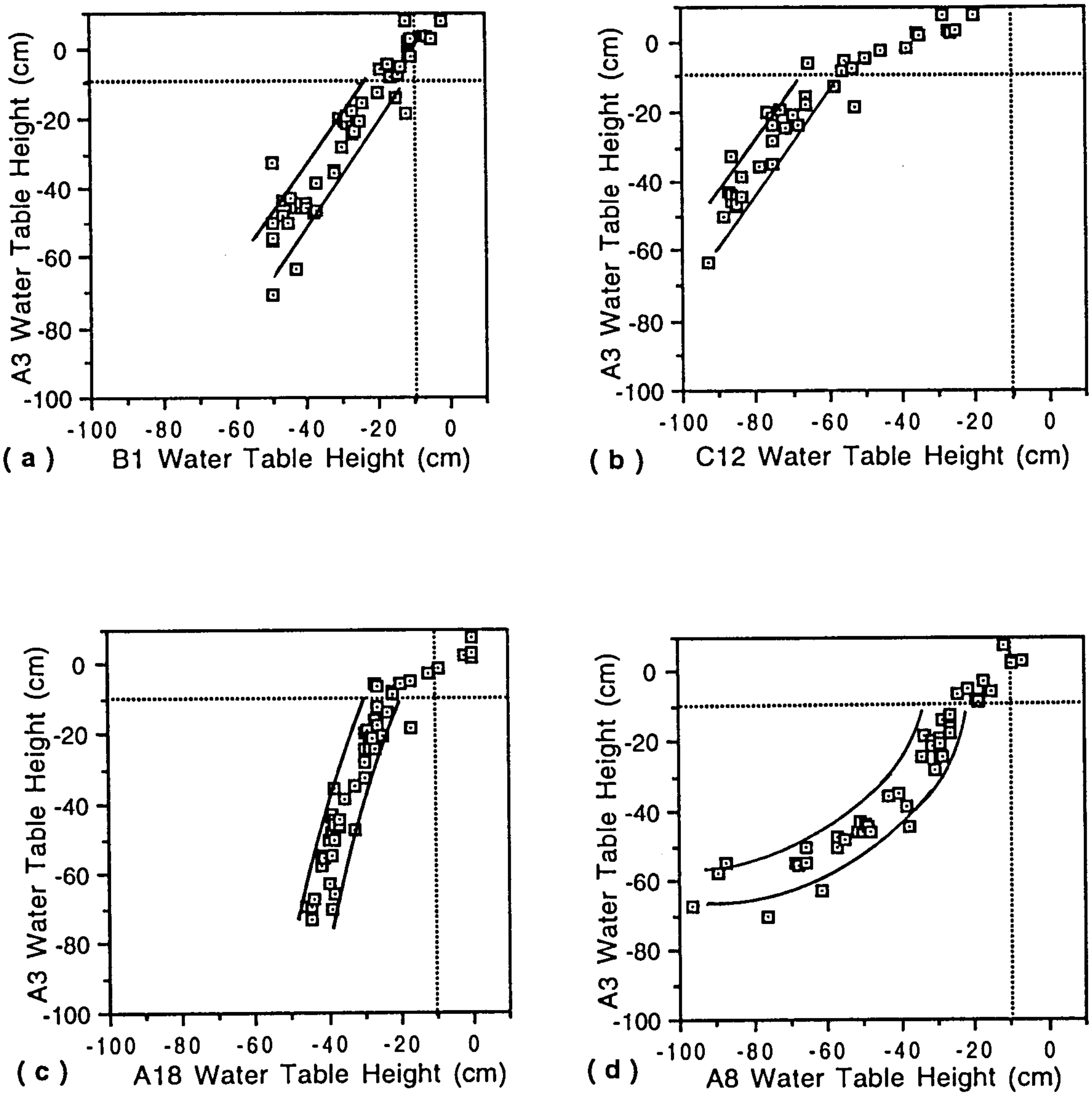


Figure 3.9. Water table height for pairs of wells to test the steady-state assumption. (a) A3 and B1 (b) A3 and C12 (c) A3 and A18 (d) A3 and A8. Plots include both "maximum" and "present" water table heights.

homogeneous. This result points to the importance of soil structure in controlling water table response. As found in the present study in some cases, differences in soil structure across the catchment may cause variability in water table response.

The results of these tests show that the overall response of the study catchment cannot be termed steady-state, as evidenced by the inconsistent relationships among the pairs of wells and the scatter in each relationship. This suggests that the non-steady response and hysteretic effects within the catchment may introduce scatter into relationships between water table levels and topographic indices.

B. Prediction of Water Table Levels and the Occurrence of Saturation

The variables influencing water table response were covered in detail in Chapter One. The following section will present observations of water table levels in relation to the topographic variables and indices known to influence them. The values of the topographic variables at each well location are summarised in Appendix II. In Section 2, a discriminant analysis will be undertaken to determine more precisely the accuracy of water table predictions by these same variables and indices. A discussion of results will follow.

1. Graphical Correlation Between Water Table Depth and Topographic Indices

As a preliminary test of the predictive accuracy of topographic indices, saturation occurrence was plotted against the indices W_B and $\nabla^2 Z$ for various storm events using values calculated from a DEM of 4 m grid size. The W_B and $\nabla^2 Z$ indices were chosen because they are often applied in hydrologic studies, and the storm events selected were those under which high water table levels were reached. Observations of water table levels $\geq$ -10 cm were given a value of 1, with all other water table levels given a value of 0. Low index values should be associated with low water table values, while high index values should show evidence of saturation. Although it was hypothesised that the overlap of index values between saturated and unsaturated levels would be small, Figure 3.10 reveals that the relationship is not so clear. Over all storm events studied, high index values were associated with both saturated and unsaturated levels. More consistent results are shown by examining the lowest index values which produce saturation. For the W_B index, saturation never occurred at sites with index values less than 5.8, while for $\nabla^2 Z$, saturation never occurred at sites with negative values (convex areas). Above these index values, there will be uncertainty in predictions of the occurrence or absence of saturation, while below these critical values, predictions of unsaturated conditions can be made accurately.

The TOPMODEL assumption that sites with like index values respond in a like manner is shown to be inaccurate in the study area. It cannot be assumed that a catchment-wide calculation of indices will discriminate saturated areas accurately; it will only indicate sites with a high probability of becoming saturated. Predicted sites of saturation may not show any evidence of saturation, even under wet antecedent conditions and during large storm events.

Jordan (1994) compared water table levels to the W_B index in a small catchment in Switzerland of mixed forest and pasture cover. Only two significant relationships were found over the two year study period, and these had correlation coefficients of 0.89 and 0.80. Based on the lack of significant results, Jordan concluded that problems would exist in using the W_B index as an indicator of water table levels at this site. Since regressions could not be carried out within the present study due to censoring of "empty" well data, a visual comparison was made to test Jordan's findings. Figure 3.11 shows the relationship of W_B and water table levels for various times at my study site. The graphs reveal that a general relationship does exist between the W_B index and water table levels, although the relationship is not very strong, and may be altered if water table levels of "empty" wells were known. Again, the spread about the relationship may reveal the complicating effects of hysteresis as well as uncertainty in the values of topographic variables.

To bypass the problem of including "empty" water table levels, a correlation was attempted using values for the probability of saturation occurring at each well and the topographic variables derived from the 4 m grid DEM. Figure 3.12 reveals that for each topographic variable studied, weak relationships exist. Further data transformations could not be made due to the nature of the data.

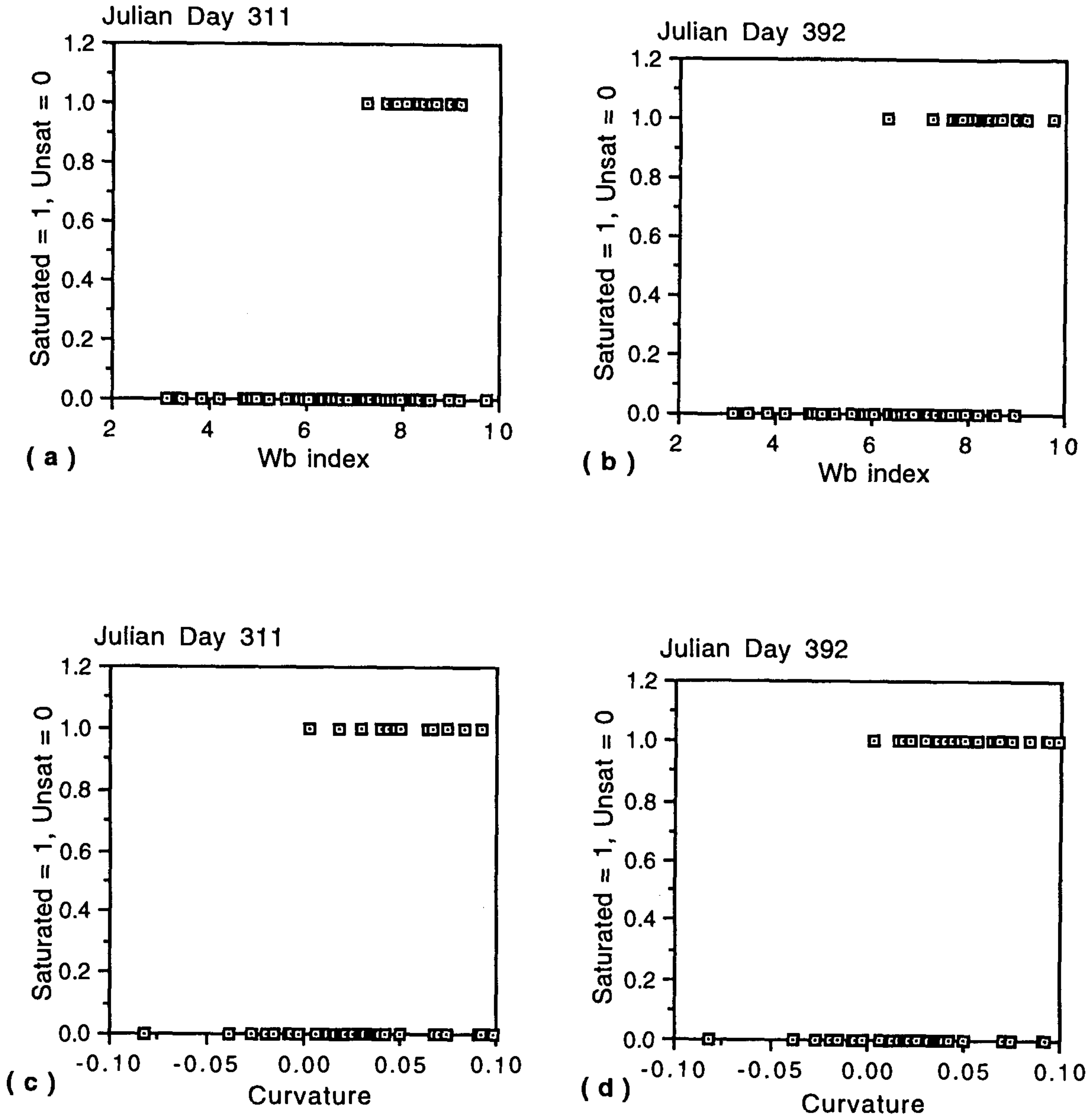


Figure 3.10. Relationship between index values (W_B, $\nabla^2 Z$) and the occurrence of saturation on Julian Days 311 (Nov. 7/92) and 392 (Jan. 27/93). In each case, evidence of saturation = 1 and all other water table levels = 0.

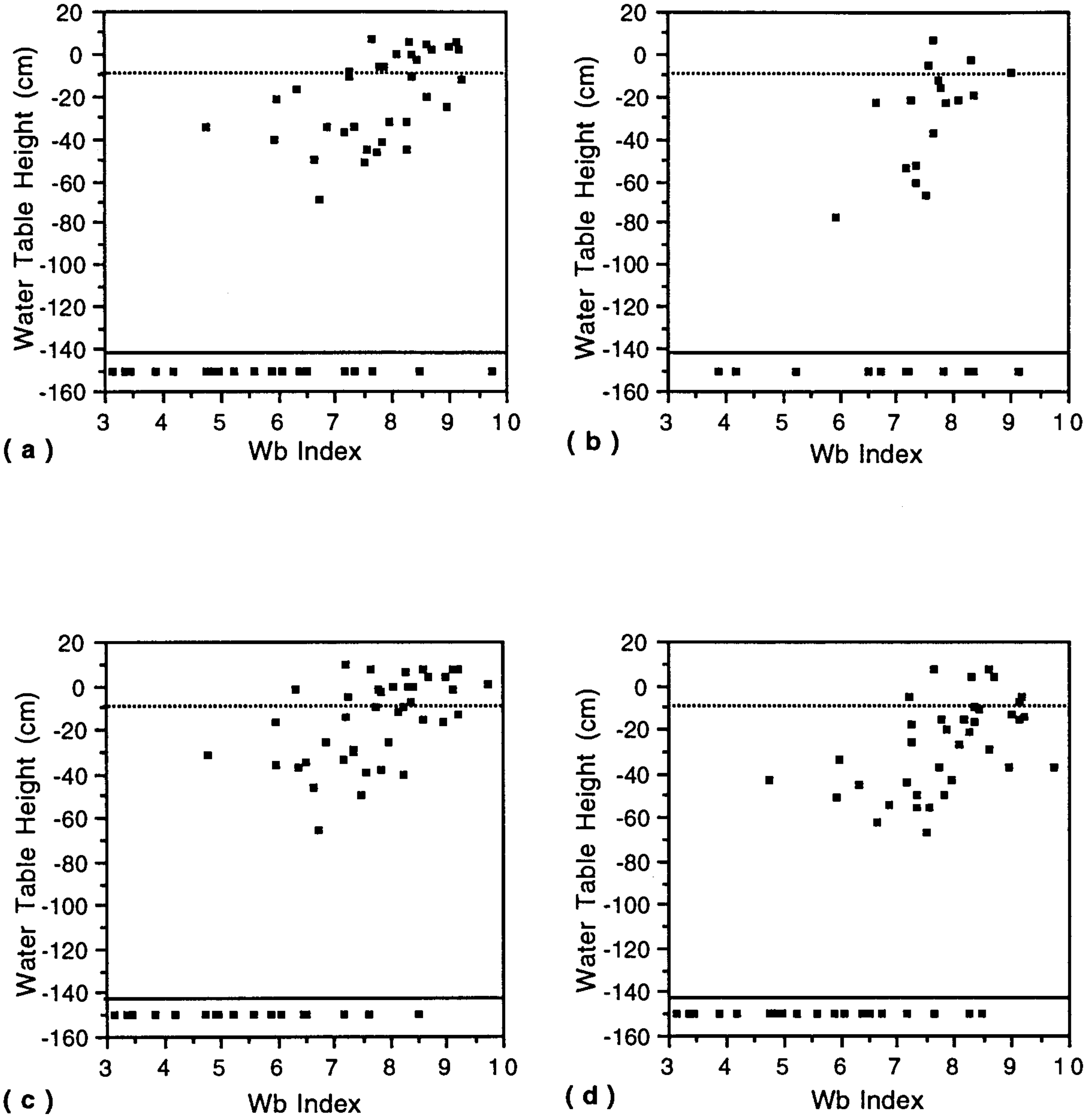


Figure 3.11. The relationship between water table depth and the W_B index for Julian Days 311, 357, 390 and 482. All are based on the 4 m grid size.

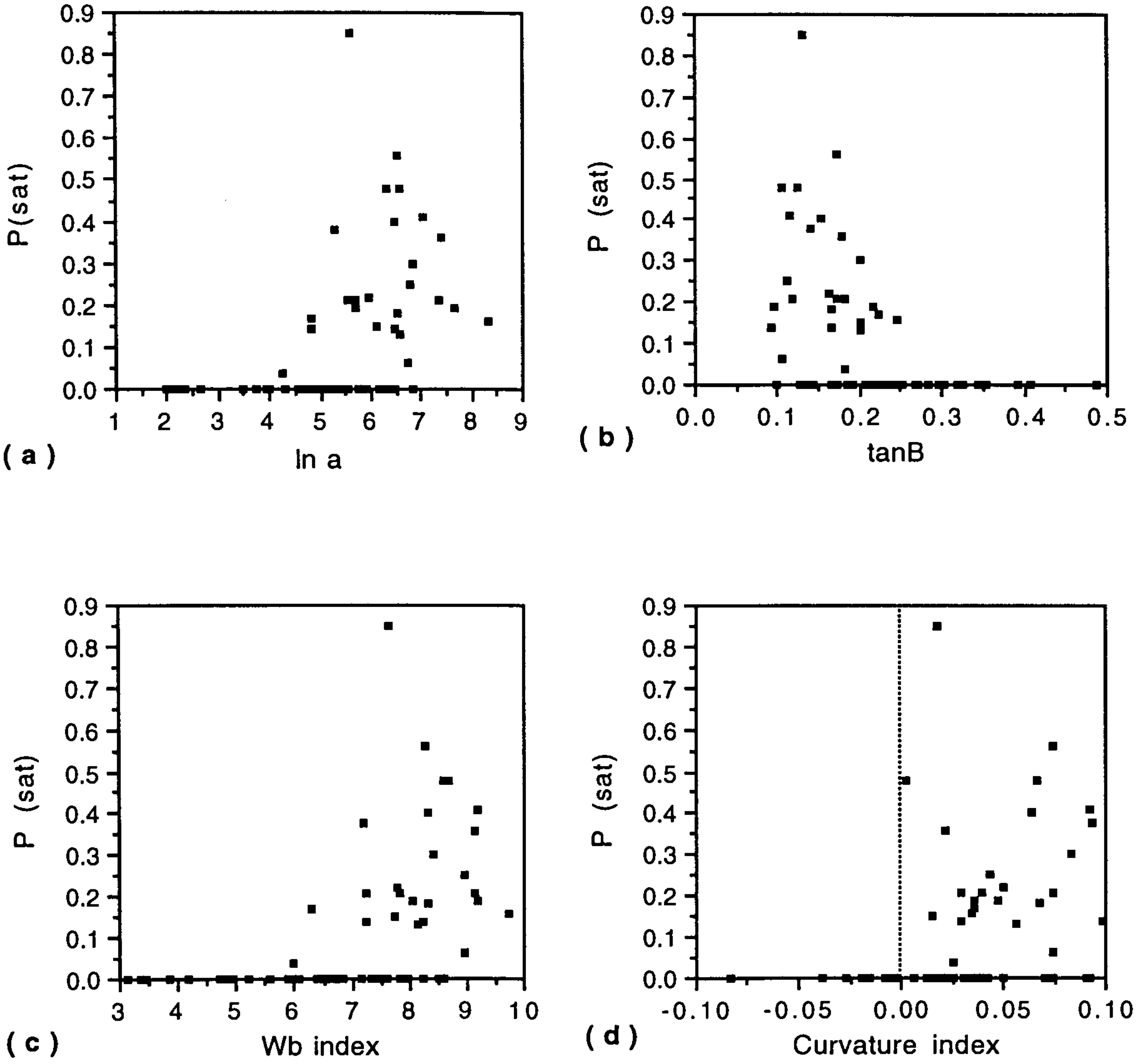


Figure 3.12. Relationship between probability of saturation and topographic variables at each well, based on values derived from the 4 m grid DEM.

2. Discriminant Analyses

In order to test the ability of topographic indices to predict water table levels, a test using either multiple regression or multiple discriminant analysis could be employed. In this case, multiple discriminant analysis was considered a more robust test because water table levels could be grouped into nonmetric categories based on hydrologic response. Data need to be grouped in this manner due to data censoring at "empty" water table levels and truncation at high (saturated) levels. Discriminant analysis was also chosen because the assumptions of regression could not be met in all cases due to the nonlinear water table response at some sites. Hair et al. (1992) stated that if all assumptions were met, multiple discriminant analysis and multiple regression would give comparable predictive and classificatory results.

This section will cover a general introduction to discriminant analysis, including the assumptions involved, methods of statistical application, and the specific tests carried out. For a more detailed review of discriminant analysis theory, Hair et al. (1992) is recommended.

a. Introduction to Discriminant Analysis

A discriminant analysis is used to predict the likelihood that an individual will belong to a particular group based on any number of independent variables. Statistically, the predictions are based on discriminant scores which are computed by maximising the variance between groups and minimising the variance within them based on the values of the independent variables (Hair et al., 1992). In this way, it is similar to a multiple regression analysis, where a function can be derived to predict unknown population values. A prediction can be made on any number of groups, and can be based on any number of independent variables. Within the present study, a two-group example would derive the best combination of independent variables (a, tanB, ∇^2Z, etc.) that would predict water table levels at a site as saturated or unsaturated. A four group analysis would allow a prediction of a range of water table levels and not solely the occurrence or absence of saturation.

Data were divided into two sections prior to analysis, with the second dataset used as an independent test of the discriminant function derived from the first dataset, because an upward bias in predictive accuracy will occur if the same data are used to both derive and test the discriminant function (Hair et al., 1992). Discriminant functions derived from the analysis dataset are tested on the second dataset by applying the discriminant function to the independent variables. Each computed discriminant score is then grouped with the group mean closest in value and predicted group membership is compared to actual group membership (Johnston, 1980).

Predictive accuracy of the final discriminant function is measured by calculating the number of correct predictions made, divided by the total number of observations. This is summarised in a classification matrix, with final classification accuracy given as a percentage of correctly classified observations to total observations. The significance of classification accuracy is tested using Press' Q statistic, which compares derived function accuracy to that expected from a chance model. If the derived accuracy is higher than that expected by chance, the results are valid and can be interpreted further. However, if the accuracy is less than that expected by chance, the differences among the groups represent sample variation only, and no further interpretation can be made (Hair et al., 1992). Press' Q statistic is calculated as

$$Q = [N - (n\,K)]^{2} / [N(K - 1)], \tag{13}$$

where N = total sample size, n = number of observations correctly classified, and K = number of groups. Calculated Q values are compared to a critical value based on the chi-square distribution (df = 1, $\alpha = 0.05$). Within the present study, insignificant functions were not interpreted further.

b. Assumptions of Discriminant Analysis

Assumptions underlying discriminant analysis include normality of the independent variables, unknown (but equal) dispersion and covariance matrices for groups, and no multicollinearity among independent variables.

A simple test for multivariate normality is to test the distribution of each variable. If these are normally distributed, it follows that the normality assumption is satisfied (Norusis, 1993). However, the normality assumption is usually disregarded, as it is not known how much non-normal distributions will affect analysis (Mather, 1976).

Box's M test is used for the equality of covariance matrices assumption in order to determine if substantial differences exist in the amount of variance of one group versus another for the same variable. If substantial variance differences exist, this will affect discrimination. Within this study, Box's M was tested at a significance level of 0.1 and data were discarded if the assumption was not satisfied.

The multicollinearity assumption states that there is no correlation among any of the independent variables. For this reason, W_B was tested in a separate analysis from the topographic variables ln a, tanB, and $\nabla^2 Z$. The variables were tested for multicollinearity through correlation matrices.

c. Analyses Undertaken

Two tests of index predictive accuracy were made on water table level data: one included saturated and unsaturated levels; the other was based on a four group discrimination of water table levels. Water table levels were grouped as: group 1 =

saturated (≥ -10 cm); group 2 = -11 to -24 cm; group 3 = -25 to -49 cm; and group 4 = <-50 cm. The saturated level of -10 cm, as previously mentioned, is based on possible measurement error and the influence of the litter layer. The choice of -25 cm as a division between groups 2 and 3 is based on the average depth of the contact between the A and B horizons. It was felt that a different response might be observed based on a probable change in hydraulic conductivity at this level. The lower grouping at -50 cm represents the deepest level of known water table heights (the depth of the shallowest well studied).

Water table groups were collapsed into more general categories of saturated (including group 1) and unsaturated levels (groups 2, 3, 4) for the second discriminant analysis. The ability of the functions to discriminate between these two groups was compared to results based on the discrimination of all four groups.

Prior to analysis, the dataset was divided into two sections so an independent test of the derived function could be made. For simplicity, this division was based on taking every second well beginning with well A1 for the discriminant analysis group, hereafter known as the analysis section. The second group, or test section, was used as an independent sample for testing the derived discriminant function. The maximum number of observations by this division were 30 in the analysis section and 29 in the test section. Actual total observations were fewer on some dates due to missing data. All tests undertaken are summarised in Table 3.3.

All tests of assumptions were carried out before any analysis was completed. Histograms of the topographic variables are included in Appendix II. The histograms reveal that, in general, the analysis and test sections were of similar distribution shape but were not always normally distributed. It was felt that the non-normal distributions would not affect final results, considering the similar distribution shapes between the analysis and test sections, and the fact that discriminant functions are not seriously affected by limited departures from normality (Mather, 1976, Davis, 1986). For all other assumptions, data were discarded if assumptions were not met.

Table 3.3. Summary of Discriminant Analysis Tests

Dependent Variable	Independent Variable(s)	DEM Grid Scale
Water Table Levels	ln a, tanB, $\nabla^2 Z$	4 m
Groups 1 - 4	W_B	4 m
	W_B	8 m
	W_B	16 m
Water Table Levels	ln a, tanB, $\nabla^2 Z$	4 m
Saturated / Unsaturated	W_B	4 m
	W_B	8 m
	W_B	16 m

Note: All analyses were computed in two sections - Analysis (to derive the discriminant function) and Test (to independently test its accuracy).

In the discriminant analysis, a stepwise selection method was chosen whereby the variable that best discriminates among the groups is entered into the analysis first. Variables continue to be entered in this manner until a minimum tolerance level is reached. In this case, Wilks' lambda was chosen to minimise with a criteria of 3.84 to enter and 2.71 to remove. Derived discriminant functions were discarded if they were not significant at the 0.05 level. In some cases, the second derived function was not used if it did not contribute significantly to the discrimination. If all groups were not represented within the analysis section, discrimination was carried out on two or three groups only. If a group was represented in the test section that was not discriminated for in the analysis section, these values were considered "ungrouped" and were not used in the classification results matrix. Missing water table level data within both sections were also classified as ungrouped.

All analyses used independent variables derived from the DEM at a grid scale of 4 m. A comparison at grid scales of 8 m and 16 m was also carried out but will be discussed in a later section. The analysis discussed in this section was carried out on water table levels for each day measurements were taken. After testing all assumptions and deleting those dates where assumptions were not met, 35 dates were available for the "variable" (ln a, tanB, $\nabla^2 Z$) analysis, and 49 were tested for the W_B analysis.

d. Results and Interpretation

Table 3.4 summarises the classification accuracy for the variables (ln a, tanB, $\nabla^2 Z$) and W_B analysis and test sections. Non-significant results are not included. Results from the entire data set for water table groups 1 - 4 reveal the influence of topographic variables and the nature of water table response at this site.

Within the discrimination of ln a, tanB, and $\nabla^2 Z$, the stepwise procedure defined the most significant variable in discriminating among the groups. The variables chosen are included in Table 3.4 and reveal that ln a appears to be the most influential topographic variable in the prediction of water table levels. The variable ln a was chosen as best predictor in 64.4% of cases, $\nabla^2 Z$ in 31.1%, and tanB in 4.4%. In most cases, only one variable was selected as significant to discriminate among the groups.

This finding is contrary to the usual assumption that both upslope contributing area and slope (in the form of W_B) will best describe water table conditions within a catchment. The W_B index has been used extensively in previous studies and single variables are not usually considered as accurate. However, the finding of ln a as the most significant variable does agree with results found by Burt and Butcher (1985).

Table 3.4 : Complete Classification Results (%) for water table groups.

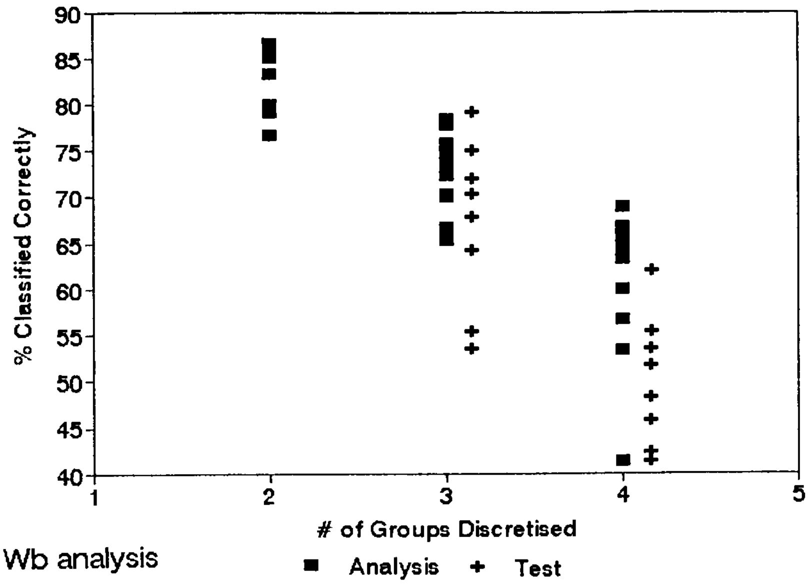
	Variables lna, tanB, $\nabla^2 Z$			Variable W_B		Groups
Date	Anal.	Test	Disc.	Anal.	Test	in Anal.
295				74.1		2 3 4
296				70.0	55.6	2 3 4
311	60.0		$\nabla^2 Z$	60.0	42.3	1 2 3 4
313	63.3		$\nabla^2 Z$	66.7	64.3	2 3 4
315	81.5	57.7	ln a, $\nabla^2 Z$	77.8		2 3 4
321	85.2		$\nabla^2 Z$, ln a	85.2		3 4
323	53.3		ln a	66.7		1 2 3 4
324	56.7	44.8	$\nabla^2 Z$	63.3	48.3	1 2 3 4
326	46.7	46.4	ln a	53.3	53.6	1 2 3 4
331	80.0		ln a	66.7	41.4	1 2 3 4
334	79.3	66.7	ln a, tan B	72.4	75.0	1 3 4
335				65.5	62.1	1 2 3 4
338	89.7		ln a	86.2		3 4
343	75.9	57.1	ln a	65.5	67.9	2 3 4
348	75.9		ln a, $\nabla^2 Z$	65.5	67.9	2 3 4
352				79.3		3 4
385	69.2	54.2	ln a	65.4	45.8	1 2 3 4
387				65.4	70.4	2 3 4
389	60.7	51.7	ln a	64.3	62.1	1 2 3 4
390	53.3	48.3	ln a	63.3	51.7	1 2 3 4
392	83.3	60.0	ln a, tan B	73.3	72.0	1 3 4
394				60.0	48.3	1 2 3 4
401	80.0		$\nabla^2 Z$, ln a	80.0		3 4
405	86.7		$\nabla^2 Z$			3 4
429	79.3		ln a	75.9	53.6	2 3 4
436	80.0		$\nabla^2 Z$, ln a	80.0		3 4
442M				66.7	48.3	1 2 3 4
442P	56.7	48.3	$\nabla^2 Z$	63.3	51.7	1 2 3 4
447M	70.0	62.5	ln a	73.3	79.2	1 3 4
447P	43.3	51.7	ln a	56.7	48.3	1 2 3 4
450	73.3	60.7	ln a	73.3	53.6	2 3 4
453	73.3	60.7	ln a	73.3	53.6	2 3 4
456				76.7		3 4
463	50.0		ln a	66.7		1 2 3 4
464	63.3	41.4	$\nabla^2 Z$	63.3	48.3	1 2 3 4
468M	50.0		ln a	66.7	48.3	1 2 3 4
468P	90.0		ln a, $\nabla^2 Z$	86.7		3 4
471M	90.0		ln a, $\nabla^2 Z$	86.7		3 4
471P	80.0		ln a	80.0		3 4
473				78.6		2 3 4
476				75.0		2 3 4
480				70.4		2 3 4
481				41.4	55.6	1 2 3 4
482				66.7	48.3	1 2 3 4
484M				69.0	41.3	1 2 3 4
484P	66.7	41.4	ln a	63.3	41.4	1 2 3 4
487	66.7		ln a	66.7	41.4	1 2 3 4
490	90.0		ln a,$\nabla^2 Z$	86.7		3 4
492				70.0	53.6	2 3 4
497	86.7		ln a	83.3		3 4

The lowest classification accuracies were associated with a discriminant analysis of all four water table level groups. This relationship is shown in Figure 3.13, which suggests a 5 to 10% decrease in accuracy with each extra group discretised. This relationship holds true for both the variable and the W_B analysis and test sections. This is probably due to the fact that the lower water table levels represented by groups 3 and 4 are likely times of baseflow or low flow conditions. In these cases, hysteresis effects will be minimised, resulting in more accurate predictions for the two-group discriminant analysis.

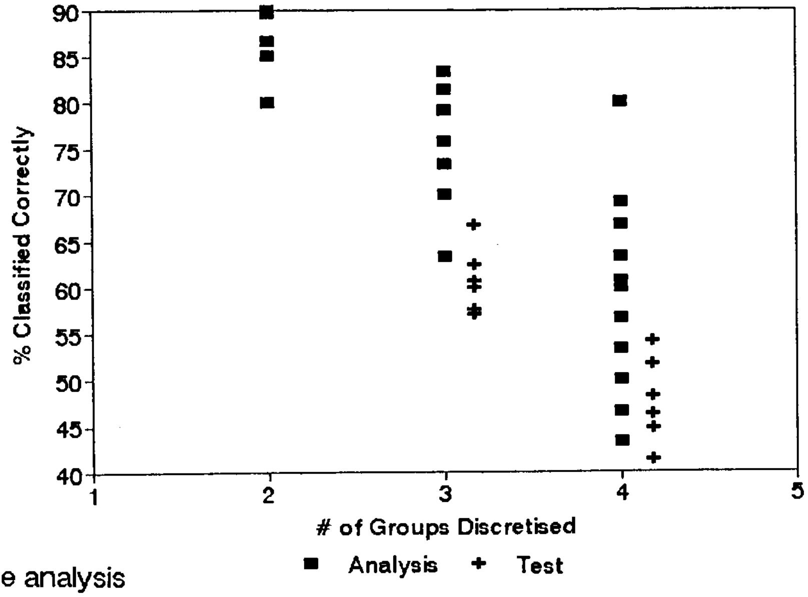
A second look at the data on a well basis revealed that a number of wells were consistently classified incorrectly, resulting in predictive accuracies less than 20% for these wells. Classification accuracy by well is summarised in Table 3.5. Within the variable analysis, the infrequent inclusion of slope in determining the discriminant function led to an overprediction of water table levels in areas of steeper slope. This was the case for water table levels at wells A10 and B6.

At wells C14, E2, and E3, overprediction of water table levels occurred frequently, but these overpredictions cannot be explained by the slope variable, as these wells were not located in areas of steeper slope. It is suggested that they may have been influenced by rapid drainage due to macropores. At E2 and E3, the proximity of two old growth trees and abundant deadfall may have allowed for rapid drainage, resulting in generally lower water table levels than would be expected.

At D1, water table levels were at the soil surface throughout most of the study period. However, the discriminant function underpredicted levels frequently. The well was located in a topographic pit, as was evidenced by the occurrence of ponded water throughout much of the study period. However, HYTOP assigned a slope value (0.129) to the well site, thereby affecting the influence of the slope value at this site of



Wb analysis



Variable analysis

Figure 3.13: Relationship between the number of groups represented in the discriminant analysis and classification accuracy. (a) W_B index (b) Variables.

Table 3.5. Discriminant analysis results from 4 m grid, variable and W_B analyses, summarising predictions correctly classified (%) on a well basis.

Anal. Well	Variable % Corr.	W_B % Corr	Test Well	Variable % Corr	W_B % Corr
A1	94	100	A2	28	33
A3	69	78	A4	44	27
A5	69	81	A6	97	100
A7	71	78	A8	33	24
A9	77	38	A10	3	7
A11	71	65	A12	29	17
A13	94	79	A14	0	11
A15	46	0	A16	28	26
A17	40	43	A18	17	45
A19	74	85	A20	78	100
B1	63	69	B2	50	66
B3	66	92	B4	56	54
B5	22	16	B6	24	24
B7	51	69	B8	34	33
B9	94	100	B10	92	100
C1	83	69	C2	42	90
C3	74	90	C4	89	84
C5	85	43	C6	38	2
C7	89	90	C8	3	27
C9	63	31	C10	53	49
C11	57	48	C12	40	79
C13	97	98	C14	17	16
C15	89	98	C16	89	100
C17	76	98	C18	62	96
C19	94	100	C20	92	100
C21	83	98	C22	86	98
C23	53	100	D1	5	23
D2	54	49	D3	88	100
E1	91	98	E2	3	2
E3	3	0			

flow convergence. This also occurred at well A15 and led to a predictive accuracy of 0% for the W_B analysis. A further reason for the underprediction of water table levels at D1 is due to its location in a canopy gap, which thereby receives more precipitation in comparison to sites underneath the canopy (Figure 2.9). The increased precipitation input (averaging 26.9% of total storm volume) may have altered the response at this site.

The effect of the slope variable at wells A15 and D1 on water table level predictions suggests that discriminant analysis results may be affected by uncertainty in the measured values of the topographic variables. Inaccuracy resulting from the derivation of topographic variables will produce a bias in predictions for individual wells. The question remains, therefore, as to the magnitude of this uncertainty and its effect on water table level predictions.

Table 3.6 summarises classification accuracy for discriminant analyses undertaken for water table levels and the occurrence of saturation under the two sets of independent variables. Analyses were performed on dates when saturation was observed at least once within the analysis section. Predictions based on the occurrence or absence of saturation were found to be more accurate than those based on water table levels and reached as high as 97% accuracy in the analysis section.

3. Conclusion

The results from the discriminant analyses reveal that topographic variables and the W_B index may both be used to predict water table levels within the study catchment, although more accurate predictions will be made if only the occurrence or absence of saturation is studied. The variable ln a was found to be the most influential single variable in describing water table levels, but did not vary significantly in accuracy from predictions based on the W_B index. Predictive accuracy ranged from 40 to 90% in all analyses completed. The effects of hysteresis were found to introduce some scatter into the relationships, and uncertainty in the derivation of topographic variables will introduce bias in predictions at individual wells.

Table 3.6. Classification Results (%) of Discriminant Analysis for 4 m grid

	Variables lna, tanB, ∇^2Z					Variable W_B			
	Groups 1 - 4		Saturated/Unsat.		Disc.	Groups 1 - 4		Saturated/Unsat.	
Date	Anal	Test	Anal	Test	Var.	Anal	Test	Anal	Test
311	60.0		90.0		∇^2Z	60.0	42.3	86.6	
323	53.3		90.0		ln a	66.7		86.6	
324	56.7	44.8	93.0		∇^2Z	63.3	48.3	86.6	72.4
326	46.7	46.4	83.0	78.6	ln a	53.3	53.6	83.3	82.0
331	80.0		96.7	72.4	ln a	66.7	41.4	90.0	72.4
335						65.5	62.1	86.2	89.6
385	69.2	54.2	92.0	79.2	ln a	65.4	45.8	91.7	70.8
389	60.7	51.7	96.4		ln a	64.3	62.1	89.3	72.4
390	53.3	48.3	83.0		ln a	63.3	51.7	83.3	72.4
394						60.0	48.3	83.3	69.0
442M						66.7	48.3	89.0	72.4
442P	56.7	48.3	93.3	75.8	∇^2Z	63.3	51.7	86.7	72.4
447P	43.3	51.7	83.3		ln a	56.7	48.3	83.3	
463	50.0		83.3	70.4	ln a	66.7		86.7	
464	63.3	41.4	96.7	75.9	∇^2Z	63.3		80.0	69.0
468M	50.0		83.3	69	ln a	66.7	48.3	86.7	75.9
481						41.4	55.6	82.8	74.1
482						66.7	48.3	83.3	79.3
484M						69.0	41.3	82.8	79.3
484P	66.7	41.4			ln a	63.3	41.4	90.0	86.2
487	66.7		90.0		ln a	66.7	41.4	86.7	79.3

C. Effect of DEM Grid Scale

Previous research on the effect of DEM grid scale on the derivation of topographic variables and model output was covered in Chapter One. This section will test the effect of grid scale on the derivation of topographic variables and on final index predictions within the present study. If large differences exist in the derived values and predictive accuracy at different grid scales, this will have significance to researchers using DEMs for hydrologic analysis. As mentioned previously, the differences found among the grid scales will be a conservative estimate, as all gridded elevation data were derived from the same density of survey points.

1. Scale Effects on Prediction of Water Table Levels

A DEM was derived from an intensive ground survey at grid sizes of 4, 8, and 16 m. Derivation of topographic variables from the DEM was outlined in Chapter Two. Due to the size of the study area, grid scales larger than 16 m were not considered. In order to determine the effect of grid size on the derivation of topographic indices, cumulative frequencies of W_B and $\nabla^2 Z$ values were generated as fraction of image area covered (Chairat and Delleur, 1993, Zhang and Montgomery, 1994). The image output from HYTOP was used to test the grid size effect at the present site.

Figure 3.14 shows the frequency distribution of the W_B index. As grid size increases, averaging results in a loss of detail and a smaller range of index values. The differences at lower index values reveal that divergent areas, including areas of steeper terrain and convexities, are being averaged, resulting in a loss of detailed terrain features. However, the distributions for all grid scales converge at higher index values, suggesting that there will be little difference in the likelihood of higher index values being attained at different grid scales. This suggests that differences in the occurrence of saturation (represented by higher index values) may not be significantly different at coarser scales, or at the very most, coarser grids will show slightly higher probabilities of including high index values.

Results incorporating the $\nabla^2 Z$ index are shown in Figure 3.15. Similar to the previous test, there is a smaller range of index values as grid size increases. With an averaging of terrain features, areas of convergence and divergence are in effect "smoothed out" at coarser grid scales. The likelihood of saturation occurring will be decreased due to the loss of concave areas which promote flow convergence and higher water table levels. However, this effect may not be significant overall because convex areas, which are unlikely to become saturated, are also averaged out at coarser grid scales. It is not known whether this averaging will result in the prediction of larger zones of saturation or smaller zones on a catchment scale at coarser grid scales, although it is probable that the 4 m grid will delineate specific zones of saturation most accurately. The relationship also suggests that the differences between the 8 m and 16 m grids are not significantly different.

A visual comparison of grid scale was undertaken by deriving maps of index values across the entire image. Figure 2.20 showed the values of W_B across the image at the 4 m grid scale, while Figures 3.16 and 3.17 show the loss of resolution at coarser grid levels of 8 m and 16 m. Coarser grids reveal both a loss of topographic detail and less accurate flow path delineation, as shown by the shift in highest index values (black cells) away from specific drainage lines.

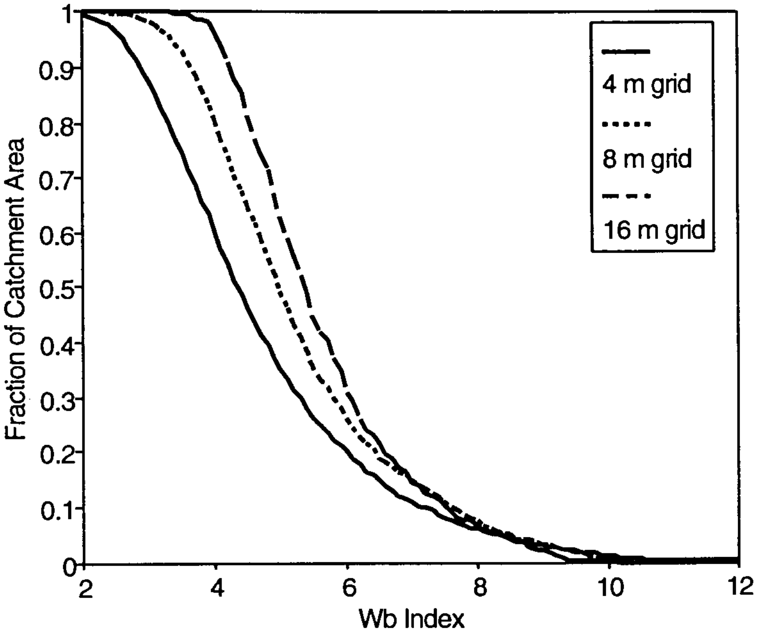


Figure 3.14. The effect of grid size on the distribution of the W_B index over the image.

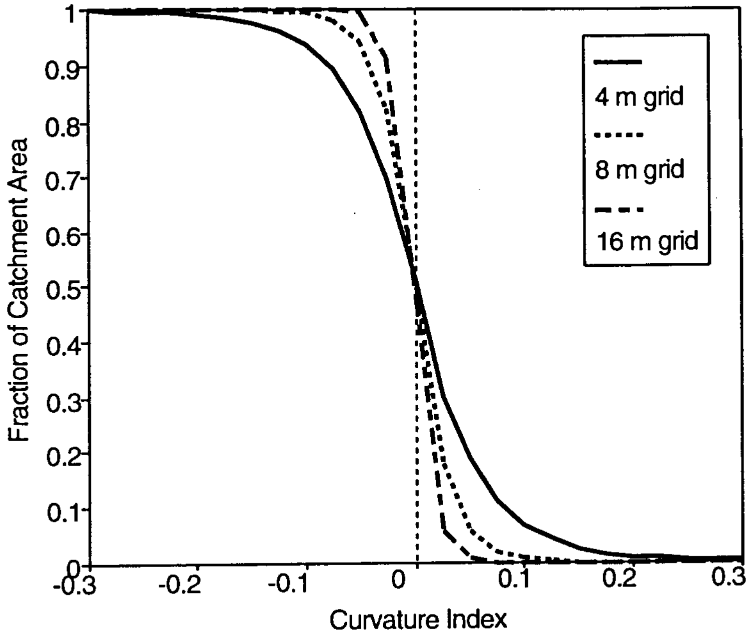


Figure 3.15. The effect of grid size on the distribution of curvature over the image.

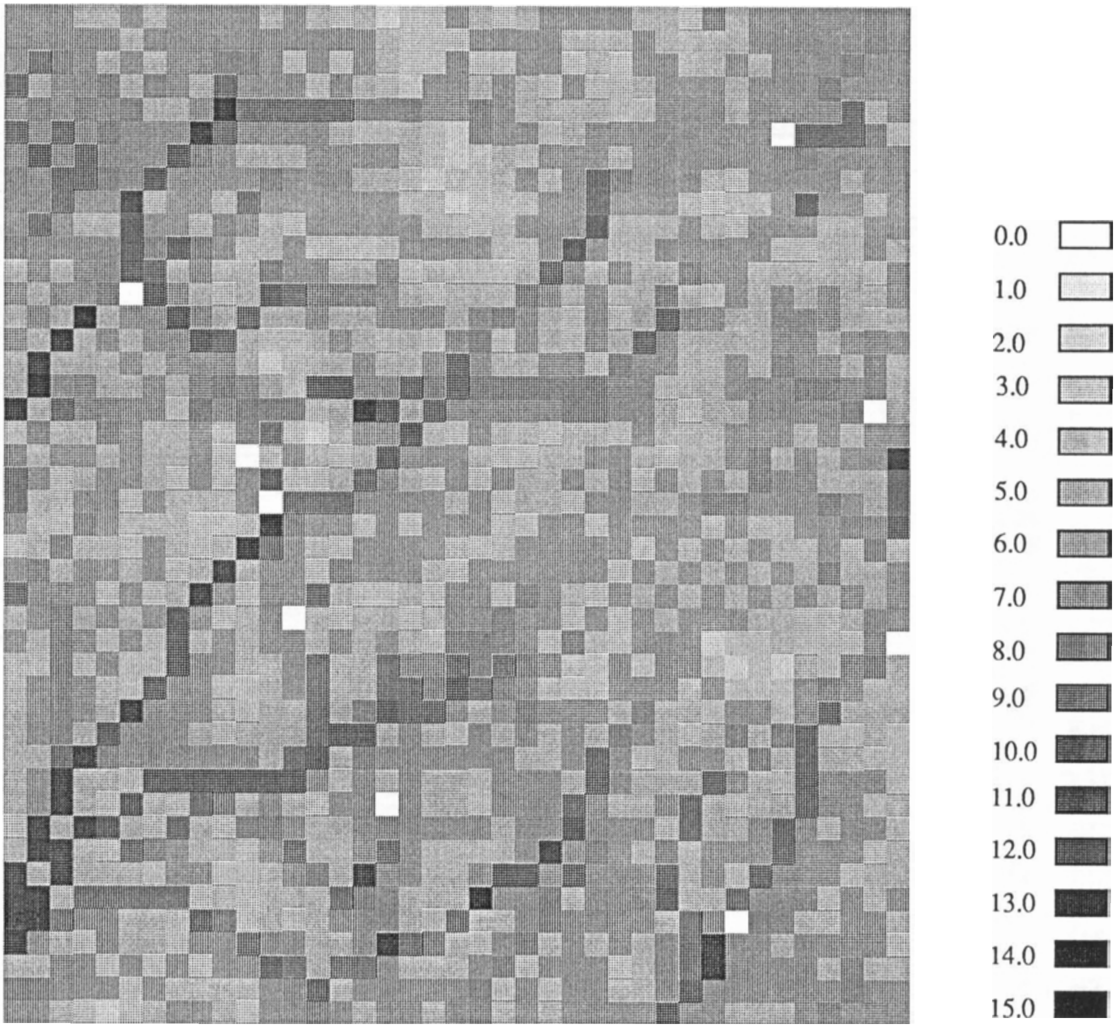


Figure 3.16. Image of W_B values at the 8 m grid scale. White cells indicate "pits", while black cells show drainage paths.

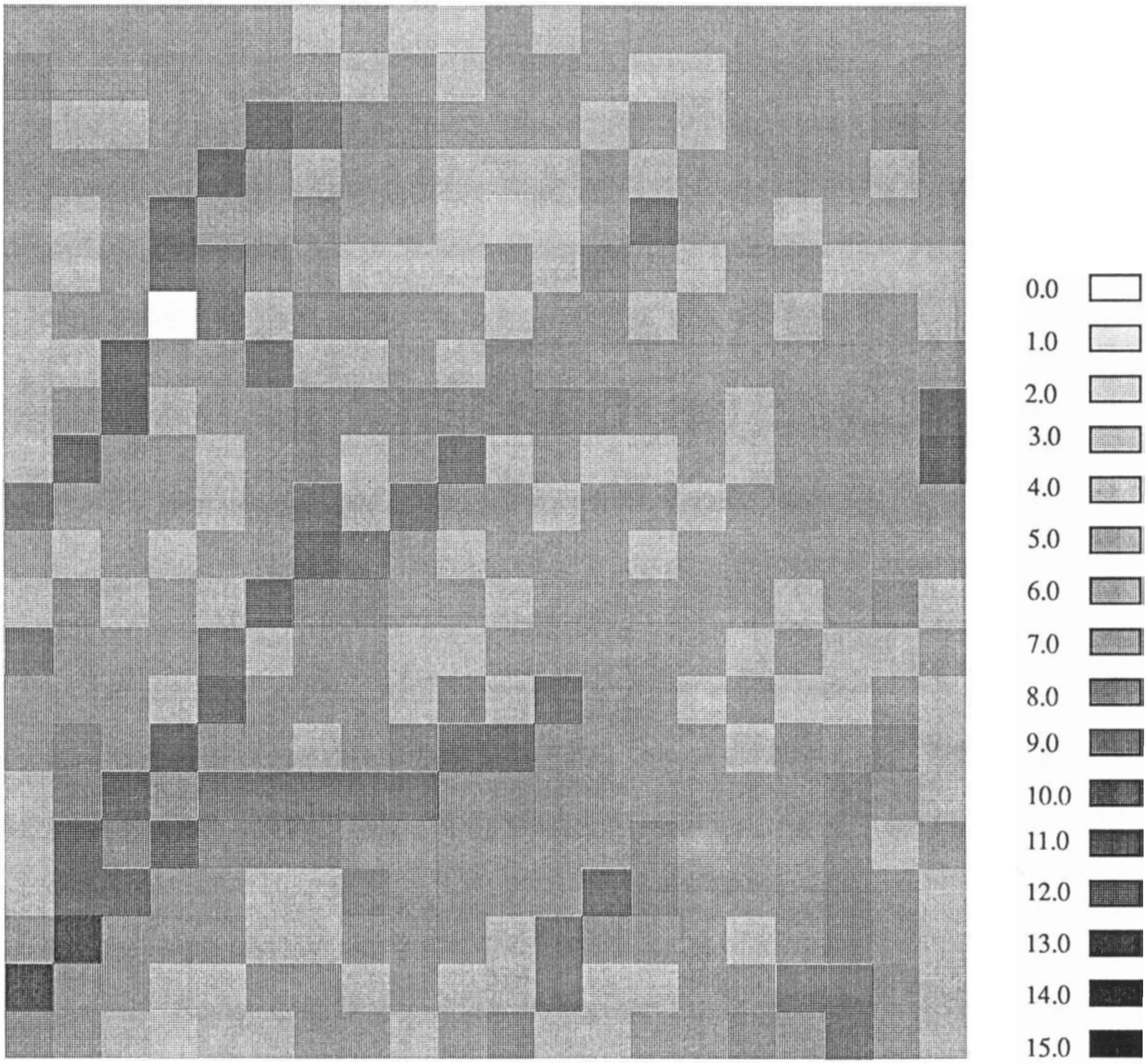


Figure 3.17. Image of W_B values at the 16 m grid scale.

Figure 3.18 shows the effect of topographic resolution on the relationship between water table levels and the W_B index for Julian Day 311. The smaller range of W_B values at coarser grid scales results in the relationship becoming less defined, due to a weakening in the ability of topography to describe water table response at larger grid scales.

A comparative study was undertaken using the results of the discriminant analysis from the previous section to assess the predictive accuracy of the W_B index at grid sizes of 8 m and 16 m. These values were tested in the same manner as the discriminant analysis based on topographic variables derived from the 4 m grid, although the analysis was performed on a subgroup of dates chosen to represent a range of hydrologic conditions. Again, all assumptions were tested and Press' Q statistic was used to measure the significance of the final classification results. Results from the water table analysis of groups 1, 2, 3 and 4 are summarised in Table 3.7, and those from the saturated/unsaturated analysis are summarised in Table 3.8.

These results further show the effect of decreasing accuracy at increasing grid scale. Topographic variables based on the 16 m grid led to less accurate water table predictions in all analyses, with more non-significant results found overall. As found in the 4 m grid discriminant analysis, prediction of saturated/unsaturated conditions was more accurate than predictions of water table level groups. The prediction of saturated conditions at the 16 m grid reached classification accuracies as high as 83%, suggesting that the larger grid size may be used with some degree of accuracy for this type of analysis. However, there were still more non-significant results at the 16 m grid size (compared to the 4 m and 8 m grids), which further reveals the limitations of describing topographic features based on coarse DEM grids.

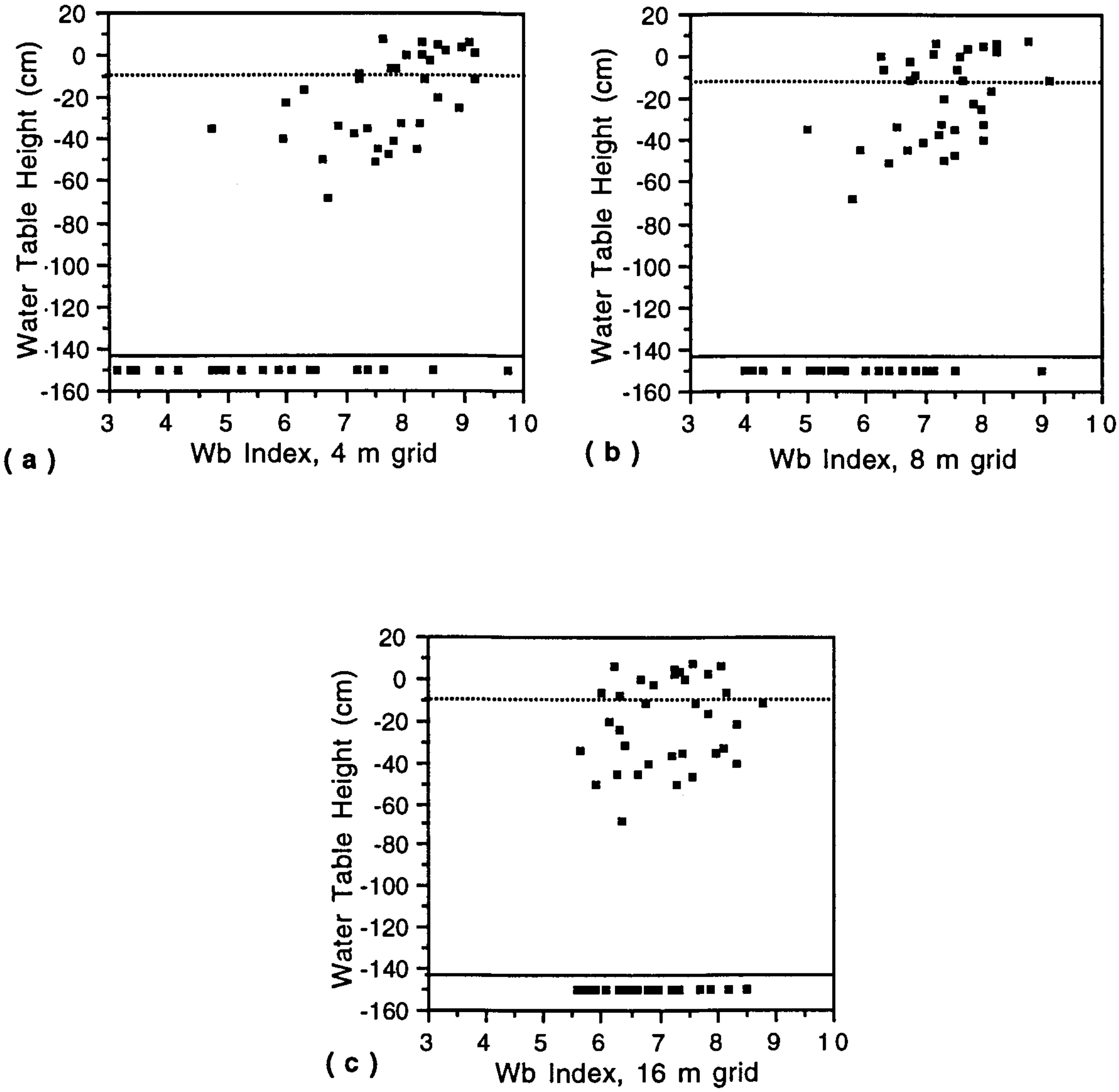


Figure 3.18. Relationship between water table height and W_B index at grid scales of 4 m, 8 m, and 16 m on Julian Day 311.

Table 3.7.Classification Results (%) of Discriminant Analysis for W_B index for groups 1 - 4 at grid scales 4, 8, 16 m.

	4 m		8 m		16 m	
Date	Anal.	Test	Anal.	Test	Anal.	Test
311	60.0	42.3	50.0	46.2	53.3	38.5
313	66.7	64.3	60.0		60.0	
321	85.2		70.4			
324	63.3	48.3	56.7			
326	53.3	53.6	50.0		60.0	
334	72.4	75.0	69.0	54.2	55.2	50.0
335	65.5	62.1	62.1		55.2	
343	65.5	67.9	58.6		58.6	50.0
348	65.5	67.9	62.1		62.1	57.1
387	65.4	70.4	61.5		57.7	
389	64.3	62.1	50.0	44.8	53.6	
390	63.3	51.7	46.7			
392	73.3	72.0	63.3	48.0	60.0	
429	75.9	53.6	58.6			
442M	66.7	48.3	59.3			
442P	63.3	51.7	56.7			
456	76.7		70.0	72.4		
468M	66.7	48.3	63.3	41.4		
480	70.4		63.0			
481	41.4	55.6	51.7	40.7	51.7	
487	66.7	41.4	60.0		60.0	
492	70.0	53.6	63.3			
497	83.3		73.3			

Table 3.8 Classification Results (%) of Discriminant Analysis for W_B index for saturated/unsaturated analysis at grid scales of 4, 8, 16 m.

	4 m		8 m		16 m	
Date	Anal.	Test	Anal.	Test	Anal.	Test
311	86.6		70.0			
324	86.6	72.4	86.7	75.9		
326	83.3	82.0	73.3		76.7	75.0
334	82.8	78.6	82.8		75.9	
335	86.2	89.6	75.9			
389	89.3	72.4	82.0	69.0	78.6	
390	83.3	72.4	70.0		76.7	
392	86.7	75.9	83.3		76.7	
442M	89.0	72.4	81.5	72.4		
442P	86.7	72.4	86.7	75.9	70.0	
481	82.8	74.1			75.9	
487	86.7	79.3	73.3		83.3	75.9

2. Conclusion

These results illustrate that the chosen DEM grid size will affect final model output, represented here by the predictive accuracy of the discriminant analysis based on the W_B index. The 4 m grid consistently showed the most accurate predictions in analyses of both the water table level groups and the occurrence or absence of saturation. This reveals the problems of topographic averaging over larger scales, which results in a loss of areas of topographic convergence and divergence. The results suggest that grid size will have an effect on the derivation of topographic variables and hydrologic model output.

This finding will have importance to researchers using models such as TOPMODEL and TOPOG in areas of similar topography to the study site. A poor representation of hydrologic processes and the delineation of saturated areas will occur at the present study site of steep, dissected terrain if DEMs are based on the often-used 30 m grid size. If storm hydrograph predictions are needed, it may possible to use coarser grids and accept a slight decrease in accuracy in order to save computing time. However, the final decision as to the appropriate DEM grid scale to use must be based both on the local relief and degree of topographic dissection in the study area, and on the specific purpose for which the model is being used.

CHAPTER FOUR - CONCLUSIONS

The aims of this study were to describe water table behaviour, to assess the applicability of indices and topographic variables in predicting both water table levels and the occurrence of saturation, to test the effect of DEM grid scale on the derivation of topographic variables, and to suggest the consequences of these results to hydrologic models based on these indices. Each of these aims was met, and the conclusions are reviewed below. Suggestions for future research will follow this review.

A. Water Table Fluctuations

In forested catchments of southwestern British Columbia, previous research concluded that the primary stormflow mechanism was subsurface stormflow above an impermeable layer (e.g. Cheng et al., 1975, Tischer, 1986). However, zones of surface saturation had never been investigated in detail. The present study has revealed that in many storm events, runoff may be generated from areas of saturated soil, where the water table has risen to intersect the soil surface. At the study site, complete saturation of the soil occurred at a number of wells throughout the field season even though all storms studied had return periods of less than two years. Therefore, it is suspected that runoff from areas of saturated soil will have greater importance in the larger storm events which may be expected in this area.

Water table fluctuations at the site can be described as very responsive, rising and falling on average between 15 and 50 cm over the larger storm events studied. The presence of macropores may cause a more rapid water table response, although at some wells it is suspected that flow through macropores actually helped divert water away from the site, leading to lower water table levels as a result of rapid drainage. Water table response is also spatially variable, depending primarily on the topographic characteristics at each well. Convex areas of steep slope generally showed little to no measurable water table response, while some sites in concave areas near stream channels frequently became saturated to the soil surface.

Hydrologic variables influencing water table behaviour were also investigated. Correlations between water table levels and hydrologic variables at a number of wells indicated that maximum storm discharge and 24 hour throughfall intensity had the strongest relationship with maximum water table levels. Soil characteristics such as colour, texture, and horizonation were found to be typical of soils within the Research Forest (Klinka, 1976). Commonly-used soil indicators of frequent saturation, including soil colour, mottling, gleying, and thickness of the A horizon, were not applicable at this site. This result may have consequences to soil scientists using these indicators as drainage descriptors in similar regions.

A number of TOPMODEL assumptions were tested for applicability to the study site. The TOPMODEL assumption of subsurface flow following surface topography was studied over two well transects in the lower catchment. It was found that the water table did not always parallel the soil surface, and it is suggested that this may influence the accuracy of water table level predictions based on topographic variables. However, the significance of this effect on overall predictive accuracy could not be tested.

The assumption that the catchment responds to storm inputs in near steady-state conditions was tested by plotting water table levels in pairs of wells. Relationships were not identical in all cases and showed much scatter, which was likely due to differences in soil structure throughout the catchment, and the hysteretic effect of lags in water table response. It was concluded that the steady-state response assumption is not valid at this site, and that the effect of hysteresis will probably introduce scatter into the relationship between water table levels and topographic variables.

B. Prediction of Water Table Levels and Saturation Occurrence

A discriminant analyses was undertaken to determine the ability of topographic variables to describe water table behaviour. Upslope contributing area (ln a) was found to be the best predictor of water table levels (in the variable analysis) as it was chosen most often to describe the discriminant function. The W_B index was found to be as accurate as any single variable in predictive accuracy. This result was not expected, as previous research has generally accepted the W_B index as the most accurate predictor of water table levels. Predictions based on the occurrence or absence of saturation were more accurate than those based on grouped water table levels. Predictive accuracies for the occurrence of saturation ranged from 69 to 97% for both the variables and the W_B analyses, while predictive accuracy ranged between 41 and 90% for the grouped water table levels analyses. The range of results reveal the bias introduced by uncertainty in topographic variables derived from the DEM, and the potential inability of these topographic variables to predict water table levels. The larger variability of the water table group analysis is possibly due to the effect of hysteresis at higher catchment wetness levels when a discrimination based on all four water table groups was made. The results from the analysis of the occurrence or absence of saturation suggest that topographic variables are useful indicators of saturation at this site, and support the use of the W_B index in hydrologic modelling (at a fine grid scale).

It was found that the DEM grid scale chosen for derivation of topographic variables affected the predictive ability of the discriminant function to a large degree. The most accurate predictions were made by topographic variables derived from the 4 m grid, with a loss in predictive ability at coarser grids as averaging of catchment topographic characteristics occurred. The prediction of water table levels decreased in accuracy by 15% in some cases at the larger grid sizes. More accurate results were found with the analysis based on the occurrence of saturation, although predictive accuracy still decreased at coarser grids due to averaging effects. Predictive accuracies of 70 to 83% were found at the 16 m grid size, suggesting that at this site, a grid size up to 16 m may still prove acceptable. However, at this level more analyses were classified as non-significant.

As many DEMs are based on the 30 m grid scale, it is expected that hydrologic modelling at such a coarse grid size will result in significant differences in output as compared to finer grid sizes. This will affect model output most significantly if detailed delineations of saturated zones are necessary to the study in question. However, these conclusions can only be applied to areas of similar relief and topographic dissection to the study site, because coarser grids may prove useful in areas of gentle relief and rolling terrain.

C. Significance of Results to Hydrologic Models

Past studies have tested the accuracy of TOPMODEL and TOPOG based on the assessment of storm hydrographs in comparison to model output. The only study to compare water table levels to topographic indices as a measure of model accuracy was Jordan (1994). As the models purport to accurately delineate saturated zones within a catchment, it is imperative that these predicted zones be compared to actual field measurements before model output is accepted.

This study has shown that the use of the topographic index W_B within these models is valid as a predictor of zones of saturation. However, there are limitations to its use, including the DEM grid scale at which the topographic variables are derived, and the degree of vertical resolution needed in the delineation of water table levels. If the occurrence of saturation is needed, the indices are useful, but a lower accuracy level is reached when they are applied to the prediction of water table levels. In the present study, the most accurate predictions were made using W_B to predict the occurrence or absence of saturation based on topographic variables derived from a fine (4 m) resolution DEM. Overall, the study revealed that the W_B index is valid for hydrologic modelling, but no conclusions can be made concerning the models as a whole, as the discriminant analysis did not take into account the effect of varying antecedent wetness or storm characteristics.

D. Suggestions for Further Research

One avenue of future research lies in testing the predictive power of topographic indices in different environments. This study has verified the use of indices in predicting water table levels in a forested catchment of variable relief, but the indices should be tested on both more and less varied topographies, especially with regards to the effect of DEM grid scale.

Further study is also needed as to the accurate derivation of topographic variables from DEMs. Many questions still remain as to the effect of DEM algorithms on the values of derived topographic variables. For example, the use of single versus multiple flow paths should be investigated, as should the accuracy of the various interpolation methods (inverse distance, kriging, etc.) used to derive grid point elevations. The topographic variables derived from each method could then be compared to variations in predictive indices or overall model output. If any one method is found to be significantly more accurate, it should be incorporated into general model use. In this vein, the effect of scale on model output should continue to be investigated, to develop a sound knowledge of the effects of generalisation within models.

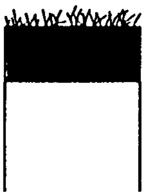
The present study referred to hydrologic models solely in the context of assessing the applicability of predicting water table levels based on topographic variables. Further model assumptions may also be investigated to improve accuracy, including the spatial variability of throughfall and soil characteristics within the catchment, and other topographic descriptors. In areas where shallow subsurface flow dominates the storm hydrograph with overland flow generated from saturated zones, topographic variables are believed to accurately represent the controls on runoff processes (Jordan, 1994). In the past, these variables have generally only included upslope contributing area, slope gradient, aspect, and curvature. It is suggested here that subsurface topography should be investigated further, in the form of depth to bedrock, which would have an influence on the development of subsurface flow above an impermeable layer. New methods of measurement, including ground-penetrating radar, may make this variable relatively easy to quantify and examine.

APPENDIX I - SOIL PROFILES

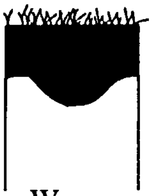
This section includes soil information from the nine pits studied. Their location within the catchment is shown in Figure I.1. A generalised schematic profile is included as well as detailed written descriptions of each horizon. The depth of the associated water table well is also included. Soil colours were taken in the field and later rechecked under dry conditions in the lab using a Munsell soil colour chart. General textures are included in the profile description and a detailed textural breakdown is shown in Table 2.3 in the main body of text. Because no textural separation of the fines was carried out, texture descriptions are general and follow soil family descriptors as shown in Olson (1981, Figure 14). The structure description is separated by grade (strength of structure); class (size of soil particle aggregation); and type (form of structure). In general, most horizon structures fall into a weak distinctness, 1-2 mm in size (fine), and a granular type. Moist consistence as measured in the field is defined as loose, friable, or firm. Boundary transitions are outlined below and were followed as closely as possible in the schematic profiles. All notations are described in detail in Olson (1981).

Distinctness	
Abrupt	< 2 cm
Clear	2 - 5 cm
Gradual	5 - 15 cm
Diffuse	> 15 cm

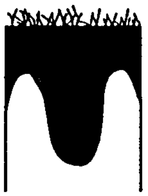
Form



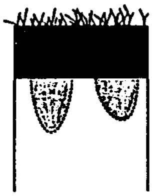
Smooth



Wavy



Irregular



Broken

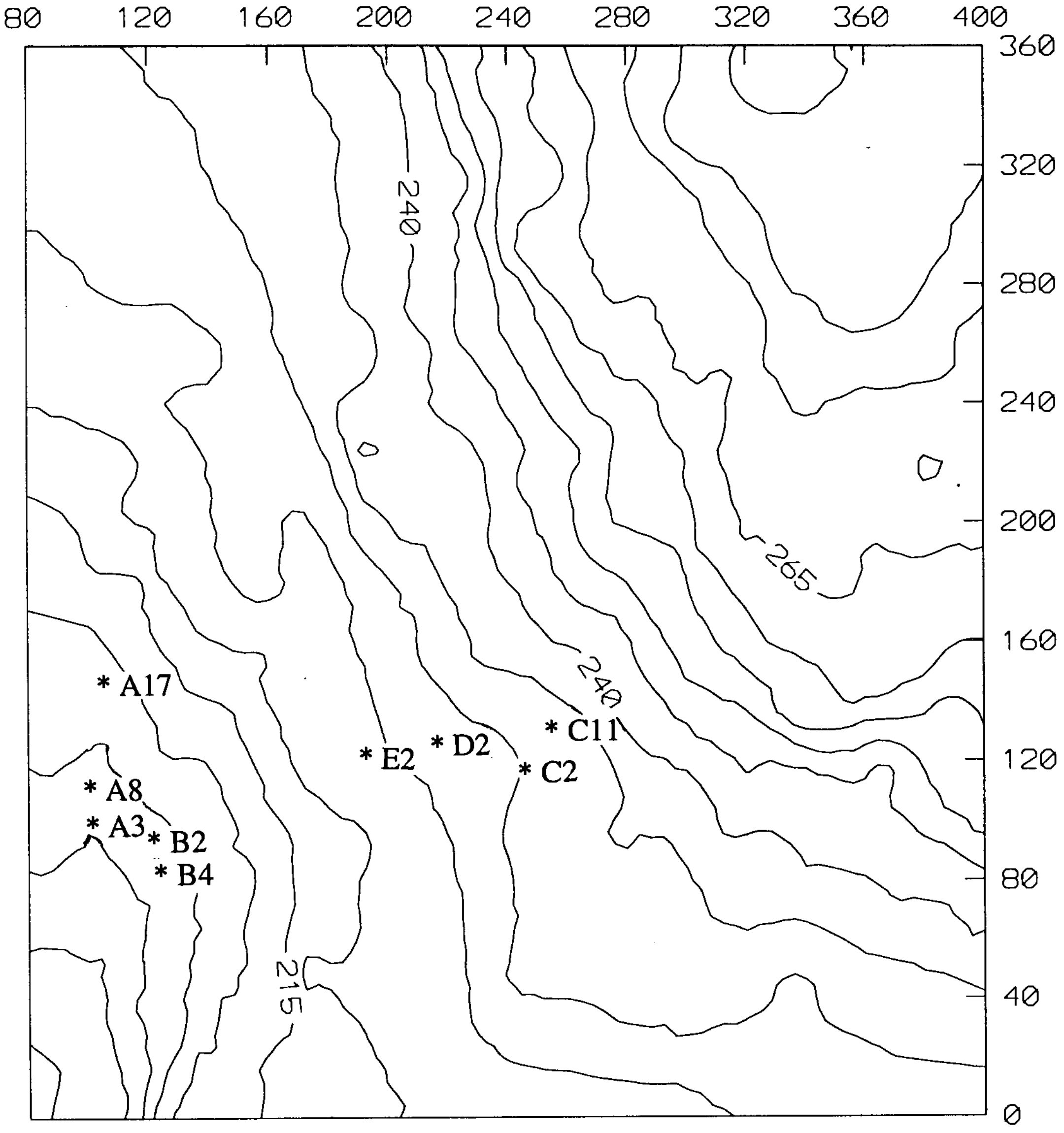
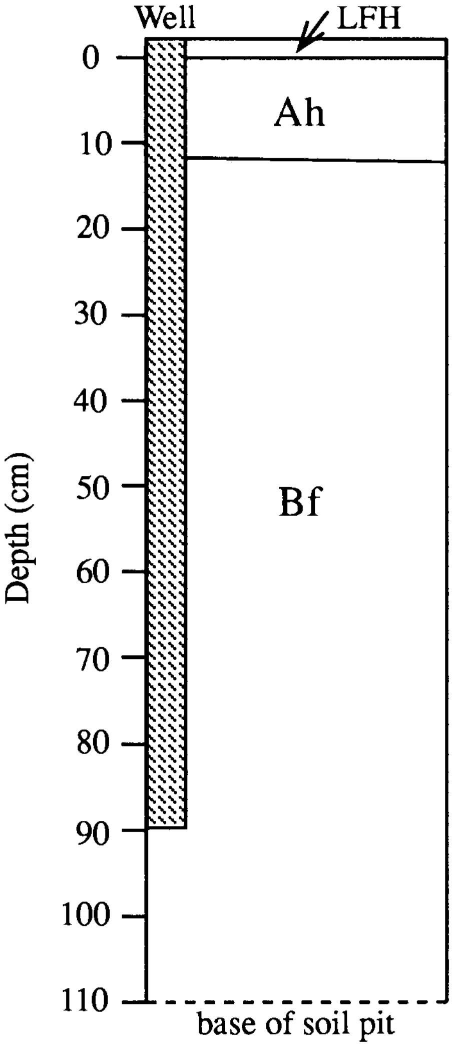


Figure I.1. Location of soil pits within the study catchment.

Eastings and Northings are in m.

Soil Profile, Pit A3

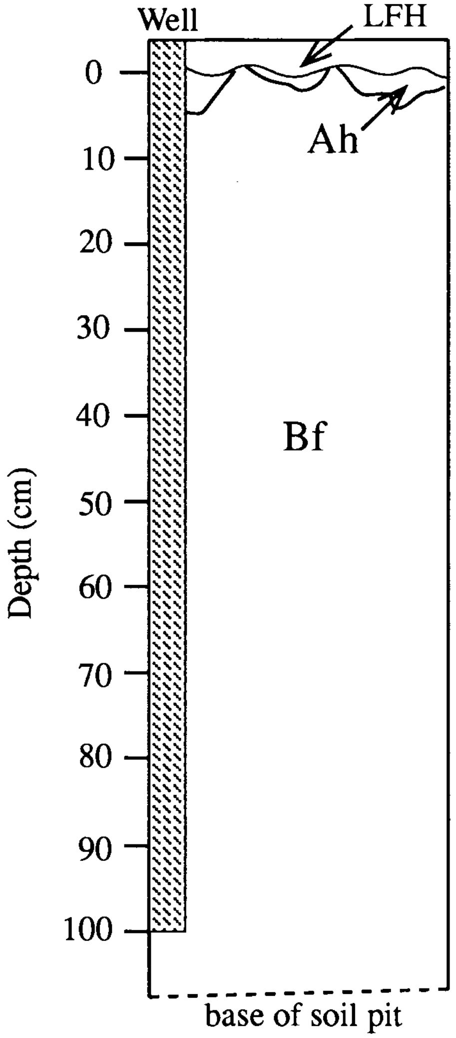


LFH Depth 1.5 to 0 cm; abrupt, smooth boundary.

Ah Depth 0 to 11.5 cm; black (10YR2/1); sandy texture; no mottles; weak, fine, granular structure; moist consistence firm; 10% coarse fragments; rooting abundance plentiful; abrupt, smooth boundary.

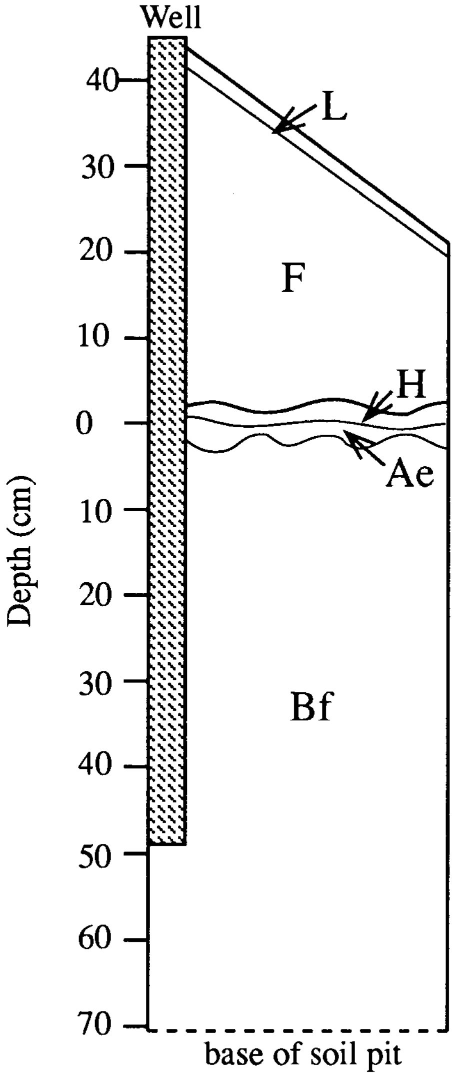
Bf Depth 11.5 to >110 cm; brown/dark brown (7.5YR4/4); sandy loam texture; no mottles; weak, fine, granular structure; moist consistence friable; 35% coarse fragments; rooting abundance few.

Soil Profile, Pit A8



LFH	Depth 2 to 0 cm; abrupt, irregular boundary.
Ah	Depth 0 to 4 cm; very dark grey (10YR3/1); sandy texture; no mottles; no structure; moist consistence friable; 10% coarse fragments; rooting abundance plentiful; clear, broken boundary.
Bf	Depth 4 to >107 cm; brown/dark brown (7.5YR4/4); coarse loamy texture; no mottles; weak, fine, granular structure; moist consistence friable; 55% coarse fragments; rooting abundance few.

Soil Profile, Pit A17



L Depth 46-20 to 45-19.5 cm; roots abundant; abrupt, smooth boundary.

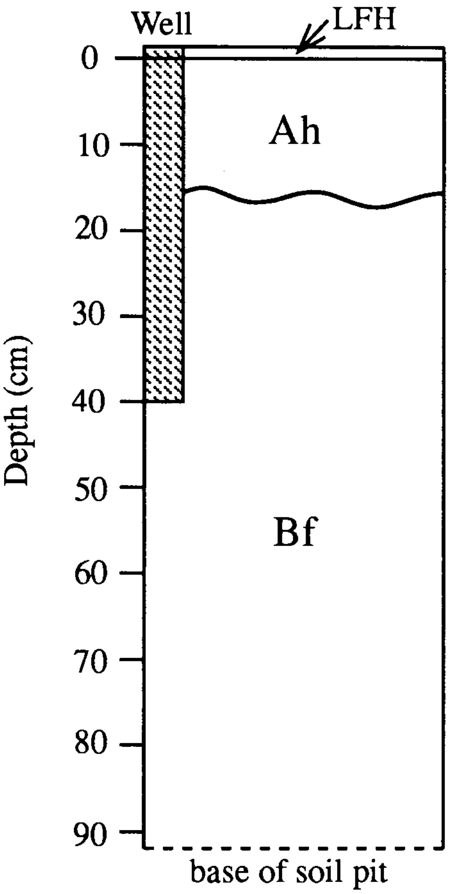
F Depth 45-19.5 to 0.5 cm; roots abundant; clear, irregular boundary.

H Depth 0.5 to 0 cm; roots abundant; abrupt, irregular boundary.

Ae Depth 0 to 2cm; grayish brown (10YR5/2); fine to coarse loamy texture; no mottles; weak, fine, granular structure; moist consistence firm; 10% coarse fragments; rooting abundance few; abrupt, irregular boundary.

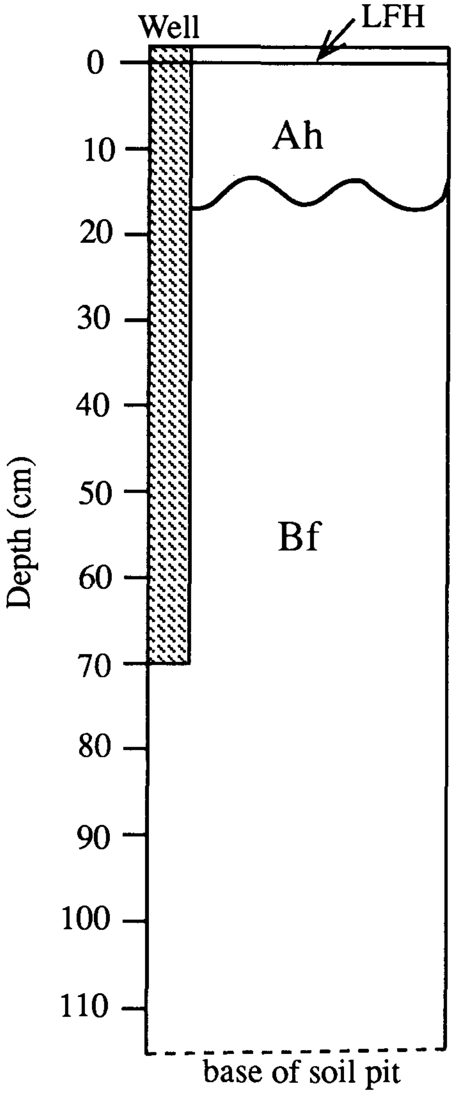
Bf Depth 2 to >70 cm; yellowish brown (10YR5/4); fine to coarse loamy texture; mottles dark grayish brown (10YR4/2), 2-20% abundance, size 5-15mm, constrast distinct; weak, fine, granular structure; moist consistence friable; 25% coarse fragments; rooting abundance very few.

Soil Profile, Pit B2



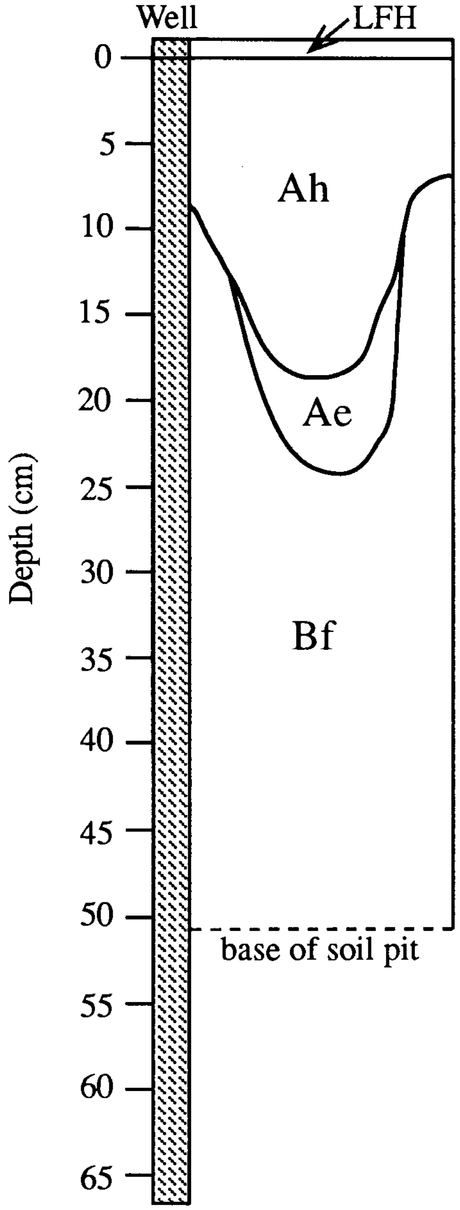
LFH	Depth 1.5 to 0 cm; roots plentiful; abrupt, smooth boundary.
Ah	Depth 0 to 16.5 cm; very dark grayish brown (10YR3/2); sandy texture; no mottles; weak, fine, granular structure; moist consistence friable; 10% coarse fragments; rooting abundance many; clear, wavy boundary.
Bf	Depth 16.5 to >92 cm; brown/dark brown (7.5YR4/4); fine to coarse loamy texture; no mottles; weak, fine, granular structure; moist consistence loose; 40% coarse fragments; rooting abundance very few.

Soil Profile, Pit B4



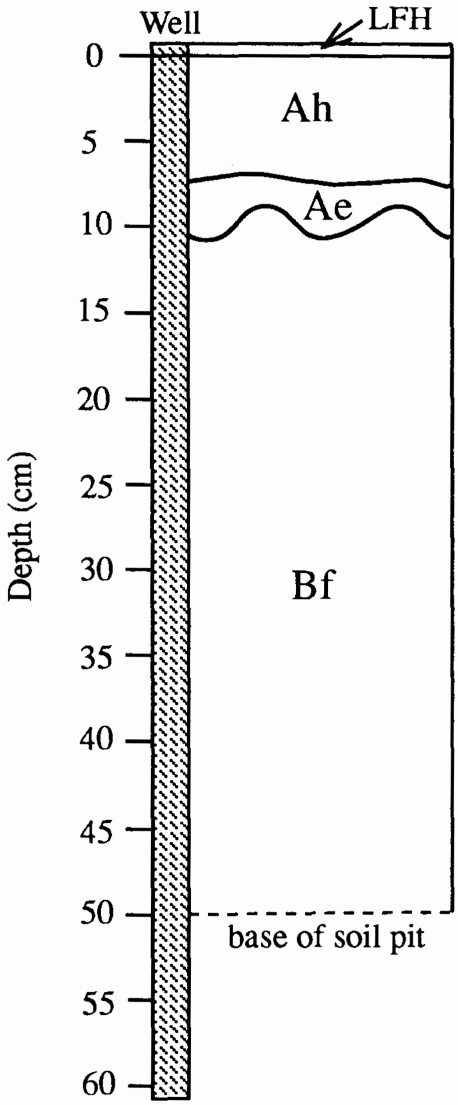
LFH	Depth 1.5 to 0 cm; roots plentiful; abrupt, smooth boundary.
Ah	Depth 0 to15 cm; black (10YR2/1); sandy texture; no mottles; weak, fine, granular structure; moist consistence very friable; 50% coarse fragments; rooting abundance many; clear, irregular boundary.
Bf	Depth 15 to >115 cm; brown/dark brown (7.5YR4/4); fine to coarse loamy texture; no mottles; weak, fine, granular structure; moist consistence loose; 70% coarse fragments; rooting abundance very few.

Soil Profile, Pit C2



LFH	Depth 1 to 0 cm; rooting abundance many; abrupt, smooth boundary.
Ah	Depth 0 cm to 6-19 cm; black (10YR2/1); fine to coarse loamy texture; no mottles; weak, very fine, granular structure; moist consistence friable; 10% coarse fragments; rooting abundance many; clear, irregular boundary.
Ae	Depth 19 to 25 cm; dark brown (10YR3/3); fine to coarse loamy texture; no mottles; weak, very fine, granular structure; moist consistence firm; 10% coarse fragments; rooting abundance few; clear irregular boundary.
Bf	Depth 6-25 to >52 cm; yellowish brown (10YR5/6); sandy texture; no mottles; weak, fine, granular structure; moist consistence loose; 35% coarse fragments; rooting abundance very few.

Soil Profile, Pit C11



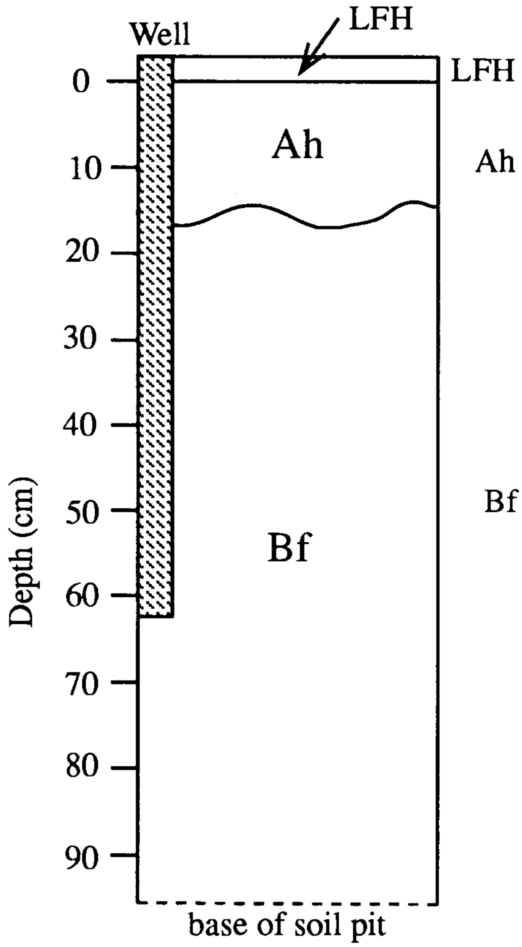
LFH Depth 1to 0 cm; abrupt, smooth boundary.

Ah Depth 0 to 8 cm; black (10YR2/1); sandy to coarse loamy texture; no mottles; weak, fine, granular structure; moist consistence friable; 5% coarse fragments; rooting abundance plentiful; clear, wavy boundary.

Ae Depth 8 to 10 cm; dark grayish brown (10YR4/2); sandy to coarse loamy texture; no mottles; weak, very fine, granular structure; moist consistence firm; 5% coarse fragments; rooting abundance many; clear, irregular boundary.

Bf Depth 10 to >49 cm; strong brown (7.5YR5/6); coarse loamy texture; no mottles; weak, fine, granular structure; moist consistence loose; 40% coarse fragments; rooting abundance very few.

Soil Profile, Pit D2

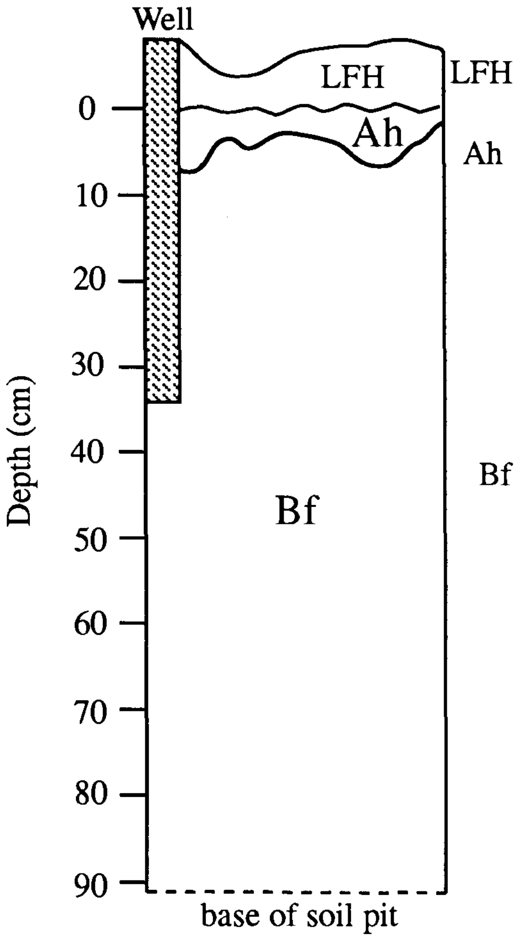


LFH Depth 3 to 0 cm; roots abundant; abrupt smooth boundary.

Ah Depth 0 to 15 cm; very dark brown (10YR2/2); sandy texture; no mottles; weak, fine, granular structure; moist consistence friable; 10% coarse fragments; rooting abundance plentiful; abrupt, wavy boundary.

Bf Depth 15 to >95 cm; brown (7.5YR4/4); fine to coarse loamy texture; no mottles; weak, medium, granular structure; moist consistence loose; 50% coarse fragments; rooting abundance very few.

Soil Profile, Pit E2



LFH Depth 5-10 to 0 cm; roots abundant ; abrupt, irregular boundary.

Ah Depth 0 to 2-8 cm; black (10YR2/1); fine to coarse loamy texture; no mottles; weak, fine, granular structure; moist consistence friable; 10% coarse fragments; rooting abundance plentiful; clear, irregular boundary.

Bf Depth 2-8 to >90 cm; brown (7.5YR4/4); fine to coarse loamy texture; no mottles; weak, fine, granular structure; moist consistence loose; 55% coarse fragments; rooting abundance few.

APPENDIX II - INDEX VALUES

This appendix includes topographic variable values for all well sites, the probability of saturation occurring at each well during the study period, and the x, y, z coordinates at each well. Following the value tables are histograms of the topographic indices used in the discriminant analysis, grouped by index and grid size.

Well	x	y	z	P(sat)
A1	95.9	100.2	200.7	0.00
A2	98.5	100.6	200.1	0.18
A3	100.0	100.2	199.9	0.41
A4	102.8	100.5	200.0	0.22
A5	105.0	100.1	200.4	0.00
A6	95.4	112.4	203.3	0.00
A7	97.4	111.2	202.4	0.00
A8	99.0	110.8	202.1	0.13
A9	100.2	110.4	201.9	0.30
A10	101.8	110.7	202.2	0.00
A11	103.0	110.6	202.6	0.00
A12	101.0	126.5	204.7	0.21
A13	102.8	126.2	204.5	0.56
A14	104.2	126.4	204.9	0.00
A15	99.2	148.9	208.0	0.00
A16	102.3	147.3	207.1	0.21
A17	104.0	147.2	207.4	0.00
A18	99.7	154.5	207.8	0.19
A19	102.5	153.9	208.4	0.00
A20	107.8	106.0	202.3	0.00
B1	109.7	97.8	200.7	0.19
B2	113.2	94.1	201.1	0.36
B3	121.6	88.9	202.6	0.00
B4	123.4	84.1	202.4	0.04
B5	129.6	81.3	203.1	0.16
B6	126.4	73.3	201.6	0.00
B7	122.8	67.6	200.3	0.17
B8	120.4	62.9	200.1	0.00
B9	116.9	60.9	199.2	0.00
B10	118.7	57.4	200.1	0.00

Well	x	y	z	P(sat)
C1	228.9	111.6	226.9	0.21
C2	246.5	118.3	229.9	0.48
C3	251.4	119.7	230.4	0.48
C4	252.9	117.4	230.8	0.00
C5	260.8	115.1	232.0	0.00
C6	266.7	111.5	232.2	0.38
C7	260.0	122.4	232.0	0.00
C8	260.6	127.9	232.2	0.00
C9	256.8	126.3	231.3	0.15
C10	251.3	124.1	230.6	0.25
C11	252.4	126.0	230.7	0.40
C12	251.4	127.5	231.0	0.00
C13	252.8	130.5	231.5	0.00
C14	243.8	130.7	230.1	0.14
C15	245.1	137.0	231.4	0.00
C16	248.0	150.4	235.0	0.00
C17	264.2	134.9	233.9	0.00
C18	261.4	146.4	236.4	0.00
C19	273.6	136.5	238.1	0.00
C20	281.1	134.7	240.8	0.00
C21	281.4	141.9	241.8	0.00
C22	280.3	148.4	242.5	0.00
C23	287.0	161.7	247.5	0.00
D1	215.1	116.0	225.2	0.85
D2	216.4	126.6	225.9	0.14
D3	215.9	137.8	227.5	0.00
E1	198.1	122.9	223.5	0.00
E2	192.5	122.9	222.4	0.06
E3	194.3	118.1	222.4	0.00

	4 m grid				8 m grid				16 m grid			
Well	ln a	tanB	Wb	Curv	ln a	tanB	Wb	Curv	ln a	tanB	Wb	Curv
A1	2.67	0.221	4.18	0.022	3.92	0.186	5.60	0.025	5.14	0.161	6.97	0.007
A2	6.53	0.165	8.34	0.068	5.07	0.183	6.76	0.034	5.81	0.169	7.59	0.008
A3	7.02	0.114	9.19	0.092	5.41	0.179	7.13	0.035	6.11	0.174	7.85	0.008
A4	5.97	0.163	7.78	0.050	5.83	0.176	7.57	0.042	6.44	0.184	8.13	0.009
A5	4.30	0.191	5.95	0.032	6.31	0.184	8.00	0.039	6.68	0.191	8.34	0.010
A6	2.30	0.210	3.86	-0.008	3.62	0.228	5.10	0.006	5.04	0.158	6.88	0.011
A7	5.78	0.209	7.35	0.007	4.51	0.229	5.99	0.016	5.05	0.164	6.86	0.011
A8	6.55	0.202	8.15	0.057	5.00	0.227	6.48	0.022	5.08	0.172	6.84	0.009
A9	6.82	0.201	8.42	0.083	5.26	0.225	6.75	0.026	5.14	0.177	6.87	0.009
A10	6.33	0.223	7.83	0.050	5.50	0.226	6.99	0.028	5.10	0.184	6.79	0.008
A11	5.76	0.242	7.17	0.021	5.65	0.225	7.15	0.031	5.14	0.189	6.80	0.007
A12	5.54	0.182	7.24	0.040	5.05	0.164	6.85	0.031	4.50	0.167	6.29	0.005
A13	6.53	0.172	8.29	0.074	5.33	0.157	7.18	0.040	4.46	0.177	6.19	0.006
A14	6.82	0.172	8.58	0.092	5.47	0.155	7.33	0.046	4.42	0.185	6.11	0.006
A15	5.91	0.098	8.23	0.038	3.61	0.100	5.91	0.003	4.42	0.158	6.26	0.001
A16	5.70	0.119	7.84	0.075	4.28	0.132	6.30	0.026	4.22	0.175	5.96	0.002
A17	5.42	0.126	7.49	0.091	4.49	0.149	6.39	0.039	4.24	0.188	5.91	0.005
A18	5.72	0.096	8.06	0.047	4.27	0.135	6.27	0.014	4.94	0.179	6.66	0.011
A19	5.01	0.184	6.70	0.036	3.94	0.164	5.75	0.026	4.73	0.197	6.35	0.010
A20	4.01	0.303	5.21	0.034	5.25	0.261	6.60	0.022	6.28	0.207	7.86	0.007
B1	7.67	0.218	9.20	0.036	7.57	0.219	9.09	0.023	7.20	0.204	8.78	0.013
B2	7.41	0.179	9.13	0.022	7.68	0.226	9.16	0.011	7.27	0.212	8.83	0.014
B3	4.80	0.206	6.38	0.034	3.72	0.217	5.25	0.018	6.78	0.240	8.21	0.009
B4	4.26	0.181	5.97	0.025	6.40	0.240	7.82	-0.006	6.93	0.250	8.31	0.009
B5	8.33	0.244	9.74	0.035	7.62	0.258	8.97	0.020	7.20	0.275	8.49	0.007
B6	6.83	0.322	7.96	0.037	6.72	0.278	8.01	0.022	6.83	0.283	8.09	0.010
B7	4.81	0.222	6.31	0.036	6.85	0.283	8.11	0.008	6.56	0.277	7.85	0.012
B8	3.50	0.285	4.75	-0.082	3.78	0.293	5.01	-0.028	6.66	0.276	7.95	0.013
B9	2.32	0.353	3.36	0.021	2.85	0.300	4.05	-0.012	6.89	0.266	8.21	0.013
B10	2.00	0.324	3.12	-0.038	3.12	0.317	4.26	-0.020	6.46	0.287	7.71	0.010

Well	4 m grid ln a	tanB	Wb	Curv	8 m grid ln a	tanB	Wb	Curv	16 m grid ln a	tanB	Wb	Curv
C1	7.36	0.173	9.12	0.030	6.52	0.184	8.21	0.021	6.29	0.169	8.07	0.004
C2	6.60	0.123	8.69	0.003	6.15	0.129	8.20	0.008	5.50	0.174	7.26	0.006
C3	6.32	0.105	8.58	0.067	5.89	0.120	8.01	0.020	5.52	0.175	7.26	0.011
C4	5.22	0.144	7.15	0.021	5.38	0.130	7.25	0.016	5.39	0.165	7.20	0.009
C5	5.49	0.126	7.56	0.017	4.78	0.146	6.70	0.015	4.84	0.170	6.61	0.011
C6	5.26	0.140	7.22	0.093	5.12	0.158	6.97	0.030	4.05	0.171	5.81	0.015
C7	4.81	0.190	6.48	0.019	5.17	0.188	6.84	0.022	5.60	0.206	7.18	0.018
C8	6.16	0.233	7.62	0.074	5.76	0.255	7.12	0.037	5.89	0.239	7.32	0.023
C9	6.13	0.201	7.74	0.016	5.86	0.191	7.52	0.030	5.99	0.207	7.56	0.024
C10	6.79	0.112	8.98	0.044	5.82	0.147	7.74	0.021	5.66	0.190	7.32	0.016
C11	6.45	0.154	8.32	0.064	5.79	0.165	7.60	0.023	5.80	0.198	7.42	0.020
C12	5.56	0.167	7.35	0.071	5.72	0.171	7.49	0.021	5.77	0.203	7.37	0.020
C13	5.08	0.213	6.63	0.007	5.74	0.207	7.31	0.021	5.77	0.219	7.29	0.020
C14	6.45	0.166	8.25	0.099	5.60	0.188	7.27	0.008	4.82	0.208	6.39	0.009
C15	5.07	0.251	6.45	0.013	5.55	0.233	7.01	0.016	4.98	0.240	6.41	0.009
C16	3.74	0.297	4.96	-0.003	4.41	0.300	5.61	0.001	4.60	0.278	5.88	0.002
C17	5.45	0.351	6.50	0.031	4.40	0.357	5.42	0.031	5.36	0.289	6.60	0.013
C18	5.56	0.271	6.86	0.042	5.40	0.318	6.54	0.014	4.48	0.315	5.63	0.004
C19	4.70	0.409	5.59	-0.016	4.13	0.406	5.03	-0.037	4.97	0.336	6.06	0.008
C20	4.56	0.269	5.87	-0.019	5.32	0.350	6.37	-0.014	4.68	0.354	5.72	0.002
C21	5.38	0.345	6.45	-0.027	4.59	0.381	5.56	0.006	4.75	0.369	5.75	0.002
C22	3.95	0.392	4.89	0.026	3.00	0.390	3.94	0.010	4.74	0.374	5.73	0.006
C23	4.01	0.486	4.73	0.091	4.68	0.447	5.48	0.037	4.78	0.404	5.69	0.010
D1	5.60	0.129	7.65	0.018	6.67	0.123	8.76	0.014	5.85	0.180	7.56	0.003
D2	4.83	0.091	7.23	0.030	5.55	0.123	7.64	0.039	5.11	0.196	6.74	0.003
D3	2.12	0.268	3.44	0.026	3.34	0.269	4.65	0.035	4.10	0.227	5.58	-0.005
E1	4.92	0.319	6.06	-0.007	4.70	0.223	6.20	0.016	4.46	0.163	6.28	0.003
E2	6.71	0.106	8.95	0.075	5.91	0.132	7.94	0.029	4.39	0.147	6.31	0.012
E3	6.48	0.134	8.49	0.040	5.69	0.161	7.52	0.023	4.66	0.161	6.49	0.008

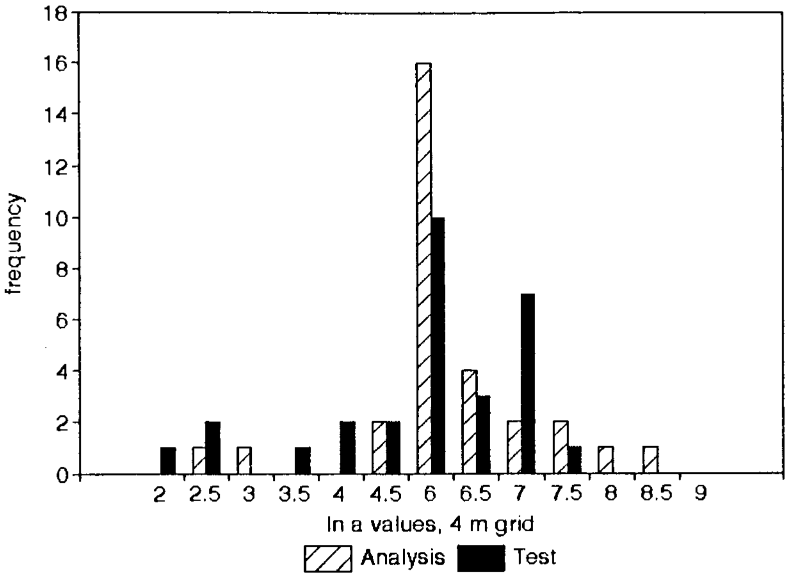


Figure II.1. Histogram of ln a values derived from the 4 m grid DEM which were used in the discriminant analysis; analysis and test section.

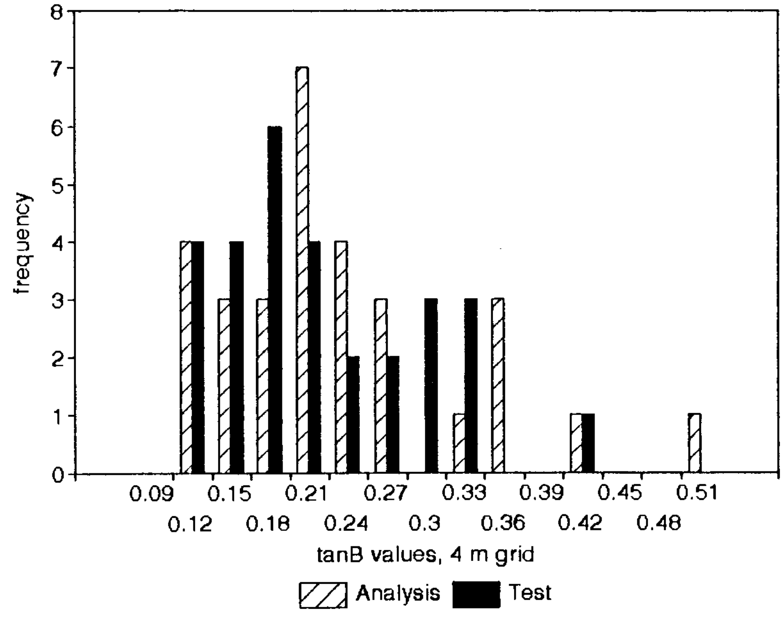


Figure II.2. Histogram of tanB values derived from the 4 m grid DEM which were used in the discriminant analysis; analysis and test section.

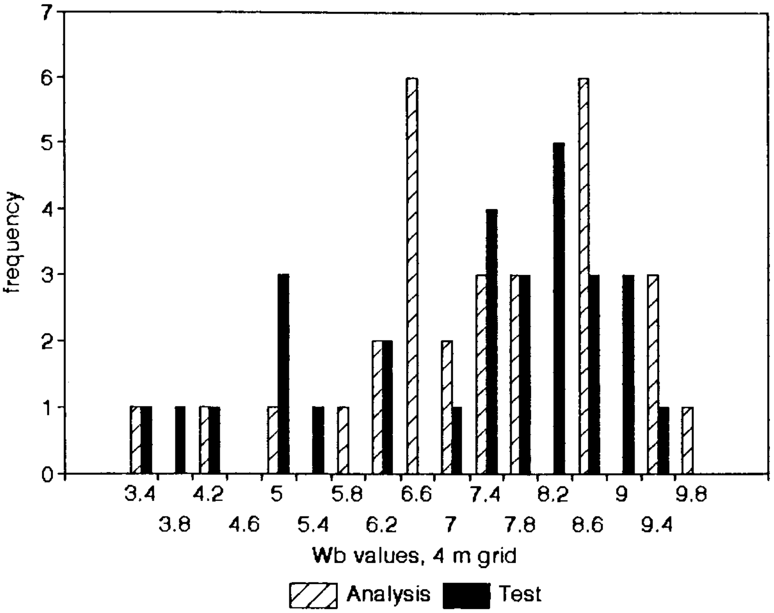


Figure II.3. Histogram of W_B values derived from the 4 m grid DEM which were used in the discriminant analysis; analysis and test section.

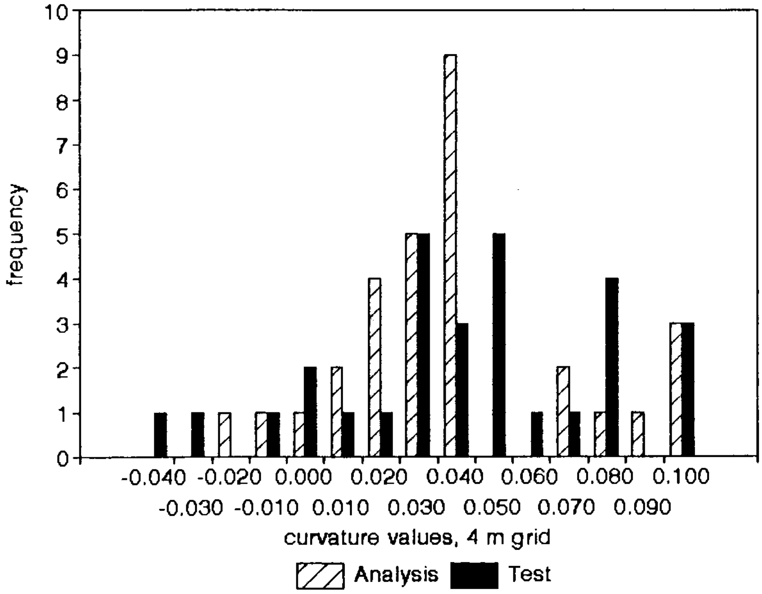


Figure II.4. Histogram of curvature values derived from the 4 m grid DEM which were used in the discriminant analysis; analysis and test section.

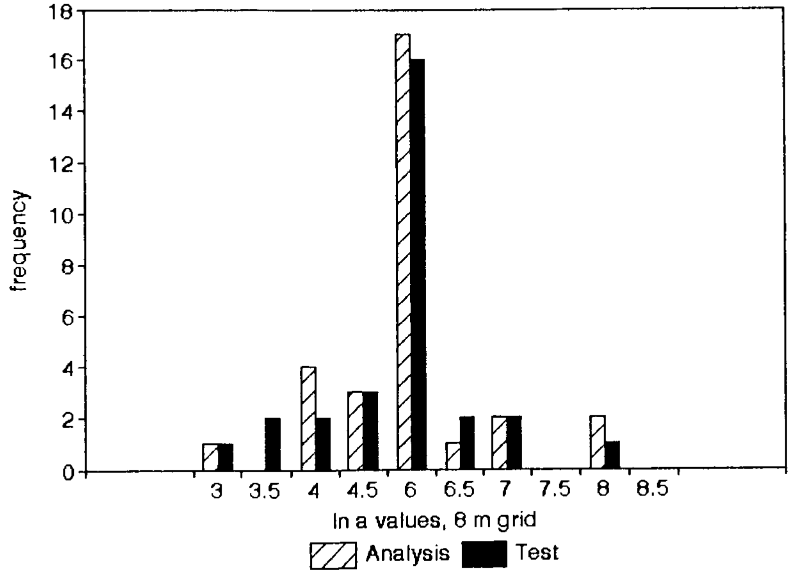


Figure II.5. Histogram of ln a values derived from the 8 m grid DEM which were used in the discriminant analysis; analysis and test section.

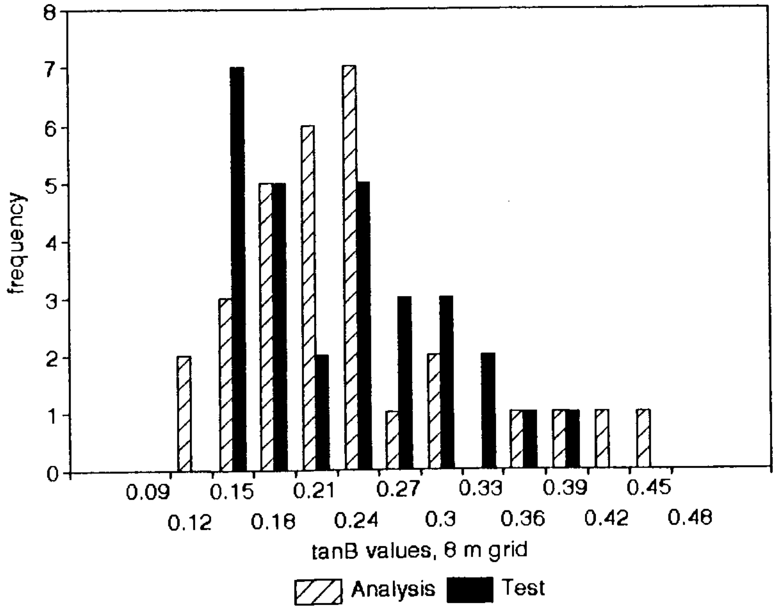


Figure II.6. Histogram of tanB values derived from the 8 m grid DEM which were used in the discriminant analysis; analysis and test section.

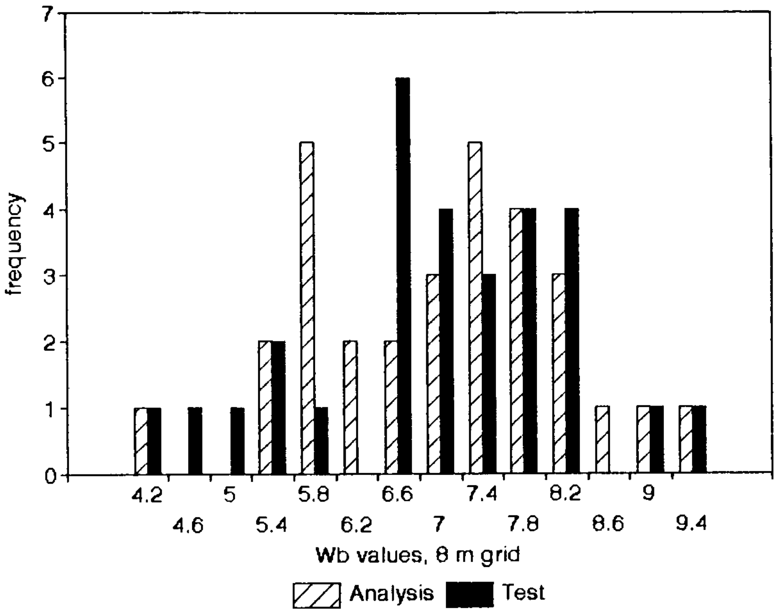


Figure II.7. Histogram of W_B values derived from the 8 m grid DEM which were used in the discriminant analysis; analysis and test section.

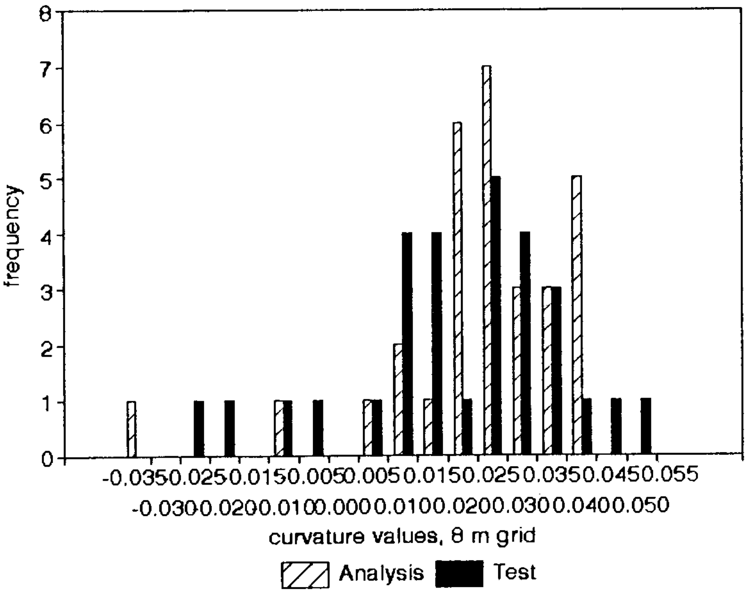


Figure II.8. Histogram of curvature values derived from the 8 m grid DEM which were used in the discriminant analysis; analysis and test section.

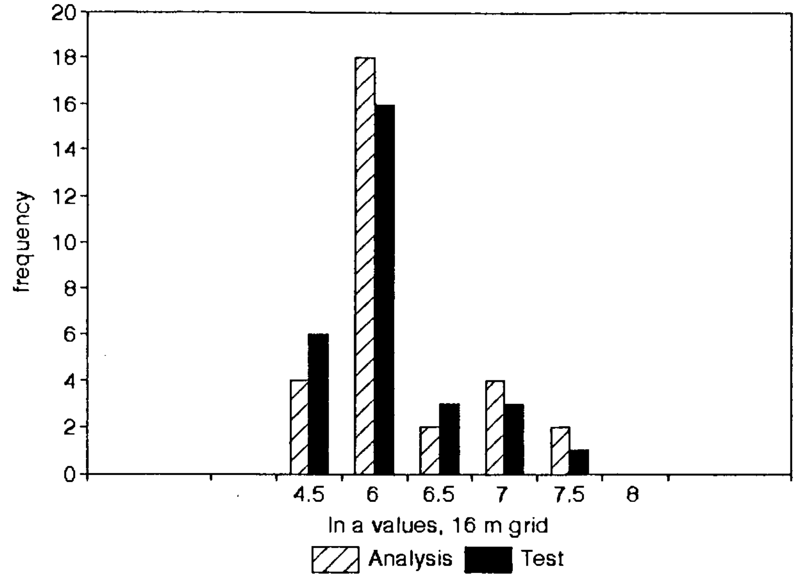


Figure II.9. Histogram of ln a values derived from the 16 m grid DEM which were used in the discriminant analysis; analysis and test section.

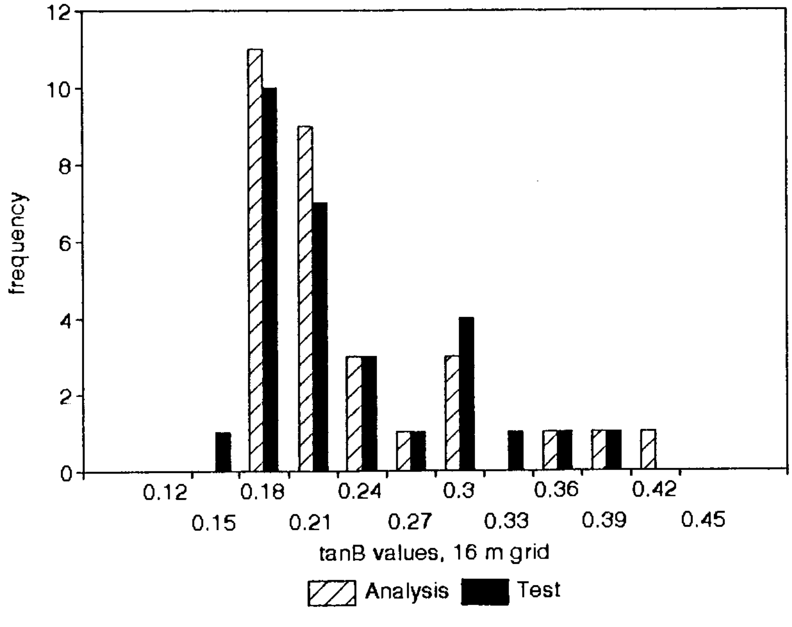


Figure II.10. Histogram of tanB values derived from the 16 m grid DEM which were used in the discriminant analysis; analysis and test section.

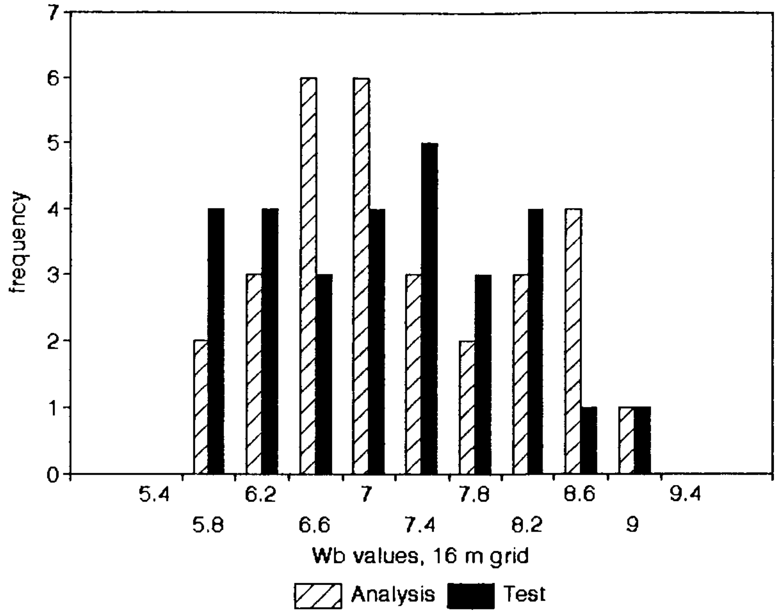


Figure II.11. Histogram of W_B values derived from the 16 m grid DEM which were used in the discriminant analysis; analysis and test section.

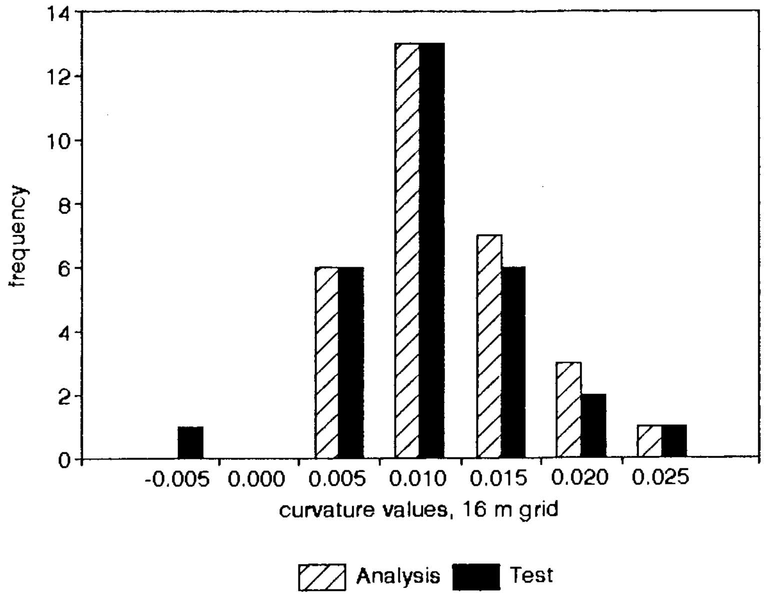


Figure II.12. Histogram of curvature values derived from the 16 m grid DEM which were used in the discriminant analysis; analysis and test section.

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