FOREST GROUNDWATER HYDROLOGY:

IMPLICATIONS FOR TERRAIN STABILITY IN

COASTAL BRITISH COLUMBIA

by

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ABSTRACT

The groundwater regimes of two coastal British Columbia field sites in landslide prone terrain have been assessed. The first site involved instrumentation of a landslide headscarp area with tensiometers and piezometers to characterize the groundwater regime over one year. Piezometers were designed and manufactured specifically for use in this project. Data collected from the study site indicate a highly variable distribution of storm-induced positive pore pressures across a small area. Field observations combined with data analysis suggest that macropore flow is responsible for the pore pressure distribution and rapid drainage.

The second site involved analysis of piezometric and precipitation records from the Carnation Creek Experimental Watershed. Analysis of records spanning almost 8-years revealed a number of observations of temporal and spatial distributions of groundwater behavior that deviate from simple hydrologic models. The study area is characterized by frequent occurrence, and a complex spatial distribution of high groundwater levels. Most piezometric sites displayed a 'capped' groundwater level that is rarely exceeded with increasing precipitation. Analysis of records also showed that forest harvesting could cause an increase in the response of soil water to precipitation. An increase was manifested in some, but not all of the chosen study piezometers that were within the harvested area, suggesting that the impacts of harvesting on groundwater may be site-specific.

A model of groundwater hydrology that parameterizes the effect of topography on the distribution of watershed groundwater levels was assessed for its ability to predict observed piezometric recordings from a small coastal watershed. The hydrologic model is a component of a terrain stability model named SINDEX. Piezometric recordings were available for a number of hillslope positions and aspects. The model was found to have satisfactory predictive capabilities of relative groundwater levels if conservative input parameters are used.

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NOMENCLATURE AND ACRONYMS

a	Hydrologic contributing area (m^2/m)
b	Width of hydrologic grid cell
c	Cohesion
D	Depth of soil
D_w	Depth of groundwater above impermeable surface
D_w/D	Groundwater ratio
DEM	Digital Elevation Model
GIS	Geographic Information System
IDF	Intensity Duration Frequency (measure of precipitation)
q	Net hydrologic influx
T	Transmissivity
VHF	Very High Frequency (radio)
W	Wetness Index

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1.0 INTRODUCTION

1.1 Stability of Forest Soils

Slope stability problems have plagued the forest industry in western British Columbia for years. Due to the lack of easily accessible valley bottom timber, forest development has increasingly moved onto steeper slopes, which are dominant in the rugged, mountainous terrain. These steep slopes are generally characterized by thin covers (1-2 m) of morainal or colluvial soils, and have a high natural occurrence of landslides (Schwab, 1998). Paramount in the initiation of landslides is the role of critical pore water pressures induced by the high levels of precipitation common to the region. In the effort to mitigate the occurrence of landslides directly affecting or associated with forest development, much research has been focused at understanding the physical factors controlling stability, and developing tools and techniques to predict occurrences and relative factors of safety (Fannin et. al., 1997). It has become well known that major deficiencies in understanding largely center around pore water pressure development in soils, and their spatial and temporal distribution.

Clear-cut logging practices, which are dominant in the British Columbia forest industry, have been the target of social and scientific pressures due to associated environmental degradation. A relationship between clear-cut logging and an increased frequency of mass wasting has been documented for the Queen Charlotte Islands, B.C. (Schwab, 1998). Primary factors believed to contribute to increased mass wasting are the loss of rooting strength, soil disturbance, and the influence of logging on soil hydrology. Assessments of the influence of logging on groundwater regimes are hindered by difficulty of characterization. Several experimental watersheds have been established to quantify the local effects of harvesting, and have shown widely variable results (Megahan, 1982; Hetherington, 1982). It is recognized that a steadfast cause and effect relationship derived from any of these experiments might be only locally applicable. Nevertheless, these experiments have been carried out to further the understanding of the forest hydrological cycle and its sensitivity to disturbance, and permit more informed decisions by professionals working in the forest industry.

With the introduction of the Forest Practices Code for British Columbia (BCMoF, 1995) came a requirement for assessments of terrain stability of forest lands. These assessments focus on delineating slopes into polygons of similar slope and geomorphic attributes, and assigning hazard ratings to them. Assessments are typically carried out by geoscientists or engineers using a combination of field and office based techniques. Although guidelines for these assessments of terrain stability have been set, the products are often subjective, relying on the experience of the mapper. Recent suggestions for improving assessments include incorporating an objective component into terrain stability mapping by development and application of Geographic Information System (GIS) based models (Pack, 1997) and probabilistic techniques for assessment of landslide initiation (Wilkinson, 1996). Key to these terrain stability models are reasonable estimates of groundwater levels. These are typically provided either through a sound model for topographically distributed groundwater levels, or by a simple single value groundwater input. Underlying these slope stability models is a basic infinite slope model, as discussed in Hammond et al. (1992). Any slope stability calculations require a reasonably accurate estimate of groundwater level, often represented as a ratio, such as D_w/D (Hammond et al. 1992), where D_w is the depth of water and D is the depth of soil.

1.2 Project Objectives

Objectives of this thesis broadly surround the investigation of temporal and spatial distribution of groundwater behavior in coastal forest soils. The general objectives were achieved by a combination of developing, installing, and monitoring instrumentation; analysis of an existing database; and an exercise in computer modeling of groundwater flow. Specific components of this study were as follows:

- Design and commission a robust, automated, continuously recording groundwater monitoring system that has the capability for remote data acquisition. The system was designed to be installed on a forested slope in landslide prone terrain.
- Monitor and characterize the soil pore water pressures, including negative and positive, above a recent debris slide headscarp for one year.
- Determine if land use changes, in the form of clear-cut harvesting, had an effect on the groundwater regime of a small instrumented watershed in the Carnation Creek Experimental Watershed.
- Study patterns and magnitudes of peak groundwater levels within the Carnation H Creek watershed in order to determine a general understanding of where, how, and how often potentially slope destabilizing groundwater ratios (D_w/D) occur.
- Evaluate a topographically driven, deterministic, physically-based flow model for its capability of predicting relative levels of groundwater across a watershed area by comparison with field measured levels.

The many avenues of study within this thesis are intended to amalgamate to give the reader an understanding of the nature of groundwater flow in steep forest slopes. Observations, results, and discussions are intended to have relevance to professionals involved in the assessment of forest slope stability, and for those involved in research of forest groundwater hydrology.

2.0 FOREST GROUNDWATER HYDROLOGY

2.1 General

Soils on forest slopes in Coastal British Columbia present a very complex hydrogeologic environment. Common soil types include colluvium, morainal soils, and less commonly, completely weathered bedrock. Distributions of these soils depend on local bedrock, regional genetic histories, and localized processes. Generally, soils are commonly of a sandy matrix base allowing for moderate to high hydraulic conductivity. Upper soil profiles are dominated by organic soil development, affecting all forest soils to varying degrees. Hydrologically speaking, the complexity of these soils arises as a result of a number of factors, including:

- high & low permeability zones;
- biologically altered zones;
- erosional features;
- zones of divergence and convergence (Barling et al. 1994);
- variable slope gradients and soil thickness;
- bedrock recharge and discharge zones;
- vegetation and surface cover (Lim et. al. 1996);
- effects of land use change.

Considering the way in which these factors may individually, or in conjunction, complicate the downslope movement of groundwater, it may seem futile to try and attempt to characterize the groundwater regime of a watershed through discrete point measurements using piezometers. It has been recognized for over 30 years that characterization of flow is difficult due to the transitory nature of subsurface flows (Betson et al. 1968).

Echoing Megahan (1983), it is key to our understanding of hydrologic cycles, and of hillslope stability, that we attempt to better understand the nature of groundwater flow in forest soils. To better understand the complex relationships between rainfall-induced landslides, or the effects of land-use changes on groundwater levels, it is also essential to study the individual components of hydrologic cycles, and their interconnection.

2.2 Experimental Work

Experimental watersheds established to monitor groundwater levels are sparse on the West Coast of North America. The driving interests behind the installations of the monitoring schemes have varied widely. Validation of groundwater flow models using piezometric recordings has been performed by Moore and Thompson (1996), and Reddi and Wu (1991). Recordings have been used to assess changes in hydrologic regimes due to forest practices (Gray, 1973; Hetherington, 1982). Instrumentation has also been installed to improve the understanding of the initiation of pore pressure induced debris slides. Data collected from debris slide prone areas have been discussed by many, including Wu et al. 1979; Pierson, 1980; Sidle and Swanston, 1981; and Johnson and Sitar, 1990. Observations from instrumented sites have also led to validation of postulated processes occurring within hydrological cycles. Recent studies by Anderson (1997) point to the highly complex nature of the movement of water through a combination of the vadose zone, saturated colluvium, and fractured bedrock. Common results from studies in forest soils indicate significant spatial variability and a rapid response to storm precipitation. Difficulties in explaining variability within small, instrumented watersheds lead to limitations in transferability of findings to larger, non-instrumented watersheds. Many studies have stressed the importance and complex roles of preferential flow pathways and the partially saturated zone.

2.3 Preferential Pathways

In environments with high total annual precipitation combined with shallow forest soils, it is not uncommon for groundwater levels to reach near total saturation of the soil profile. It is uncommon, however, to witness overland flow on most forested slopes resulting from saturation in excess of the profile, or precipitation exceeding the infiltration capacity of the soils (referred to as Hortonian Flow). Forest soils tend to have a very high capacity for water transmission that can be explained by more rapid non-Darcian flow through macropore networks (Hetherington, 1995). In addition, the humus, or thick organic forest floor layer is highly porous and permeable. Features such as macropores are known to transmit large volumes of water through the slope, and are almost impossible to characterize yet they are responsible for the majority of rapid water transmission and often control slope stability. Beven and Germann (1983) have recognized the level of complexity that macropores add to the hydrologic properties of a forest soil and outline the difficulties in trying to incorporate these features into traditional predictive models. Macropores, sometimes termed soil pipes, can adversely influence the stability of a slope if they should at some point either become clogged or terminate, upon which pore pressures may locally build up. Brand and Nash (1986) and Pierson (1983) have noted field observations of the effects of pipe flow on slope stability. The effects have also been illustrated experimentally (Pierson, 1983; Sidle at al. 1995b). It is well known that attempting to trace and quantify the flow through these features is not a simple task.

Macropores may result from either decayed root holes, animal burrows, or subsurface seepage erosion mechanisms (Dunne, 1990). These features have commonly been noted at debris slide headscarps, including the Jamieson Creek and Carnation Creek study areas. It is believed that these pore structures can potentially form anastomosing networks and effectively drain storm flow through the slope much faster than natural groundwater flow through the matrix soil. Megahan and Clayton (1983) performed tracer tests in the field and found that hydraulic conductivities were an order of magnitude greater than those found on soil samples in the lab. Rapid flow rates and heterogeneous and anisotropic flow were attributed to macropores in the soil. To add to the hydrologic complexity of these features, the conditions under which they are active are not well understood. It is hypothesized, and noted in Gilman and Newson, (1980), and Sidle (1995), that macropore flow is prevalent as soil moisture increases, whereas matrix flow is dominant during storms of lower intensity and accumulation. Macropores may be responsible for conducting infiltration rapidly both vertically and laterally following saturation of the typically unsaturated upper soil profile, acting as major contributors to subsurface throughflow (Beven and Germann, 1983, Herrmann et al. 1987). In contrast, De Vries and Chow (1978) speculated that unsaturated soils in the Jamieson Creek area tend to utilize macropores immediately and saturate the matrix from the soil surface down, and through the walls of saturated macropores.

Field tests of hydraulic conductivity in forest soils have been limited and have generally produced significantly variable results across small areas (Wu et al. (1979); Megahan and Clayton (1983); Sidle (1985); Hetherington (1995)). Reported results range in orders of magnitude for soils of similar grain sizes owing primarily to preferential flow paths such as macropores. Laboratory testing of reconstituted samples of matrix soils would likely produce lower bound values of conductivity, and field tests are only indicative of hydraulic conditions at the point source being tested. The difficulty in characterization and immense variation in hydraulic conductivity complicate the development of accurate predictive hydrologic models.

2.4 Unsaturated and Partially Saturated Conditions

Unsaturated or partially saturated conditions are prevalent in most forest soils, in at least a portion of the soil profile, for considerable periods of the year. The term unsaturated refers to completely dry soil conditions, or a state where any water in the soil matrix above the water table is held in tension. Flow from this zone is attributed as a partial factor in maintaining stream base flow (Anderson and Burt, 1977). The unsaturated zone of a forest soil profile can be host to significant fluxes of moisture, which can be characterized through the use of simple tensiometers as illustrated by Harr (1977). The development of pore pressures in the unsaturated zone is influenced by factors such as soil type, evaporation, surface cover (Lim et. al. 1996), temperature, and soil depth and density. Finer grained soils are capable of reaching higher matric suctions due to smaller interstitial voids. Coastal forest soils are typically sandy with highly porous organic forest floor layer that inhibits high matric suctions. The negative pressures that are developed in the soils are quickly lost during precipitation due to rapid percolation of precipitation through the highly permeable soils.

The unsaturated zone effectively controls the infiltration capability of a soil. Hydraulic conductivity sharply decreases as soil suction increases due to a loss of soil moisture connectivity, or degree of saturation (Juca, 1993). If soil properties are adequately known, measurements of negative pore pressures in a slope can be related to the soil moisture conditions through soil-water characteristic curves (Stannard, 1992), and further used to estimate the unsaturated shear strength (Fredlund et. al. 1995). With knowledge of pre-storm antecedent suction values and soil characteristics, the amount of precipitation required to effectively saturate a column of soil of a set volume could be calculated, as was shown by Johnson and Sitar (1990) and Wolle and Hachich (1989). Saturation of this column will lead to increased capability of throughflow, as water in this zone moves slowly in a complex manner. Flow through the partially saturated zone is believed to be typically vertical, but has been shown to travel in a downslope direction by Harr (1977). The seasonally variable effects of the unsaturated zone likely regulate downslope water transmission. As soils become increasingly unsaturated, a larger amount of precipitation will be required to first increase soil moisture, prior to allowing rapid throughflow.

In many tropical residual soils, negative pore pressures are considered to be a fundamental factor in maintaining stability (Wolle and Hachich, 1987; Rahardjo et al. 1996). In western North America, negative pore pressures have been studied to monitor soil moisture fluxes and hill slope responses to rainfall (Gray, 1973; Cheng, 1987; Johnson and Sitar, 1990). Monitoring negative soil pore water pressure in forested slopes in Coastal B.C. can help in piecing together a broader understanding of hydrologic regimes. Negative pore water pressures offer indirect measures of soil moisture, which can be used to characterize different sites. For example, changes to soil moisture levels in areas that have been clear-cut could be assessed.

2.5 Precipitation - Landslide Relationships

It is well known that extreme levels of saturation on potentially unstable slopes are major triggers for debris slide initiation. Classical slope stability analyses can predict the approximate soil pore pressures necessary to destabilize a slope, but the relationship between precipitation and pore pressures is poorly understood. Numerous researchers have attempted to directly define relationships between storm attributes and debris flow frequency through development of rainfall threshold curves, such as for the San Francisco Bay area (Wieczorek, 1987; Johnson and Sitar, 1990), Sri Lanka (Bhandari and Dias, 1995), and Hong Kong (Kay and Chen, 1995). To form these curves, landslide occurrences have been related to attributes of the storm that triggered the event. If enough landslides have been documented in a geographic area, selected storm attributes corresponding to the slide event can be plotted against one another. If the plotted data points fall within a definable region of the plot, the plot can be used as a predictive tool. For example, if certain rainfall thresholds are surpassed, the likelihood of landslides increases. An example of one of these curves for the San Francisco Bay area is shown as Figure 2.1. Overlain on Figure 2.1 is a rainfall Intensity-Duration Frequency (IDF) curve for 5-year return period storms for the H Watershed, Carnation Creek. The 5-year return period IDF is nearly coincident with one of the proposed upper thresholds for slope stability. Intentions of overlaying the Carnation Creek data on the data from California are not to compare the two physiographically diverse areas, but to illustrate how the threshold curves could relate to measured precipitation data. Threshold concepts have been further extended into the development of a fully automated slope landslide warning system which continually monitors rainfall for the city of Rio de Janeiro (Orsi et al., 1997). Church and Miles (1987) found only a slight correlation between extreme 24-hour rainfall events and debris flow activity for Southwestern British Columbia. They concluded that hydrometeorologic indices are unlikely to provide consistent indications of debris flow activity.

Although the development of such relationships can serve as a useful tool in predicting debris slides, one must consider the potential pitfalls. Inherent to all of the proposed relationships noted are the problems of being able to accurately define the antecedent moisture conditions, neglecting topographic variance, and reliance on meteorological data that are often collected from distant locations. Relationships are recognized to be generally site-specific. For example, continuous high intensity rainfall has been found to be a key role in slides in San Francisco, while a combination of 1-hour intensity and daily rainfall were found to best fit the Hong Kong data.

2.6 Impacts of Forest Harvesting on Watershed Hydrology

A much debated and contentious issue in forest sciences is the postulated link between clear-cut logging and increases in groundwater levels leading to higher occurrences of slope failures. Studies of post harvesting changes in groundwater levels have been performed in many locations around the world. For Western Australia, Sharma et al. (1982) showed a significant rise in both groundwater level and soil water storage in a paired catchment experiment. Gray (1973) noted generally wetter conditions in instrumented clear-cut areas in Washington, although there was no attempt at quantification. Studies in Oregon conducted by Rothatcher (1970) and Harr (1986) both found increases in annual water yield and peak stream flow, respectively. Megahan (1983) studied hydrologic changes in a paired catchment experiment in Idaho Batholith following clear-cutting and wildfire. Increases in peak piezometric rise, total piezometric storage, and subsurface flow in a clear-cut and burned area were cited. Studies in Canada include the Nashwaak experimental watershed project (Meng et al. 1995), the Jamieson Creek basin (Golding, 1987) and Carnation Creek (Hartman and Scrivener, 1990). Each of the three Canadian watershed studies noted increases in selected hydrologic parameters following harvesting. Hypotheses for changes in groundwater levels following clear-cut harvesting primarily center around the loss of interception and evapotranspiration along with changes in the behavior of snowpack ablation and melt (Megahan, 1983; Harr, 1986). It is also likely that the hydrologic regime of a harvested slope can be modified through ground disturbance as a result of either ground-based machinery compaction or log yarding surface damage (Megahan, 1983).

Results of the pre vs. post studies should be interpreted with caution. The cited authors have used a range of methods to assess changes to the hydrologic parameters of interest. Plaguing a number of the studies is the limited time spans over which data were recorded. Natural annual climatic variability can mask the effects of harvesting or result in hydrologic changes that may be interpreted as harvesting related.

2.7 Implications for Further Studies

Although a good deal of research has been performed in the field of forest soil hydrology, the degree of transferability of findings has often been limited. Characterization of hydrologic regimes at experimental watersheds can offer some general observations of groundwater behavior applicable to sites within similar physiographic regions and climatic conditions, but in some aspects, can be very site-specific. Studies of groundwater behavior are limited on the western coast of British Columbia, where forest development on landslide prone slopes is ongoing. Arguably, any developments in the understanding of how high levels of groundwater develop, and how they are spatially distributed, would assist those involved in terrain stability assessments.

Previous experimental work has provided an understanding, and an appreciation of the complexity of processes within the larger hydrologic cycle. This understanding has been incorporated into this study through the development of a groundwater monitoring system, analyses of new and old piezometric data, and evaluation of a hillslope hydrology and slope stability model.

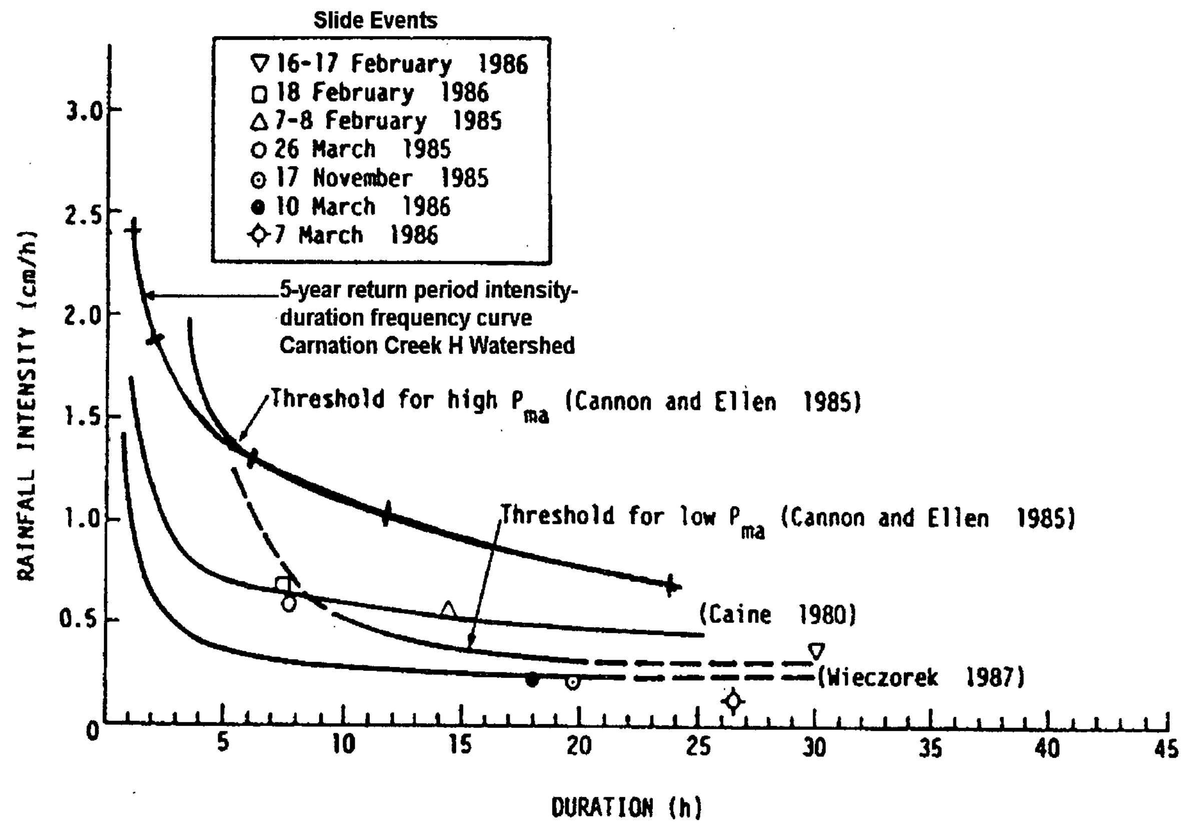

Figure 2.1 Intensity-duration threshold curves for the San Francisco Bay area showing landslide occurrences and rainfall data from Carnation Creek, B.C. (Modified from Johnson and Sitar, 1990)

3.0 CHARACTERIZATION OF GROUNDWATER STUDY SITES

3.1 General

Groundwater flow in forest soils is governed by a number of basic physical parameters that interact in a complex manner. Parameters controlling flow include those that cannot be accurately characterized across larger areas, such as the subsurface bedrock profile and in-situ hydraulic conductivity. Groundwater controlling parameters used in characterization of a site are often limited to soil textures and depth, slope gradient, shape, and position.

To achieve the research objectives outlined in Chapter 1, a field site was selected for instrumentation purposes, and the data from the Carnation Creek area were acquired. This chapter describes the reasons for selection, and the physical characteristics of the study areas used in the research project.

3.2 Jamieson Creek Slide Site

The Jamieson Creek Slide site encompasses a small area spanning 25 m immediately upslope of a large debris slide headscarp (Plate 3.1). The study area is at the upper boundary of an approximately 38 ha patch clear-cut, harvested in 1984, within the Seymour Watershed, Vancouver, B.C (Figure 3.1). This site was chosen as an ideal area for studying groundwater for a number of reasons. Physiographic features of the study area slope are representative of vast areas of Coastal British Columbia where forest development is ongoing. This in turn helps maximize the degree of transferability of findings to other areas. In terms of forest development, the Jamieson Slide area represents a 'worst case' scenario, where heavy rainfall triggered a large debris slide in a harvested area. For positioning groundwater instrumentation, the headscarp face provides an excellent cross section of bedrock and soil, along with groundwater seepage zones. These factors combine to reduce some of the uncertainty of installing instrumentation where macropores are known to control the local hydrology. The study area slope is also within close proximity to the City of Vancouver in a limited access watershed, creating an easily accessible and secure area for instrumentation. In addition, an extended history of multidisciplinary research that has been performed in the area is also available.

Attributes of the Seymour Watershed are typical of many valleys in the Coast Mountain Ranges. The valley is U-shaped with glacially over-steepened sideslopes eroded out of granodiorite bedrock. Slopes are overlain with thin blankets of surficial deposits comprised primarily of morainal and colluvial soils. A combination of steep slopes and a very wet climate combine to make this a very geomorphically active valley, with debris slides and torrents being common occurrences.

3.2.1 Soils

Soils at the headscarp area are a combination of weathered gravelly sand colluvium derived from till, with frequent sub-rounded weathered granodiorite cobbles, entirely weathered granodiorite bedrock, and ferro-humic podzols. Overlaying the weathered mineral soil is a thick root mat layer. At the headscarp rock – soil interface, a compact, silty, thin weathered layer is exposed in some locations. Grain size distributions for soils sampled from two locations near the headscarp are shown in Figure 3.2. Soils of this texture are expected to have moderately high hydraulic conductivities in the broad range of 10^{-3} – 10^{-7} cm/s (Craig, 1992; Selby, 1993). These values only consider flow through voids in the matrix of soil. Direct field measurements of conductivity are likely to be higher due to flow-controlling macropore features, as discussed in Chapter 2.3. Soil thickness varies around the slide, with side scarps averaging 1 m thick, while soils in the headscarp area are on average 1.5 m , with a maximum of 2 m.

Soil density at the site is low due to the high percentage of organics in the upper profile, and a high degree of weathering. Bulk and dry densities of the soil were measured by sampling intact, relatively undisturbed blocks from a sidescarp location near the top of the slide. Samples were taken from a depth of 1 m, near the bedrock surface, to minimize the organic content. Blocks were trimmed, wrapped in cellophane, and sealed with wax before leaving the site. Bulk density of the samples was measured by using a water displacement method. Low values of moist bulk density of 11.5 kN/m^3 and dry density of 6.3 kN/m^3were recorded. Results agree with values reported by De Vries and Chow (1978) for soils tested in the Jamieson Creek drainage. The low values are not uncommon for soils with a high organic content, as reported by Harr (1977).

3.2.2 Bedrock and Slope Morphology

Bedrock at the site is a competent diorite/granodiorite of the Coast Plutonic Complex from the Cretaceous period (Roddick and Woodsworth, 1979). The bedrock expression, as revealed on the slide scarp, is relatively planar, with minor ‘steps’ due to discontinuous vertical joints. It is evident at the site that the bedrock profile largely controls the soil topographic expression and creates an impermeable boundary for groundwater. The coarse grained quartz and feldspar crystals of the Coast Plutonic Complex bedrock are the likely source of the sandy soil matrix.

The study area site is located at the midpoint of a long, relatively planar slope at an elevation of 880 m. The upper drainage divide is a broad, gently sloping ridgeline at 1200–1300 m. Slope gradients in the vicinity of the study area average approximately 30°(58%), with short sections exceeding 35°(70%).

3.2.3 Climatic Conditions

Several hydrometric stations are located within the watershed. Average annual rainfall accumulation, measured approximately 15 km down-valley at the Seymour Falls Dam, is 3,300 mm per year. Precipitation intensity-duration frequency curves for station 28-B within the Jamieson Creek drainage area are included as Figure 3.3. Data presented for this station (Hall, 1989) are strictly for purposes of characterizing the area.

For the data analysis purposes, following in Chapter 5, rainfall records from the Seymour Crossing station were used. Station 28-B lies in the valley bottom, a distance of 4.5 km and an elevation drop of 500 m from the instrumentation site. The study area falls within the Very Wet Maritime (CWHvm) sub zone of the Coastal Western Hemlock biogeoclimatic zone (Acres International, 1993), which is characterized by average annual precipitation in excess of 2,000 mm.

3.2.4 Hydrologic Characteristics

The 40 m wide headscarp region of the Jamieson Slide is visibly a hydrologically complex area. Slope shape and topography would suggest that any flow upslope of the study area is not converging towards small streams to the north, but rather flowing through the soil down the planar slope. The underlying bedrock at the headscarp has slight undulations that are not entirely reflected in the overlying soil surface expression. During wet periods, groundwater is distinctly concentrated in five zones across the scarp face, some of which correspond with the depressions formed by the undulations. The image and assumption of uniform planar groundwater flow through the slope is quickly diminished during observations of groundwater seepage from the scarp during storms. There are sections of soil at the headscarp which do not saturate and remain only moist, even during prolonged storm events.

3.2.5 Mass Movement

The clear-cut area that hosts the study area has a history of stability problems. The most significant feature is the Jamieson Creek slide (Plate 3.1), a large debris slide which occurred in the winter of 1990 during an intense rainstorm. Plate 3.1 shows the original headscarp position that existed until sometime between 1995-1996, when the slide headscarp retrogressed approximately 10 m to near the standing timber. Field visits in 1994 revealed tension cracks upslope of, and paralleling the headscarp that forewarned of the resulting retrogression. Two smaller slides scarps exist (Slides 2 and 3, Plate 3.1) adjacent to the larger event (both within 60 m to the south) with the headscarps at approximately the same elevation. These small events involved a thin mass of soil that traveled a short distance, and are believed to have occurred within a few years following harvesting. A fourth smaller slide is visible on a slope with a southern aspect (Slide 4, Plate 3.1). A large debris slide on an unlogged slope opposite the study area in the Orchid drainage is visible from the study area, suggesting slides are not solely limited to logged areas. All of the slides are thin (1-2 m) debris slides on slopes with gradients between 30-45°(58-100%). The common occurrence of debris slides in the Seymour Watershed in both logged and unlogged terrain indicated that mass movement is a common and frequent geomorphic process.

3.2.6 Previous Studies

Previous studies relating to geotechnical and hydrological properties of relevance to this project includes work done by (De Vries and Chow (1978); Cheng (1987); Golding (1987); Thurber (1991); Acres International, (1993); Wilkinson (1996)).

3.3 Carnation Creek H Watershed

The Carnation Creek experimental watershed is located on the west coast of Vancouver Island, near the town of Bamfield (Figure 3.4). The watershed covers approximately 9.5 km^2 and has a number of smaller subdrainages. As opposed to the very localized Jamieson Creek Slide site, the area of interest within the Carnation Creek Watershed is an entire subdrainage simply referred to as 'H' Creek. H Creek is one of two subdrainages that were instrumented with groundwater monitoring devices as part of an experimental watershed project initiated in the early 1970's. The area was chosen for this study for its long term, well distributed piezometric and precipitation data. Clear-cut harvesting of a large portion of the H Watershed took place during 1977 to 1978, using cable yarders with metal spars and grapples. Access roads into the area were constructed 1-2 years prior to harvesting using Porclain shovels and D-8 Cats (Hartman and Scrivener, 1990).

This watershed location complements the Jamieson Creek site as they are both from the Coastal Western Hemlock Biogeoclimatic zones (CWHB), and have similar physiographic characteristics.

3.3.1 Soils

Soils are primarily coarse, well-drained colluvium derived from the local weathered bedrock. Depths of soils at piezometer locations vary from 30 cm to over 200 cm. Soil grain size distribution curves for soil matrix material sampled from a road cut and two debris slide headscarps in the Carnation Creek watershed are included in Figure 3.2. The materials sampled from the three sites are all considered a gravelly sand (SW) by the Unified Soil Classification System. Notable is the fact that the curves for the samples from the Jamieson site and Carnation samples are nearly coincident, although the two sites are geographically separated. Figure 3.2 also includes curves for material sampled from two other sites on Vancouver Island, which also fall within a narrow band of gradation.

Field notes from the time of installation of the piezometers indicate that soil thickness varies from 30 cm to 200 cm across the watershed. Soil profile descriptions indicate that soils are commonly capped with a layer of organic material averaging 20 cm thick. Textural descriptions reveal that sand constitutes over 60% of the soil matrix and coarse fragments (>2 mm diameter) constitute a large, but variable, percentage of the overall soil composition by volume. These soil characteristics typically lend to highly permeable conditions.

Subsurface flow rates for water flowing through forest soil over a bedrock surface were measured using a salt tracer technique in the Carnation Creek Watershed, and reported by Hetherington (1995). Measures of hydraulic conductivity were reported to range from 2.6×10^{-3} to 1.67×10^{-2} m/s. These values for flow along the bedrock surface are much higher than documented soil matrix permeabilities for soil grain sizes similar to those found at Carnation Creek site (Craig, 1992; Selby, 1993). The range and magnitude of reported values is believed to be a result of complex structural preferential pathway networks within the soil profile which are known to largely control the downslope transmission of water.

3.3.2 Bedrock and Slope Morphology

Slopes within the small H Watershed cover a range of gradients and shapes, and are short in length. The area was heavily glaciated leaving rounded ridgelines and a broad valley bottom. This subdrainage covers an area of approximately 12 ha, and ranges in relief from 150 to 330 m. Relief is not as great as in the Seymour Watershed, but steep slopes are common. Thin blankets of primarily coarse colluvial soils, overlie volcanic bedrock of the Bonanza Group from the Jurassic Period (Hartman and Scrivener, 1990). The bedrock has a very low permeability, but was observed to be highly jointed and fractured, which may create complex hydrologic pathways.

3.3.3 Climatic Conditions

The West Coast of Vancouver Island has a temperate climate, with annual precipitation in the Carnation Creek Watershed reported to range from 2100 to 4800 mm, with over 75% falling during late fall and the winter months (Hartman and Scrivener, 1990). The area receives very little snowfall, and that which falls rarely remains on the ground for extended periods. Lack of snowfall at this site is attributed to low elevations, proximity of the entire watershed to the ocean, and the specific latitude. Rainfall intensity duration frequency curves produced from data provided by Dr. Eugene Hetherington through the Canadian Forestry Service[1] are included as Figure 3.5.

3.3.4 Mass Movement

The H Watershed offers an appropriate environment for studying groundwater levels in relation to slope stability due to the history of slides. Two shallow debris slide events occurred within the subdrainage

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[1] Pacific Foresrty Centre, Canadaian Forrestry Service, Natural Resources Canada, Victoria, B.C.

during a rain-on-snow winter storm on January 23, 1982. Both slides initiated downslope of roads and were shallow failures of 1.0-1.5 m thickness over relatively planar bedrock. Concentrated areas of seepage were noted at zones along the headscarps of both slides. Initiation of the 'Eugene East' slide (Plate 3.2) may have been facilitated by two harvesting-related factors (Hetherington, 1998). Yarding of logs from the road upslope created two shallow trenches that lead to the slide area. These trenches may have acted as conduits that could transmit surface water and concentrate it near the headscarp area. Also speculated is that soil disturbance caused by logging in the slide area may have locally collapsed the macropore network and shifted flow into slower draining matrix flow, resulting in increased water table depths. The introduction of excess water, along with the already high storm induced pore water pressures, was possibly enough to trigger the slide.

Alteration of the natural groundwater flow regime by an upslope road cut was believed to be a major factor in the initiation of the 'Bob West' slide (Plate 3.3). It is speculated that excess water caught by the ditchline was transmitted to the headscarp region through permeable weathered bedrock layers (Wilford, 1982). Alternatively, or in combination with the influence of the ditchline, is that surface water running along the road surface may have diverted over the road and concentrated surface runoff into the soils in the area of the slide (Hetherington, 1998). Surface erosion at the road edge and along the fill slope noted following the slide endorses this hypothesis. A discussion of the storm event that triggered both of these slides is found in Chapter 7.5.

3.3.5 Previous Studies

By 1990, over 150 publications had arisen from data and experience collected from Carnation Creek. The reader is referenced to Hartman and Scrivener (1990) for a general overview of the experiment, a review of findings from the multiyear project, and a list of publications.

3.4 Summary of Sites

Each of the two chosen field sites is intended to provide answers to very different objectives. Although the two sites are separated geographically by a few hundred kilometers, the similarity of physical attributes and climatic conditions serves to maximize the transferability of findings and interpretation from one site to the other.

Key physical attributes relevant to the study of groundwater for each of the two study areas have been detailed within this chapter. The following chapters outline the procedures and outcomes of studies in each of the two sites. Chapters 4 and 5 respectively detail the instrumentation and analysis of results for the Jamieson Creek site. Chapters 6, 7, and 8 deal solely with the data collection, interpretation, and extension of findings for the Carnation Creek site.

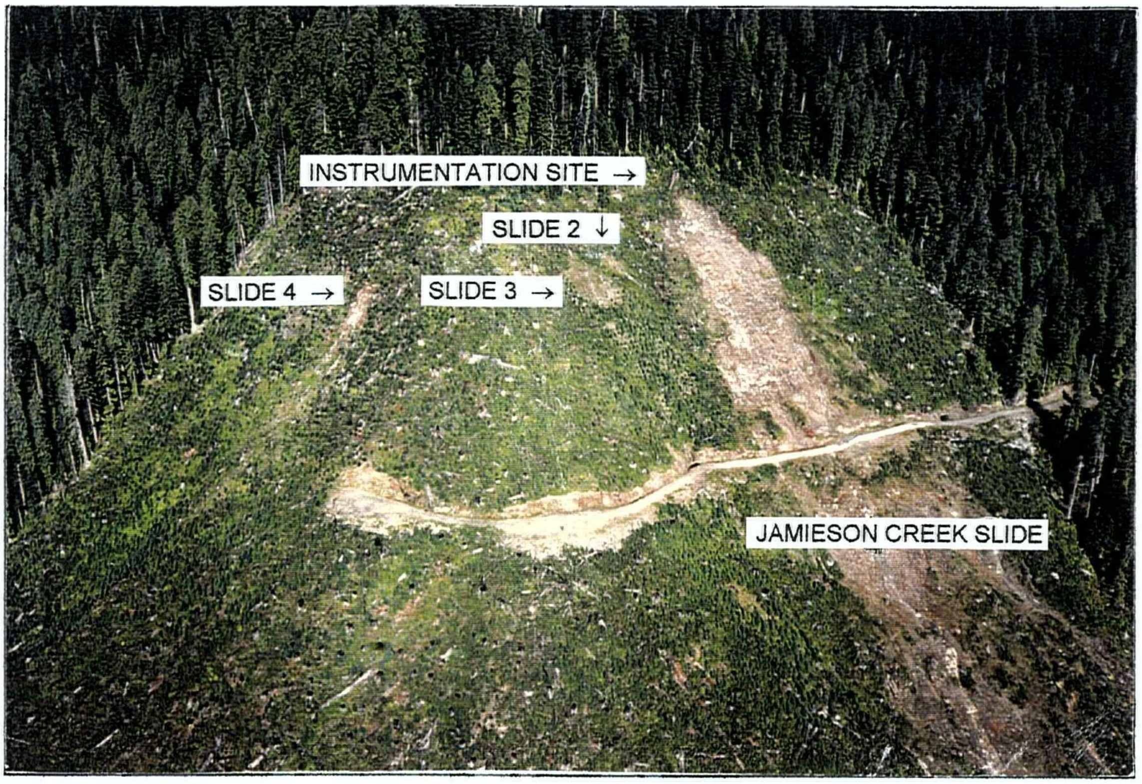


Plate 3.1 Jamieson Creek Landslide study area. Visible are the Jamieson Creek Slide and three small debris slides (Slides 2, 3, and 4) within the same clear-cut area. The instrumentation site is between the headscarp of the main slide and the standing timber.

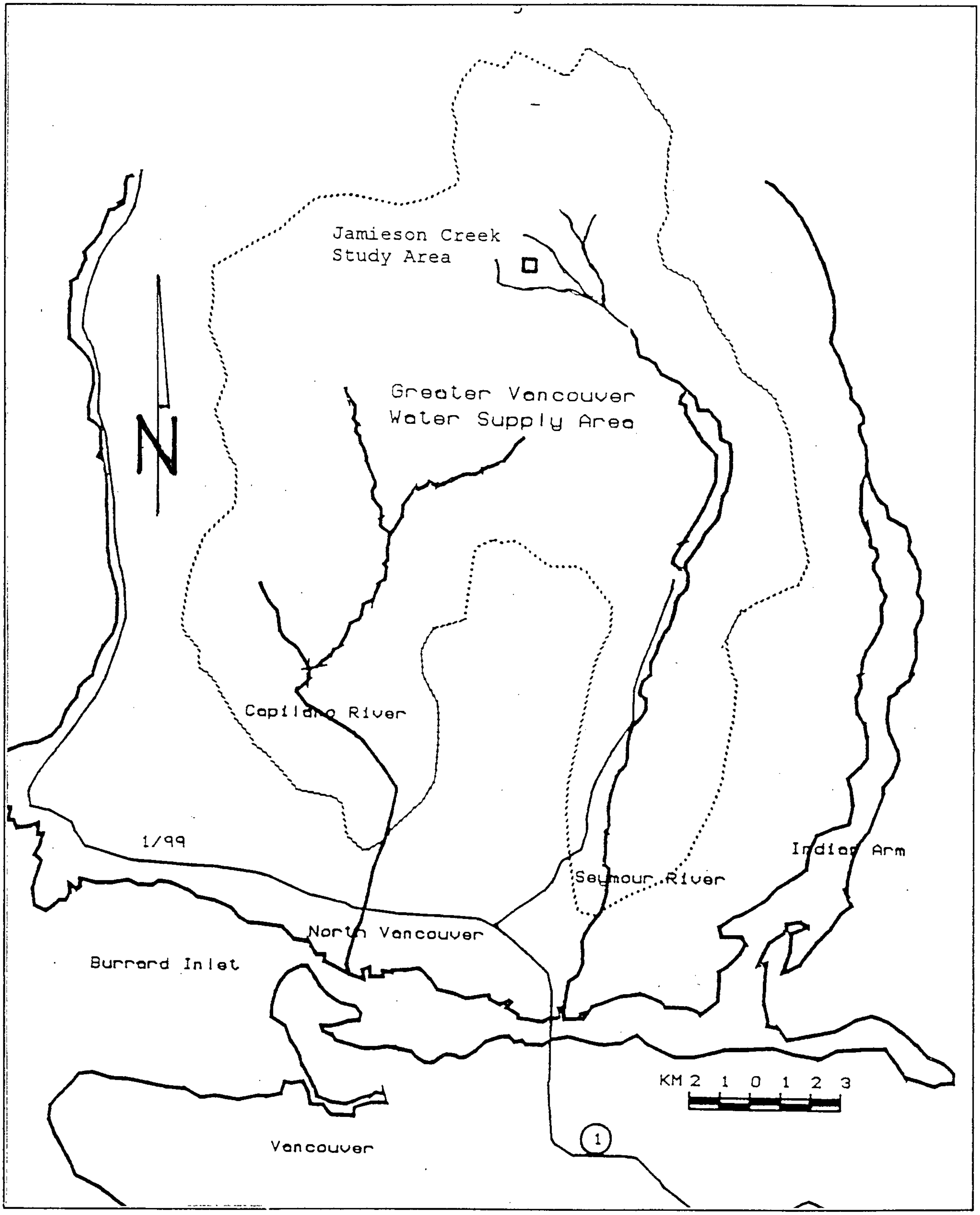


Figure 3.1 Location map – Jamieson Creek Slide study site, Seymour Watershed, Vancouver, B.C. (modified from Acres International, 1993)

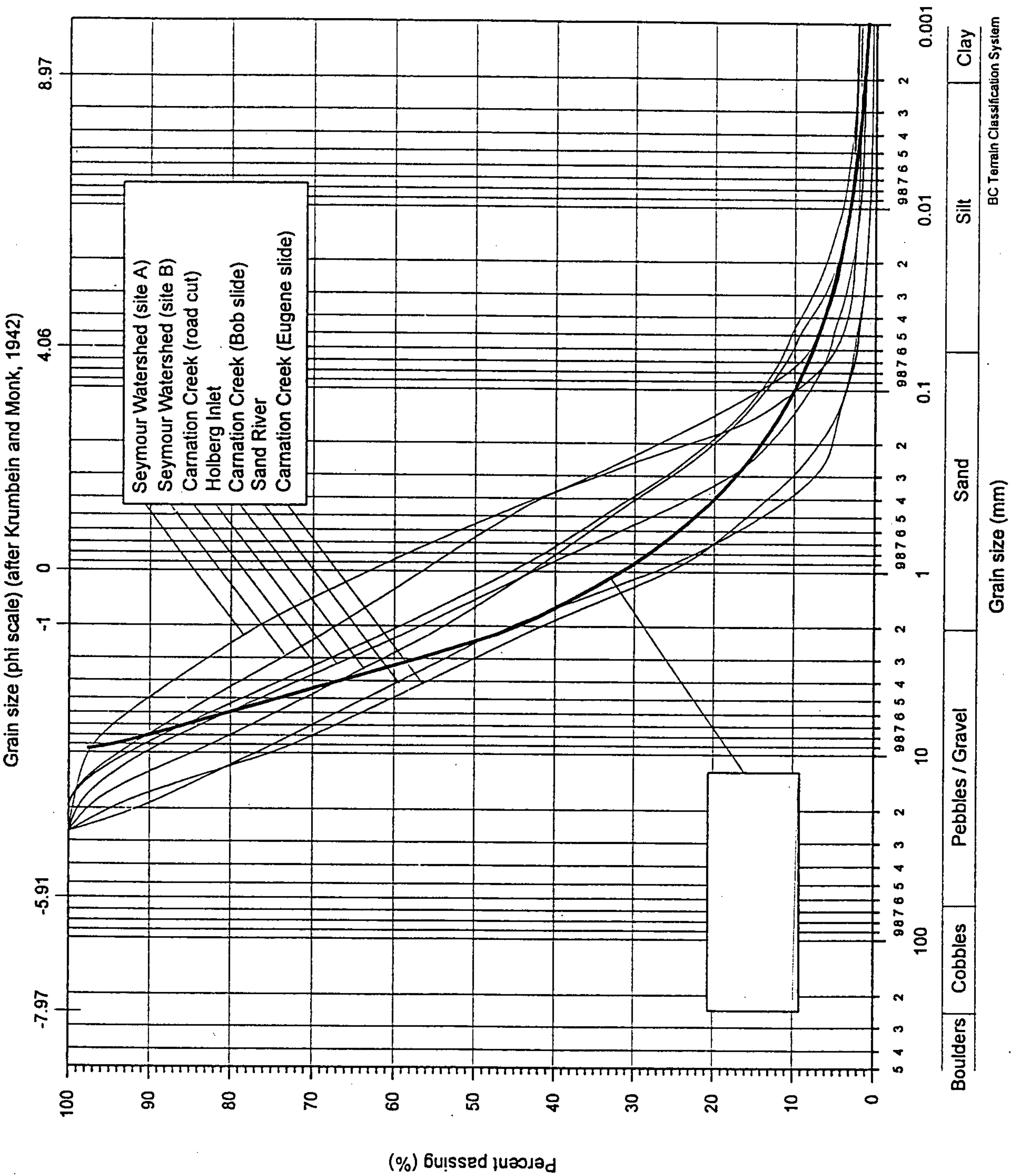


Figure 3.2 Grain size distribution curves for Jamieson Creek and Carnation Creek study sites (from Wilkinson, 1996)

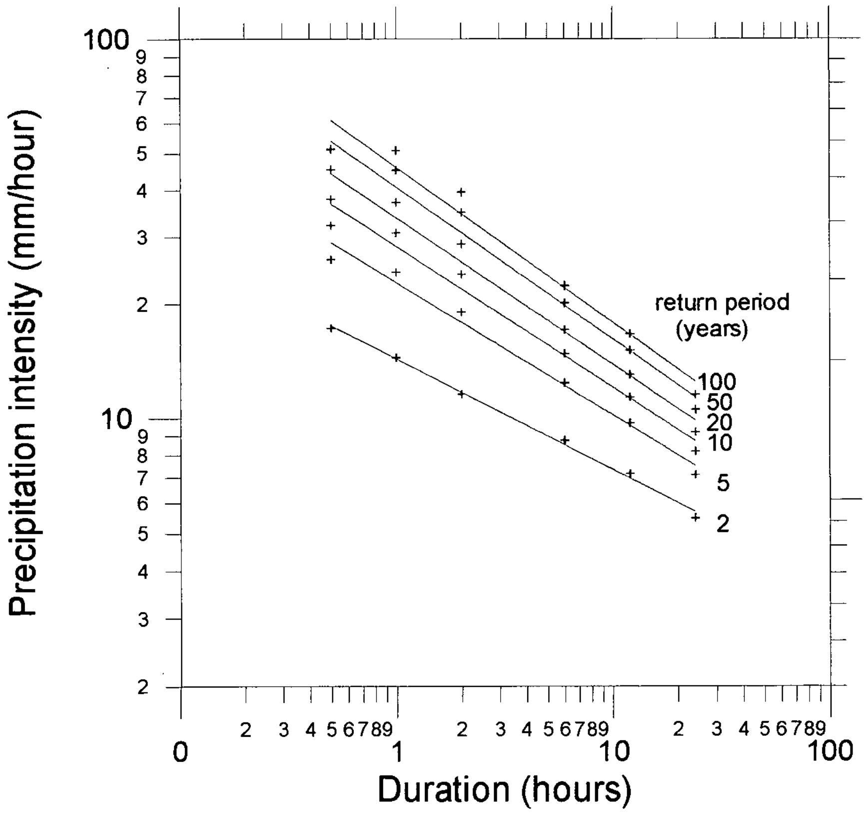
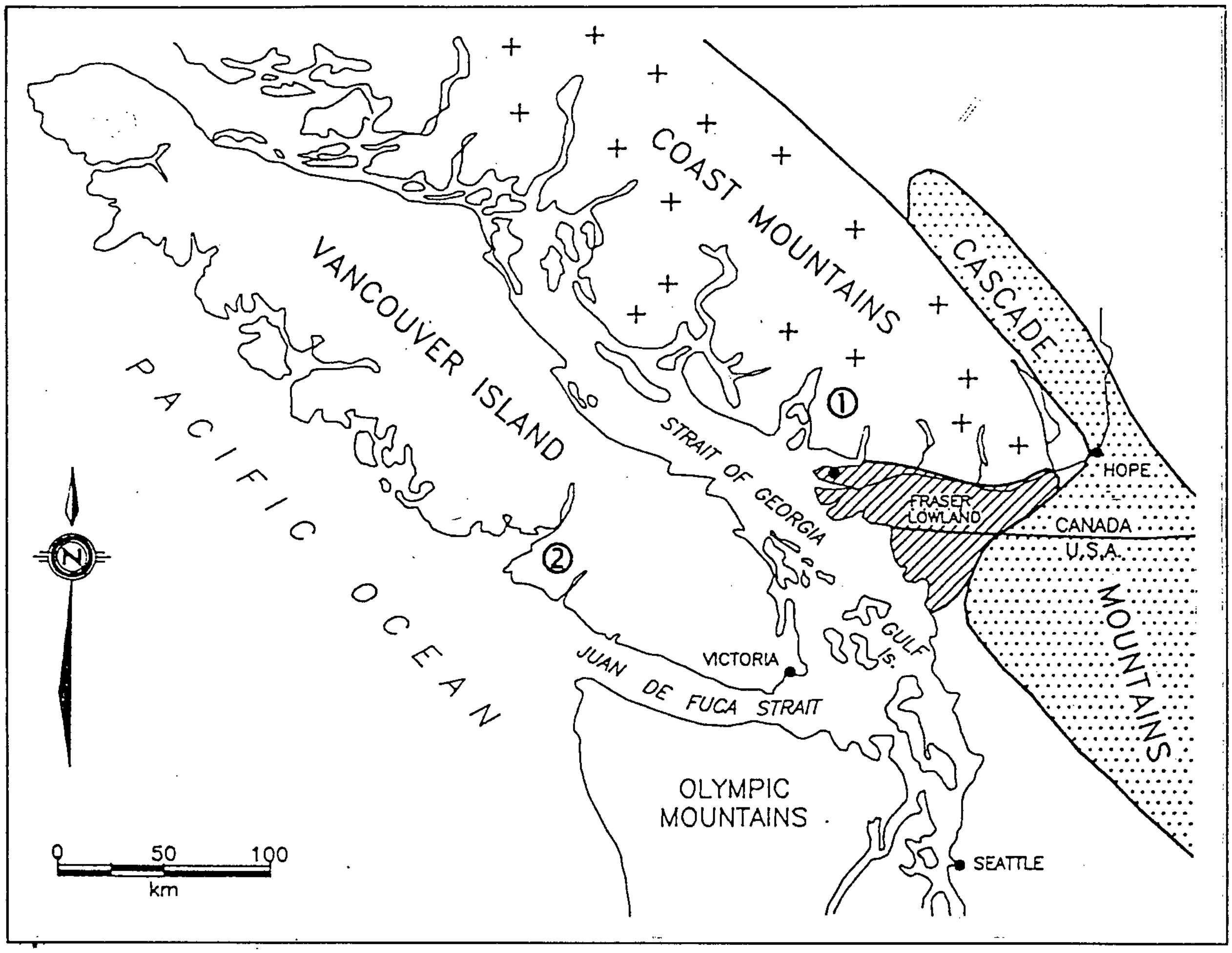


Figure 3.3 Intensity-duration frequency curves for Jamieson Creek (Station 28-B)



1 – Jamieson Creek Study Site
2 – Carnation Creek Study Site

Figure 3.4 Location map – Carnation Creek Experimental Watershed, Vancouver Island, B.C. (modified from Wilkinson, 1996)

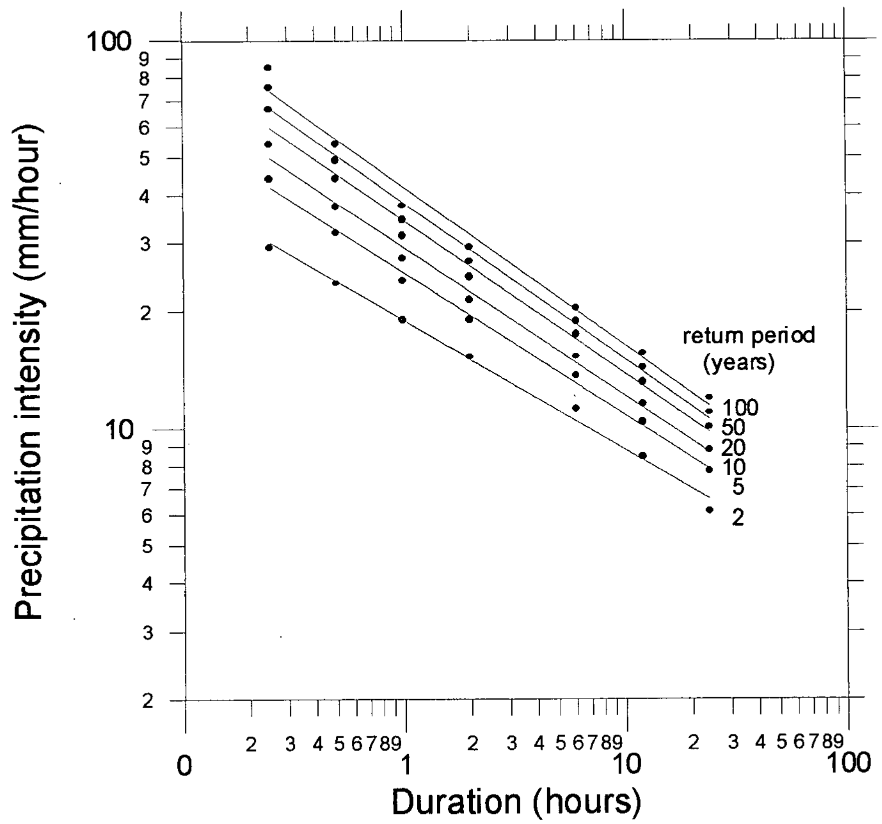


Figure 3.5 Intensity-duration frequency curves for Carnation Creek H Watershed Stn. E.

Plate 3.2 'Eugene East' Slide, H Watershed, Carnation Creek (Hetherington, 1984).

Plate 3.3 'Bob West' Slide, H Watershed, Carnation Creek (Hetherington, 1984).

4.0 JAMIESON CREEK INSTRUMENTATION SITE

4.1 General

Characterization of groundwater response to rainfall is essential in identifying the precipitation events and hillslope positions that are susceptible to debris slide initiation. Current limitations in the understanding of groundwater response include the paucity of data from studies on steep forest slopes with thin soils, and the limited means to adequately characterize such a complex relation. Inherent difficulties in the characterization of groundwater are centered on adequately distributing monitoring devices. The chosen type of instrumentation, field site, and the layout of instrumentation can also have an impact on the quality of data collected.

The Jamieson Slide instrumentation site was selected to provide firsthand experience in development and installation of instrumentation, along with collection and interpretation of data. This chapter introduces the site and the instrumentation scheme utilized. The complete process in design, calibration, and implementation of the instrumentation is outlined. Alternatives to the instrumentation scheme are also presented and discussed.

4.2 Review of Objectives

The Jamieson Slide was intended to serve as an experimental site for which a groundwater monitoring and data collection system could be designed, installed and evaluated. One of the objectives in the design of the system was that it could serve as a model for further applications in the forests of British Columbia. With that in mind, readily available equipment was specified for the majority of the installation. Adding to the transferability of the design, the chosen field site has slope, soil, and climatic conditions representative of vast areas of Coastal British Columbia.

Specific monitoring objectives were to characterize the very localized hydrologic regime at the headscarp of the Jamieson Slide. Groundwater monitoring devices were strategically positioned and recorded pore pressures for one year to assess the soil-water response to storm events. Using the recorded data, the storm relation to changes in pore pressure, the significance of the maximum pressures, and the range of responses could be assessed. The data should also provide some indication of the factors that contributed to the initiation of the slide. Experience gained from the Jamieson site was then applied in the interpretation of the Carnation Creek data reported in Chapter 5.

4.3 Common Groundwater Instrumentation

Instrumentation schemes used in the characterization of positive pore pressure regimes in forest soils involve the installation of a number of piezometers. The most common design of piezometer is an open standpipe or crest tube style, where water is free to flow into a vertical pipe through a filter screen at some depth. The top of this vertical pipe typically protrudes from the ground surface from where measurements can be made. Pore pressure is recorded simply as the height that the water reaches in the pipe above the screen. These piezometers can be fitted with a pressure transducer to accommodate continuous recording. Installation often entails excavation of a hole larger than the diameter of the piezometer tube. The bottom of the excavation is then filled with sand of known properties, following which, the tube is held in the center of the excavation and sand is back-filled to some depth around the tip of the piezometer. The purpose of the sand is to allow free hydraulic passage of groundwater into the tip of the unit, and to act as a filter that prevents fines from entering the piezometer tube with time. With the desired depth of sand covering the tip of the unit, a hydraulic barrier (commonly bentonite) is sometimes placed over top of the sand to isolate the zone of measurement. The remainder of the excavation is then back-filled with native material.

The standpipe piezometer is widely used, reliable, and inexpensive. Limitations include potential clogging of the filter and screen over time, and the time lag in response with the rise and fall of water level. The installation process, which involves the introduction of foreign materials, creates an unnatural hydrologic condition that effectively acts as a drainage sink at low levels of saturation. The impact of this modified zone is greatest where soils are highly heterogeneous and anisotropic, or controlled by macropores. Changes in groundwater level are reflected by changes in water level within the standpipe piezometers. The time required for water within the standpipe to equalize to the groundwater level is known as the hydrodynamic time lag. This problem is common to standpipes (Hanna, 1985), but most pronounced in fine-grained soils and increases with the diameter of the piezometer tube.

Strain gauge type piezometers have long been used in large construction projects as they do not require a protruding tube at the ground surface, have short time lags, and are readily set up for accurate automated recording. Short time lags are attributed to the small size of the fluid cavity acting on the strain gauge. These piezometers must be placed in excavations and carefully back-filled. Cost and the complexity of the systems has been a major restrictive factor in the implementation of these units.

Several commercially available piezometers were evaluated for the project. Most currently available designs are not robust enough to withstand a forceful installation in which an intimate connection is created between potentially rocky soil and the filter element of the unit. Standard standpipe-type piezometers were avoided due to the excessive ground disturbance and creation of a hydrologic anomaly resulting from the installation procedure, and limited accuracy. Most other designs had the same inherent shortcomings, in addition to the lack of serviceability of any installed pressure transducers. Costs of the more accurate strain gauge style piezometers were found to be quite high. With these limitations and high costs in mind, the option of designing and manufacturing a piezometer suitable for Coastal forest soils was investigated.

4.4 Piezometer Development

A number of criteria for the characteristics of the piezometer were set out in the planning stages. The main criteria were as follows:

- The ability to be continuously recorded by a conventional data logger
- Durable enough to be installed into a hole of equivalent diameter through variable, rocky soils, and remain reliable throughout the winter season.
- Having an accuracy of approximately 1 cm of water, and a rapid response time
- Of a reasonable cost
- A minimum of servicing needs

Several options revolving around the concept of creating a serviceable piezometer that could be driven into dense soil were investigated. The final design, shown in Plate 4.1 and Figure 4.1, was deemed to be a viable and simple piezometric tip which can be driven into soils with standard 3.3 cm diameter steel water pipe, and allows for a pressure transducer and to be installed after the desired depth is reached. The design principle is that pore pressure acting on the tip filter (Figure 4.1) will be transmitted through a fluid and act upon a pressure transducer. Glycerin was used to saturate the filter and fill the inner cavities of the tip. Glycerin is miscible with water and was chosen for its high air entry tension characteristics to prevent loss of saturation. To reduce the potential for error, the cavities of the piezometers were minimized. The design incorporates a double sealing, modified Swagelock fitting system. One half of the fitting is permanently attached to the piezometric head, while the other half is attached to the electronics. Once the tip has been driven to the desired depth, the top half of the fitting, including the electronics, can be lowered into place creating a connection for water pressure to act upon the transducer. This connection and tip design has the added benefit that the unit can be modified to sample groundwater.

Sensym 19CO15AM pressure transducers were selected for use with the piezometers. These units have an appropriate range and accuracy for the pressures being measured at the site, and are of a reasonable cost. Signal amplifiers for the transducers were designed and assembled at U.B.C.

Filter elements are highly porous polyethylene plastic that has a much higher hydraulic conductivity than the soils being monitored. Prior to installation, the filters were saturated with glycerin to maintain hydraulic continuity with the glycerin filled piezometer cavity and the soil water. The potential of the filter partially draining glycerin and displacing with air was addressed. Diffused air can affect the accuracy of recordings, as shown by Peck (1960), where groundwater pressure changes can compress diffused gas within the measuring apparatus, leading to inaccurate recordings. In the case of this application, the pressures being measured are so low that any trapped air within the filter should transmit pressure without the problems of gas volume change under pressure. Calibration tests described in section 4.6 were designed to evaluate the sensitivity of the piezometer tips to a range of operating conditions. The nature of the tip and filter design is such that they are capable of transmitting negative pore-water pressures to the transducer when the soils in contact with the filter reach an unsaturated state. The piezometers are not however calibrated to record in the negative range.

The resulting design is similar to a Cambridge Type piezometer (Dunnicliff, 1988) with a transducer, and was partially modeled after a U.B.C. developed water sampler for a Cone Penetration Test (CPT) (Campanella, 1982). In an effort to develop a piezometer that does not require excavation and back-filling of soils, the casing of the unit was designed to be driven into a hole of equivalent diameter, while the tip is driven through relatively undisturbed soils until it reaches the bedrock surface. The entire unit is manufactured from stainless steel to avoid corrosion and maintain integrity during the installation process. Unique design features include the ability for the transducer assembly to be installed once the tip of the unit

(Figure 4.1 and Plate 4.1) has been driven into place, thus avoiding potential damage to the transducer. The transducer assembly can be removed from the tip if there is a need for servicing or re-calibration. Key features also include a low air entry porous filter and a low volume internal cavity to minimize the time lag in response and potential for air accumulation error.

4.5 Tensiometers

The most common and cost-effective method of monitoring negative pore pressure is with the use of tensiometers. Tensiometers have been commonplace in geotechnical field studies and agriculture for several decades and are simple in design. In applications where several tensiometers are installed, the directions of moisture fluxes in the unsaturated zone can be monitored. Designs of tensiometers vary in form according to the requirements of the application. The most common type of tensiometer is the vacuum gauge style (Figure 4.2) due to its simplicity and low cost, but it lacks in response time and accuracy. A typical unit is comprised of a one bar air entry porous ceramic cup attached to a water-filled plastic tube with an airtight stopper and vacuum gauge or transducer at the ground surface. Once installed, the ceramic cup forms a hydraulic connection with soil water. When the soil becomes unsaturated, tension will act upon the saturated ceramic cup and attempt to pull water out of it. The matric suction is transferred through the column of water and registers in the recording gauge. The effective range of measurement for standard tensiometers is from zero to approximately -90 kPa, at which point cavitation, or vaporizing of pure liquid water, will begin to occur.

For this project, standard vacuum style tensiometers (Figure 4.2) supplied by Soil Moisture Equipment Corporation were chosen to characterize the negative pore pressure range of the soils. The Jet Fill 2725 series were specified for the field site. Lengths and installation positions are detailed in Section 4.7 below. Lengths of units reflected the desired depths of installation at the sites (see Section 4.7.2). The units were outfitted with the same model of pressure transducers that the piezometers utilize to improve the accuracy, response time, and hysteresis of recordings, as well as gaining the ability to record continuously.

Tensiometers require periodic maintenance in the form of purging. Over time, air diffuses through the porous cup and enters the tube, while water evaporates from the cup and is lost from the unit. This effect is most prevalent at high suctions. Air is removed from the system through purging, either by refilling the tube with water and applying a vacuum pump to the top of the tube, or by using the Jet Fill reservoir (Figure 4.2). During purging, air is pulled out of the system, and the tube is manually topped off with de-aired water.

4.6 Calibrations

As with any newly-developed instrumentation, a wide range of calibration and response tests were conducted in the laboratory to ensure field performance. Tests were run in the lab on all of the assembled piezometers and tensiometers and on the transducer assemblies alone. The tests were designed to meet criteria suggested by Dunnicliff (1996). A design feature of the instrumentation scheme that lends faith to the accuracy of the readings is the fact that all of the transducers used on the piezometers and tensiometers are the same model and have been calibrated identically. Tests included:

- air pressure calibration of transducers;
- tank tests, where assembled units were submerged in known depths of water and recorded;
- temperature bath testing from 0°C to 20°C;
- response rate tests, where the time required to stabilize a reading to sudden changes in water pressure is tested;

- assembled tensiometers were left out in room temperature to test the range of the units and the integrity of the porous cups through evaporation tests;
- evaporation tests on the assembled piezometer tips to determine potential loss of glycerin.

Tank testing showed that the piezometers record the depth of water accurately and register changes rapidly. The recorded pressures were insensitive to repeated wetting and drying, where the unit would be pulled out of the tank to dry, and rapidly submerged. Resolution of all of the transducer assemblies used is the equivalent of 0.7 cm of water, and accuracy of recordings was found to be ± 1.4 cm calibrated over the range of –843 cm to +422 cm H_2O.

Some transducer units were affected by temperature changes during temperature bath testing (Appendix I). Average change in pressure recorded by the transducer assemblies is the equivalent of 3.5 cm of water over a range of 0°C to 20°C. The most sensitive transducer assembly is that used at T2-60 (see following section), displaying a change in pressure equivalent to 5.6 cm of water. Data have not been corrected for temperature variations. Selected calibration curves are included in Appendix I.

4.7 Installation Design and Procedure

The 13 groundwater devices (8 tensiometers, 5 piezometers) were installed a short distance upslope of obvious hydrologically active zones and natural bedrock depressions at the headscarp (Figure 4.3). Initially, four zones of seepage at the headscarp were chosen, and a location lying between 3 and 6 meters directly upslope from the seepage zone was cleared. Units were placed this distance back from the headscarp to minimize the potential hydrological boundary effects, and to leave a safety buffer to avoid damage to equipment due to slumping and erosion at the scarp. Once a location was cleared, several measurements of soil depth were made by driving a 1.3 cm diameter steel rod to refusal. Holes that did not encounter rocks within the soil profile were flagged as potential installation locations. Each location was to contain a pair of tensiometers (of different lengths) and one piezometer. Units at each location were placed within a 1 m radius in order to minimize the effects of variability of soil and moisture regime conditions on data interpretation. An exception to this layout is Location 3, where a clean hole for the longer 120 cm tensiometer could not be augered due to large rocks or roots in the soil profile. The 120 cm unit had to be installed 2 m away from the paired tensiometer. A site plan is shown in Figure 4.3, and instrumentation details are outlined in the following table. The name of each unit carries information about the monitoring device, for example P1-137, where P is the type of unit (piezometer, vs. T for tensiometer), 1 represents the location number (Figure 4.3), and 137 represents the length of the unit, or conversely, the depth of the filter or ceramic cup below the soil surface in cm. Table 4.1 indicates the height of the piezometer tip or tensiometer cup above the bedrock profile. This measure is considered when comparing positive pore pressures to determine if the pressures registered by more than one unit at the same location are hydrostatic.

Table 4.1 Instrumentation details

Unit	Length of unit (cm)	Height of tip or cup above bedrock (cm)	Date installed	Location
Piezometers				
P1-137	137	3	07/18/97	Location 1
P2-142	142	3	07/27/97	Location 2
P3-197	197	3	07/16/97	Location 3
P3-130	130	3	12/02/97	Location 3
P4-203	203	3	07/27/97	Location 4
Tensiometers				
T1-45	45	92	07/18/97	Location 1
T1-90	90	47	07/07/97	Location 1
T2-60	60	82	07/18/97	Location 2
T2-120	120	22	07/11/97	Location 2
T3-60	60	137	07/18/97	Location 3
T3-120	120	77	08/21/97	Location 3
T4-60	60	143	07/18/97	Location 4
T4-120	120	83	07/18/97	Location 4

4.7.1 Piezometer Installation

The primary objective in installing a piezometer was to have the filter element (Figure 4.1) as close to the bedrock surface as possible. To achieve the desired depth, a 1.3 cm rod was driven to refusal and withdrawn, followed by augering a 2.2 cm hole to a depth 5 cm above the refusal depth. With the pilot hole in place, a 3.3 cm diameter hole (matching the diameter of the piezometer tube) was then augered to a depth 6 cm less than the 2.2 cm hole. The three-step process of creating a hole allowed for an excavated shape that closely resembles the piezometer unit, resulting in minimal ground disturbance during installation. Once the hole was prepared, a piezometer was pushed and hammered down the hole until the tip reached refusal at the bedrock surface. The last 5 cm of the hole were not augered to ensure intimate contact between the soil and the filter element through driving of the tip. During installation, the soils had a high moisture content, so raveling soils into the hole was not a major concern.

Prior to installation of the piezometers, the tips of the units (Figure 4.1, Plate 4.1) were prepared. The filter elements were left to saturate in a tank of glycerin for several days prior to installation, while the cavities of the head were filled immediately prior to installation. To fill the cavity, glycerin was flushed through the assembled tip, until it readily beaded out of the filter. The double sealing nature of the head allows for the tip to remain saturated during installation and while it remains in-service. Although leakage of glycerin from the tip is unlikely, an apparatus to re-saturate the tip from the ground surface was developed and tested. The device consists of a top half of a sealing Swagelock fitting, and a column of glycerin, which could be lowered down the piezometer tube and pressurized to flush out the tip and filter.

Once the piezometer tip and steel pipe were driven into an augered hole in the field to the desired depth, the transducer unit could be installed. Attached to the transducer is one half of a sealing Swagelock fitting, which is mated to the opposite half of the fitting already connected to the piezometer tip (Figure 4.1 and

Plate 4.1). The transducer is simply lowered down the steel water pipe and forced to make a connection between the two halves of Swagelock fitting by applying pressure with a hollow aluminum tube that fits inside of the steel pipe. Once the connection is made, a cap is placed on the top of the piezometer tube, which keeps pressure on the sealing fitting transferred through the rigid aluminum tube.

4.7.2 Tensiometer Installation

Tensiometers were installed in pairs to record the vertical distribution of pore water pressures, and complement the pressures recorded by a piezometer at four specific sites. To achieve the recording objectives, tensiometers were inserted into the soil very close to one another, but to separate depths. Once the tensiometers and piezometer were installed at a Location, there would be three points of measurement distributed vertically in the soil profile (Figure 4.3). Piezometer tips would be placed to the bedrock surface and the cup of the longer tensiometer a minimum of 30 cm above the piezometer tip. The shorter tensiometer cup would be positioned either 45 cm or 60 cm above the tip of the longer unit. All three of the units would be installed within as tight of a radius as possible to minimize the effects of spatial soil variability.

Prior to augering an installation hole, the root mat was partially removed from the ground surface. Pilot holes, the exact diameter (2.2 cm) and depth of the tensiometers, were augered. Tensiometers were prepared with saturated tips and algae inhibiting fluid as per the instructions supplied by the manufacturer. Prepared tensiometers were pushed directly down the holes until seated in the bottom. Holes in which the ceramic tip experienced excessive friction due to rocks were discarded. Once the unit was at the desired depth, the transducer unit was threaded into the gauge port on the unit, the fluid was topped up, and a vacuum was applied to the top of the tensiometer tube using a hand pump to draw out any air trapped within the tube. Once the tensiometer and transducer assembly was installed, a protective and insulative cover (Plate 4.2) was placed over top.

Upon assembly and preparation of the tensiometer units, the transducer reads a value offset from the atmospheric pressure, equivalent to the length of column of water between the center of the porous cup and the diaphragm of the transducer. Hence, the pressure measured is given as:

$$Tw = Tp - h*\rho_{H2O} \text{ (see Figure 4.2)} \quad (4.1)$$

Where Tw is the pressure at the porous cup, Tp is the pressure at the transducer port, h is the length between the two points, and ρ_{H2O} is the density of water. Data interpretation takes this offset in pressure into account.

4.7.3 Installation Discussion

A major concern with excessive probing for appropriate locations for installation of the groundwater devices was the potential for alteration of the natural hydrological regime. Up to six 1.3 cm probing holes were driven at each Location to measure the depth to bedrock. These small diameter holes are not anticipated to remain open and should have little effect on the groundwater flow. Of concern are the series of larger diameter abandoned augered tensiometer holes due to rocks or other factors. If a hole was abandoned, efforts would be made to backfill the hole, and the next hole would be placed upslope to avoid the newly created hydrologic anomaly.

With the installation any groundwater monitoring devices, there is an inevitable disturbance of the soil. Objectives of this field installation were to minimize these disturbances. By augering holes of a dimension matching the groundwater instruments, the potential for soil compaction was minimized and the need for back-filling around the instruments was eliminated.

4.8 Data Acquisition System

A Lakewood Systems Ltd. UL16 datalogger with 64 K of memory and 16 recording channels was chosen to record the groundwater sensors at the instrumented Jamieson site. The system is operated by using Lakewood System's LS-4 software ver. 4.39. The software allowed the attributes of the datalogging, such as recording interval and recording precision, to be modified remotely.

The system has can be set to record at regular intervals, or set to an exception setting mode in which it has the capability of skipping readings if they do not meet desired criteria. For example, the system can be set to only record values above, or below a certain reading, or to record a value if the analog value exceeds a set zone, after which, it repositions the zone. This feature keeps the memory from filling with stagnant values.

4.9 Communications

With only seasonal access to the Jamieson Creek site available, a number of systems for data transfer from the site were evaluated. Some of the key criteria utilized in choosing a system were universal applicability, cost effectiveness, and reliability. After testing several forms of telemetry configurations and techniques, a conventional Very High Frequency (VHF) radio telemetry system was chosen. The site lies approximately 20 km from city limits, yet connecting to existing cellular and UHF radio systems was attempted with little success. The limiting factors turned out to be the confining valley walls of the steep terrain and the pronounced change in direction of the otherwise linear Seymour Valley. A cellular based system would have been preferred based upon simplicity of operation and regulations, but the signal strength from the site was found to be too weak. VHF systems are simple to operate, have a low set up cost, and have a long history of use. VHF relies heavily on line of sight transmissions, but has ability to 'bend' over terrain.

Two handheld Standard HX340 VHF radios connected to Yagi antennas were used to establish communications. Data transfer was made possible by connecting Kantronics KWM1200 radio modems to each of the radios. Communications are powered by a Sunlyte 12-500x 100 amp-hour, 12 volt rechargeable battery, which is continually charged by 70 watt Siemens SP70 photovoltaic solar panel (Plate 4.3). The data logger and groundwater monitoring sensors are powered by a separate 12 volt, 3 amp-hour battery. A schematic of the data acquisition and communications system is shown in Figure 4.4.

The Lakewood Systems data acquisition system is designed to work with a cellular modem system but can be modified to work with radio telemetry. Retrofitting the system with radio communications components resulted in the speed of data transmission dropping to a baud rate of 1200 bps. Remote downloads at this rate became time consuming. Weak transmission signals, which would on occasion be lost and have to reconnected, also hindered the efficiency of the downloading process. Future applications for similar site installations should be dictated by the most effective, available, and cost efficient mode of communication. To simplify the commissioning of a data telemetry system, a data logger designed to be compatible with the chosen mode of communications could be specified.

4.10 Field Precautions

All equipment left at the site was environmentally protected to ensure long-term performance through heavy rainfall, deep snowpacks and freezing temperatures, possible lightning strikes, and damage by wildlife. The datalogger, radio and modem were housed inside a sealed Pelican 1400 protective case with a bag of silica gel to remove any moisture. The case and rechargeable battery were placed within an insulated and weatherproofed plywood box. The solar panel and radio antenna were mounted on an aluminum pole, which was securely attached to a large stump. Stainless steel guy wires were attached from the pole to surrounding trees to keep the pole stable in the wind. Snow precautions included mounting the solar panel at a 15° angle to prevent snow accumulation. Exposed tops of tensiometers and piezometers were covered with insulated plywood covers (Plate 4.2) to minimize the effects of temperature fluctuations on the electronics, and to protect the units from wildlife. A 1.5 m steel rod was driven into the ground 3 m from the datalogger and grounded to act as lightening protection.

4.11 Instrumentation Costs

A breakdown of equipment costs (CDN$, 1997) for the Jamieson study site is given in the following table.

Table 4.2 Jamieson site instrumentation costs – purchased equipment

Piezometers*			
qty.	item	cost per unit	total
6	transducers – Sensym 15 psia	$120	$720
6	amplifier components and electronics	$40	$240
100 m	cable (4 conductor)	$0.40/m	$40
6	Swagelock fittings	$100	$600
Tensiometers			
8	Soil Moisture tensiometers Model 2725	$100	$800
8	transducers – Sensym 15 psia	$120	$960
8	amplifier components and electronics	$40	$320
100 m	cable (4 conductor)	$0.40/m	$40
Barometric Sensor			
1	transducers – Sensym 15 psia	$120	$120
1	amplifier components and electronics	$40	$40
Data Logger			
1	Lakewood UL16oem with software, cables, memory expansion,	$1200	$1200
Data Radio			
2	TNC KPC3 data modems	$225	$450
2	VHF antennas with cables	$125	$250
2	VHF portable radios	$400	$800
	miscellaneous installation hardware	$100	$300
Power Source			
1	sealed lead acid battery (100Ah)	$300	$300
1	Solar Panel (70 watt)	$600	$600
1	charging circuitry	$100	$100
Miscellaneous			
1	auger (7/8")	$40	$40
1	auger (1 ¼")	$50	$50
1	mast for antenna & misc. hardware	$300	$300
		Total	**$8270**

*Omitted are cost estimates for raw materials and machining costs for the stainless steel piezometer tip sections.

The cost breakdown is complicated by the fact that the machining of piezometers and assembly of electronics was performed 'in-house' at UBC. Costs for labour and some raw materials have not been factored into the total estimate of $8270. In addition to the performance benefits of the piezometer design, opting to manufacture rather than purchase piezometers had considerable savings.

4.12 Summary of Field Instrumentation Design

The original instrumentation site design was implemented and operated continuously with very few problems from October 1997 to August 1998. Layout of the instrumentation was highly site-specific in this case, and the implications of the chosen design are discussed in Chapter 5. The newly developed piezometers for this study met the originally set design criteria and were considered to be a success. The units have a resolution of 0.7 cm and an accuracy of ±1.4 cm calibrated over a range of −843 cm to +422 cm H_2O. Tip design relies on saturation of the filter and internal cavities with low air-entry glycerin to transmit pressure from the soil pores to the transducer. Even if partial loss of saturation occurs over time, the accuracy of recorded pressures should not be significantly affected. Any air trapped in place of lost glycerin is expected to transmit the low range of potential positive pressures, limited to less than 200 cm by the soil thickness, without gas volume change presenting a significant error. Data recorded by the piezometers were complemented by negative and positive pore pressures recorded by a number of installed tensiometers. Pore pressure data from the site were remotely downloaded using radio telemetry at regular intervals throughout the monitoring period. There is potential for application of this piezometer design, as well as for the entire instrumentation network, or a modification of it, to similar future groundwater studies. Data collected from the instrumented site are presented and discussed in the following chapter.

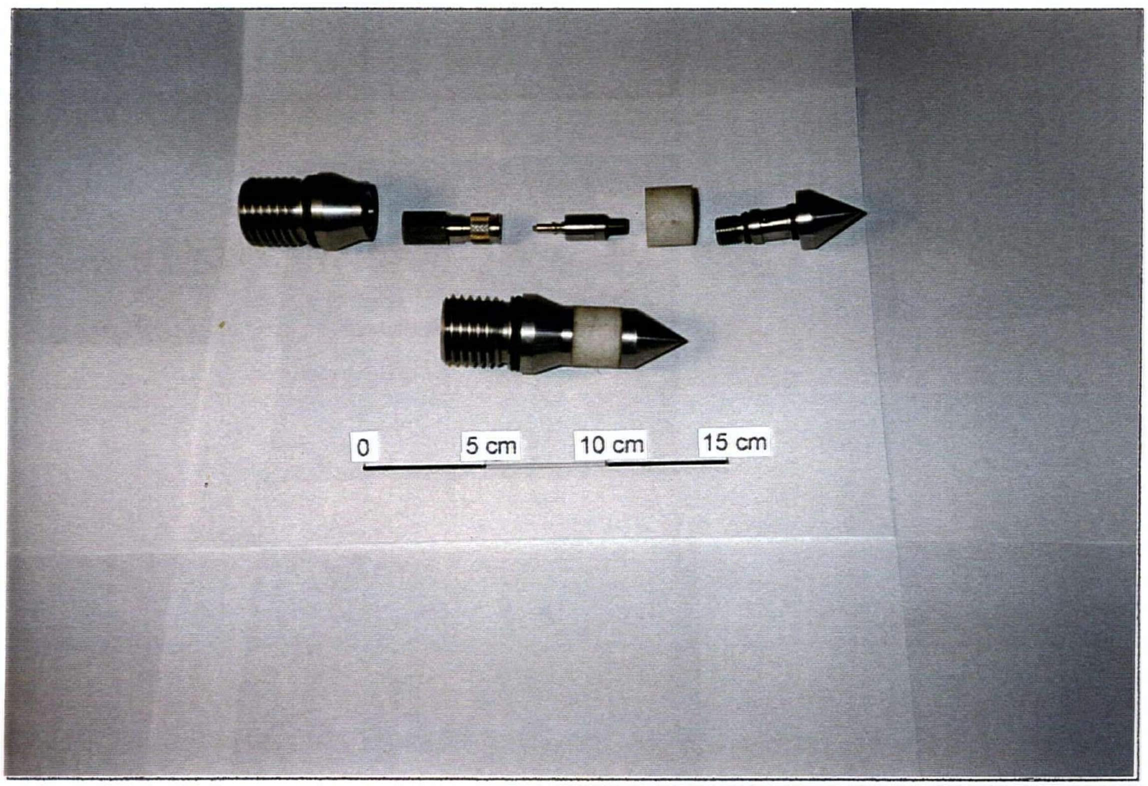


Plate 4.1 U.B.C. designed and manufactured piezometer tip assembly.

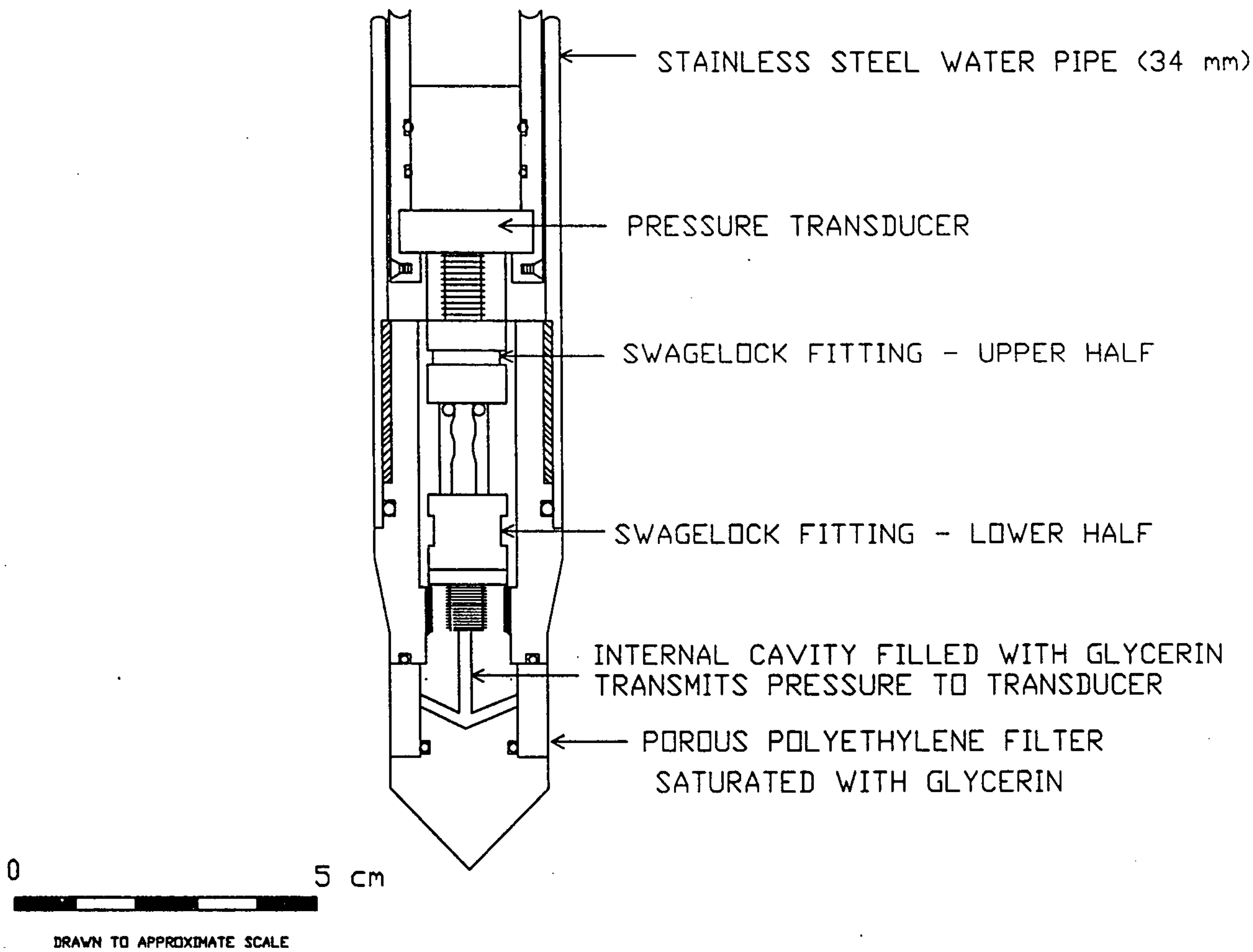


Figure 4.1 Cross section of UBC designed and manufactured piezometer tip.

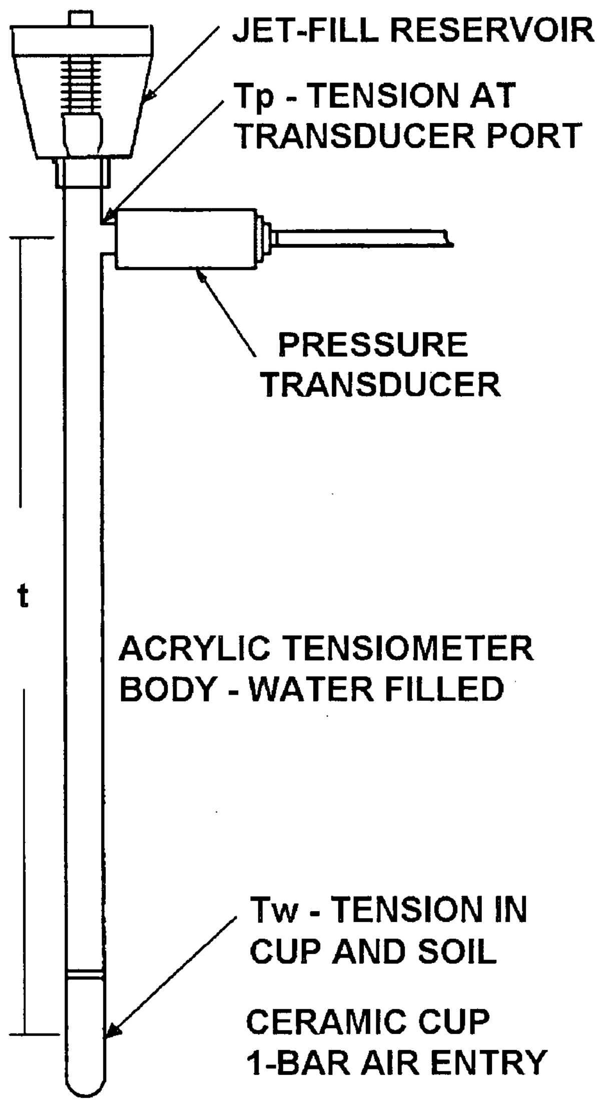


Figure 4.2 Standard vacuum gauge-style tensiometer with transducer.

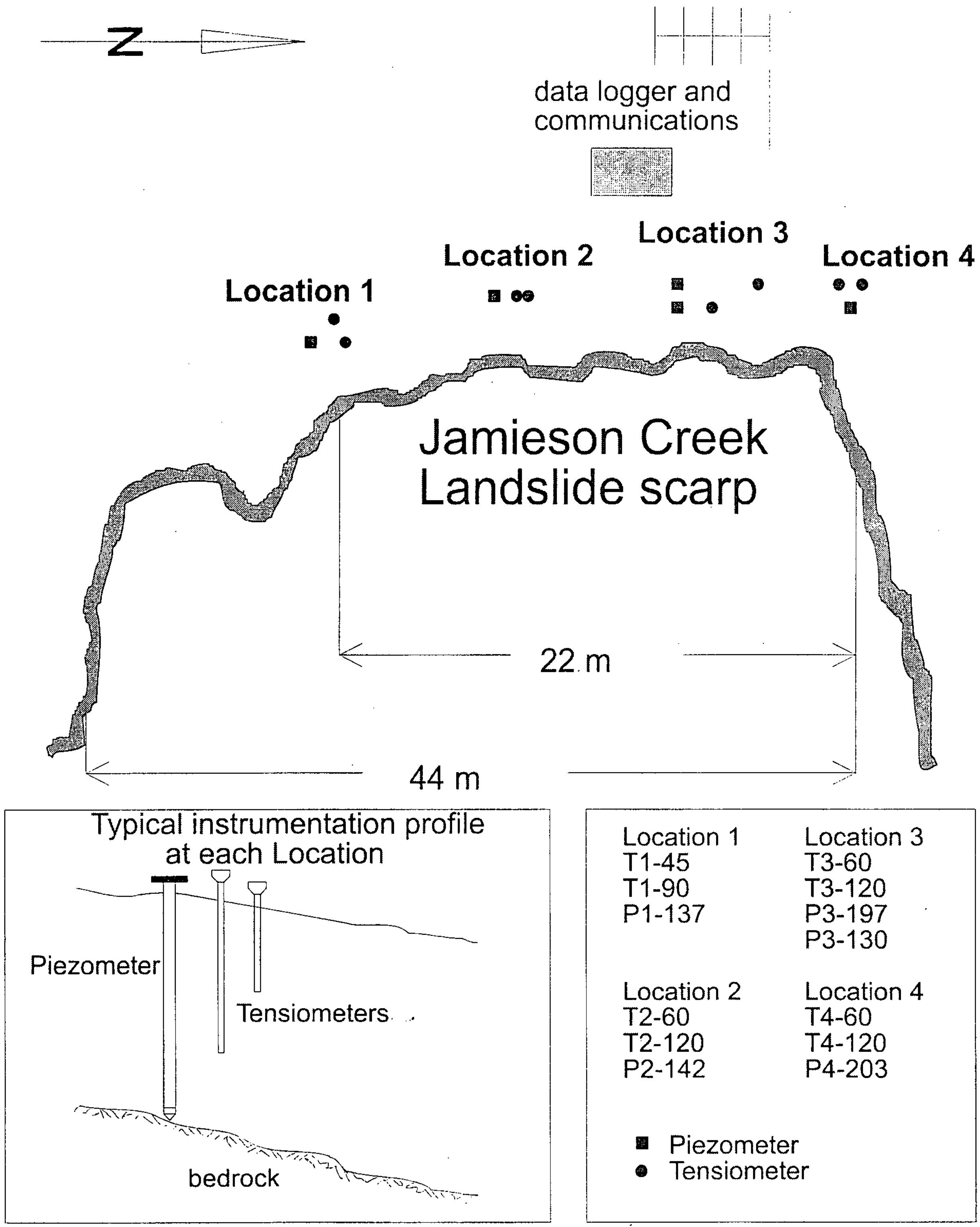


Figure 4.3 Instrumentation layout at Jamieson site.

Plate 4.2 Insulating and protective covers overtop 2 tensiometers and 1 piezometer at Location 4.

Plate 4.3 Radio communications antenna and solar panel at Jamieson Creek study site. Also visible is underbrush atop of headscarp (dark zone).

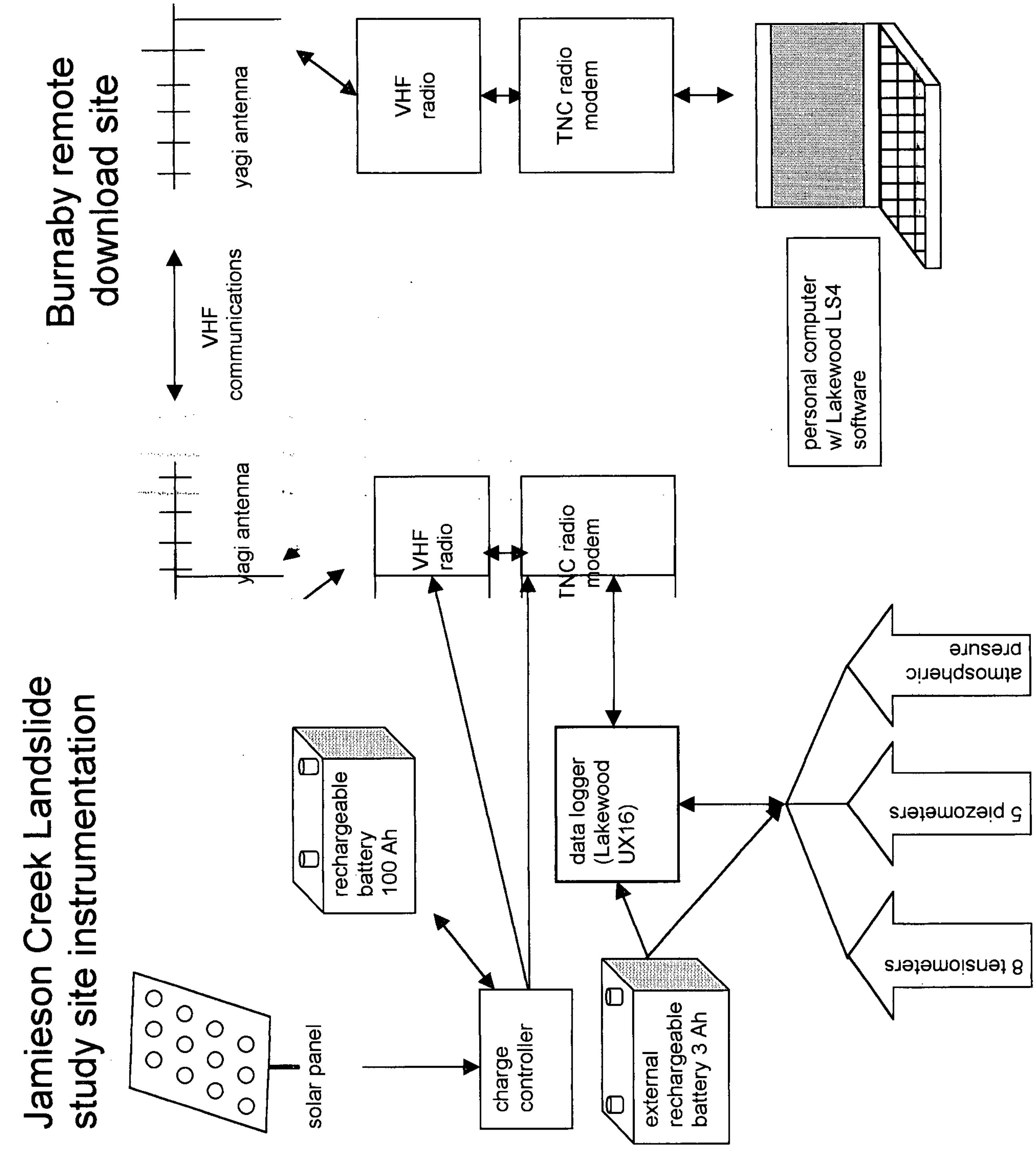


Figure 4.4 Data acquisition and communications schematic

5.0 JAMIESON CREEK INSTRUMENTATION SITE RECORDED DATA

5.1 General

The headscarp area of the Jamieson Creek Slide provided a unique locale to install groundwater monitoring instrumentation as it offers a visible cross section of the soil and bedrock profile, in addition to revealing zones of water concentration. The location allowed for positioning of the instrumentation with confidence that they were in fact intersecting areas of groundwater convergence. Objectives for the instrumentation scheme were to:

- characterize the soil moisture transition from negative to positive pore pressures with time;
- capture the magnitude of high groundwater levels induced by storm events;
- characterize the variability of pore pressures across a small area;
- gain experience in the installation of instrumentation and interpretation of collected data.

The instrumentation recorded pore pressures continuously from October 1997 throughout the winter, and continues to record at the time of publication (August 1998). Results are presented and discussed within this chapter. Quantitative data gathered from the study site are supplemented with qualitative observations of groundwater flow from the scarp face during storm events. It is the synthesis of field observations and recorded data that definitively characterizes the site.

5.2 Recorded Data

Figure 5.1 displays a time series plot of atmospheric pressure, tensiometer recordings, and piezometer recordings at 20 minute intervals, along with hourly precipitation for the month of October 1997. Time series plots for the other months of recordings are found in Appendix II. Data were recorded at 20-minute intervals with a maximum of 14 recording channels operating at once. The recording interval was deemed short enough to capture the rapid rise and fall of pore pressures, while long enough to avoid filling up the memory capacity too quickly. Using a 20-minute interval, the datalogger memory would take 25 days to fill. Atmospheric pressure was recorded on-site throughout the study period to allow for accurate correction of pore water pressures. Shifts in barometric pressure are directly reflected in pore pressures, and can change by as much as 3 kPa, or the equivalent of 30 cm of water over a month (Figure 5.1). Without an accurate correction for atmospheric pressure, the recorded pressures on site would be erroneous, particularly at lower pressures.

All five piezometers were operational through the winter, with four units fully operational from October 1997, and the fifth one (P3-130) installed in early December. Only six of the eight tensiometers were left to record through the winter. Two tensiometers were decommissioned for fear of potential freezing of the water column and subsequent expansion that could lead to damage of the ceramic cup or the transducer diaphragm. These precautions were later deemed unnecessary. Four of the six tensiometers leaked considerably through the winter, progressively adding error to the recorded values. Leakage is attributed to either diffusion of air through the ceramic cup, or air entry through the transducer port threading (Figure 4.2). It is difficult to determine until which point in time the recordings were accurate. This is not crucial because soil moisture remains very high during the winter months, leading to consistently low measures of negative pore pressure. It is the dry periods as well as the cycles of wetting and drying that are of interest at this site.

5.3 Recorded Data Analysis - General

Figure 5.1 displays four time series plots that correlate with one another. Hourly precipitation intensity can be used to visually delineate individual storms, although small amounts of precipitation are common throughout the month. The more significant storms correlate with temporary drops in atmospheric pressure indicating low-pressure systems. Tensiometer and piezometer responses are clearly related to the hourly precipitation intensity. Interpretations of the soil response to rainfall are detailed within this section.

Tensiometer recordings indicate that precipitation quickly diminishes negative pore pressures in partially saturated soils. Relatively short duration and small accumulation storm events were registered by tensiometers as sharp increases in pressure, reflecting a sudden increase in soil moisture. It would take several days for negative pressures to be re-established following the storm events. The recorded tensiometer data shown in Figure 5.1 reveals that the differences in responses between units are small, and changes in pressure occur simultaneously. Tensiometers responded remarkably similarly until servicing terminated in December. Following the end of servicing, leaking, diffusion of air into the unit, and damage by animals (see discussion in section 5.8) progressively added to the inaccuracy of readings. In addition, precipitation events had little effect on the consistently low tensiometer recordings during the winter months. For these reasons, the recorded tensiometer data from December to late April have not been considered for analysis and progressively deleted from the data plots in Appendix II.

Recorded piezometric data correlate well with the tensiometer data for larger storm events. Positive pore pressures would be registered by piezometers shortly after the tensiometers reached zero suction, suggesting that once the soil has been wetted throughout, positive pore pressures can build up. Figure 5.2 exemplifies this cycle of rainfall induced transition from negative (recorded by tensiometers) to positive pressures (recorded by piezometers), and the drying trend back into the negative range. The piezometer responses tended to react in unison to larger precipitation events, with a rapid rise and fall in pressure. Notable on Figure 5.1, is that changes in intensity of precipitation are reflected in the response of positive pore pressure. An exception to the rapidly draining piezometer behavior is unit P4-203, which appears to drain much slower than the other units and mimics the response of tensiometer T4-60. The similar pattern responses from a tensiometer and a piezometer at Location 4 adds confidence to the performance of the installation design.

The sensitivity of the soil pore water response to storms is not consistent between all of the piezometer units. Units P1-137 and P3-197 react to larger storm events, while P2-142 and P4-203 are far more sensitive and seem to respond to almost all precipitation events. The range in magnitudes of response over thee entire recording period is considerable. P1-137 reached up to +94.9 cm, equating to a maximum groundwater ratio (Dw/D) of 0.69, while the remaining four piezometer units did not exceed +32.6 cm. The following table outlines a summary of the responses of all 13 units.

Table 5.1 Summary of responses, Jamieson Creek study site

Unit	Range of Response (cm ±1.4 cm) (October 1997 – June 1998)	Comments
	Piezometers	
P1-137	0 to +94.9	highest positive recorded value
P2-142	0 to +18.4	reacts to most precipitation
P3-197	0 to +31.6	does not register significant negative pressures
P3-130	poor data	noise in signal
P4-203	0 to +32.6	mimics response of adjacent tensiometers
	Tensiometers	
T1-45	-63.2* to +22.4	recorded positive pressures
T1-90	-50 to 0	Manually recorded with Bourden Gauge
T2-60	-51.0 to +22.4	recorded positive pressures
T2-120	-45.9 to 5.1	
T3-60	-69.4* to 3.1	installed in loose soils
T3-120	-73.4* to +21.4	recorded positive pressures
T4-60	-82.6* to +4.1	highest negative pressures
T4-120	-64.3* to 4.1	

* recorded in either August or September 1997 during sporadic intervals.

The range of pressures recorded, with the exception of P1-137, is similar for most units. Units are differentiated by slight variations in the response to precipitation events. Following is a series of observations that help to define the patterns of soil pore pressure changes at the site.

I. Wetting of the soil during small precipitation events may not penetrate through the entire profile. Unit T2-60 would respond to small precipitation events while the T2-120, only 1 m away but 60 cm deeper, would not respond (Figure 5.3, November 20, 1997). Similar behavior is noted for the pair T4-60 and T4-120 during the same precipitation event.

II. The tensiometer pair T2-60 and T2-120 concurrently enter the negative pressure range, with T2-60 reaching higher negative pressures (Figure 5.1). Oddly, the shallower one will register positive pressure while the deeper one (T2-120) will not (Figure 5.3, November 29, 1997).

III. P3-197 and P1-137 respond in unison to precipitation events, but P1-137 reaches much higher maximums (Figure 5.1 & 5.2). At the headscarp face, P1-137 appears to be a much wetter location.

Maximum piezometric recordings, and positive range recordings for the tensiometers were generally coincident for a few major precipitation events. The majority of maximum piezometric and positive tensiometer recordings were triggered during storm events on October 28-31 and November 28-30. The November storm was in the form of two events separated by 15 hours. Statistics for these storms are as follows:

Table 5.2 Storm attributes responsible for maximum recorded pore pressures

Storm Attribute	October 28-31, 1997 (Figure 5.1)	November 28-30, 1997 (Figure 5.3) (split into two events by 15 hours)	
total accumulation (mm)	173	105	113
duration (hours)	69	34	27
average intensity (mm/hour)	2.5	3.1	4.2
maximum intensity (mm/hour)	7	6	11

5.4 Discussion of Data

The negative range response reached a maximum of –82.6 cm of water pressure (T4-60), which is in the range of values reported by Cheng (1980) for work within the same drainage. This value is low compared to data reported from sites on the coast of Oregon (Harr, 1977) and San Francisco (Johnson and Sitar, 1990). A few of the tensiometers measured values in the positive range to a maximum pore pressure of +20 cm H_2O during larger storms.

Measures of positive pressures by tensiometers were related to those pressures measured by the neighboring piezometer at the same location. The pressures were not always hydrostatic between the units. To illustrate this difference in recorded pressures, Figure 5.4 displays a storm that began on October 27, 1997, and the associated responses of piezometers and tensiometers. The lower portion of Figure 5.4 displays the equivalent groundwater levels calculated from the positive pressures recorded by piezometers and tensiometers at Locations 3 and 4. It is clear that the levels do not correspond to one another, although the units are separated by a maximum of 2 m at the surface. Possible explanations for this discrepancy include temporary zones of perched saturation as a result of the conductivity of the soil being exceeded by the rate of downward infiltration, or gradients of flow between the two points of measurement. The spikes of positive pressure recorded by the tensiometers are usually very short in duration. Therefore, in summary, the occasional measures of positive pore pressure recorded by tensiometers at the field site do not necessarily equate to the hydrostatic groundwater implied by measures at neighbouring tensiometers or piezometers at the same Location.

5.5 Discussion of Instrumentation Scheme

In a hydrologically complex zone such as this, designing a piezometric monitoring scheme to study the localized pore pressures presents a considerable challenge, as piezometers are only capable of recording information about pore pressures at a very finite location in the soil profile. The layout used at the Jamieson site was intended to capture pore pressure build-up around suspected areas of groundwater concentration, namely near soil pipes and seepage zones. The obvious difficulty with the application is that the piezometer tips were driven into the soil behind the headscarp, where the tip may not intersect the actual subsurface drainage zones. Furthermore, the fact that the units were positioned within 5 m of the headscarp is also a concern. Release of the slide mass created a new hydrologic boundary condition at the headscarp that may have drawn down the storm induced upslope potentiometric surface. This new boundary condition may have also altered the natural flow configuration to one where convergence and draining through larger macropores provides the path of least resistance. The outcome of the rerouting could potentially be a lowering of pore pressures in the region immediately behind the scarp (where the piezometers are located). This hydrologic condition was understood prior to establishment of the instrumentation site. Recalling the objective, the intentions were not to attempt to characterize the pre-slide conditions, but rather the 'post-slide' hydrologic conditions at this complex location.

Design of the piezometer units proved to be effective as shown by the calibration testing in the lab (Appendix I) and in the field. The capability of being able to remove the electronics proved to be very useful in an instance where an erratic signal was being recorded for a short period. The transducer unit was removed, tested, and repaired in the lab. The concern of loss of glycerin from the filter element (as discussed in Section 4.4) resulting in error of measurement is not believed to be a significant factor considering the low pressure range of interest. The process of in-situ flushing of the piezometer tip and filter with glycerin from the ground surface (see Section 4.7.1) was tested during a preliminary recording period. Recorded piezometric values from before and after the process showed no significant difference.

5.6 Field Observations of Groundwater

Potentially the most valuable, yet simplistic information gathered from the Jamieson Creek research site are field observations taken during a visit to the site on October 10, 1997, at the tail end of a significant storm event. During the storm, 149 mm of precipitation fell in 66 hours, with a maximum intensity of 12 mm/hour. The visit allowed for observations of groundwater seepage from the headscarp area and predicated the chosen positioning of the groundwater monitoring units. Prior to installation, the non-uniformity of flow from the headscarp area was understood, but the magnitudes of flow volume and rate observed during the storm were surprising.

Prominent groundwater flow features noted during the visit included macropores and seepage springs, which were flushing large volumes of clear water onto the slide scarp. Active macropores were concentrated at the four zones of seepage where instrumentation had been installed, and exiting the scarp face primarily at the bedrock interface. As noted by Thurber (1991), soil pipes were present at the headscarp following the landslide, but "may not have developed until after the slides occurred". The slide headscarp has retrogressed approximately 20 m from the position assessed in 1991, and still hosts a number of macropore, or soil pipe features. A notable feature is a spring surfacing at Location 4 a short distance back of the crest of the scarp. During dry periods, there would be little reason to suspect that the location is host to a very active groundwater seepage area. At the time of the field visit, approximately 1 l/s of water was flowing out of the spring and cascading onto the slide scarp (Plate 5.1). Traverses upslope of the spring gave no insight into why this feature (Plate 5.2) exists where it does. There are no drainage depressions or unusual topographic features.

The volumes and rates of water exiting these features drastically complicate the hydrological characterization of the area. It stands to reason that if these conduits of flow were retarded or blocked, a high level of pressure could be built up. This clogging or blocking process may have been a factor in initiating the slide event.

5.7 Synthesis of Observations and Recorded Data.

All but one piezometer regularly recorded relatively low pore pressures throughout the recording period. The recorded pressures are considered to be benign, considering the volumes of water exiting the scarp, and the fact that extreme pore pressures at this site lead to a debris slide. All piezometers reacted to major rainstorms, but the range in response magnitude varied considerably over a small distance. Of particular note is that P1-137 reached a maximum of +80 cm H_2O on a regular basis while the other piezometers hovered below 30 cm H_2O. Based upon the initial field observations prior to installation, the rank of piezometric responses appeared to be counterintuitive. The wettest locations at the headscarp, those with seepage zones and soil pipes, yielded the lowest piezometric responses. Hypothesized reasons for the recorded behavior are as follows:

- The two piezometers at Location 3 (P3-197 & P3-130) were intended to be installed immediately upslope of the macropore/soil pipe features at the headscarp. If the tip of the unit were positioned near a flow conduit, it may register the pressure of groundwater converging towards the flow feature. Low recorded pressures suggest that the subsurface conduits are so well interconnected that the soil water readily drains out of this site and discharges through the major pipes at the scarp face.

Since the units are so close to the hydrologic boundary of the scarp, it is likely that there is little potential for pore pressure build-up, hence little response in the units. Obvious seepage conduits at the headscarp regions of Locations 2 and 4 likely have the same effect as in Location 3 on pore pressure build up.

- Alternatively, the piezometer tips may not be registering the highest pressures being generated at the scarp. Zones of pore pressure development may be distributed in a complex manner and the tips of the piezometers may be positioned in lower pressure zones where water readily drains out.
- The rapid and significant response by P1-137 at Location 1 may be a result of the piezometer tip intersecting a flow conduit.

5.8 Summary and Future Application

The design of the piezometer unit and instrumentation network has proven to be reliable and robust enough to endure a year of use in a remote, relatively service-free environment. Piezometer design considerations, such as stainless steel construction and removable electronics, ensure long term integrity and versatility. The design eliminated the need of over-sizing a hole and back-filling material around the piezometer, avoiding alteration of local hydrologic patterns. The design, or an adaptation of it, is well suited for accurate recordings on slopes with variable soils and a high coarse fraction, such as till and colluvium. Tensiometers worked well and responded in unison in-between servicing visits. Some of the problems encountered were leakage, and damage by curious animals. It is believed that marmot sized animals had a penchant for the soft black Jet-Fill tensiometer reservoir lids. The animals tore through the protective covers and chewed on the rubber lids. In so doing, they damaged two of the plastic reservoirs, and jostled the tensiometers enough to cause leaks. Animals also chewed some protective cover off the solar panel cable, which was also made of a similar soft black rubber.

Recorded data reveals that the soil responds to precipitation events within hours, and non-uniformly. Recorded piezometer data reveal a few points of interest:

- Groundwater flow passes through the site in a non-uniform distribution, where positive pore pressures vary greatly across a distance of only 22 m. Maximum groundwater pressure head can vary from 30 cm to 94.9 cm (D_w/D of 0.69) for the same storm event (Figure 5.3, November 30, 1997). This distribution complicates the use slope stability analyses based upon the infinite slope equation (Hammond et al, 1992), where groundwater is assumed to flow parallel to the surface and of a uniform depth across a planar slope.
- Piezometric response generally occurs when sustained precipitation intensities of greater than 3 mm/hour are surpassed. Response at Locations 1, 2, and 3 (Figure 4.3) rise and fall reflecting changes in precipitation intensity within hours. The fourth location (Location 4, Figure 4.3) maintains elevated pore pressures for days after precipitation, although the instrumentation is only 6 m from the headscarp. The rapid or 'flashy' response of groundwater at Locations 1, 2, and 3 is illustrated by the close correspondence with rainfall intensity (Figures 5.1 and Appendix II). Data analysis and field observations both confirm that little base flow or saturation occurs at this free draining area only 24 hours after precipitation.
- Tensiometer data offered insight into the distribution of soil pore water pressures and the movement of water through the partially saturated zone. Negative pore pressures reached during dry periods are small (-81.6 cm H2O maximum), and they are reduced to zero with very little precipitation. These Coastal forest soils maintain a high soil moisture content throughout the year, equating to the

small negative values. Following are some general observations and interpretations of tensiometer data:

- Smaller accumulations and low intensity precipitation would wet the upper soil profile, but not always reach the deeper tensiometers (see section 5.3).
- Positive pressures can be generated at shallow depths (60 cm) that do not correspond with hydrostatic pressures measured at deeper points in the soil profile (Figure 5.4). This observation suggests either a complicated wetting down process, where positive poor pressures are temporarily generated in the soil profile, or pulses of groundwater flow passing through the site in a non-uniform lateral and vertical distribution.
- The magnitudes of negative poor pressures do not vary significantly across the study area, and do not always increase with depth (see section 5.3).

The Jamieson pore pressure data have illustrated the complexity of forest soil groundwater hydrology. Impressions of laminar isotropic groundwater flow paralleling the soil surface are quickly dispelled following interpretation of the recorded data (see Figure 5.4). Variance in the recorded groundwater level is found between units at each location, and between the four locations.

Variability in piezometric recordings across the scarp area, in conjunction with the observations of where the majority of flow was exiting the scarp, clearly illustrates the difficulty involved in the characterization of groundwater flow in forest soils. It is this appreciation of spatial variability and complexity of flow patterns that is used in the following analyses of the Carnation Creek database.

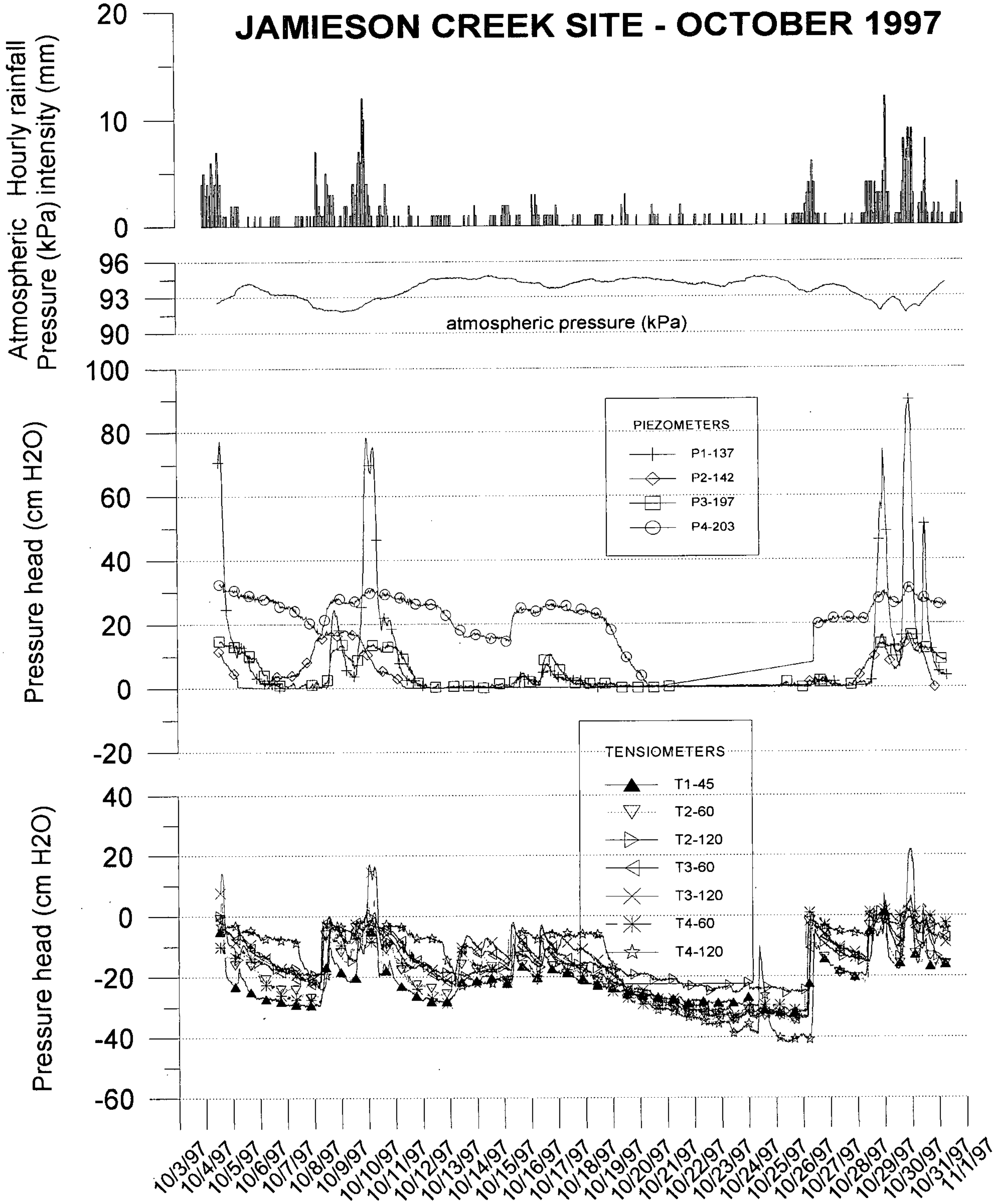


Figure 5.1 Data recorded at Jamieson creek site – October, 1997.

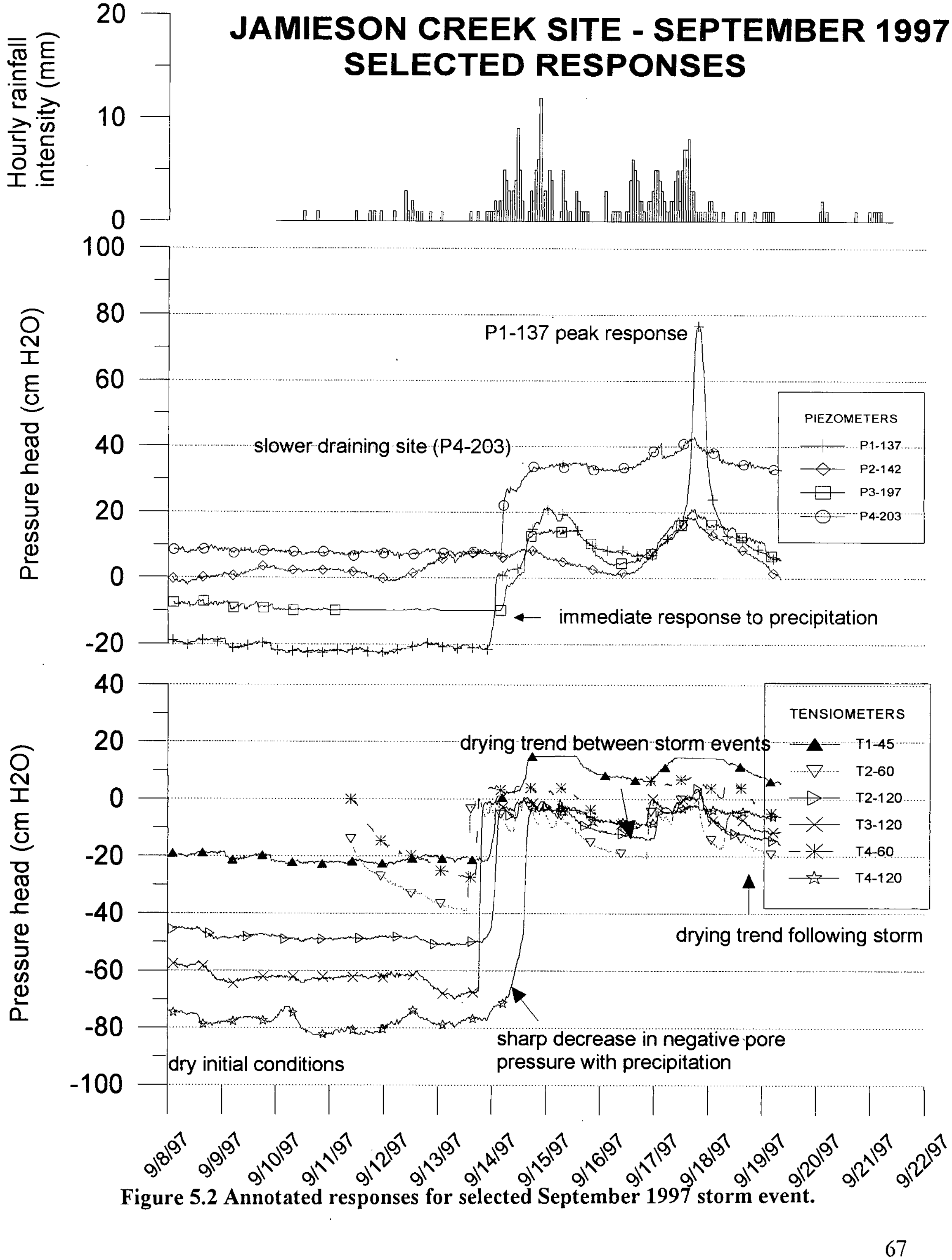


Figure 5.2 Annotated responses for selected September 1997 storm event.

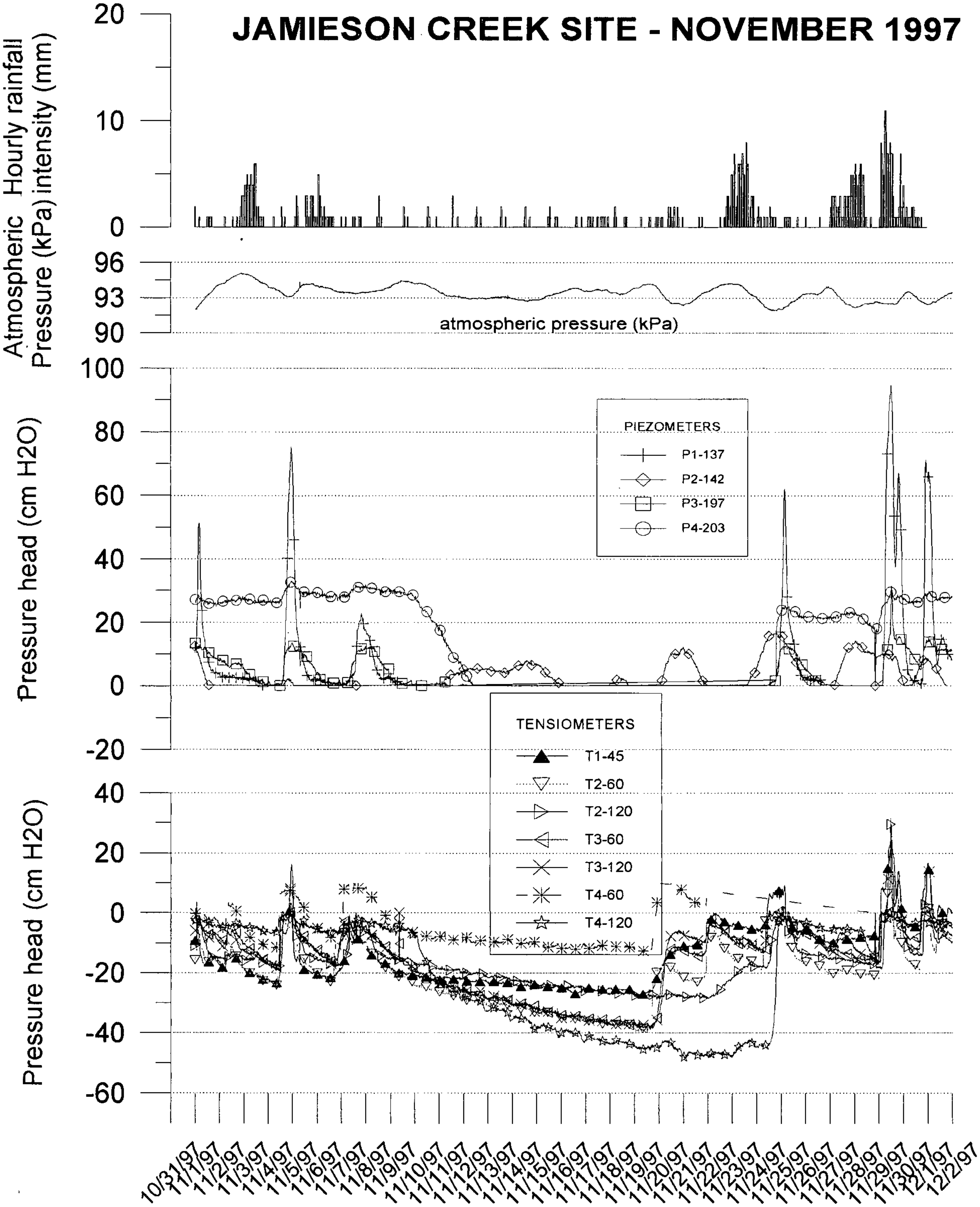
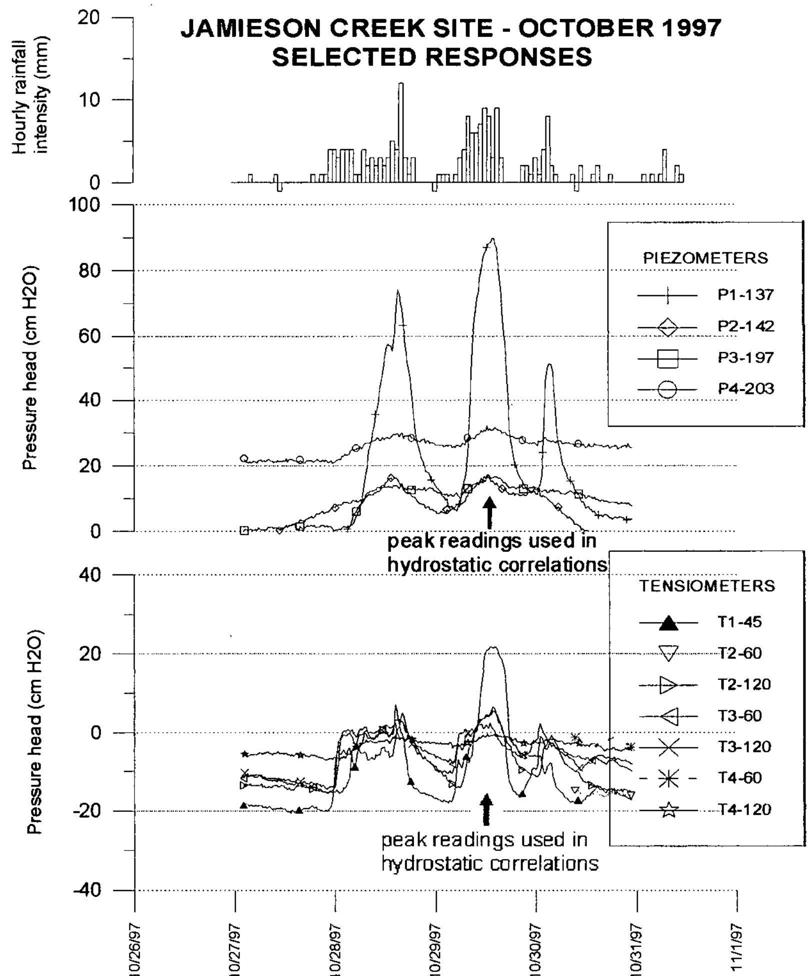


Figure 5.3 Data recorded at Jamieson creek site–November, 1997.



Recorded pore water pressures at Location 3 and 4 – calculated hydrostatic groundwater elevations from bedrock surface

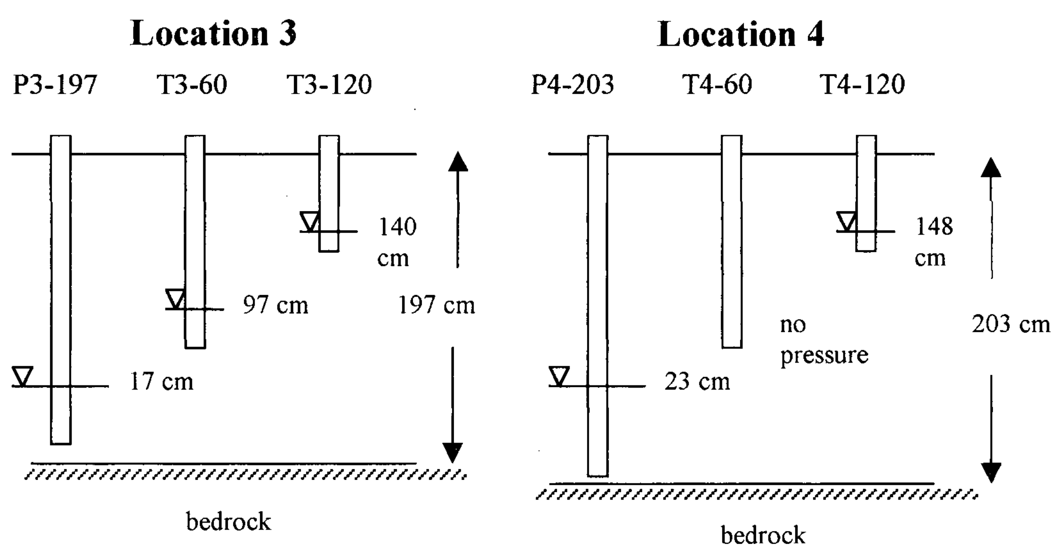


Figure 5.4 Hydrostatic pressure correlation between units at Locations 3 and 4 during October 1997 storm

Plate 5.1 Water that originates from a small ephemeral spring down-slope of Location 4 and 1 m back from headscarp cascading over the headscarp of Jamieson Slide. Photo taken at the end of a 3 day storm (October 1997).

Plate 5.2 Surface expression of ephemeral spring responsible for flow shown in Plate 5.1. 30 cm machete for scale.

6.0 CARNATION CREEK EXPERIMENTAL WATERSHED

6.1 General

Carnation Creek represents the most extensive database of precipitation correlated groundwater records on the West Coast of B.C. These records are paramount in attempting to develop understanding of groundwater processes and precipitation relationships for this physiographic region of B.C. Although comparable and respected studies with piezometric records have been performed in North America, their application is limited due to vastly different glacial histories, bedrock and surficial geology, and climatic patterns. For example, snowmelt provides dominant sources of water input into the hydrologic cycles in the Idaho Batholith (Megahan, 1983) and the Nashwaak Watershed (Meng et. al., 1995) experiments, whereas Carnation Creek sees very little snowfall. In addition, average annual precipitation accumulations in the Carnation Creek watershed are up to three times greater.

A number of hydrometeorological parameters were measures through the Carnation Creek Watershed (Hetherington, 1998). Considered in this study, is the 'H' watershed is a small (12 ha) first order drainage basin within the Carnation Creek watershed. It is one of two small basins that were instrumented with groundwater monitoring equipment with the intentions of studying the effects of forest harvesting on the hydrologic regime. The instrumented site was operational between 1975 and 1983, with varying numbers of piezometers recording at any one time. Harvesting of a large portion of the H Watershed took place during 1977-1978, dividing the recording periods into pre- and post-harvesting periods. This chapter outlines the layout of the instrumentation, justifies the selection of data used in the analyses that follow in Chapter 7, and discusses some of the previous work that used data from this site.

6.2 Description of site

The instrumentation consisted of primarily standpipe piezometers with crest tubes. Spatial distribution of the instrumentation focused on locating units in groups and linear transects, both parallel and perpendicular to slopes, to characterize the groundwater levels at various hillslope positions and aspects. Installation locations included above and below roads, at the head of H Creek, along gully sidewalls, and in unlogged areas to serve as control units for comparative purposes (Figure 6.1).

Standpipe piezometers were constructed from a mix of standard 25 mm and 50 mm inner diameter PVC tubes with two vertical rows of holes, on opposite sides of the pipe, drilled into the lower 150 mm. The holes are 6.4 mm in diameter and spaced 25 mm apart. The bottom of the tube was sealed with a flat piece of PVC and the holes were covered with a glued on, fine nylon mesh to filter out soils. Crest tubes were constructed from 1.27 cm outside diameter, 0.925 cm inside diameter PVC tubing. A 0.635 cm diameter cylindrical styrofoam float inside each tube was used to record water levels. The crest tubes had a wire across the open bottoms to keep the styrofoam float inside. Piezometers that were configured to record data continuously used either Stevens 'F' Type chart recorders, or specially constructed nitrogen gas-bubbler recorders that used Belfort rain gauge drum chart mechanisms.

Piezometers were installed in two ways. Some were placed in holes augered to a compact surface, but at many sites the soils were too rocky to properly determine the locationof bedrock or compact till surface. In these cases, narrow trenches (60 cm wide by 90 cm long) were excavated to the bedrock profile or impermeable dense till surface, and a narrow 30 cm long slot cut into the corner of the upslope wall. Piezometers standpipes were installed vertically at the upper end of the slot. The piezometers were placed in this manner to minimize the effect of the soil pit on the groundwater levels measured in the piezometers. All piezometers were installed with sand surrounding the filter screen at the bottom, and the remainder of the excavation back-filled with native material. Depths of installation ranged from 26 cm to 216 cm, with all units placed on the compact surface. Plate 6.1 illustrates a continuously recording piezometer with a nitrogen gas-bubbler type recorder in operation.

6.3 Selection of Piezometers

Over the course of the H Watershed study, a total of 77 piezometers were installed by the Canadian Forest Service. Of the 77 units, 17 were configured for continuous recording. The remaining 60 units were manually recorded at irregular intervals of two or three times per month, at which time a maximum level since the last recording was read, along with the current level. The records of the manually recording piezometers provide a good spatially distributed data series of maximum groundwater levels across the study area, but it can be difficult to relate each maximum recording to an individual storm event. In addition, the characteristic behavior of individual piezometers cannot be determined solely from peak recordings. These peak data were used to cross check suspect spurious readings from nearby continuously recording piezometers. Due to the infrequency of the measurements, the non-automated units were not suited to a storm by storm response analysis. The 17 continuous units included four piezometers that were installed above two small slide headscarps, and were operational for only a short period in the winter of 1982/1983. These four units are not considered in the analyses that follows due to the limited record length, leaving a total 13 units for analysis (Table 6.1).

Table 6.1 Piezometers used in analyses

Piezo-meter	soil depth (cm)	Slope Aspect	Upslope Gradient ° (%)	Local Slope ° (%)	Downslope Gradient ° (%)	Elevation (m.a.s.l.)	Side of H Creek	Status
P803	88	NE	18(32)	40(84)	18(32)	211	south	logged
P814	163	NE	29(55)	20(36)	20(36)	259	south	control
P816	85	NE	20(36)	20(36)	20(36)	243	south	logged
P820	123	NW	22(40)	22(40)	22(40)	245	south	logged
P823	178	NE	19(34)	19(34)	19(34)	248	south	control
P825	128	NE	38(78)	23(42)	38(78)	232	south	logged
P845	96	NE	32(62)	23(42)	23(42)	186	south	control
P847	105	NE	31(60)	31(60)	32.5(64)	200	south	control
P849	100	NE	21(38)	21(38)	21(38)	208	south	control
P856	103	S	22(40)	22(40)	22(40)	232	north	logged
P858	130	SE	34.5(69)	29(55)	29(55)	259	north	logged
P859	107	SW	29(55)	29(55)	29(55)	175	north	logged
P863	125	SW	15(27)	15(27)	15(27)	163	north	logged

Six of the thirteen piezometers were operational by late 1975, while the remaining seven began recording during the fall of 1976 (Figure 6.2). Figure 6.2 reveals that the recording periods of the piezometers were discontinuous. The most notable lapse in the record is during 1978, while units recording was halted to accommodate harvesting of the watershed. A second lapse in noted during 1982, when the system was shut down and then partially reactivated to match recordings by piezometers installed above the 'Bob West' and 'Eugene East' slides.

6.4 Description of Data

Continuous data from the chart recordings had been digitized into 15 minute intervals, converted into a digital time record, and made available for this project by Dr. Eugene Hetherington through the Canadian Forest Service. The records are largely consistent, with short periods where selective units were non-operational due to malfunctions, servicing, or other reasons.

A precipitation station was operational adjacent to, or within the H watershed continuously for 19 years between 1972 and 1991, and is the source for all piezometric - precipitation data correlations. Intensity duration curves for the rain gauge Station E (Figure 6.1) are given in Chapter 3, as Figure 3.5. Precipitation was collected in a vertical standpipe, and measured by a Stevens water level recorder between 1972 and 1978. Between October 1978 and December 1980, data from a Belfort recording gauge at Station H (Figure 6.1) 1 km west of Station E were used. In February 1980, the Station H Belfort gauge was moved a short distance to a new location (300 m northwest of original Station E), where it operated until 1986. Gaps in the data were filled with precipitation records from another station located outside of the H Watershed. To assess the effects of moving the recording precipitation gauge from Station E to H, monthly precipitation totals from Station H between October 1978 and October 1982 were compared to records from a Sacramento storage gauge that remained at the original Station E. Over the four years of records, the monthly precipitation totals from Station H were on average 4% less than from the storage gauge at Station E. The greatest variance between the two monthly precipitation totals occurred during relatively dry months with accumulations less than 100 mm. The difference between the two stations is not expected to have a significant effect on the analyses of precipitation – rainfall relationships that follow in Chapter 7.

Although there was not a long historical record at the site prior to the piezometric recording period, the precipitation stations are of great value as they were within a 1 km radius of all of the piezometers. The benefit of having a rain gauge in close proximity is that it can record very localized intense rainfall. Precipitation events in Coastal B.C. are known to have a high spatial variability with localized intense rainstorms (Church and Miles, 1987; Loukas, 1995), which can lead to spatially variable responses of groundwater. Changes in rainfall intensity are often reflected in the piezometric records due to the highly permeable nature of the soils.

6.5 Previous Studies

Groundwater instrumentation was collected from the H Watershed to study the changes to the hydrologic regime of the entire watershed following harvesting (Hartman and Scrivener, 1990). Findings by Hetherington (1982) pointed to harvesting-related changes in peak groundwater levels at a site above and below a road in the H Watershed. Changes were gauged by comparing peak levels at the piezometers in question with a control unit response. The piezometers from the above road location (P803) and control location (P814) are included in the set of units considered in the analyses following in Chapter 7.

An analysis of piezometric records from the H Watershed by Wilkinson (1996) attempted to determine if a difference exists between the pre- and post-harvest maximum, mean, range, and standard deviation of the groundwater levels. Based on a linear regression best fit between pre- and post-harvest measurements, little observable difference was cited. The method of assessment looked solely at magnitudes of piezometer recordings and did not consider the characteristics of the storms responsible for the recordings. Difficulty in interpretation arises from the fact that pre-harvest values are chosen from a single year of record versus up to five years of post-harvest records.

6.6 Current Research

The piezometric and precipitation data collected from the Carnation Creek site provide a wealth of data which can be used to better the understanding of numerous facets of slope groundwater hydrology. The current research project follows the same initial research objectives by looking for changes in groundwater levels due to harvesting. In addition, the study looks at the primary factors that control slope stability, such the storm response timing, magnitude, and spatial distribution of maximum groundwater levels. The following chapters outline the observations and conclusions made based upon the available data sets. Given that the physiographic and climatic parameters at Carnation Creek are similar to other areas on Vancouver

Island and Coastal B.C., there is great value in studying the groundwater regime while being cognizant of the site-specific variability.

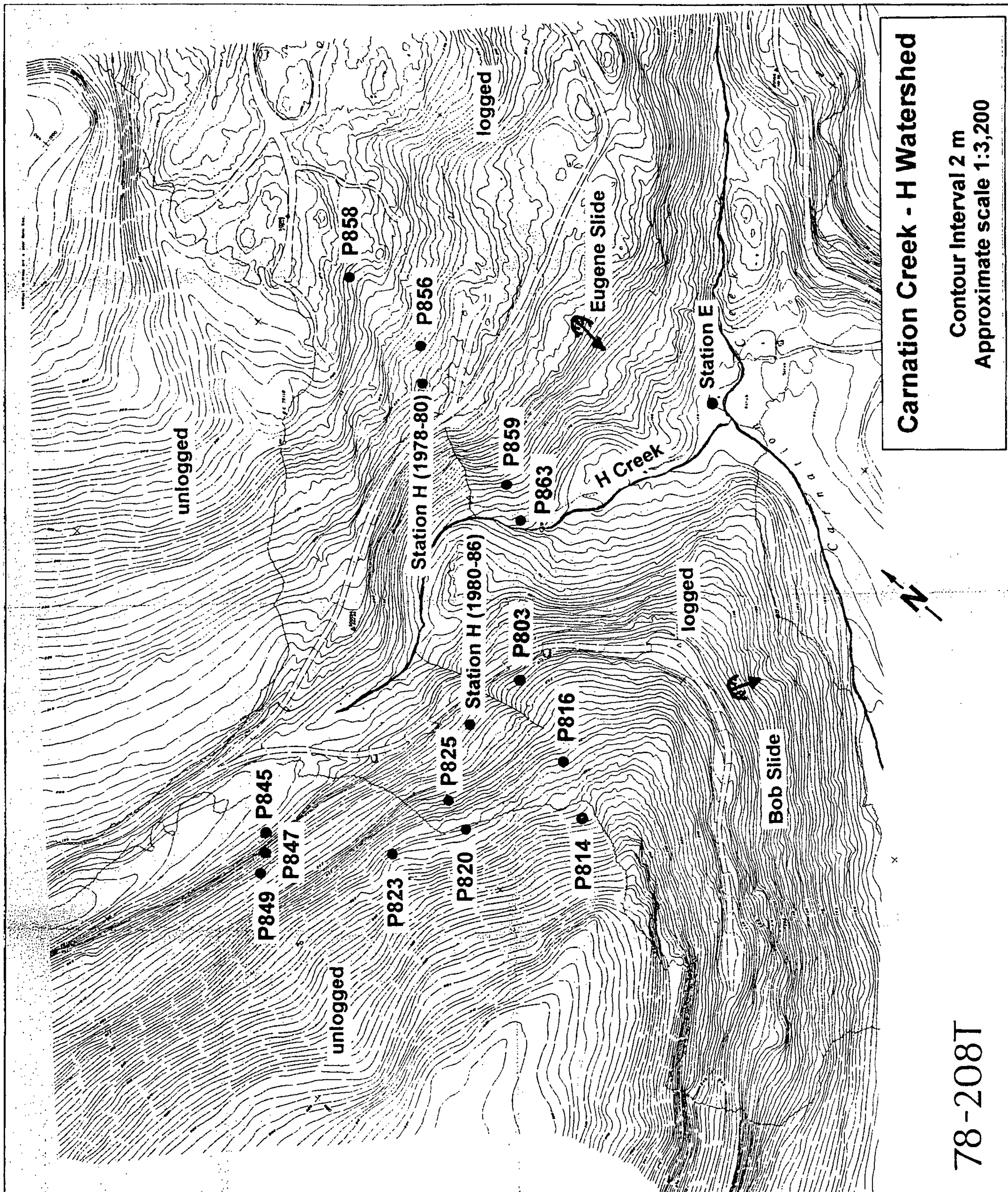


Figure 6.1 Contour map of H Watershed, Carnation Creek.

Plate 6.1 Continuously recording piezometer (P847, Nitrogen gas-bubbler type) in H Watershed, Carnation Creek.

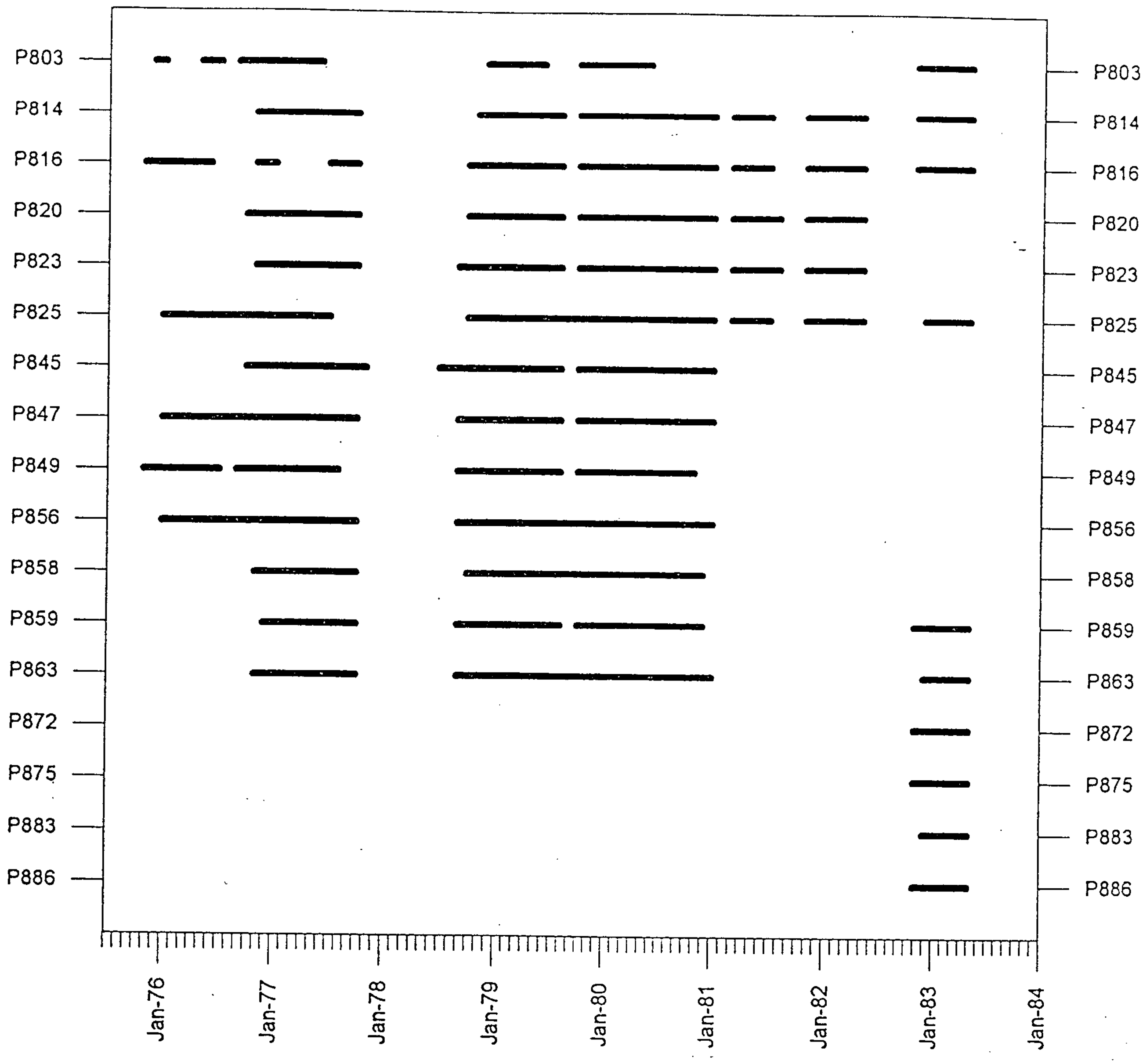


Figure 6.2 Recording periods of continuously recording piezometers – H Watershed (Wilkinson, 1996).

7.0 CARNATION CREEK DATA INTERPRETATION

7.1 General

Land use changes in the form of clear-cut logging have been cited to cause increases in the hydrologic budget of forest watersheds (Megahan, 1983; Meng et. al. 1995). Long term monitoring of hydrologic parameters in carefully designed and implemented experimental areas is the only way of quantifying these types of changes. Results from these studies are expected to have limited transferability across different physiographic regions. The unique value of the Carnation Creek Experimental Watershed is that it offers the most comprehensive data set on the West Coast of British Columbia for assessing these postulated changes.

The response of groundwater levels in forest hillslopes to precipitation is a poorly understood relationship. It is this lack of understanding, and the direct impact on slope stability that plagues the process of identifying potentially unstable terrain by professionals working in the forest industry. The occurrence of extreme maximum levels of hillslope saturation is of critical concern to slope instability. Professionals often require a reasonable estimate of maximum groundwater ratio (D_w/D) to carry out routine slope stability calculations. In order to be able to recognize critical slopes and periods, the distributions, both spatial and temporal, of groundwater levels must be understood. The Carnation Creek database provides an opportunity to study the distribution of the water levels across a small but topographically variable area.

The objectives of this chapter are essentially twofold. Firstly, the effect of clear-cut logging of the study area on the groundwater regime is assessed. The method of assessment uses piezometric response to precipitation events from before and after harvesting as a gauge to detect changes. Secondly, the groundwater regime of the study area is characterized for its response to precipitation. The study looks at the occurrence and significance of extreme piezometric levels across the study area. Using the data, a number of conclusions about the spatial and temporal distributions of groundwater levels, along with precipitation-groundwater level relationships are presented. Also discussed, are two small debris slides that occurred during the recording period, with specific reference to the precipitation event responsible.

7.2 Pre- vs. Post-Harvesting Groundwater Analysis

A primary objective of the Carnation Creek experimental watershed hydrology studies was to evaluate the effects of forest harvesting activities on the hydrologic regime of a small coastal watershed. One objective of this thesis was to revisit the data and assess if logging caused changes to groundwater levels. Prior to being able draw any conclusions on the effects of altering the physical nature of the watershed, a representative set of piezometers had to be selected from the database. An in-depth analysis of each of the candidate piezometers was undertaken in order to characterize the nature of individual and group responses to storms across the area. In this thesis, the term 'storm' represents any period of continuous precipitation. To meet the objective of the study, the responses of the chosen piezometers were assessed for changes between the pre- and post-harvest period. This section outlines the steps involved in building an understanding of how each chosen piezometer responds over time, and then describes a method with which to assess potential changes resulting from harvesting.

Work presented hereafter outlines an alternate approach to addressing the question of whether or not harvesting affected the groundwater regime of the H Creek area. The approach uses individual storms as an index against the associated response of each piezometer. Selected storms and responses can be divided into pre- and post-harvest periods, allowing for any changes in the indexed response between the two periods to be observed. The hypothesis being tested is that piezometers in areas which were not logged (control units) should show little variation in the range of responses to the index storms over the entire recording period.

Units within harvested areas may see a positive shift in the trend of magnitude of response vs. precipitation if the effect of decreased interception and transpiration is physically significant. Conversely, if a decrease in the trend is noted, it may be indicative of the effect of harvesting related soil disturbance in the area of the piezometer. The benefit of this style of approach over simply analyzing the highest maximum recorded levels of pre- and post-harvest records, is that it takes into consideration the magnitudes of storms which induce the groundwater levels. Neglecting climatic trends would be an oversight, particularly considering that the pre-harvest period spans only between one and 2 years, while the post-harvest record is much longer. If the maximum groundwater level at a piezometer was directly related to storm size, any post-harvest storms exceeding the magnitude of pre-harvest storms might incorrectly be flagged as having experienced a change.

7.2.1 Selection of Piezometers

The H Watershed has a total of 13 automatically recording piezometers that operated for period of length covering both pre- and post-harvesting periods. To satisfy the objectives of this section, data from a set of control piezometers from unlogged areas, and from all of the piezometers in harvested areas were required. All of the continuously recording units discussed in Chapter 6.3 were considered for analysis, but unit P847 was omitted. P847 experienced a dramatic increase in average response two years following harvesting, and after four years of recording, which is not reflected in any of the other surrounding control piezometers. Overall maximum recorded groundwater levels at P847 following this change were up to 30 cm higher. Given that this unit lies within the area that was not harvested, it is highly possible that the unit underwent some sort of disturbance or malfunction. The final distribution of selected piezometers covered four units on the north side of the creek (all in harvested terrain), and eight on the south side (four of which were in harvested terrain, and four control units) (Table 6.1, Figure 6.1).

There is some concern that three (P816, P820, P825) of the four units in harvested terrain on the south side of the creek may not be representative of the potential effects of clear-cut logging. The three units are located less than 40 meters downslope from the cutting boundary and have had little change in the tree cover of their hydrologic catchment area when compared to units on the north side. Topographic catchment, or contributing area, is responsible for accretion of groundwater levels (Barling et al. 1994). Should harvesting increase groundwater levels, removal of tree cover and harvesting related soil disturbance from a catchment area, and the associated hydrologic impacts, are assumed to be major factors responsible for the changes. Little change in piezometric response of the three units in question is anticipated between the pre- and post-harvesting periods.

7.2.2 Data Filtering and Analysis Procedures

To develop the required indexed curves, represented by straight lines on a semi-log plot, the precipitation and piezometric records between 1975 and 1983 were processed using the following procedure:

- the hourly precipitation files were systematically divided by beginning with a September 1st start date, and defining the start of a storm by the onset of recorded precipitation greater than 0.5 mm/hour;
- storm precipitation accumulation would be tabulated until a break of at least eight hours of zero recorded precipitation had elapsed. The value of eight hours was chosen to define an individual storm based upon the work of other authors (Pierson, 1980), and reflects the time required for partial subsidence of water levels for most of the piezometers;
- if the storm accumulation surpassed 20 mm, the storm would be numbered and statistics (namely duration, accumulation, maximum intensity, and average intensity) would be recorded;

- piezometric records were matched to the corresponding precipitation events and the antecedent groundwater level at the time of storm initiation was recorded, as was the storm induced maximum level and the time at which it occurred.

The storm data set was limited to events greater than 20 mm and less than 200 mm because there were no storms with an accumulation greater than 200 mm in the common pre-harvesting year 1976/1977. For the pre-harvest period of 1975-1977, a maximum of 53 storms fall within the range set for extracting piezometric recordings. The number is reduced to 29 for units operational for only the 1976/1977 period (Figure 6.2). The actual number of extracted piezometric recordings depended upon the recording span of the individual unit (Figure 6.2). The number is also reduced for slower responding units that did not drain before the onset of the next storm. A maximum of 71 eligible storms were selected from the post harvesting period of 1978-1983.

Many of the piezometric recordings of antecedent and maximum levels revealed seasonal trends. During winter months, the recorded differences between the antecedent and peak values were found to be generally less than during drier periods of the year. This observation is not surprising as the frequency of storm events is much higher and cooler temperatures result in higher soil moisture contents for extended periods. In some units with a slower 'draining' time, the storm recordings were rejected for further use if the following storm commenced prior to a distinct peak and falling of piezometric level.

A number of different precipitation parameters were tested as indices against the maximum piezometric levels to determine the best relationship between cause and effect. Measures of maximum 24-hour accumulation, maximum 1-hour intensity, and total storm accumulation were all tested to determine which parameter had the strongest relationship with the maximum induced groundwater level. A generally linear relationship is formed when maximum storm induced groundwater level is plotted against total storm accumulation on a semi-logarithmic scale. Pierson (1980) also proposed a simple logarithmic relationship between 24-hour rainfall and piezometric response for the Perkins Cr. Watershed in Western Oregon. Maximum groundwater level recordings are often reached during the course of a storm near the point of maximum accumulation, and are only loosely linked to rainfall intensities at some piezometer locations. Measures of antecedent moisture conditions were considered for incorporation into the relationship, but a sound index or measure was not found, and such measures are considered to be highly subjective. Multiple regression analyses incorporating more than one storm parameter were avoided due to the inevitable masking of the influence of each individual parameter.

Three of the piezometers used in the analyses (P825, P849, and P856) were operational during the 1975/1976 and 1976/1977 recording periods (Figure 6.2). Having two separate years of pre-harvest records increased the pre-harvest baseline curve and allowed for a statistical comparison between two pre-harvest curves to ensure there was no annual bias in the control data. Bias may occur in the form of abnormal snow cover or unusual weather patterns. Statistical tests of variance at a 95% confidence interval were performed on the three piezometric records of concern, revealing no significant difference between the two pre-harvest best-fit curves. A plot of the two pre-harvest years for P856 is shown in Figure 7.1. The plot uses maximum groundwater level as a ratio D_w/D plotted against total storm precipitation. The close correlation between the best-fit curves of pre-harvest data adds confidence to the further application of the pre- vs. post-harvest test methodology.

7.2.3 Results of Analyses

Figures 7.2-7.13 present the plotted relationship between maximum groundwater level (D_w/D) vs. storm accumulation for each of the assessed continuously recording piezometers. Each plot has a best-fit line representing extracted data for both the pre-harvest and post-harvest periods. Following is a partially qualitative description of the plotted relationships and the interpretation of the behavior of each piezometer. Section 7.2.4 adds to the qualitative descriptions of the relationships with tests of statistical significance between the pre- an post-harvest data. The assessed piezometers are separated into control units and units which were within the logged area (Figure 6.1).

P803 (logged)

This unit experienced a dramatic positive shift in level and slope between the pre-harvest to post-harvest data. The unit is positioned over 120 m downslope of the cutting boundary at a lower-to-mid slope position and harvesting has denuded the tree canopy from a large portion of the contributing area of this piezometer location. Hetherington (1998b) noted that this piezometer location did undergo some degree of surficial disturbance during yarding of logs.

P814 (control unit)

This unit is positioned 15 outside of the cutting boundary and was intended to act as a control unit. Comparison of the best fit curves for pre- vs. post-harvesting show little difference in the magnitude or shape suggesting no change over time in response to storm events. The best-fit curve parallels the pre-harvest curve at a slightly lower level, likely a result of the broad range in response data for the post-harvest period. Maximum groundwater levels defining the upper band of data are from a combination of pre- and post-harvest recordings again suggesting there was no change.

P816 (logged)

Positioned approximately 40 m downslope of the cutting boundary, and 50 meters downslope of P814, this unit was anticipated to show little difference in response following harvesting as discussed in section 7.2.1.

Although the unit lies within the harvested area, very little change in the characteristics of the upslope catchment area. The plotted results show little difference between the responses. The slopes of the curves are very similar to those of P814 suggesting that the sites have similar sensitivity to precipitation and groundwater accretion. Broad scatter of data points for smaller storm accumulations in the post harvest period are largely due to storms of low average intensity (i.e. <1 mm/hour).

P820 (logged)

This unit is positioned within 15 m of the cutting boundary. The response is similar to that of the control unit P814 in that the post-harvest responses roughly parallel the pre-harvest curve at a lower value. The majority of data points defining the upper maximums are from pre-harvest storms. Poor fit of the curve is attributed to the broad scatter responses for smaller storms.

P823 (control unit)

The shapes of the pre- and post-harvest curves are very similar to one another, as would be expected for a control unit. The only significant variance between the sets of data is in the lower range of values, where low small post-harvest storms induced a wide range of responses. The curve has very little slope, meaning the response of the piezometer is not highly dependent upon the size of storm, and reaches a high groundwater level (between D_w/D of 0.7 - 0.8) regularly.

P825 (logged)

Both the pre- and post-harvest responses are within a tight range at a low magnitude, with little slope to the curve. This site appears to be limited to low groundwater levels, and has little dependency on the size of storm. Groundwater levels rarely exceed 40% of the soil thickness during storms of less than 200 mm accumulated precipitation. This unit is located 25 m downslope from the upper cutting boundary, and within 30 m of piezometer P820. Little or no change was anticipated from this unit, as discussed in section 7.2.1, and such was the case. The upper maximum data points are largely from the pre-harvest period, and the best-fit post-harvest curve parallels the pre curve at a lower level.

P845 (control unit)

This is one of three control units positioned in a transect at the western limit of the instrumentation layout. A comparison of the pre- and post-harvest curves reveals that the post-harvest curve appears lower than the pre-, suggesting a drop in groundwater levels in the period following harvesting.

P849 (control unit)

Although this unit is positioned only a short distance upslope from P845, the magnitude of response and slope of curve are much lower than those of P845. The behavior of the pre-/post-harvest relation is the same as P845, where a drop in indexed response in the post-harvest period occurred.

P856 (logged)

The curves have moderate parallel slopes, and vary little in magnitude. Upper maximums are defined by a combination of pre- and post-harvest recordings, suggesting that no significant changes took place. This unit is positioned on a slope where the entire catchment area has been clear-cut. If removal of the tree canopy had uniform negative impacts on groundwater levels across the slopes of the watershed, data from this location should have indicated a change.

P858 (logged)

This area is a very wet site where groundwater levels reach a D_w/D ratio of greater than unity on a number of occasions. The slope gradient of the best-fit curves is low suggesting little difference in response to storms of varying magnitudes. Small storms are able to induce high groundwater levels, largely due to the fact that this site remains wet throughout the season. This piezometer location is unique in that the upslope contributing area is broad and relatively flat. The unit was installed on a slight bench immediately below a short steep pitch. The post-harvest best-fit curve is visibly above the pre-harvest curve suggesting that harvesting had an impact on the groundwater response to storms at this site.

P859 (logged)

This is one of two lower slope piezometers positioned considered that were down-slope from a road within the harvested area. Considerable range is noted between the curves and the smaller storm response leading to poor correlation coefficients. The slopes of the curves are steep, as would be expected for a lower slope location with a large contributing area. Pre-harvest data defines most of the upper maximum points suggesting that if any change did occur, there had been a drop in the response at this site following harvesting.

P863 (logged)

This unit is located near H Creek just downslope from P859. Post-harvest data points are visibly higher than the pre-harvest points. It appears that this unit experienced an increase in the response of groundwater to precipitation.

7.2.4 Statistical Tests

To supplement the observations of piezometric response between pre- and post-harvesting periods, statistical tests were carried out in an attempt to assess whether statistically significant differences exist between the best-fit curves. An appropriate method to assess these differences is covariance analysis. This method is used to analyze the variance of the differences between regression line slopes to determine whether significant differences exist between the relationships, or if they are satisfactorily represented by a single regression. This type of analysis is common in studies of natural phenomena, where simple linear regressions are used to characterize cause and effect relationships.

The standard covariance analysis procedure tests two groups of data to see if they can be represented by a single equation. The first step in assessing two groups tests to whether the hypothesis of equal slopes is true. Slope represents the sensitivity of a particular location to increasing precipitation. The second step tests the hypothesis of no difference in levels of data. Level represents the magnitude of groundwater response to storm events. If there are differences in either level or slope, the data indicate that a change in response has occurred. Statistical analyses results are included in Table 7.1, where results of analysis of covariance tests for slope and level are listed as 'same' or 'different', indicating either no-change, or a change from the pre-harvest response. A discussion of potential explanations for different scenarios follows in section 7.3.5. All data were tested at a 95% confidence interval.

Following is a summary of the statistical analyses for each piezometer.

Table 7.1 Summary of covariance analysis test results

Piezometer	Status	No. of Sample points (pre/post)	Total No. of Sample Points	R^2 Coefficient (pre/post)	Test Result – Slope (F ratio)	Test Result – Level (F ratio)	Comments
P803	logged	26/53	79	.480/.647	different (9.78)	different (47.11)	post above pre
P814	control	19/71	90	.588/.546	same (.053)	different (6.87)	pre above post
P816	logged	23/49	72	.539/.316	same (0.19)	same (0.64)	no change
P820	logged	19/45	64	.456/.353	different (0.49)	same (0.69)	poorly fitting data in post set affects slope
P823	control	22/57	79	.215/.336	different (5.80)	same (1.03)	poorly fitting data in post set affects slope
P825	logged	49/63	112	.329/.361	different (6.75)	different (17.72)	pre above post
P845	control	25/41	66	.442/.464	same (2.38)	different (5.38)	pre above post
P849	control	35/43	78	.652/.338	same (0.024)	different (29.97)	pre above post
P856	logged	53/44	97	.487/.543	same (0.79)	same (3.29)	no change
P858	logged	20/37	57	.502/.492	same (0.0034)	different (8.29)	post above pre
P859	logged	23/63	86	.655/.393	same (0.13)	different (5.19)	pre above post
P863	logged	26/63	89	.741/.623	different (72.42)	different (41.31)	post above pre

The results from the tests of significance do not yield a clear trend. Some of the units that were earmarked as ones most likely to show change (P803, P863), as they had either most or all of the catchment area clear-cut, display a statistically significant increase in response. Adding confidence to the design of the test is the fact that the control units (P814, P823), and units anticipated to behave as control units (P816, P820, as discussed in section 7.2.1), did not reveal a positive shift in level following harvesting. The data are complicated by the fact that post-harvest best-fit curves are in fact lower in level (D_w/D ratio) than the pre-harvest curves for some units (P814, P825, P845, P849, & P859). Of the five units displaying this trend, three are control units where no change would be expected. Units P859 and P863 are in close proximity to one another in the harvested area, yet the post-harvest response of the two units is opposite, with P859 decreasing and P863 increasing. Potential explanations for the reverse trend could be that very site-specific forest floor disturbance has taken place, or that there are inherent limitations in the chosen index relationship. Variability in the selection of storms represented on the graphs may also lead to increased scatter in the range of responses for some units.

7.2.5 Discussion of Pre- vs. Post-Harvesting Results

Statistically significant harvesting related changes in slope and levels of best-fit lines were found in covariance analysis of piezometric records. This section proposes general interpretations for the changes in both slope and level indicated in Table 7.1. Figure 7.14 indicates three general cases of changes between the pre- and post-harvest periods witnessed in Figures 7.2-7.13.

Hypothesized reasons for the changes in slope or level are as follows:

Case 1 – ***Increase in level***

This condition was witnessed in a total of three piezometers (P803, P858, and P863), all within the clear-cut area. The physical interpretation of the positive shift in level is that the entire groundwater regime response had been amplified with the removal of tree cover and/or soil disturbance.

Case 2 – ***Decrease in level***

A negative shift in the level of the curve was found in four piezometers (P814, P825, P845, and P859). This condition suggests that ground disturbance may have altered the localized groundwater regime at the locations of P825 and P859 resulting in lower responses. However, P814, P845, and P849 are control units that were not expected to change. It is difficult to make any conclusions about net negative offset, as there is little detailed information on where on the hillslope degradation took place.

Case 3 – ***Change in slope***

Five piezometers displayed a change in slope between the pre- and post-harvest period relationships. Changes in slope are likely a result of changes in the sensitivity of the soil to either larger or smaller storm events. The trend of higher responses for smaller storms (P863) could be explained by the loss of interception and transpiration, while the limited change in larger storm response could be a result of a localized predisposition for the soil to have a set maximum groundwater limit. P803 saw a significant increase in slope where post-harvest maximums for larger storms were larger than for pre-harvest storms. Changes in slope in units P820, P823, and P825 are attributed to scatter in the data points and the resulting poorly fitting curves.

The overall shape of the curve also characterizes the nature of the groundwater regime at each piezometer location. Curves with low slope gradients represent sites where the D_w/D ratio is insensitive to storm accumulations. These sites will 'wet up' to a similar level, regardless of the size of storm. Such a behavior could occur if the site is continually wet and experiences very little change in groundwater level with precipitation. If the slope of curve is steep, as would be expected in rapidly draining soils, it would indicate that the piezometric level attained is directly related to the amount of precipitation. As the curves become steeper, it may signify that the effects of accumulated throughflow from the contributing area are prevalent. Intuitively, a piezometer at a lower hillslope position should experience greater magnitude pulses than an upper hillslope piezometer due to accumulated throughflow.

7.2.6 Discussion of Analysis Method

Notable in the data of indexed pre vs. post response is the sizable scatter in data points and poor R^2 values for the best-fit curves. To potentially improve the statistical fit and analysis of variance between groups, a multiple regression approach could be applied which considers effects other than accumulated storm precipitation. Factors that could be incorporated include measures of contributing area, other storm attributes, some measure or index of antecedent moisture, and local slope. Pierson (1980) improved the relationship between rainfall and piezometric response by incorporating a measure of antecedent moisture through three different methods. In the interest of avoiding applying inputs which cannot be directly quantified (such as antecedent moisture), the study was kept to a simple relationship. Further improvements in some of the piezometer regression R^2 coefficients could be made if the data were limited to a narrower range of storms by omitting smaller events. The drawback of limiting the range is that the number of sample points drops significantly.

The chosen method of displaying the cause and effect relationship between total precipitation and maximum piezometric level produces statistically significant best-fit logarithmic curves. Scatter in the response data complicates the development of firm relationships, and makes it difficult to detect changes. Among the simple factors that might explain some of the variation with each individual unit is the fact that accumulation of precipitation is not rate dependent and does not consider any other storm parameters such as average intensity and maximum intensity. In addition, there is no distinction between the season in which the storm occurred, which overlooks soil moisture conditions, possible snow cover, and temperature effects.

Antecedent moisture conditions, strictly in the form of the water level at the start of each storm, were not factored into the development of the curves. It was assumed that neglecting this factor would have the greatest effect on smaller storms. For example, if a piezometer had 50 cm of water in it as opposed to being initially dry, a 30 mm precipitation event would have produced a markedly different maximum level. To assess if a relationship exists between the accumulated precipitation and the increase in groundwater level between the antecedent condition to the maximum level (ΔD_w) at each piezometer, the ΔD_w for each storm were plotted against the accumulated precipitation. The relationships for each piezometer revealed a broad range in the increment of ΔD_w for each storm accumulation, and was dependent on the initial groundwater level. Interestingly, the maximum groundwater level attained for many of the larger storm accumulations (> 100 mm) do not appear to be dependent upon the initial level. For example, if the piezometer location had a significant depth of groundwater prior to the storm event, the ΔD_w increment may be quite small, whereas if the piezometer location was dry, the ΔD_w increment would be much larger for the identical storm. Both conditions would often result in a similar maximum level. The implication of this observation is that resulting maximum groundwater level depends very little on the antecedent level of groundwater. This interpretation is validated by the relatively narrow range of maximum groundwater ratio response for larger storm accumulations (i.e. > 100 mm) in Figures 7.2-7.13.

A potential inaccuracy in comparing the curves for relationships is that not all of the piezometers use the identical set of storms. Storms had to be selectively filtered for each unit if the piezometric level had not subsided from the previous storm and displayed a falling trend even during the onset of the next storm. In many cases, a unit was not operating at the start of storm, or stopped recording prior to a distinct maximum being reached, again negating the use of the index storm. Selected smaller storms (i.e. <50 mm) were often rejected if they occurred shortly after a major event to avoid unrepresentative responses.

7.2.7 Pre- vs. Post-Harvesting Analysis Conclusions

This specific study of harvesting related groundwater changes did not produce widespread statistically significant evidence strengthening the postulated negative effects of harvesting on the groundwater regime.

Results suggest that the H Creek Watershed experienced unit-specific positive and negative shifts in the magnitude of response following harvesting. There were no spatial patterns between units that experienced a change. Control units did not show any statistically significant positive shifts in level following harvesting, adding confidence to the design of the test. Hampering the study is that three of the eight piezometers within the clear-cut area are very close to the cutting boundary. Other than noting very site-specific changes, no general conclusions can be made about the overall groundwater regime following harvesting. The increases do have direct implications to the stability of the soils in the affected areas. Any increases in groundwater levels will lead to localized decrease in effective stress and shear strength. It should be noted that the design of this analysis is limited in scope and solely addresses increases in storm induced groundwater levels within a certain range of storms.

7.3 Piezometric Observations

Encompassed within the analysis of maximum piezometric levels was the opportunity to characterize how a number of spatially distributed piezometers respond to varying storm events. Figure 7.15 provides an example of the typical, varied piezometric response to a single storm event on February 15, 1977. Time series plots such as Figure 7.15 have served as a partial basis for interpretations of soil behavior that follow in this chapter. It should be noted that observations and interpretations within the following sections do not consider the influence of harvesting. Control and logged units have been considered equally in the analyses. Interpretation of the data records allows for a number of general observations to be made that can be applied, to a limited extent, to other regions of similar physiographic characteristics. Soils in the Carnation Creek area are typical of many coastal forest hillsides, with a sandy matrix and a high coarse fraction. These soils have high a capacity for water transmission, which is evident in several of the piezometric records.

Broad ranges of maximum groundwater levels were recorded across the study area. Figure 7.16, modified from previous work by Wilkinson (1996), shows a plot of monthly maximums of the normalized groundwater level ratio (D_w/D). This figure illustrates the temporal and spatial variability of groundwater responses in the watershed. The two following subsections address the temporal and spatial variability, but many of the observations of the two are invariably intertwined.

7.3.1 Temporal Variation

Rapid piezometric rise is typically noted to begin within hours of rainfall inception, and reach a peak during the course of the storm. Groundwater pressures typically drop for a period of 8 hours to over 30 hours following a storm, depending upon the individual unit and time of year. Seasonal effects are also noted in the monthly maximum records of piezometer response. Figure 7.17 shows the division of data in Figure 7.16 into winter and summer periods. Figure 7.16 reveals that the ranked monthly maximums have a bi-linear trend for the majority of the units. The break in slope generally represents the change in seasonal responses, with the higher maximums representing winter months where high maximums are regularly reached (Figure 7.17b). The steeper section of the curve represents the wide range in responses expected during drier months (Figure 7.17a) due to variability of storm events, and in the degree of unsaturated water storage described in Chapter 2.

Pore pressures were found to be highly transient and the timing of peaks across the area were offset. The movement of water downslope at this site is believed to behave in 'pulses' during rainstorms, as had been noted by Johnson and Sitar (1990) in the San Francisco Bay area. An analysis of storm response recordings between 1977 and 1979 from piezometers P845 and P849 (Figure 6.1) positioned within 40 meters of each other showed that P849 would peak between 1 to 16 hours prior to P845, but would reverse the order of peaks on occasion. Similar trends are noted at different hillslope locations. For example, units P820 and

P825 (Figure 6.1), which are separated by only 26 meters, also varied in the time of peak response. Counter-intuitively, the downslope piezometer (P825) peaked several hours prior to the upslope unit for the majority of storms. Curiously, the timing of the units switched during a few storms in which the upslope unit would peak up to 10 hours before the downslope unit. Differences in the time of the peak recordings were attributed to the sensitivity of specific locations to various attributes of storms. For example, a piezometer location may react quickly to storms of high intensity.

7.3.2 Spatial Variation

Clearly illustrating the spatial variability is Figure 7.15, where a plot of time series response for all 12 of the continuously recording piezometers illustrates the behavior of the groundwater regime at each unit location for a single storm. The localized hydraulic conductivity, the upslope contribution to soil water, the presence of preferential pathways, and slope gradient likely control the rate of rise and fall at each piezometer. Notable on Figure 7.15 is that units P814, P823, and P858 have a high level of groundwater at the start of the storm, and maintain a high level for several hours following. These units are believed to be at less rapidly drained sites on the hillslopes. These wet areas may be areas of groundwater convergence, or supplied by bedrock seepage, in which case they could be part of the hydrologic cycle that maintains low-flow levels in H Creek throughout dry periods of the year. All of the piezometers in Figure 7.15 react quickly to intense precipitation.

In addition to indicating the temporal distributions of groundwater behavior, Figure 7.16 also illustrates the spatial variability of groundwater response. Highest recorded maximums range from $D_w/D = 0.4$ (40% groundwater level equivalent to 40% of the soil thickness) to 1.2 (groundwater pressure in excess of the soil thickness). The range is not surprising as the units cover areas of different topographic expression and hillslope position. Values in excess of one are generally not expected in soils of such free draining nature, and can have serious negative impacts on slope stability. Piezometers P858 and P859 regularly exceeded this value. Possible explanations for the behavior are low permeability layers in the soil profile creating a confining layer, macropores with artesian pressures, or upward gradients, possibly due to groundwater recharge from bedrock (Iverson and Major, 1987). Groundwater pressures in excess of hydrostatic are not uncommon. Sidle et al. (1985) reported this phenomena on forested slopes in Alaska. Units P825 and P849 have characteristically low responses and lack the well-defined break in slope on Figure 7.16 common to the majority of other units. A physical interpretation is that the units have a low range in response to storms of vastly different magnitudes.

Common to all of the piezometers, except for unit P858, is that there is very little difference between the 1-year and 5-year return period maximum groundwater ratios. It appears that the majority of units behave in a 'capped' manner with a predisposed maximum groundwater capacity, where there is little dependency on the magnitude of storm. Maximum D_w/D vs. precipitation curves (Figures 7.2-7.13) and Figure 7.16 show a flattening trend of groundwater level as the storm sizes or return period increase. In effect, increasingly large storms will have little or no incremental effect on the groundwater level. This level may be anywhere between 40% (P825) to 90% (P820) of the soil profile thickness. A hypothesis for the trend is that water will rise within the soil profile until it reaches either a porous root zone or a high capacity macropore system, which will effectively rapidly drain either downslope or laterally. No longer would the soil matrix be the regulating factor of flow, but the structure of the root zone and the interconnection of voids would allow for drainage. The mechanism is analogous to a sink or bathtub with an overflow drain. This overflow mechanism is likely sufficient to explain the maximum responses of the majority of piezometers, except for units P858, & P859, which have recorded pressures in excess of hydrostatic. This phenomenon has a significant bearing on the ability of flow models to predict relative groundwater levels. With typical models, if the input flux is gradually increased (simulating larger storms), the groundwater level will continue to rise until overland flow occurs. Overland flow is rarely witnessed on forest slopes, which may be a result of this proposed soil cap and overflow mechanism. Implications of this 'capped' nature are that it suggests that the concept of extrapolating a 10 or 20-year return period D_w/D from a probability density function (PDF) based on the 5 years of data would grossly overestimate maximum probable levels of groundwater. Interestingly, the two units (P859 and P863) that do not illustrate the capped behavior are of the three that exceed pressures in excess of complete saturation of the soil thickness.

The highest recorded D_w/D value for each piezometer in Figure 7.16 was expected to be a result of either the same storm, or a small group of major storms. Upon investigation, it was found that maximum responses could not be related solely to any particular storm type or feature. The single highest groundwater level recorded by each of the thirteen piezometers were in fact due to ten different storm events. The ten different storm events that caused extreme groundwater levels, were analyzed using the following parameters:

- total accumulation (mm)
- maximum 1 hour intensity (mm/hour)
- duration (hours)
- average intensity (mm/hour)
- 24 hour preceding accumulation (mm)
- 7 day preceding accumulation (mm)

The following table lists all of the storm attributes and the resulting maximum D_w/D ratio..

Table 7.2 Storms responsible for highest recorded groundwater levels

Unit	D_w/D max	total accumulation (mm)	max. intensity (mm/hr)	duration (hours)	average intensity (mm/hr)	24 hr antecedent (mm)	7 day antecedent (mm)
P803	.805	418.3	10.2	229	1.8	0	31.2
P814	.867	142.7	13.5	21	6.8	12.8	101.0
P816	.854	135.8	14.1	58	2.3	0	26.6
P820	.886	149.9	9.0	70	2.1	26.0	71.7
P823	.814	149.9	9.0	70	2.1	26.0	71.7
P825	.505	129.7	12.7	62	2.1	10.6	63.2
P845	.795	109.1	7.3	35	3.1	0	27.8
P849	.513	313.2	11.2	147	2.1	0	103.8
P856	.744	112.5	21.8	58	1.9	0	1.3
P858	1.233	373.3	12.1	323	1.2	0	0
P859	1.748	142.7	13.5	21	6.8	12.8	101.0
P863	.877	135.8	14.1	58	2.3	0	24.6

Storms with a high total accumulation of precipitation appear to be the dominant factor in triggering the response in P803, P849, and P858. High hourly intensities are recorded in the storms triggering maximums at P816, P825, P856, and P863. High one day and seven day antecedent rainfalls with moderately high storm total accumulations appear to be responsible for peaks in P814, P820, P823, P849, and P859. It is not to say that each of these units is preconditioned to only respond to a certain type of storm. However, the parameter indicated appears to be responsible for the extreme response of the unit over a period of up to 6 years and over 100 storms. Complicating the analysis is the fact that no physiographic or soil factors are considered in the comparison of critical factors, and that the recording periods are not equivalent between all units.

When the remaining plotted data points, apart from the highest maximums, were assigned a corresponding storm event, it became evident that it was rare if more than a few units recorded an equivalent rank of monthly maximum during the same storm. Generally, some non-spatially related groups of piezometers respond similarly to certain types of storms. Figure 7.18 shows how a single storm can cause quite varied responses in terms of piezometric magnitude. The figure shows the ranked monthly maximum piezometric responses for two storms. 'Storm 1' (Figure 7.19a) represents the storm event with the highest hourly precipitation intensity for the recording period. This event triggered the highest recorded level in one piezometer (P856) at a 5-yr return period, but the remainder of units registered a magnitude with a return period of 6 months or less. 'Storm 2' (Figure 7.19b) is a typical large storm with an accumulated precipitation of 165 mm. Storms of this magnitude are common during the winter months at this site. Notable is that this storm triggered the highest recording at P858 (Figure 7.18) with close to a 5-year return period, but resulted in average 6-month to 1-year maximums at all of the other piezometers. Further analysis of maximum levels revealed that the wide-spread distribution in the rankings, or return periods, of maximum levels reached during major storms was common. Attempts were made to try to correlate particular hillslope positions or groups of piezometers to specific storm events to see if certain areas are more sensitive to storms of particular characteristics. No clear patterns of rankings of response were noted. Most piezometers record a monthly maximum during a major storm event, but the rankings of the response rarely correlate. It is hypothesized that a complex mix of storm characteristics and soil moisture conditions combine to enable infrequent, extreme groundwater levels. It is this complex relation which makes prediction of landslide occurrences based solely on analysis of simple storm parameters such a complicated task.

7.4 The January 1982 Debris Slide Events

Two small debris slides (Figure 6.1) occurred in the H Creek study area approximately three years following harvesting. It is fortuitous that a few piezometers and the rain gauge were operational when the slide events occurred. The wealth of long term data from the watershed, and well-documented post-slide observations and survey notes combine to provide a unique opportunity to examine factors involved in their instigation.

Named the 'Bob West' and 'Eugene East' slides, the events were relatively small in volume, with a maximum width of approximately 20 m. Soil depths at the headscarps of the slides ranged from 1.1-1.5 m. Both events initiated a short distance below access roads on slopes of approximately 35°. Possible factors attributed in initiating the slides are modification of the groundwater regime at the road prism, and in the case of the 'Eugene' slide, ground disturbance caused by yarding. Log yarding with poor deflection created two shallow trenches that may have either acted to concentrate surface water into the headscarp region, or modified subsurface water flow pathways. Debris from the Eugene slide traveled downslope and deposited at the base of the slope on flatter terrain near H Creek, while that from the 'Bob' slide terminated mid slope. The 'Bob' slide was believed to have initially occurred as a small event, following which, retrogression of the headscarp occurred (Wilford, 1982).

While it is virtually impossible to accurately extrapolate what the groundwater levels may have been at the headscarp regions of these slides, the limited data does provide an opportunity to comment generally on the type of storm event and the associated responses elsewhere in the watershed. The two slides are known to have initiated during a storm event on January 23, 1982, at a time when between 30 and 50 cm of snow was on the ground. The piezometers that were operational at the time (P814, P816, P820, & P825) were all on the south side of H Creek and all recorded a monthly maximum during the time of the storm. Rankings of the monthly maximums were respectively 5th, 15th, 10th, and 1st. The range in ranking again exemplifies the spatial variability of groundwater responses across a small area. It appears that the locations of P825 and P814 were highly sensitive to the type of storm event that occurred, although it was not considered an extreme event. Storm statistics were as follows:

- Total accumulated precipitation 129.2 mm
- Duration 62 hours

- Maximum hourly intensity 12.7 mm/hour
- 24 hour preceding precipitation 10.5 mm
- 7 day preceding precipitation 63.2 mm

The comparatively average storm event suggests that the effect of rain-on-snow events was critical at this site in elevating groundwater levels.

Less than a year after the slides occurred, piezometers were installed above the headscarps of both slides to try to characterize the type of groundwater levels that may have initiated the slides. A total of six piezometers were installed at each site, of which two were continuously recording units and the remaining manually recorded standpipes. These units, along with six of the original continuously recording piezometers were commissioned and monitored for approximately five months. In general, the slide scarp piezometers responded in unison in timing, but not magnitude, to each major storm event. Spatial variability of soil conditions and hydrologic pathways across the sites is attributed for the differences in magnitudes. These records have not been used in analyses in this thesis due to their relatively short recording period.

The nature of the debris slide events is such that they do not directly tie into studies of the effects of harvesting on groundwater levels and, subsequently, the stability of slopes. External factors, such as the upslope road cuts, the magnitude of the storm, and noted yarding damage are likely prevalent factors in the initiation of the slides. It would have been negligent to omit a discussion of the occurrence of these events from this work, but the scope of this study is limited to open slope groundwater level responses to storms. There is potential for future studies in attempting to model the probable levels of groundwater at the headscarp at the time of the slide using a combination of post-slide piezometric recordings, and storm response relationships from the rest of the watershed.

7.5 Summary of Piezometric Analyses

The long-term records of well-distributed piezometric response to precipitation have enabled an assessment of the effects of clear-cut logging, and a detailed study of the spatial and temporal distribution of maximum groundwater levels. A relationship correlating accumulated storm precipitation and maximum piezometric level was used as a basis for interpreting changes between pre- and post-harvest periods. Results from the pre vs. post-harvest analysis point to statistically significant changes in groundwater levels at some clear-cut locations in the watershed, while a decrease, or no change was noted at others. The limited number of piezometer records used in the analysis, and the nature of the spatial distribution of piezometers, complicates the generalization of the impacts of logging on the groundwater regime of the area. Increases in groundwater levels are considered to be site-specific, and affected by hydrologic contributing area and site disturbance.

Analyses of piezometric records revealed a number of site-specific, and potentially transferable characteristics of groundwater flow in forest slopes. Following is a summary of some of the findings:

- Groundwater levels respond rapidly to storm events.
- Water flows in 'pulses' downslope, where peaks are offset in time between piezometers, but not always occurring in the same spatial pattern.
- Piezometer locations are not equally sensitive to storms. The magnitude of response from a piezometer is a result of the particular sites propensity to respond to certain storm attributes. For example, not all piezometers will respond to extreme 1-hour precipitation intensities.
- Wet antecedent moisture conditions are a factor in inducing maximum piezometric levels, but are not essential for them to occur.

- Most hillslope positions have a maximum or 'capped' overflow groundwater level, after which, further precipitation will have little effect. An exception to this observation is that there are some piezometers that have recorded groundwater pressures in excess of the soil thickness.

The understanding of temporal and spatial distribution of groundwater maximums, along with general observations of piezometric behavior, is particularly useful for the detailed assessment of groundwater modeling. A number of the observations challenge the fundamental assumptions of many hillslope hydrology models.

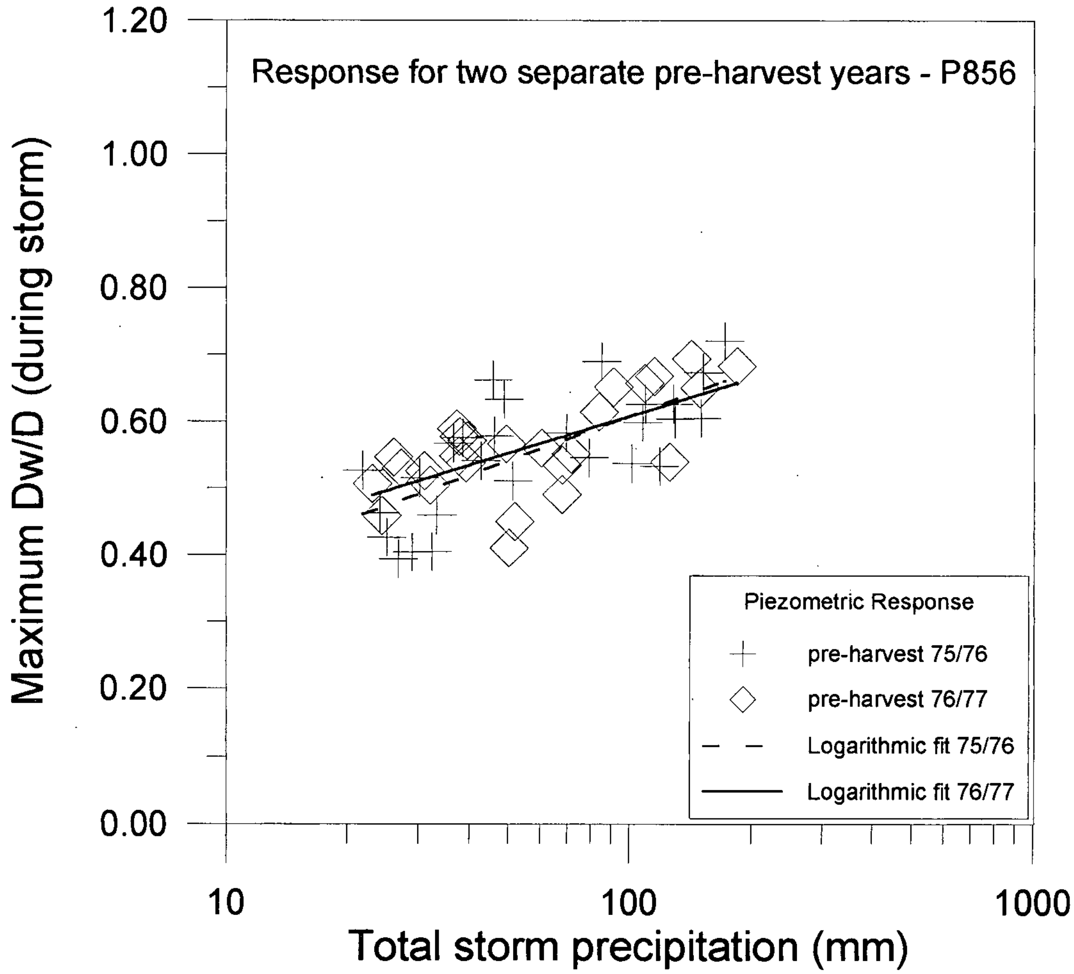


Figure 7.1 Best-fit lines for two years of pre-harvest records, P856.

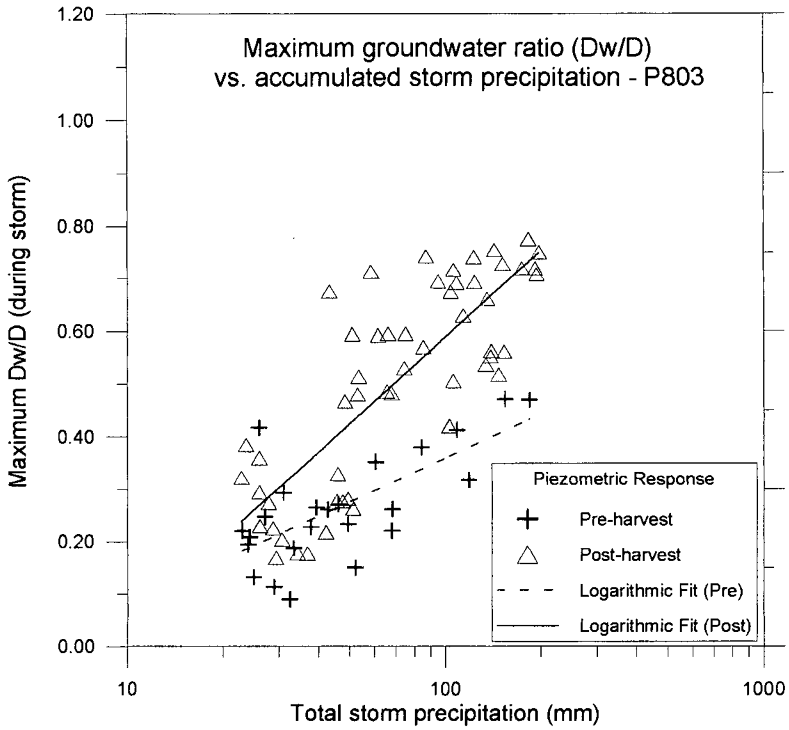


Figure 7.2 Groundwater ratio Dw/D and storm accumulation relationship P803

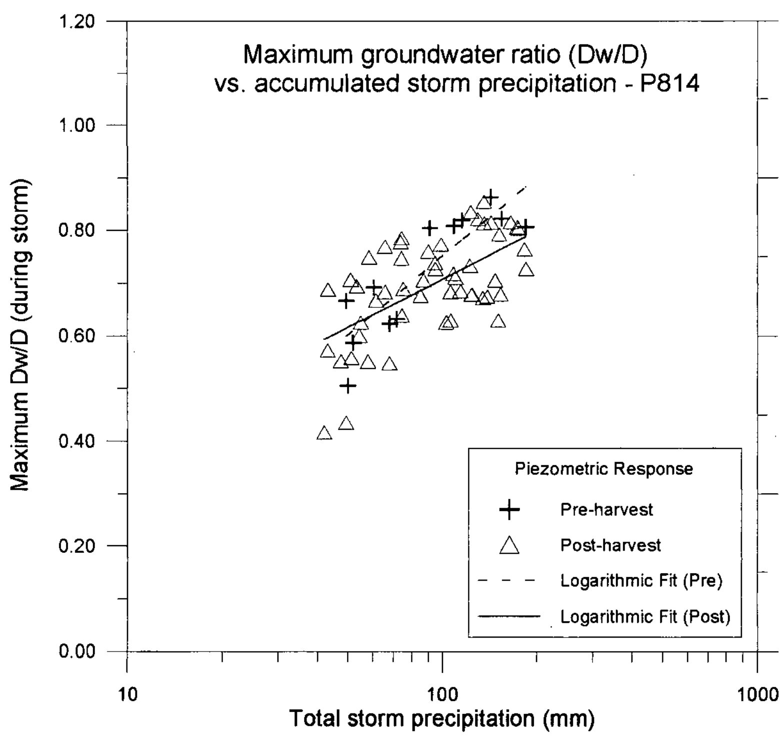


Figure 7.3 Groundwater ratio Dw/D and storm accumulation relationship P814

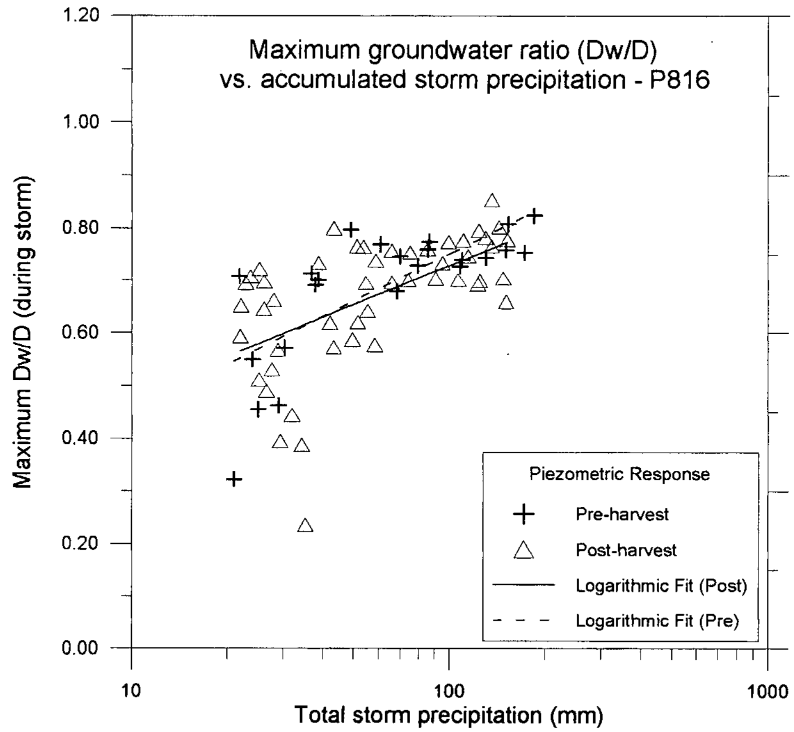


Figure 7.4 Groundwater ratio Dw/D and storm accumulation relationship P816

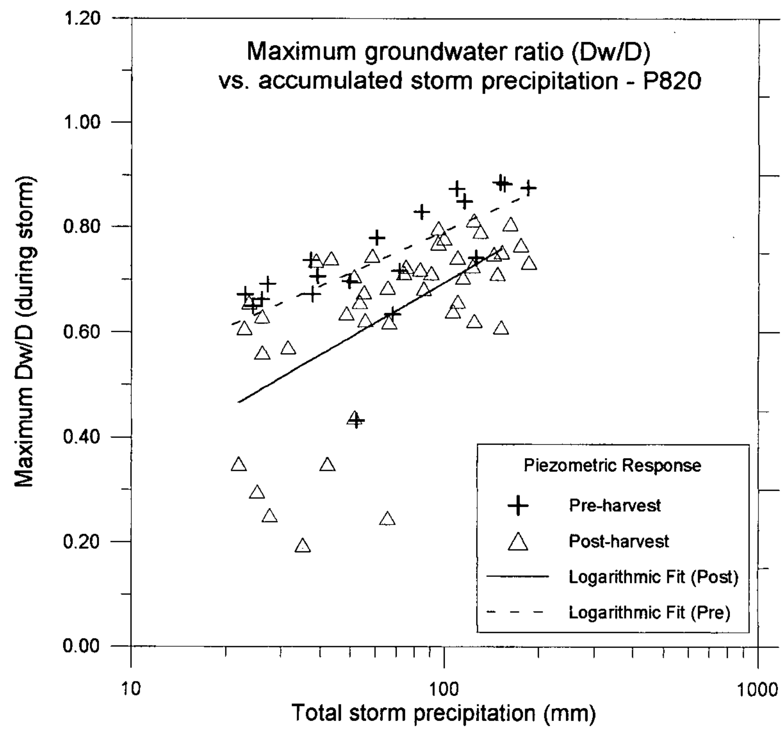


Figure 7.5 Groundwater ratio Dw/D and storm accumulation relationship P820

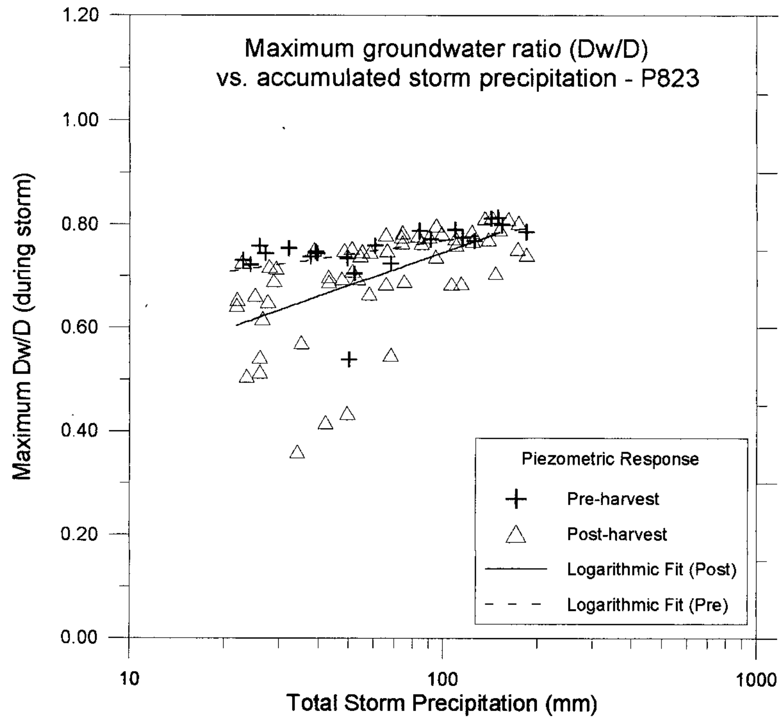


Figure 7.6 Groundwater ratio Dw/D and storm accumulation relationship P823

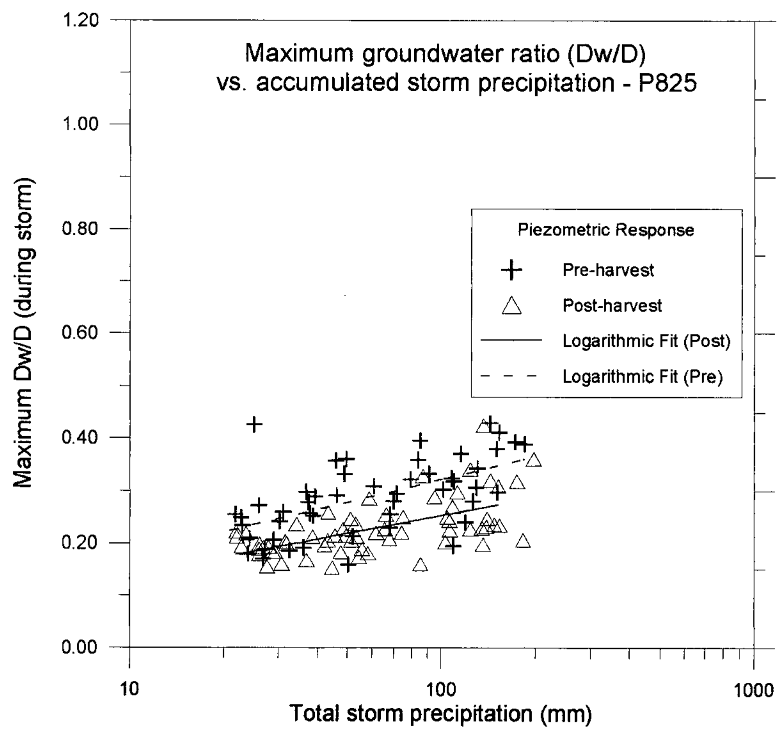


Figure 7.7 Groundwater ratio Dw/D and storm accumulation relationship P825

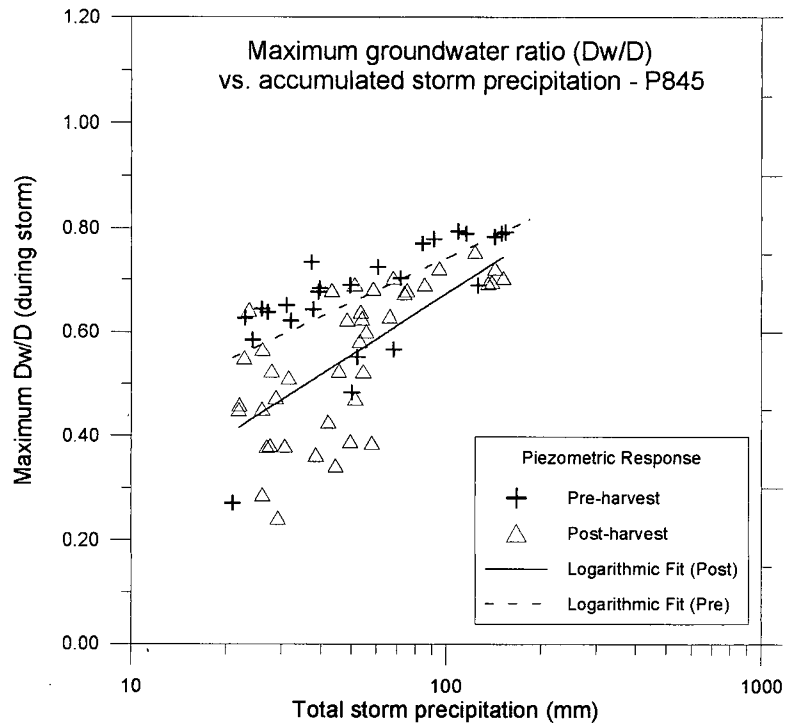


Figure 7.8 Groundwater ratio Dw/D and storm accumulation relationship P845

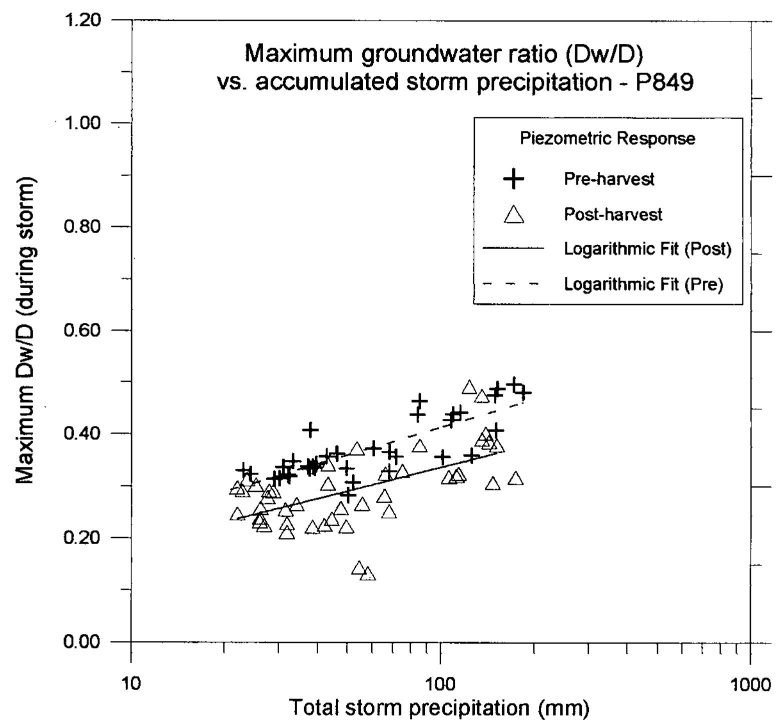


Figure 7.9 Groundwater ratio Dw/D and storm accumulation relationship P849

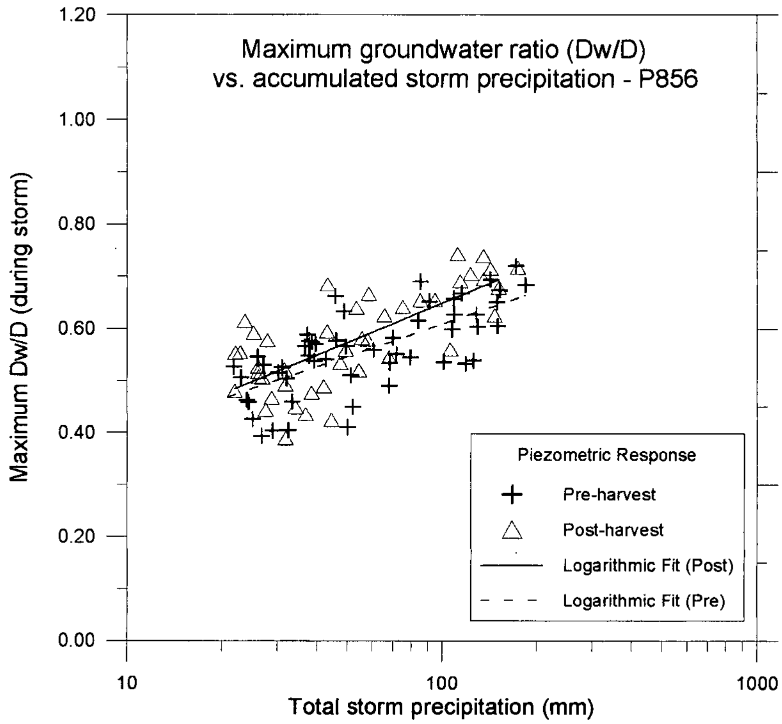


Figure 7.10 Groundwater ratio Dw/D and storm accumulation relationship P856

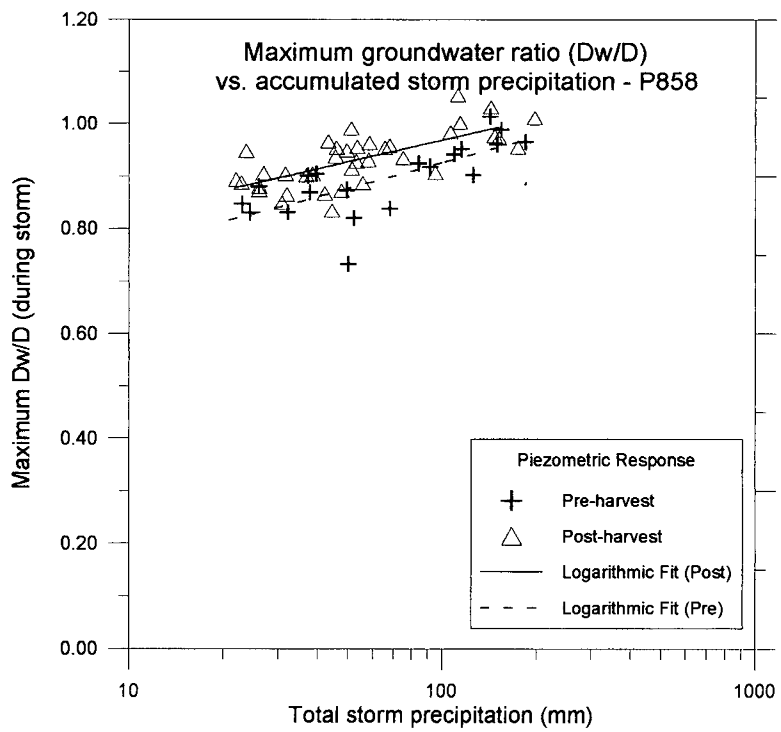


Figure 7.11 Groundwater ratio Dw/D and storm accumulation relationship P858

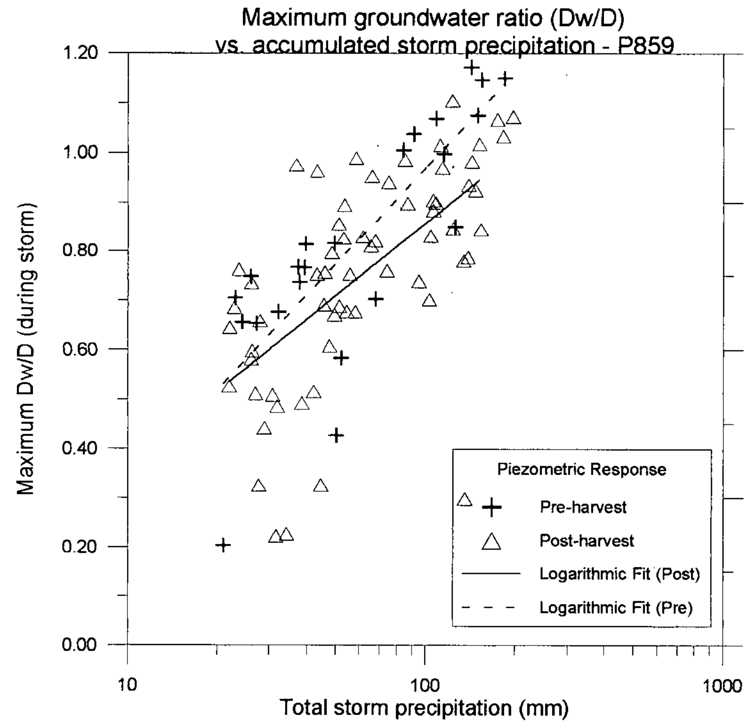


Figure 7.12 Groundwater ratio Dw/D and storm accumulation relationship P859

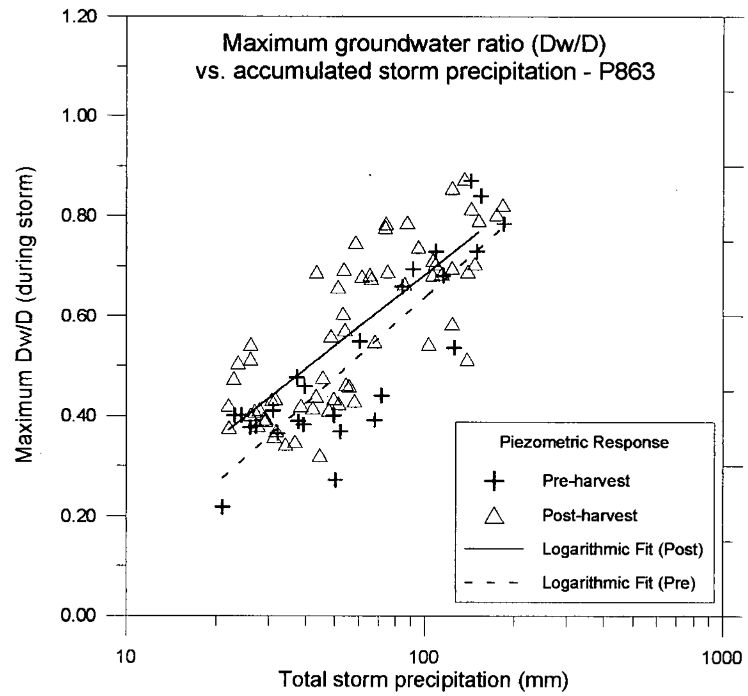


Figure 7.13 Groundwater ratio Dw/D and storm accumulation relationship P863

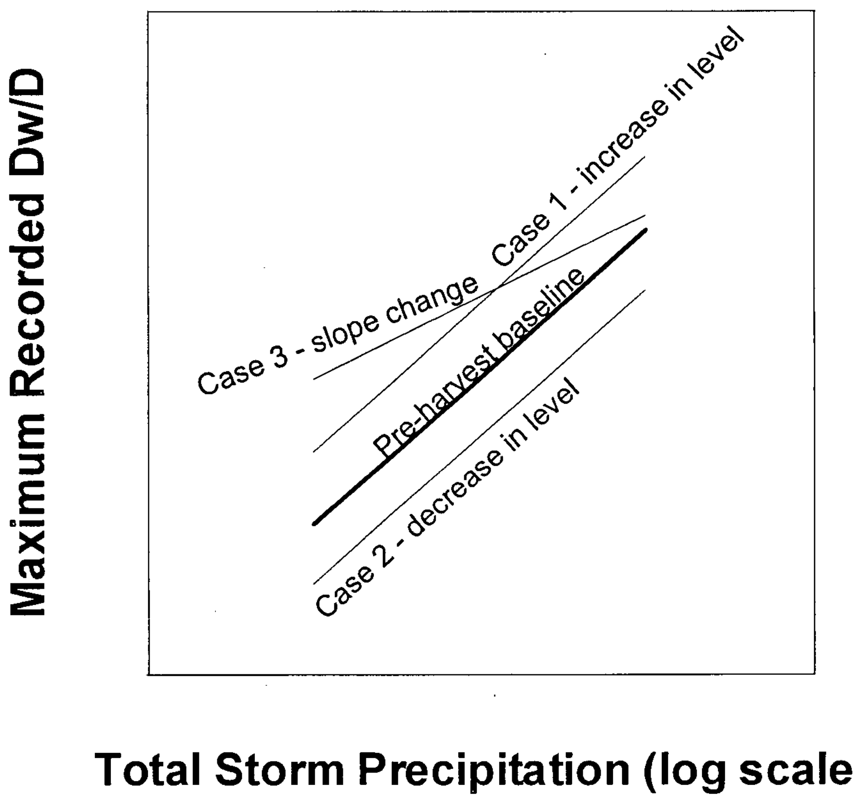


Figure 7.14 General cases of change in pre- vs. post-harvesting analysis.

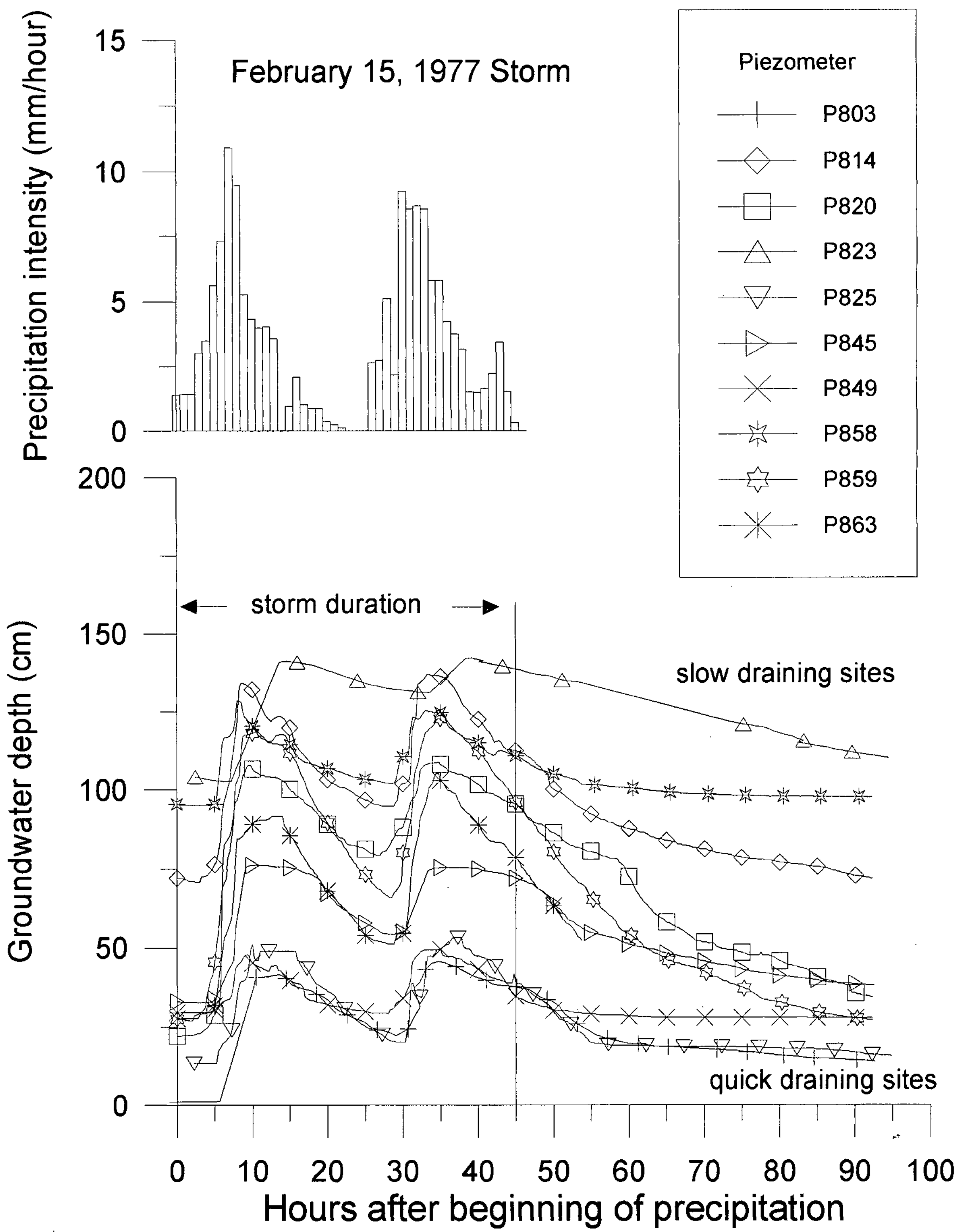


Figure 7.15 February 15, 1977 storm event – piezometric responses.

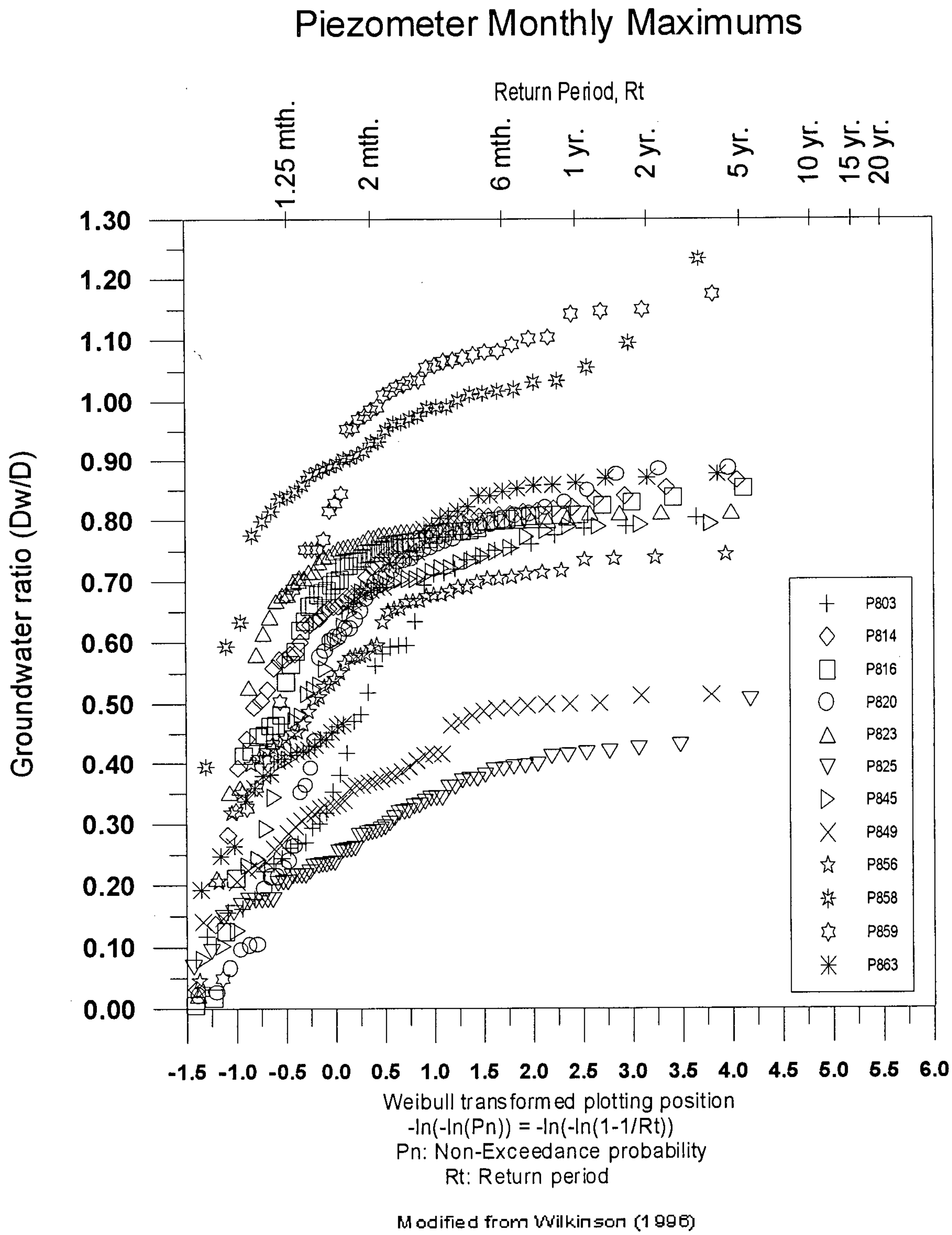
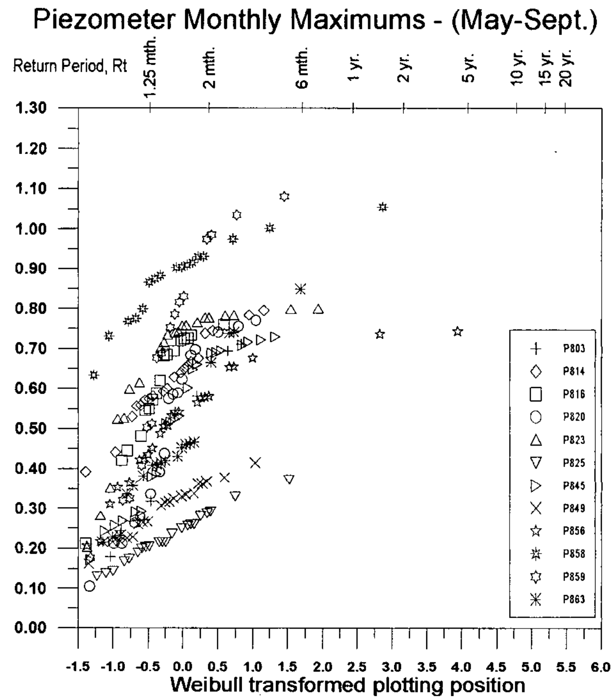


Figure 7.16 Weibull extreme value series monthly maximums for piezometers in H Watershed, Carnation Creek.

a)



b)

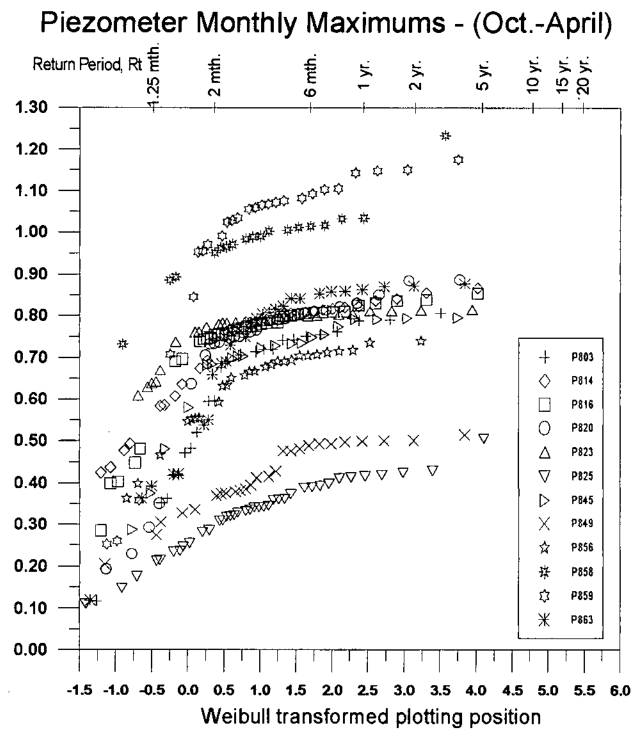


Figure 7.17 Extreme value monthly maximum series, summer & winter months.

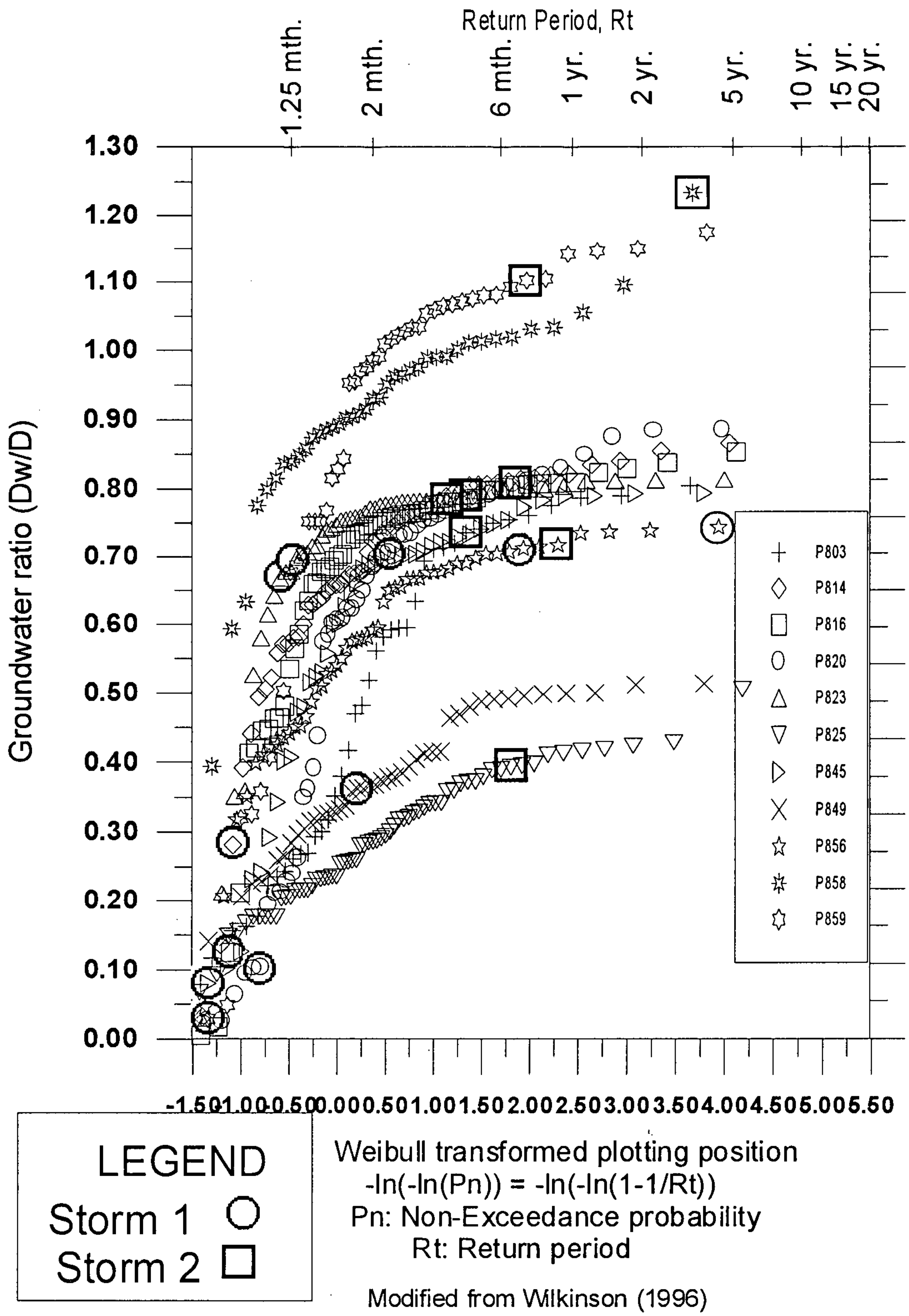
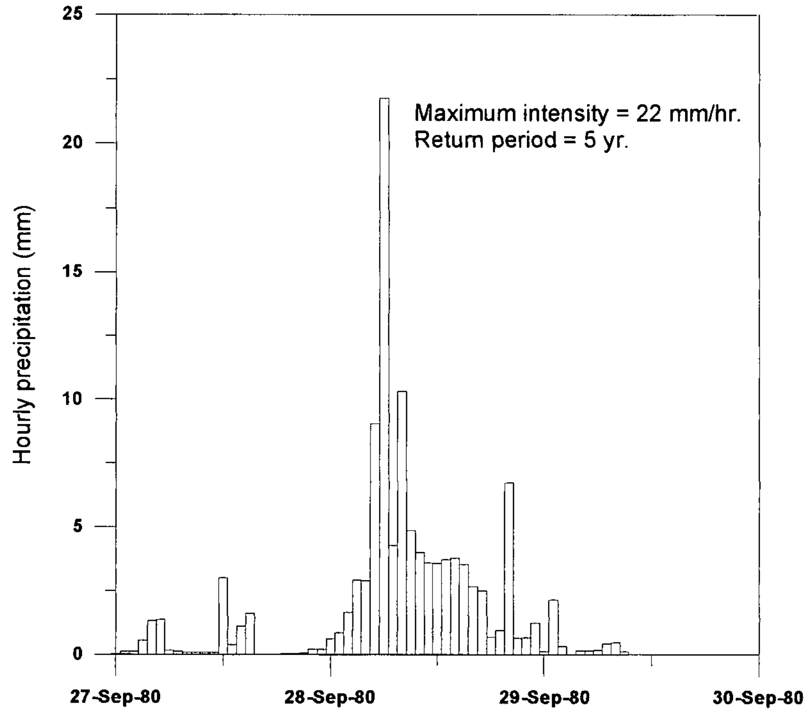
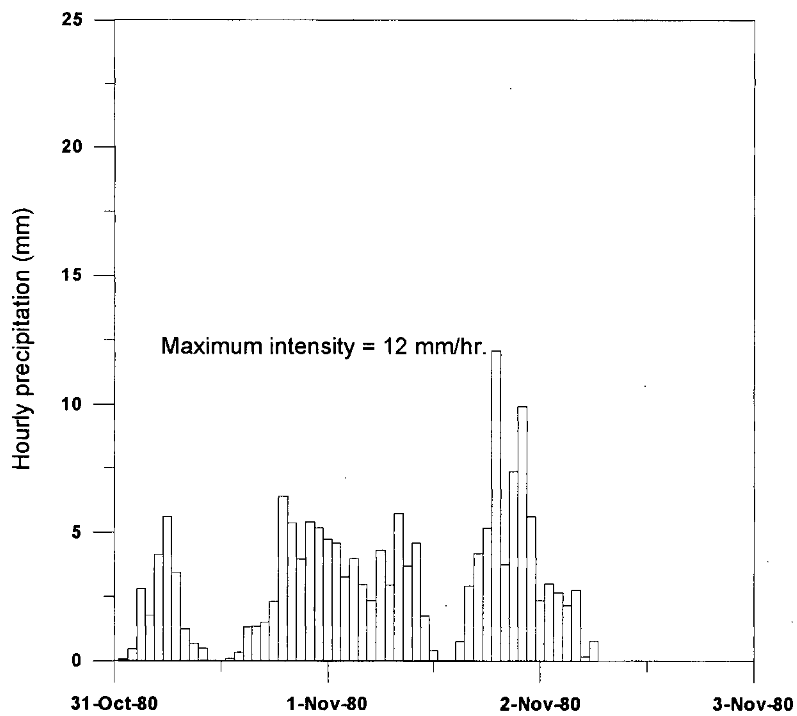


Figure 7.18 Selected storm event responses.



a) Hourly precipitation - Storm 1



b) Hourly precipitation - Storm 2

Figure 7.19 Storm events 1 & 2.

8.0 GROUNDWATER MODELING

8.1 General

The use of models for prediction of hydrologic processes and slope stability has become increasingly common at watershed scales. Modeling is gradually being accepted into terrain stability assessments of watersheds in forest practices, alongside the increasing use of Geographic Information Systems (GIS). Many models operate within GIS frameworks, using digital elevation models (DEM) created from digital elevation data, which are readily available through government ministries for large areas of the province of B.C. at scales as large as 1:20,000. Output from models can assist specialists in delineating areas of potential instability, and provide an objective, quantitative analysis of terrain stability to complement the qualitative field and office-based assessments of common to current practice. The Carnation Creek H Watershed offers a unique opportunity to apply a model to a well-studied, characteristically wet West Coast location.

The objectives of the flow modeling exercise were to see how well a topographically driven model named SINDEX (Pack, 1997), based on a simple steady state flow concept, could predict the relative levels of groundwater within a small and topographically variable watershed. Modeled output could be compared directly to recorded piezometric levels to determine the degree of accuracy the model can achieve, and determine where discrepancies arise. The exercise ran the model using a DEM created from a 1:1,200 contour map of the H Watershed. Unique to this project is that Carnation Creek is the only watershed in Western Canada that has long-term piezometric recordings with which to validate a flow model using real data. The scale of work is also larger than any other reported thus far, which tests the limitations of both creation of DEMs for this type of application and of the predictive abilities of the model. This chapter reviews several available modeling techniques, and discusses their assumptions and limitations. Following which, the SINDEX model is described, input parameters are defined, and the relevance of the output is discussed.

8.2 Review of Modeling Techniques

Several mathematical techniques have been developed to model the storm-induced build-up of groundwater on inclined slopes. Physically based techniques generally model the relationship between input to a slope and the resultant groundwater response. A few common approaches include one-dimensional (Beven, 1981; Buchanan et. al. 1990) and two-dimensional (Reddi et. al. 1990; Jackson and Cundy, 1992) finite element / finite difference and kinematic storage mass balance approaches, as described in Reddi et al., (1990) and Sloan and Moore, (1984). The level of complexity varies in approaches, and the value of the output depends greatly upon the accuracy of the input parameters. Simplified models often neglect temporally transient flow through the unsaturated zone and assume that the rate of infiltration is always greater than the rate of input, meaning any rainfall becomes instantaneous recharge to the groundwater profile. More realistic, yet complex models, consider the effects of the unsaturated zone. They incorporate changes in the rate of downward percolation through the unsaturated zone, which requires some estimate of effective porosity or volumetric moisture content (Freeze, 1969; Reddi and Wu, 1991; Jackson and Cundy, 1992). Almost all flow models described incorporate the common assumptions of uniformly constant soil depth and an impermeable subsurface layer parallel to the ground surface.

Many physically based models that use a variable contributing area to predict groundwater levels within a basin have largely been built upon work done by Beven and Kirkby (1979). Their basic flow model is driven by topographic slope and transmissivity of the soil, while lateral flux is related to the contributing area. Extensions of the topographically driven models have spawned both dynamic approaches (Grayson and Moore, 1991; Wu and Sidle, 1995), and steady state (O'Loughlin, 1986; Dietrich et. al. 1992) (Figure 8.1). The dynamic model is based upon the kinematic wave form equation proposed by Beven (1981). The benefit of using a dynamic model is that particular storms can be input into the model; a useful feature if the flow model is incorporated into a predictive slope stability model (Wu and Sidle, 1995). Difficulties in using a dynamic model at a watershed scale are that values for soil porosity and hydraulic conductivity are required. The steady state approach generally models a temporal water table equilibrium as a function of the input influx parameter and the outflow. Steady state models include the TOPMODEL model developed by Beven and Kirkby, (1979), and subsequently built upon by: O'Loughlin, (1986) with TOPOG; Pack, (1997) with SINDEX; Montgomery and Dietrich, (1996). The hydrologic input parameter into these models is a simplified value that accounts for rainfall less evapotranspiration and drainage losses into the substrata. Outflow is represented by a value of transmissivity (T) (m^2/s), which is a product of hydraulic conductivity (K) (m/s) and depth of soil (d) (m). The model assumes that small variations in soil depth and hydraulic conductivity are expected to compensate over larger areas. Complex field conditions such as varying unsaturated hydraulic conductivities and potential gradients, in addition to variation in precipitation intensity, will obviously have a great influence on the effective contribution of water. Work by Dietrich and Sitar (1997) attempts to account for natural variability of the soil profile by incorporating changes in the hydraulic conductivity with depth. This feature essentially simulates the effects of weathering of the soil profile on the ability of the soil to transmit water.

Mathematical differences in the variable contributing area concept result from the way in which the DEM is divided. Models such as SINDEX rely on a common grid-based structure as opposed to an alternate approach taken by Moore and Grayson (1991) in their development of the TAPES-C program. The TAPES-C predicts saturation and run-off by vector partitioning the input DEM topographic data into a set of interconnected elements, which in effect creates stream tubes originating from topographic peaks (Figure

8.1). The final DEM is divided into stream tubes that contain a series of irregularly shaped cells that are bound by original input contour lines and the created stream tubes. An assumption of the model is that the stream tubes are 'no-flow' boundaries, which eliminates the effect of unnatural dispersion seen with many grid based flow algorithms. Flow direction is forced to enter and exit a cell orthogonal to the upper and lower contour lines. An obvious limitation of the model is that the scale and accuracy of the contour map will entirely control the direction of flow as the cell sizes are dictated by the contour interval.

8.3 Model Selection

An attractive approach for modeling groundwater levels at a watershed scale is the use of lumped parameter models. Lumped parameters can account for spatial variability and uncertainty of parameter inputs where physical parameters are either unknown, or have only been measured in limited locations. Alongside a simplified parameter input scheme should be a mathematically sound framework which accurately takes account of the effects of converging and diverging topography on groundwater levels. The SINDEX model, developed by Pack and Tarbotan (Pack, 1997), was chosen for this project based upon its ability to meet the set criteria. The model was developed as a slope stability predictive tool, within which is a hydrologic flow modeling component. The flow modeling is based upon the assumptions and framework developed for TOPMODEL (Beven and Kirkby, 1979) and subsequent TOPOG (O'Loughlin, 1986) models. All of these models use the surface topographic expression to route flow downslope, assuming the subsurface hydrologic boundary parallels the surface. All of the models assume a uniform soil thickness and hydraulic conductivity. The SINDEX model is controlled by only a few simplified inputs: T (transmissivity) (m^2/s), q (m/s) (a precipitation input which accounts for evaporation, evapotranspiration, and bedrock infiltration), slope gradient (θ), which is determined from the DEM, and contributing area (a) (m^2/m), also calculated from the DEM. An attraction of the modeling approach is that it allows for simplification of parameter inputs for the H Watershed that are only partially known. Output from the flow component of the model gives a measure of groundwater level, or "relative wetness" for each grid cell of the DEM, defined as

$$W = q\ a/T \sin\theta \qquad (8.1)$$

The relative wetness represents the steady state equilibrium of groundwater for each grid cell based on the given input parameters. Values range between 0 and 1.0, where 1.0 represents 100% saturation of the soil profile. Once 100% saturation is exceeded, the model assumes overland flow. The only flow-controlling model input requirement is an upper and lower bound ratio for T/q. The range in ratio is intended to address some of the uncertainty of parameter inputs, and to cover conditional overland flow scenarios. For example, if a grid cell is calculated to exceed a relative wetness of greater than one for both the upper and lower T/q input values, a value of 3 is output. If overland flow is predicted for the lower bound of T/q, but not the upper, a value of 2 is output.

Unique to the SINDEX flow model, is a recently developed algorithm called D∞ (Tarbotan, 1997). The routine is used for representation of flow direction and calculation of upslope contributing area using a rectangular grid based DEM. Among the advantages of the internal algorithm are that it is not limited in potential flow directions, limits unnatural flow dispersion between grid cells, and avoids grid bias. Conceptually, the D∞ algorithm provides an improvement over other commonly used methods such as the D8 (Tarbotan, 1997) in the sense that water routing within cells is free from directional restrictions.

8.4 DEM Creation

Made available for the H Creek study area was a 1:1,200 contour map with a 2 m contour interval, providing a highly detailed topographic base for the flow model work. To create a DEM, each contour line of the 1:1,200 scale map area was digitized using AutoCAD at intervals ranging from 2 mm for detailed surface features and steeper slopes, to 10 mm for shallower slopes. The resulting map data was a series of points with X, Y, & Z coordinates, that were then converted to a surface grid using Quicksurf ver. 5.1 (Schreiber Instruments, 1994). The grid format was converted and imported into the Global Information System (GIS) program ArcView Spatial Analyst (ESRI, 1996). The SINDEX program has been developed to operate as a series of scripts within the Spatial Analyst extension and allows for the application of a suite of GIS functions. Two DEM grids were created for the H Watershed area, one at a 2 m grid cell size, and the other at 5 m. An annotated contour map extrapolated from the 2 m DEM grid is shown in Figure 8.2, which closely resembles the original contour map (Figure 6.1). The 2 m grid was intended to capture highly detailed surface features, and represents the smallest size of grid cell that can be accurately used, based upon the contour interval of the original map. The larger 5 m grid was tested against the results from the 2 m trials to assess the sensitivity of the model to grid size.

After several trials of running the model, it became evident that the contours that defined the road prism and minor through-cuts completely controlled the flow routing, resulting in unnatural representation of water flow. A major assumption of the flow model is that the surface topography reflects the subsurface impermeable boundary. In the case where the topography defines a constructed road prism, the model assumption falls short. Problems arise because algorithms for calculating flow direction from one cell to another use the steepest gradient. Where a cell falls entirely within topography defining the road surface, the majority of water would route directly down the road grade. Where the road passed through minor through-cuts, no water would pass over the road surface. These conditions would partially hold true in nature, where water intercepted by ditchlines will typically route down the road grade, but eventually pass under the road through a culvert. Groundwater which passes under the ditchline, through culverts, or precipitation that infiltrates the road bed, would likely move downslope rather than in the direction of the road. It is this water that must be accounted for in modeling. To alleviate the effect of road controlled water, some of the contours defining the crest of the road fill were modified slightly to allow flow to partially pass across the road surface. The resulting topographic model is akin to a partially deactivated road surface with a less pronounced flat surface. The original topographic map also masks where obvious culverts would be located. Where a natural draw passed through a road, the contours of the road were shifted to create a drainage pathway mimicking the effect of a culvert.

Inherent in the algorithms used to calculate flow is the requirement of topographic drainage divides. If a divide is not defined on the modeling area, much of the area downslope of the missing divide cannot be used in the modeling calculations. In the case of the H watershed, not all of the divides are defined on the 1:1,200 map sheet. For some key areas of interest, topographic drainage divides were extended artificially within the DEM to make the flow model work. Extrapolated divides were verified by consulting air photos and a 1:5,000 topographic map.

8.5 DEM Discussion

A major consideration when creating a DEM for grid based modeling is the choice of grid cell size. Zhang and Montgomery (1994) analyzed the effect of grid cell size on the portrayal of land surfaces and hydrologic simulations. Their research evaluated the effects of varying grid cell size from 2 m to 90 m on the output of TOPOG (O'Loughlin, 1986) and TOPMODEL (Beven and Kirkby, 1979). Base maps for their study included 0.3 km^2 and 1.2 km^2 areas, using 6 m and 5 m contour intervals, respectively. Findings from the study suggest that little difference in resolution and model output is noted between trials with 2, 4, and 10 m grid cells. The lower bound of grid cell sizing is limited by the spacing of original data used to create the DEM. The scale of aerial photography and amount of spot elevation data collected during creation of the original map also limit sizing. Considering the scale of the base maps and contour intervals used by Zhang and Montgomery, the 2 m and 4 m grids would have required excessive extrapolation. Hence, a balance should be reached between a minimum size that is reasonably extrapolated, and a maximum size beyond which accuracy is compromised.

The H Watershed is small area (0.12 km^2) and has been mapped in greater detail (2 m contour interval) than the other studies discussed thus far. Grid cell sizes of 2 m and 5 m were tested on the study area. Both sizes had certain merits and problems. Using the smaller of the two created a far more detailed DEM, which in turn created a detailed road surface leading to flow routing problems. Furthermore, the 2 m grid may be too small in areas of low slope gradient where input data is sparse, resulting in excessive extrapolation of the DEM. It became evident that the 5 m size lacked accuracy in modeling flow in some sensitive areas such as draws. The coarse grid cell size resulted in overestimation of the size and extent of natural drainage pathways. It was decided to utilize both grid sizes in all of the analyses to determine the sensitivity of the output to grid sizing.

8.6 Strategy for Comparison of Recorded vs. Predicted Groundwater Levels

To meet the objectives of the modeling exercise, modeled relative wetness output derived from a range of input T/q values was compared with observed maximum piezometric levels from the Carnation Creek H Watershed database. The T/q value that resulted in a 'best-fit' to the observed piezometric levels was sought in order carry out relative wetness and slope stability calculations for the entire watershed area. To determine the single most accurate input value, the modeled output value for wetness index (W) was recorded for the DEM grid cell corresponding to the known piezometer locations. Also recorded for each piezometer location were the calculated contributing area (a) and slope gradient (θ). For the 2 m grid, calculated output values for the grid cell corresponding to the piezometer location, as well as the eight connected perimeter cells, were also recorded to determine an average response from a 6 m x 6 m square zone. Averaging cell recordings at the smaller grid cell size was carried out to account for some of the uncertainty in the exact location of the piezometers, and address the high variability of calculated values from cell to cell. For example, at some piezometric locations, the wetness index (W) may register a relatively low 0.15 or 15% saturation, while the adjacent cell would register a wetness index (W) of 3 (permanently saturated) on a slope section which would be considered uniform.

A range for the groundwater input parameter T/q was attained by considering the known and estimated parameter values. Soil depth (d) was taken as an average based upon the documented depths of installation at the piezometer locations. Measures of hydraulic conductivity (K) are taken from reported values for the area (Hetherington, 1995), along with values documented according to soil texture (Craig, 1992). The values reported by Hetherington (1995) represent maximum recorded in-situ test values measured for groundwater flow over bedrock near the H Watershed area. Hydrologic input flux is conservatively estimated from 5-year return period recorded precipitation intensities for 6 and 12-hour storms. Calculated ranges are given in the table below:

Table 8.1 T/q Parameter Input Ranges

T (transmissivity = Kxd)		q (input flux) (mm/hour)	T/q (m)	
K (m/s)	d (m)		min ($=K_{min}d/q_{max}$)	max ($=K_{max}d/q_{min}$)
$K_{max} = 1.67x10^{-2}$ [i] $K_{min} = 10^{-4}$ [ii]	1.5 [iii]	$q_{max} = 13$ [iv] $q_{min} = 10$ [v]	41	9017

[i] Hetherington, 1995
[ii] Craig, 1992
[iii] average watershed value
[iv] taken from precipitation IDF curves – 5-year return period 6-hour maximum (Figure 3.5)
[v] taken from precipitation IDF curves – 5-year return period 12-hour maximum (Figure 3.5)

Notable is the significant variation between the T/q_{min} and T/q_{max} calculated values. Variation is largely a result of the uncertainty of the values for hydraulic conductivity input, which Hetherington (1995) showed can vary by orders of magnitude across small areas. If the minimum of five recorded values for in-situ hydraulic conductivity was used, rather than the reported maximum, the minimum T/q ratio would increase by an order of magnitude. A range of input parameters, based upon the range calculated in Table 8.1, were tested in the SINDEX program. Figure 8.3 shows a sensitivity plot of the calculated Wetness Index (W) at each piezometer location for a number range of input values. Figure 8.3 serves to graphically display the sensitivity of the calculated Wetness Index (W) to T/q, and provides a basis to narrow the range of T/q values for the comparative component of the modeling exercise. For example, T/q values greater than 2000 result in modeled relative wetness (W) of less than 0.30 (30% soil profile saturation) at all of the corresponding piezometer locations. It is known that many of the piezometers regularly record groundwater levels in excess of 70% ($D_w/D > 0.7$, Figure 7.17) of the soil profile thickness. Therefore, the effective range of T/q values for the H Watershed is limited to values less than 2000.

The observed piezometric levels chosen for comparative purposes are the 5-year return period maximums for each piezometer from Figure 7.17. In most cases, the 5-year return values represent the maximum, or close to the maximum level that the piezometer had reached during the recording period, and the maximum length of record for most of the units. For each piezometer, the 5-year return period values are not necessarily induced by the same storm event (discussed in Chapter 7.4), but the model is not intended to be storm specific. It is the maximum levels of groundwater that are considered critical in a predictive slope stability tool.

Because the model assumes a uniform soil depth throughout the watershed, two approaches can be used to compare the recorded piezometric vs. the modeled values. Either the modeled Wetness Index can be multiplied by the assumed modeling depth and compared directly to measured groundwater levels, or the recorded piezometric groundwater depths can be normalized to the assumed modeling depth and compared to the Wetness Index ratio. The latter of the options was chosen, resulting in a normalized recorded piezometric ratio given as 'D_w/D_m', where D_w is the depth of water, and D_m is a uniform modeling depth of 1.5 m. The value of 1.5 m was chosen as it is a reasonable estimate of average soil depth, and normalizes all groundwater recordings to less than unity. Although pressures in excess of hydrostatic were recorded at some piezometers, SINDEX cannot model values of saturation in excess of hydrostatic pressure. It simply indicates that overland flow will occur.

8.7 Comparative Results

Modeling trials using T/q values of less than 2000 revealed that a T/q of 500 provides the best-fit between the predicted and observed values. The T/q value of 500 is close to the minimum of the T/q range in Table 8.1, indicating that conservatively low hydraulic conductivity or high input flux are required. Figure 8.4 indicates that for many of the units, the Wetness Index predicted by SINDEX using T/q of 500 does not represent the selected normalized recorded piezometric levels. This is shown by the fact that only 5 of the 12 piezometer location data points are close to the 1:1 line of predicted vs. observed values. The other 7 units that show poor correlation are grouped into either very high predicted wetness (P820, P845, & P825), or very low calculated values for most T/q ratios (P858, P823, P859, & P863). The group predicted to be very high have modeled to have overland flow, but have been plotted with a wetness of one for simplicity. A discussion of the two outlying data point groups follows in Section 8.10.

8.8 Relative Wetness and Slope Stability Index Output

Using the T/q ratio of 500, which best represents the observed 5-year return period groundwater levels, relative levels of wetness and slope stability of the H Watershed were modeled. The relative wetness calculations are given in Figures 8.5 and 8.6, representing a 2 m and 5 m grid, respectively. Blank white areas on Figures 8.5 and 8.6 within the map boundary are a result of zones where upslope drainage divides are not defined (as discussed in section 8.4). Piezometer locations used in this study all fall within the areas that can be modeled.

The SINDEX model was designed as a mapping tool for identifying areas of potential slope instability. To carry out the slope stability calculations, values for saturated soil density ρ_s, and strength parameters ϕ (angle of internal friction) and c (cohesion), accounting for soil and root cohesion, are required. In the same way that input values of T/q must be calibrated to match field conditions, the strength parameters must be calibrated until the SINDEX output matches the observed areas of landsliding. By matching the predicted areas of instability with the known areas landslides, the user is able to identify other landslide prone areas from the output.

This thesis is primarily concerned with the evaluation of the groundwater component of SINDEX, but stability calculations of the H Watershed area were performed to illustrate the final output of the model. The model was run with input parameters of $\rho_s = 18$ kN/m^3, $\phi = 45°$, and cohesion = 0.25 (dimensionless, where 0 = no cohesion and 1 signifies that cohesion alone would hold the soil at a 90°) along with a T/q of 500. The SINDEX output predicted large areas of instability (Figure 8.7 & 8.8). This value of T/q = 500 represents an approximation of the highest 5-year return period groundwater levels and the resulting stability of slopes. Two landslides that did occur during the recording period at Carnation Creek are shown on Figure 8.2. The locations of the slides are not within the most critical areas, indicated as *Defended* on Figures 8.7 and 8.8. Drainage altered by roads and/or surface disturbance leading to altered groundwater flow patterns are believed to have been factors in the initiation of the slides, making them unrepresentative events to use in calibration of the stability model.

Attempting to model the slope stability of the H Watershed using parameters chosen to fit extreme recorded groundwater levels has produced conservative results. In terms of uncertainty, groundwater level variability far surpasses the variability of soil strength parameters within a watershed area. Consequently, without a mathematically sound and physically representative flow model, slope stability ratings would have little physical significance.

8.9 Discussion and Conclusions

Working at such a large scale with detailed field records allows for critical analysis of predicted vs. observed values of groundwater ratio. In particular, the two outlying groups of piezometers, as alluded to in Section 8.7, present interesting modeling challenges. The piezometer locations calculated to have a very high wetness index, yet low observed groundwater levels, are all in locations with high calculated contributing areas but have physical field restraints on the groundwater maximums. The plotted positions of P845 and P825 suggest that there is a poor relationship between the maximum groundwater levels and contributing area, which largely controls the Wetness Index. These two locations may in fact have a capped field condition, as discussed in Section 7.4.2. Those data points that have a very low predicted Wetness Index, yet high observed groundwater levels (P823, P858, P859, & P863) suggest that either the calculated contributing area is erroneous, or that the topographic expression is not a sufficiently accurate basis for distributing flow. In the case of P859 and P863, the DEMs at both the 2 and 5 m scale are very sensitive to a slight topographic 'nose', or protrusion, approximately 10 meters upslope of P859. The effect of the nose is that the flow routing algorithm diverts water entirely around the surface feature, resulting in low contributing area for the piezometer locations downslope of the feature. The low contributing area results in a low Wetness Index (W) as they are directly related (Equation 8.1). However, observed piezometric levels showed that the groundwater levels reach high maximums on a regular basis at these locations. This discrepancy suggests that surface feature may not always be an adequate representation of the underlying bedrock profile. Furthermore, there may be other subsurface flow features such as macropores directing water into these locations.

Modeling of the transect of P845, P847, and P849 (Figure 6.1) also reveals the sensitivity of the flow routing algorithm to slight changes in topography. The units are within 35 m of one another on a relatively uniform slope, yet the calculated contributing areas, particularly for the 2 m grid DEMs range considerably between the units as shown in Table 8.2.

Table 8.2 Contributing areas for select piezometers

Piezometer	Contributing area (m^2/m) 2 m grid	Averaged contributing area* (m^2/m) 2 m grid
P845	418.6	290.5
P847	138.9	142.4
P849	178.6	148.3

* for piezometer location and 8 surrounding grid cells

Visual analysis of the original contour map suggests that there should be little difference between the three sites in terms of contributing area. It is possible that unnatural dispersion of flow between grid cells impacts the piezometer locations that register higher contributing areas. The rankings of the calculated Wetness Index and contributing areas do not match the rankings of the observed groundwater levels between the three units.

Calibration of the groundwater modeling component of SINDEX model requires selection of appropriate parameters to ensure modeled output is a reasonable representation of the observed field conditions. A difficulty with the calibration process is that the modeled output has also been shown to be grid cell size dependent at most of the piezometer locations. Visual assessment of Figures 8.5 and 8.6 reveals that a larger percentage of the terrain is reaches a higher Wetness Index using a 2 m grid. Significant differences between the modeled outputs at the piezometer locations of the 2 m and 5 m grid cell sizes were found. It is recognized that these differences represent the output for a single grid cell (piezometer location), whereas the model is designed to assess large areas. The modeled differences may be a result of variability of output from one cell to another, as discussed earlier in Section 8.5

Although it has been shown that grid size partially dictates the accuracy of the final DEM to be used, accuracy can be gained in the establishment of more precise original elevation data. Researchers working with, and developing models are generally of the consensus that for the models to be effective and more reliable, more accurate and higher resolution topographic data are required (Dietrich and Sitar, 1997; Pack, 1997). Topographic maps have been created by interpretation of air photos and known spot elevation marks for tens of years. Considerable deviation from the true ground surface is to be expected, particularly at smaller scales where the contour intervals become so large that topographic features that may control groundwater become masked. The advent of laser topographic mapping shows great promise in improving the accuracy of at least the true surface elevation input data. Greatest gains in modeling with laser derived topographic maps would likely be made at smaller scales (i.e. 1:20,000 or smaller), where a grid size of $20m^2$ is quite common due to the large 20 m contour intervals.

The SINDEX model has been designed to provide a tool for reconnaissance stability assessments of larger areas, such as at a scale of 1:20,000. Pack (1997) suggests that the SINDEX model can be used at a scale of 1:5,000 in TSIL B/C (BCMoF, 1995) mapping. Also suggested by Pack, was manually delineating areas of concern that smaller scale DEMs (1:20,000) might miss, and inputting them separately into the GIS landslide inventory. By doing so, the user could add to the predicted areas of concern. This approach would allow qualitative input by a terrain mapper into the computer based deterministic output.

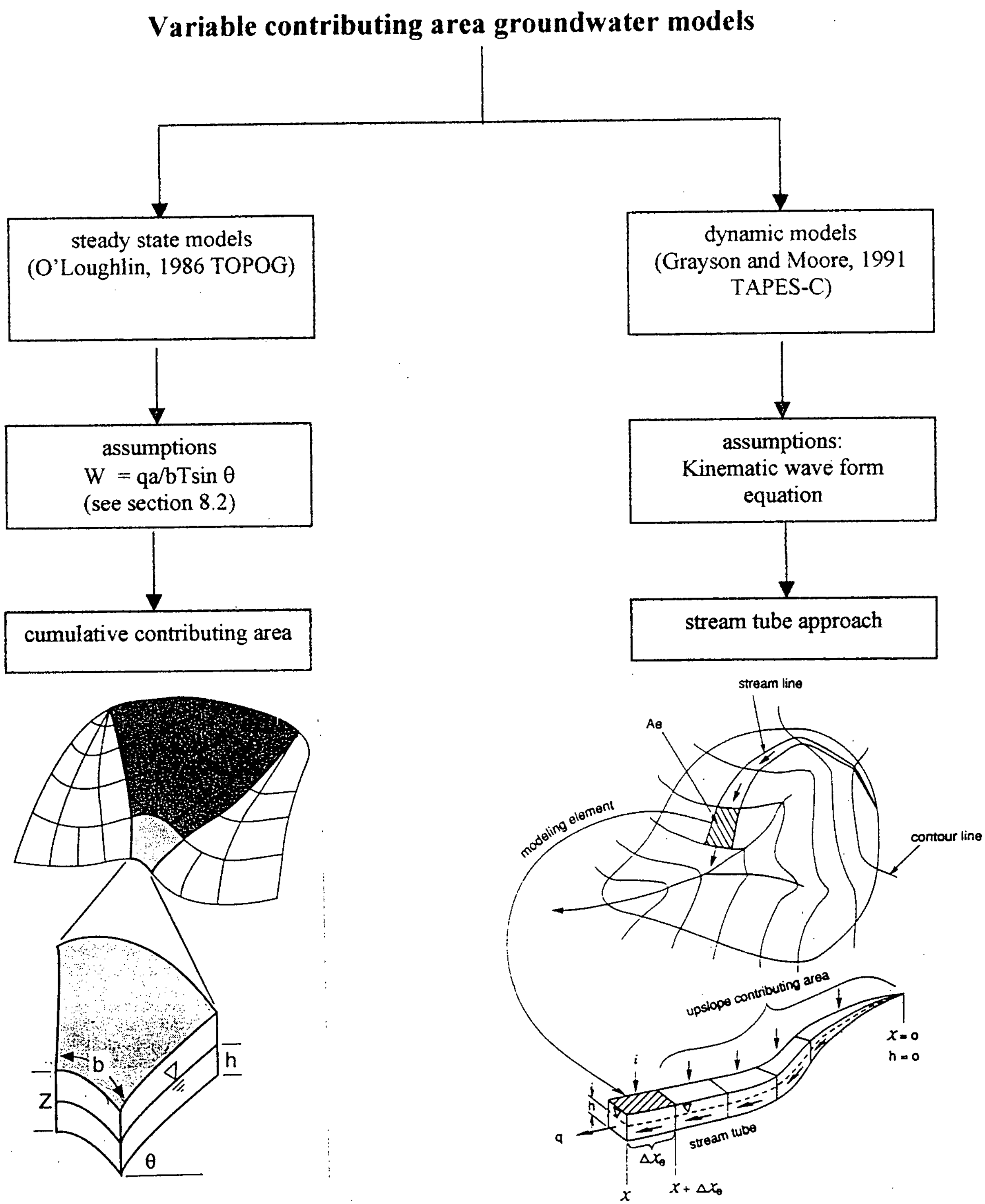


Figure 8.1 Examples of two topographically driven variable contributing area groundwater flow models

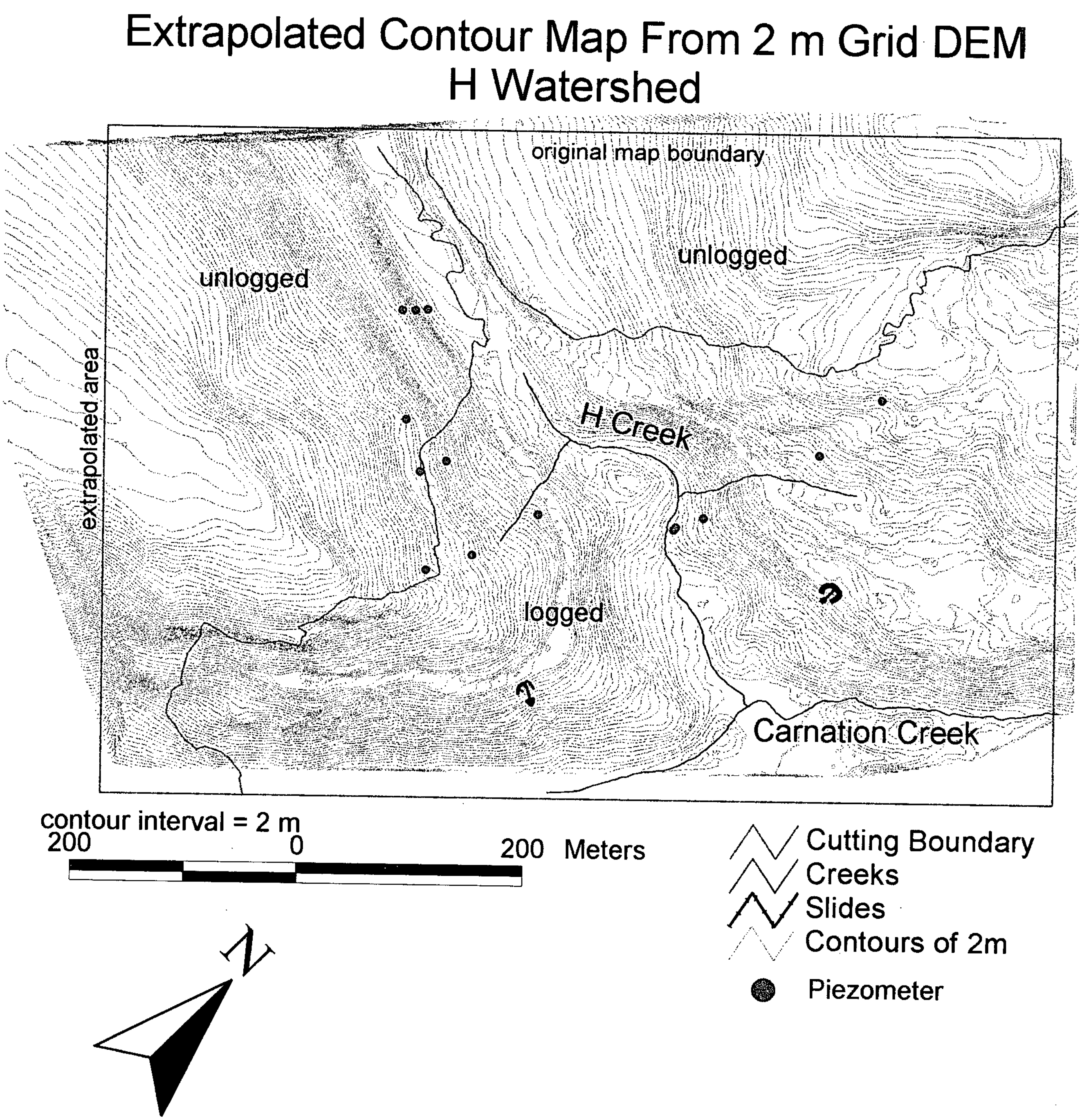


Figure 8.2 SINDEX output – extrapolated contour map (2 m grid)

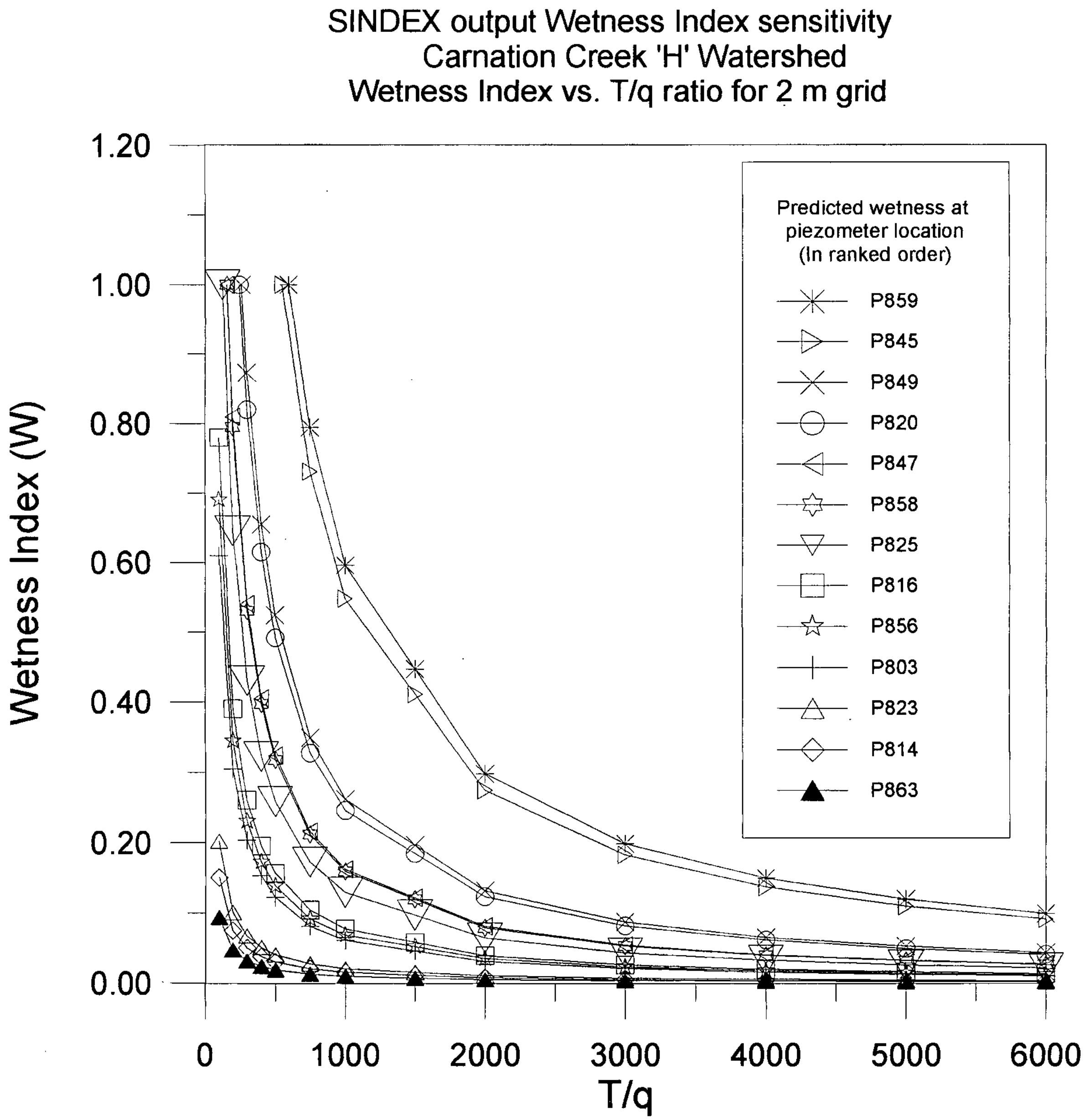


Figure 8.3 Sensitivity plot of SINDEX output to T/q ratio at piezometer locations.

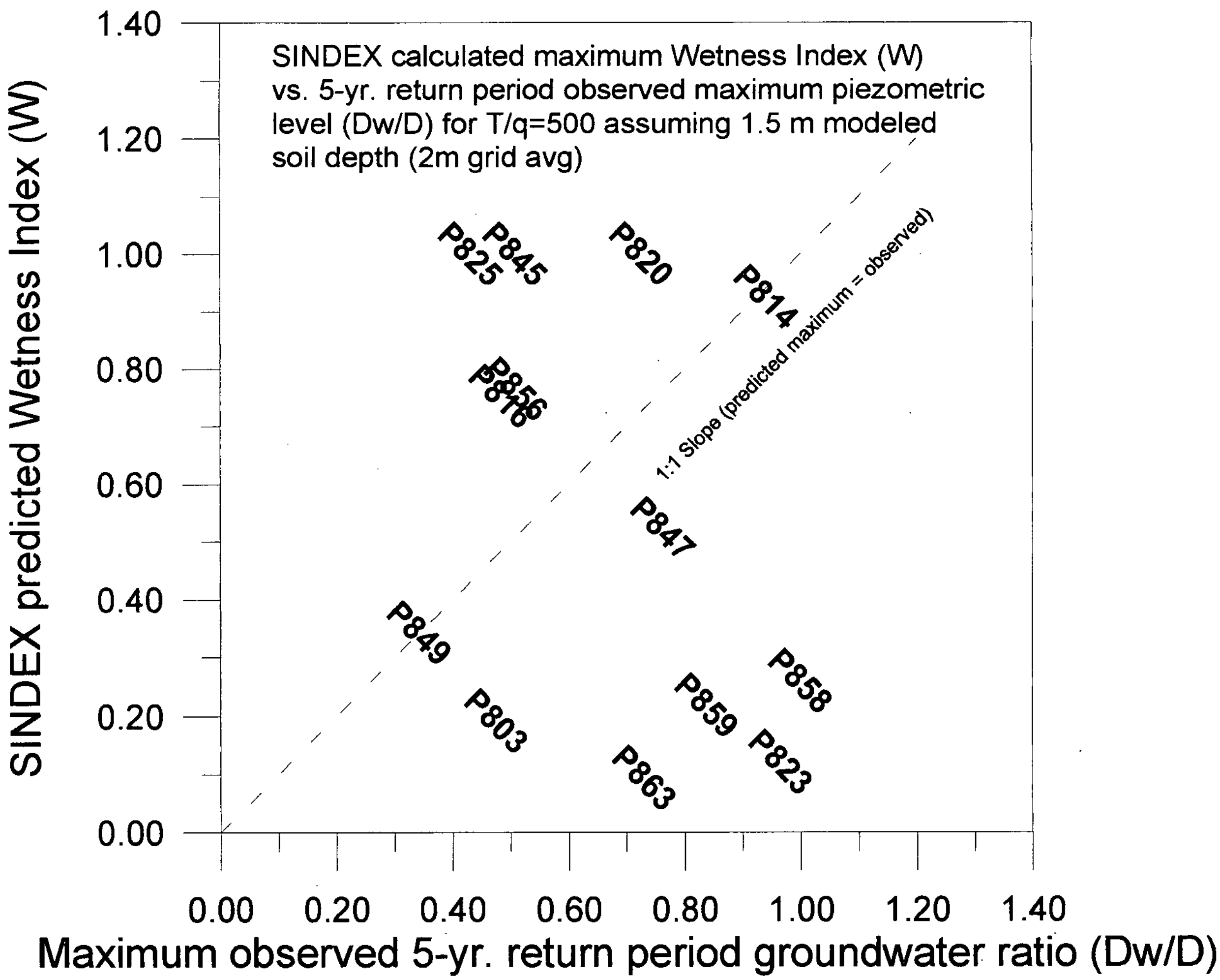


Figure 8.4 Comparison of modeled groundwater ratio to observed groundwater ratio.

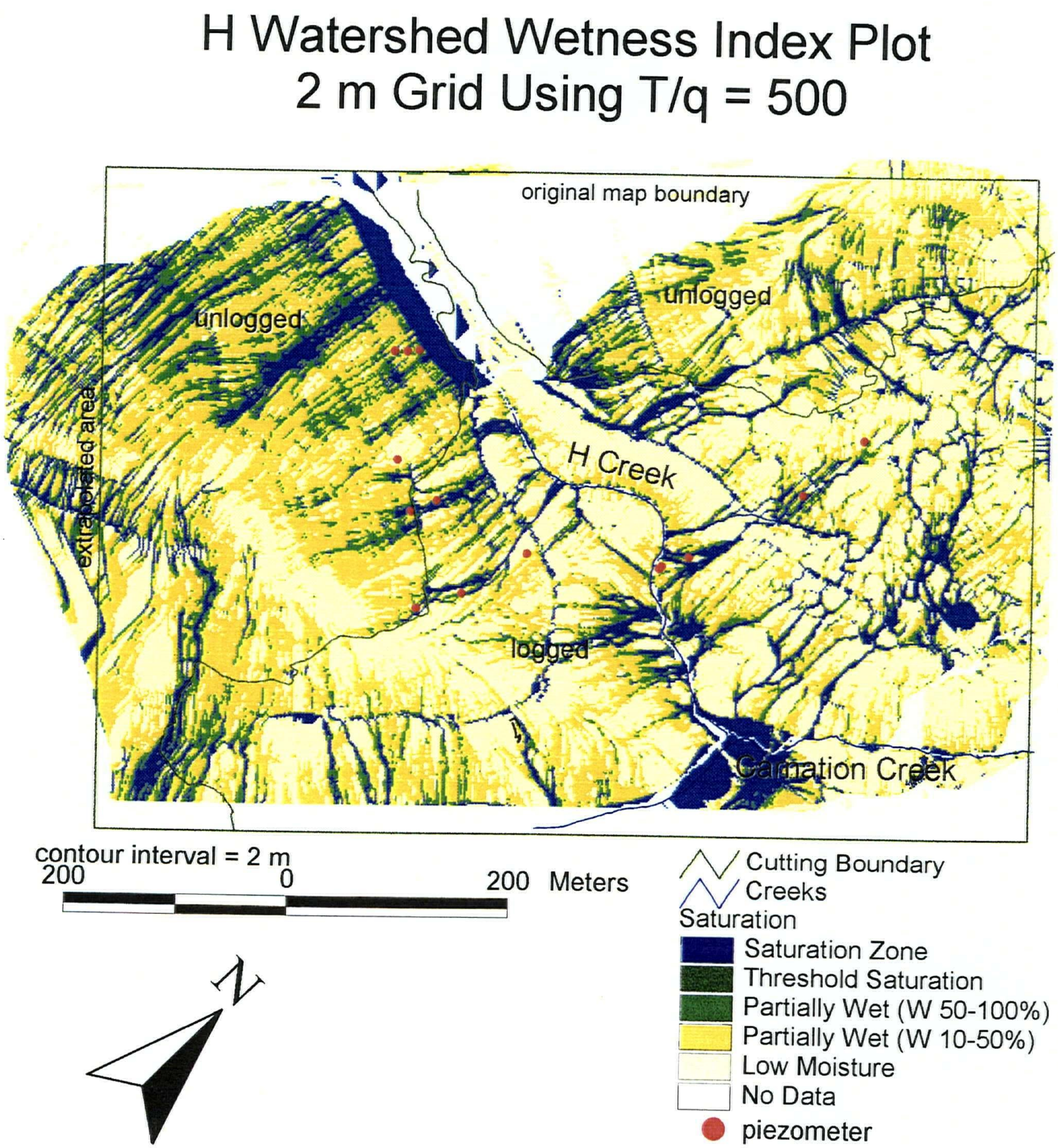


Figure 8.5 SINDEX output – wetness index (2 m grid)

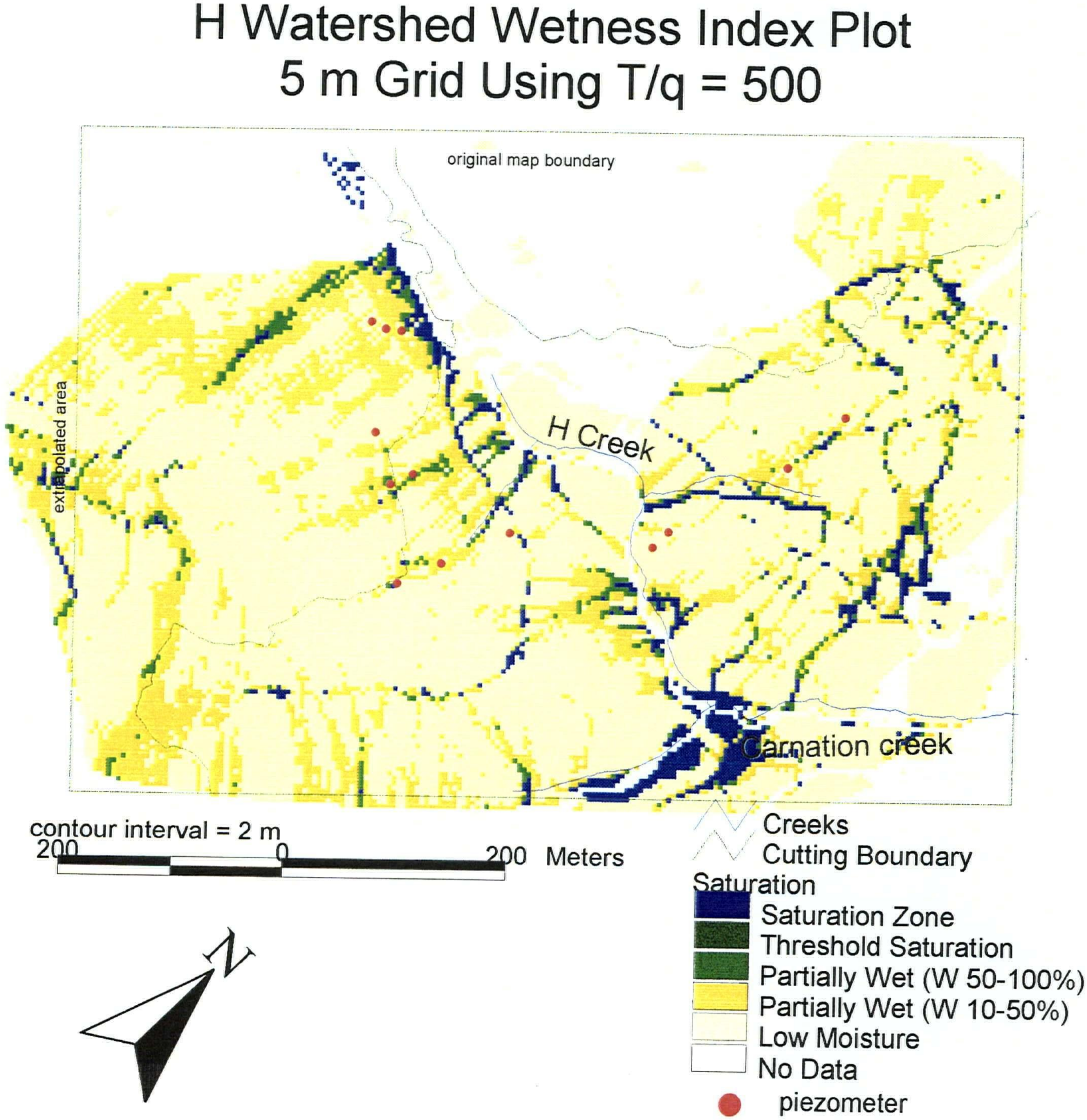


Figure 8.6 SINDEX output – wetness index (5 m grid)

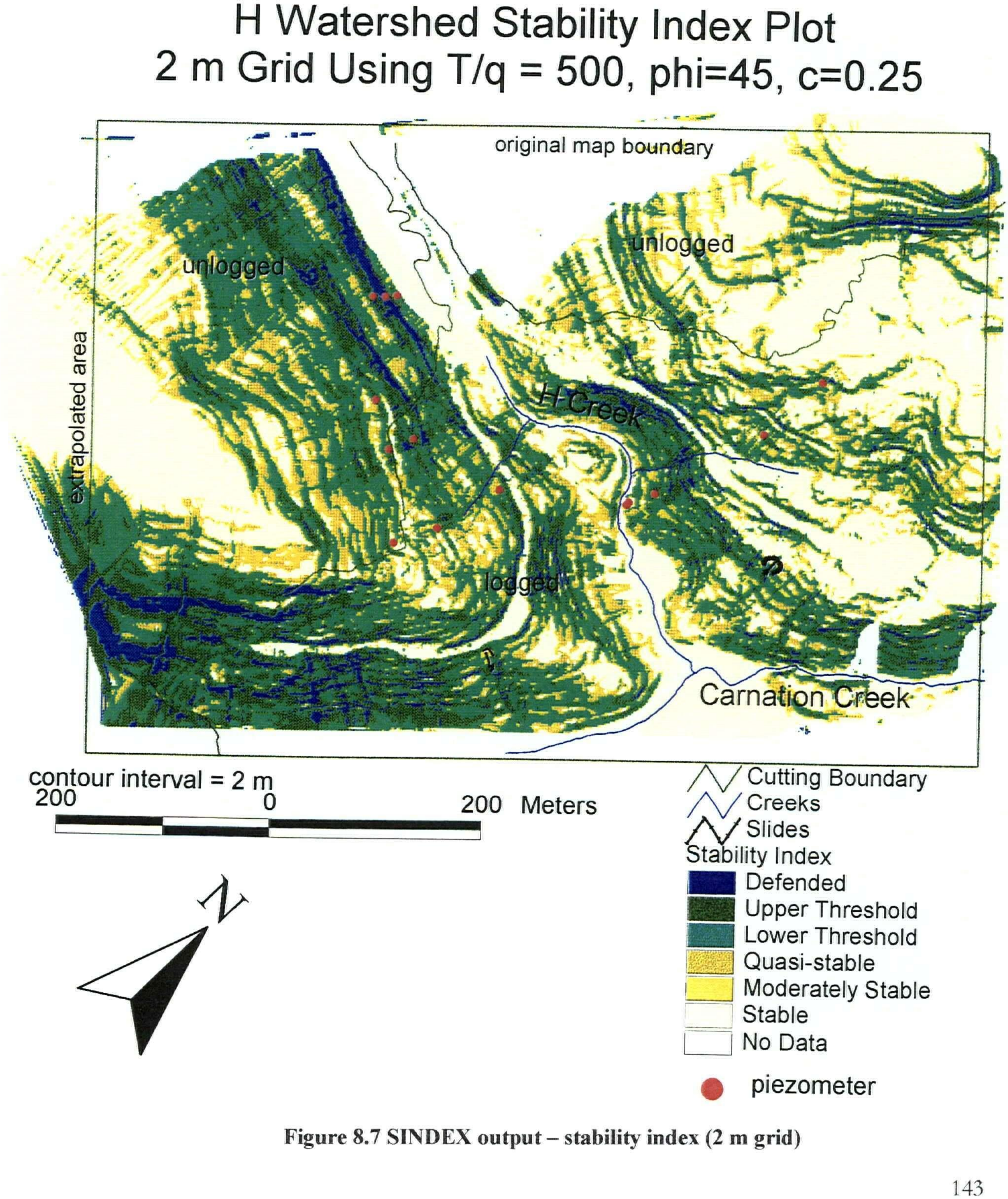


Figure 8.7 SINDEX output – stability index (2 m grid)

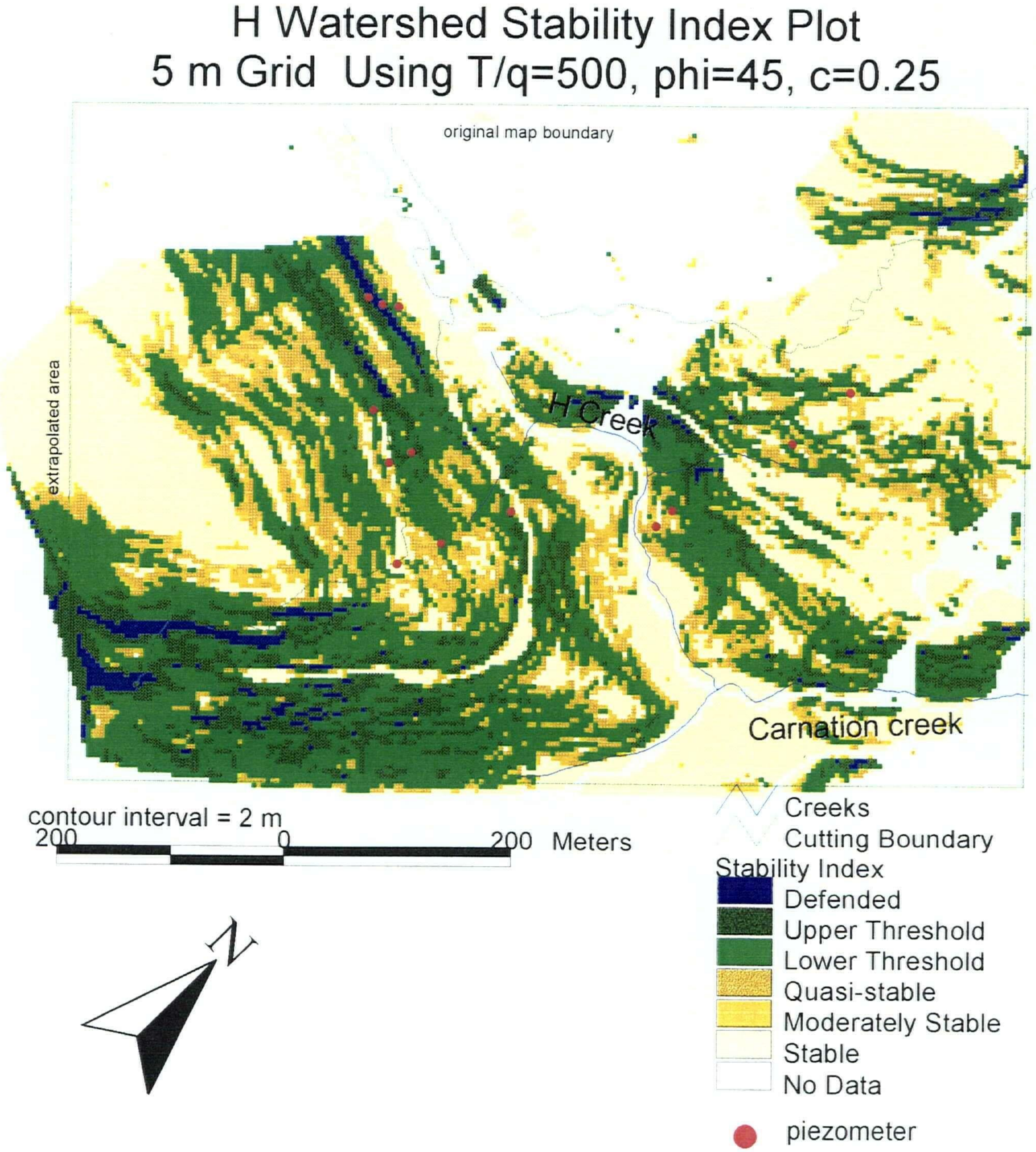


Figure 8.8 SINDEX output – stability index (5 m grid)

9.0 DISCUSSION AND CONCLUSIONS

9.1 General

Field and office based assessments of forest slope stability are commonly carried out with a great deal of uncertainty due to the lack of knowledge of controlling physical parameters. In the case of the Infinite Slope Equation adapted to model forest slopes (Hammond et. al., 1992), the groundwater level is not only one of the most sensitive parameters influencing stability, but also the most difficult to characterize. Groundwater is understood to move in a complex manner through forest soils, utilizing paths of least resistance. It is this complexity that plagues the understanding of when, where, and how landslides occur in forested terrain. Work within this thesis has used two field sites in landslide prone terrain, and studied the groundwater regime at each. Interpretations of data from each of the two study areas have taken the complexity of flow into account.

There is a distinct lack of documented studies of groundwater hydrology for forest soils in western British Columbia, where storm induced landslides are a common occurrence. Presented within this study are results and interpretations from groundwater studies at two geographically separated field sites in landslide prone watersheds. Objectives of the studies were to:

- develop an accurate, robust piezometer and incorporate it in an automated, continuously recording groundwater monitoring system, capable of remote downloading;
- field install and record pore pressures for one year to characterize the pore pressure regime of a landslide headscarp;

- using experience gained from development of instrumentation and analysis of data, characterize groundwater response to precipitation in the Carnation Creek Experimental Watershed;
- assess the impacts of forest harvesting on groundwater levels in the Carnation Creek Watershed;
- assess a topographically driven, variable contributing area groundwater hydrology model for its ability to predict recorded groundwater levels.

Considering the lack of piezometric studies on forested slopes in western British Columbia, any transferable findings from the two study areas are of unique value.

9.2 Jamieson Creek Study

The Jamieson Creek field instrumentation site proved to be a valuable experiment in which a combination of existing and newly developed groundwater monitoring equipment were installed and tested. Major objectives of this application were to offer an improved piezometer design and instrumentation scheme as a model for future applications, and provide site specific and general groundwater response characteristics of Coastal forest soils. An instrumentation site was chosen immediately upslope of the Jamieson Creek Landslide headscarp. Intentions were to monitor pore pressures at this complex hydrologic zone, where critical pore pressures triggered a landslide. The project met the original objectives of designing, commissioning, and monitoring an automated groundwater monitoring system.

A combination of tensiometers and piezometers were installed at the site to monitor negative and positive pore pressures. The selected tensiometers are commercially available, while the piezometers were designed and manufactured at U.B.C. Design features such as stainless steel construction and the ability to remove and calibrate the electronics make the piezometers ideally suited for long term performance in forest soils. Data collected at the site was retrieved from Vancouver through radio telemetry. The use of standard portable handheld VHF radio communications, with some modifications, proved that data transfer could be reliably and inexpensively performed. The automated instrumentation scheme proved to be reliable and durable, operating throughout the winter season without need for servicing.

Positioning of the field instrumentation at the Jamieson site focused on characterization of pore pressures across a 22 m section of a landslide headscarp. Selection of installation locations was aided by using the headscarp face as a cross section of seepage, soil type and thickness, and bedrock profile. Data collected have revealed that the soils retain a high moisture content throughout the year, reaching maximum negative pore pressures of only –82.6 cm H_2O. Maximum recorded positive pore pressures ranged between +18.4 cm and +94.9 cm H_2O between the piezometers. The range illustrates the complex distribution of pore pressure development across a small spatial area. Significant groundwater flow was observed to exit the scarp immediately below the locations of instruments. This flow is believed to bypass the locations of piezometric tips that recorded low pressures by utilizing well-connected macropore networks that drain the soils near the headscarp. The U.B.C designed piezometer tip can only capture the soil water pressure if it comes in direct contact with the small tip. These macropore networks may drain the soils so rapidly that there is little potential for the soil matrix to build up high pore pressures. This finding speaks to the applicability of any piezometers to be able to characterize the true hydrologic nature of a forest slope where macropores and soil pipes are expected to be present. Random installation of piezometers may provide some idea of site specific spatial and temporal distribution of groundwater response to rainfall, but the maximum pore pressures recorded may only represent a fraction of the true maximum levels. In terms of slope stability, it is the pressures that can be built up in the macropores and soil pipes that are of concern.

General observations of groundwater behavior from recorded data are similar to those made for the Carnation Creek database. Positive pore pressures rise within hours of the start of storm precipitation and change with precipitation intensity, indicating free-draining conditions. This behavior is consistent with reported hydraulic conductivities for the grain size analyses for soil samples from the site (see Chapter 3). Tensiometers at different depths responded in unison to wetting and drying, suggesting that the soil profile is fairly homogenous in terms of soil moisture. Timings of recorded peak pore pressures were generally coincident across the study area, and often reflected the point of maximum storm intensity. The potential for further data interpretation from this field experiment is constrained primarily by the length of record. A single season of records is not of adequate duration to draw many conclusions of groundwater response to rainfall. Inherent variability in the response to precipitation could easily be accounted for by annual climatic variation or snow cover differences over the winter season.

The experience gained from the Jamieson site in designing and implementing instrumentation, combined with interpretation of results augmented with field observations, allowed for far more objective interpretation of the data from Carnation Creek. Key to the Jamieson site findings, is the appreciation of the mechanisms of flow at the site, and the spatial variability of groundwater response to rainfall across a small area. The installation is to remain operational at the site, with only the piezometers and barometric pressure transducer recording. Tensiometers have been decommissioned due to their need for servicing. The entire installation could potentially be removed from the site and installed at another location with some excavation and reconfiguration.

9.3 Carnation Creek Study

9.3.1 Harvesting Related Groundwater Changes

The original Carnation Creek H Watershed experiment was designed in a manner that allowed researchers to study the effects of forest harvesting on the groundwater regime. Following work performed by Hetherington (1982) and Wilkinson (1996), a method for assessing potential changes was tested. The method assumes that there is a simple relationship representable by a simple curve, between the accumulated precipitation during a storm, and the maximum groundwater level induced by the storm. This relationship was plotted for pre- and post-harvest periods for 12 spatially distributed piezometers, of which eight were in logged terrain. The objective was to gauge if statistically significant differences existed in the relationship following logging of the watershed. The four units in the areas that were not logged were used as controls to gauge the effectiveness of the analysis technique.

Covariance analysis at a 95% confidence interval revealed that piezometer locations in areas that were not logged experienced either no increase in overall magnitude of groundwater response, or a slight drop in the response to storm events following harvesting. Results varied for piezometer locations that were within the clear-cut. Of the eight piezometer records, three piezometers had statistically significant increases in the groundwater level response, two piezometer locations showed no change, and two piezometer records showed a slight drop. Positions of these units, and interpretations of results are covered in Chapter 7. General interpretations are that harvesting can cause site-specific increases in the maximum response of soils to storm events. Implications of this finding are that these increases can in fact lead to a reduction in the effective stress, and ultimately the stability of the slope. It should be noted that although little change was cited in the overall maximum groundwater level response, the study does not address changes to the average moisture content, or the rate of rise and fall of water levels. This study is concerned with the sensitivity of rainfall induced groundwater levels to forest harvesting, and the direct impact on slope stability.

Interpretations of logging related changes to the groundwater regime in the H Watershed are limited by the period of piezometric records. Thorough characterization of the behavior of natural systems requires long-term data, spanning several years prior to harvesting, through to regeneration of vegetation cover. The analyses carried out in this work rely on one year of pre-harvest records for many piezometers to determine a baseline. Without long-term data, analyses of change may be skewed by natural annual climatic variability and factors at the time of recording, such as temperature, wind, evaporation, and transpiration. In addition, experimental control was violated by moving the precipitation gauge used to index the pre- and post-harvest groundwater levels. However, effects of this shift in position were found to have little effect on the recorded precipitation totals.

One must also consider that the results and conclusions about the groundwater regime within the watershed are being made based upon 12 continuously recording piezometers. Results of studies may also be difficult to interpret. One must consider whether the changes in a clear-cut area are site-specific, or if they are truly representative of the potential effects of logging. Factors such as changing wind patterns induced by clear-cut logging within a valley can have significant impacts on advectional forces and the associated influence on hydrologic processes (Ward, 1971).

9.3.2 Interpretations of Groundwater Flow

Through the study of piezometric response to storm events in the H Watershed, a number of findings about the hydrologic behavior of forest soils were made. All interpretations are logging independent, meaning analyses did not consider whether recordings were taken from pre or post-harvest periods, or if the location had remained unlogged. Results showed complex patterns of spatial and temporal distributions of groundwater levels. Potentially one of the more significant findings, is that groundwater levels appear to have a 'capped' maximum level, between a D_w/D of 0.4 to 0.9. The observed height of maximum groundwater level does not appear to have any spatial significance, as units separated by only 20 m may respond quite differently. For most piezometric units, the maximum level is attained on a frequent basis, and does not require extreme return period storms. A wide range of storms may in fact trigger the same level of groundwater at many piezometer locations. The implications of these simple observations are several. For researchers attempting to develop precipitation attribute and landslide frequency relationships, there appears to be several storm characteristics that result in the same maximum groundwater levels. For researchers developing models of watershed groundwater hydrology and slope stability, the concept of a spatially variable 'cap' is not feasibly incorporated. This 'cap' may in fact be a major factor in maintaining stability of slopes that may be modeled to be unstable, yet do not experience instability. A second observation that has implications for modeling of hydrologic processes is that several recordings in the Carnation Creek database had pore pressures in excess of saturation of the soil thickness. These recordings of D_w/D of greater than unity occur in two analyzed piezometers that do not display a 'capped' behavior.

Spatial complexity became evident through studying the record of storms and associated piezometric responses. The data revealed that the distributed piezometer locations are not equally sensitive to storm events. Highest recorded levels of groundwater at each piezometer location were found to be a result of a variety of major storms with varying attributes. There did not appear to be any obvious relationships between storm attributes and the propensity of a piezometer site to respond. During a storm event, extreme levels of groundwater may be recorded at certain piezometers while average high responses would occur at the others. The observed patterns of response suggest the limited applicability of developing tools or techniques that relate specific storm parameters to groundwater levels.

9.4 Groundwater Modeling

A topographically driven, variable contributing area groundwater flow model component of a slope stability model (SINDEX, Pack, 1997) was assessed for its ability to predict groundwater levels. The flow component of the model requires a base digital elevation model (DEM) divided into grid cells, in addition to one simple hydrologic lumped parameter ratio input (T/q). The DEM provides a slope gradient and specific catchment area for each grid cell in the study area, while the input ratio of T/q controls the rate of flow through the soil. Resulting output is a steady state level of saturation for each grid cell. Slight variations in the original DEM, and changes in the size of grid cell used produced significant differences in the site-specific output.

The SINDEX model must be calibrated for each study area through adjusting input parameters for soil strength and groundwater until the predicted zones of instability match observed areas. For this project, solely the groundwater input parameters were considered in calibrating the model to best match recorded groundwater levels from the H Watershed. To perform the calibration, a series of T/q ratios were input into the model and compared against recorded 5-year return period maximum groundwater levels. The 5-year return values were chosen to represent the maximum recorded values, or those that are of greatest concern stability-wise. The ratio with the best fit to the H Watershed 5-year return period data was determined to be T/q = 500, although the ratio underestimates some piezometric responses and is highly conservative in terms of physical significance.

Based upon the results of the H watershed modeling, it poses the question of whether attempting to model relative groundwater levels in larger watersheds with far less accurate base mapping in a stability model is a reasonable pursuit. Simplified models such as SINDEX provide an approximation of actual hydrologic processes and forgo some modeling complexity in favour of being operationally simple and applicable to areas where little knowledge of physical parameters exists. The assumption of an impermeable boundary that parallels the ground surface is likely a reasonable approximation for a large percentage of coastal watersheds, but becomes restrictive where soils are thinner than predicted, and in bedrock recharge and discharge zones. In the sense of being a 'tool' to assist the professional in initial delineation of potentially hazardous areas, it can be a valuable asset. By the same token, if the interpreter of the model is not well versed in the idiosyncrasies of topographically based flow models, the results may in fact be difficult to understand, overly conservative, or drastically underestimated. As shown in this work, even conservative input values of influx produced very low predicted saturation levels at some piezometer locations due largely in part to DEM based calculations. When the saturation levels are applied further into the stability model, the stability index, or factor of safety can be largely overestimated. At smaller scales with less accurate data and fewer subtle topographic features, the predicted relative groundwater levels, and resulting stability of slopes, might be a gross oversimplification.

Users of models such as SINDEX should recognize the limitations of using modeling techniques to assess slope stability. Analysis of the Carnation Creek database revealed that relative levels of saturation across a spatial area are not intuitive. For example, piezometers within close proximity to one another may record very different maximum groundwater levels (Units P820 & P825, and P859 & P863). Piezometers in a downslope transect (P845, P847, & P849) did not increase in maximum level with a lower position on the hillside, as most flow models would predict. These are just a few of the counterintuitive observations of spatial distribution of groundwater levels in the H Watershed. Groundwater flow through forest soils is known to utilize complex pathways to transmit large volumes of water downslope. Inevitably there will be varying zones of high and low saturation levels across the hillslopes, complicating the common assumption of homogenous flow through the soil profile.

The chosen grid cell size used in flow modeling component of the SINDEX model was found to have an impact on the predicted values of Wetness Index. Use of a 2 m grid versus a 5 m grid resulted in more extensive areas of predicted overland flow. A slightly better correlation between modeled and observed groundwater levels was found using the 2 m grid cell size. Further work is required to determine the effects of grid cell sizing on the average calculated values of Wetness Index or Stability Index of the slopes. A recommendation is to determine a standard grid cell vs. DEM base map scale relationship for applications of the model to separate areas within the same calibration region. This would eliminate some of the variability due solely to grid cell size on output, and leave the majority of uncertainty with the selection of input parameters.

Modelers are cognizant of the inability to model the complex manner of water transmission; the result is relying on an average hillslope response. Modeling of the H Watershed showed that to attempt to match the majority of piezometers to a predicted level of wetness, input parameters must be highly conservative. The end result produces vast areas of predicted overland flow, and still underestimates the responses at some piezometer locations.

Although there have been continual incremental improvements in modeling of forest watershed hydrologic processes through the past 30 years, there are still large gaps in the understanding and characterization of the role of fractured bedrock and macropores in the flow cycle. Modeling of the H Watershed using widely accepted mathematical representations of physical processes at a highly detailed scale, produced only satisfactory agreement with field recorded values. Data from the H Watershed reveals that large volumes of water can accumulate rapidly in zones that seem counter intuitive and have low or average modeled contributing areas.

9.5 Conclusions

9.5.1 Jamieson Creek Study

Field studies of groundwater behavior at the Jamieson Creek site have allowed for interpretations of pore pressure response to rainfall, believed to be representative of similar physiographic sites. Key observations were that pore pressures react rapidly to precipitation, and non-uniformly in the positive range across a distance of only 22 m. Macropores are believed to be responsible for spatial variability of pore pressures, and control drainage at this site. In these rapidly draining soils, negative pore pressures are low throughout the year and diminish quickly with the onset of precipitation.

Development, installation, and monitoring of a groundwater instrumentation system provided insight into the difficulties of characterizing a groundwater regime using point measurements. Discussions of experience with instrumentation used at the site should assist parties considering similar research ventures. Interpretations of groundwater behavior and 'hands on' experience gained at the Jamieson site have been applied to the analysis of the Carnation Creek Watershed database.

9.5.2 Carnation Creek

The Carnation Creek study has shown that forest harvesting can cause an increase in the response of soil water to precipitation. An increase was manifested in some, but not all of the piezometers that were within the harvested area, suggesting that the impacts of harvesting on groundwater may be site-specific. A difficult task is interpreting and applying these findings to predict what changes might be expected from similarly treated areas.

Interpretations of piezometric data from records spanning eight years at Carnation Creek storms revealed a number of observations of temporal and spatial distributions of groundwater behavior that deviate from simple hydrologic models. Professionals assessing forest slopes for stability need to be aware of the highly variable spatial distribution of high pore pressures, as well as the potential for localized extreme levels of saturation (i.e. pressures in excess of hydrostatic). As the understanding of flow through forest soils grows, this information needs to be incorporated into the development of models that predict groundwater levels.

9.5.3 Groundwater Modeling Exercise Implications

The concept of providing terrain stability mappers with a tool to delineate relative zones of potential landsliding is very attractive. Essential to any model is a mathematically sound approach to calculate variable contributing areas to account for zones of groundwater convergence and divergence. Input parameters should have physical significance, and be small in number to ensure that the applicability of the model is not constrained by uncertainty of input parameters. Based upon the well known and observed complexity of groundwater behavior, it seems difficult to justify the use of more complex flow models that attempt to incorporate more detailed processes within the hydrologic cycle. For example, models that require good estimates of hydraulic conductivity, or include transient flow through the unsaturated zone, which increases the number of required input parameters. Appreciating that macropores and the proposed groundwater 'cap' likely have a greater influence on the distribution and levels of saturation rather than any of the sub-processes, such as unsaturated zone effects, it seems more reasonable to work with a simplified base hydrologic model.

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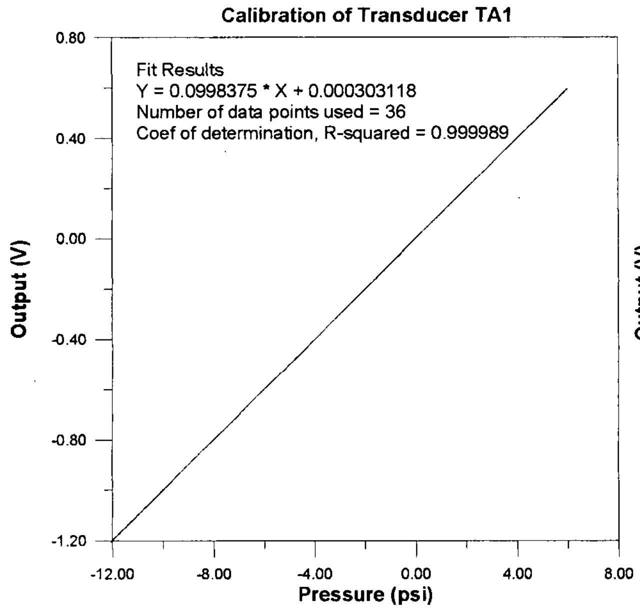
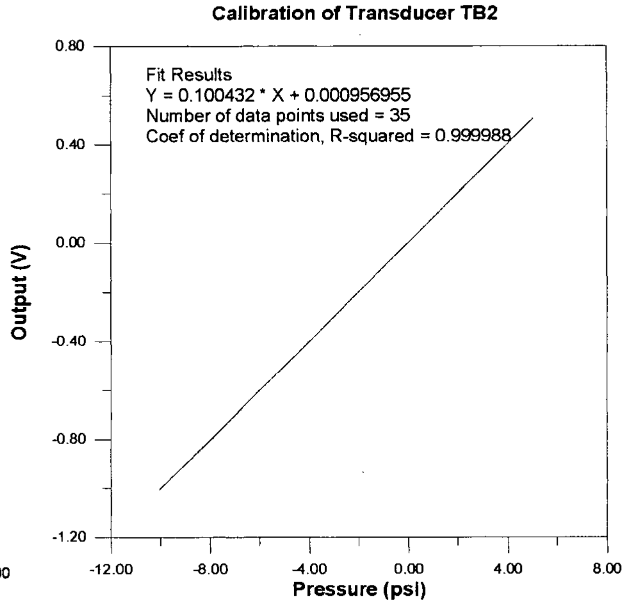
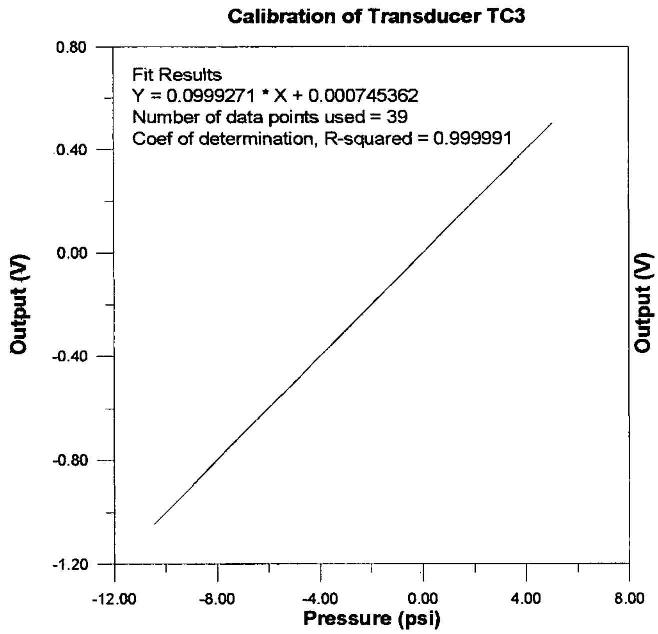
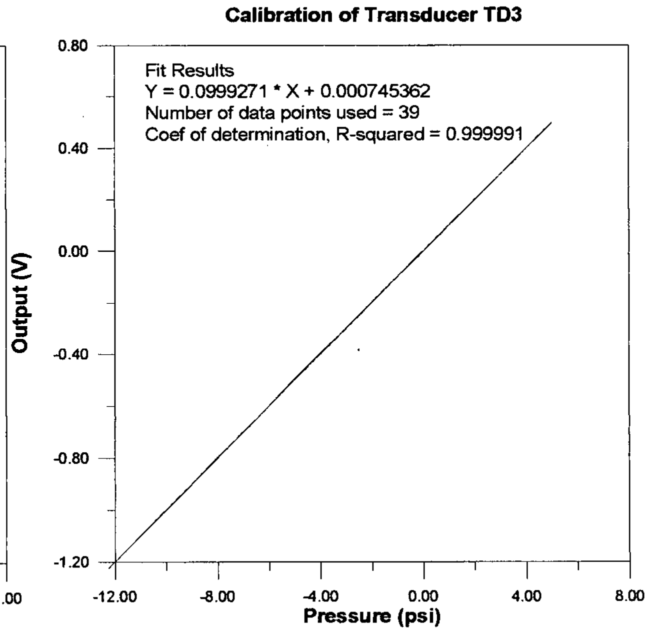
APPENDIX I

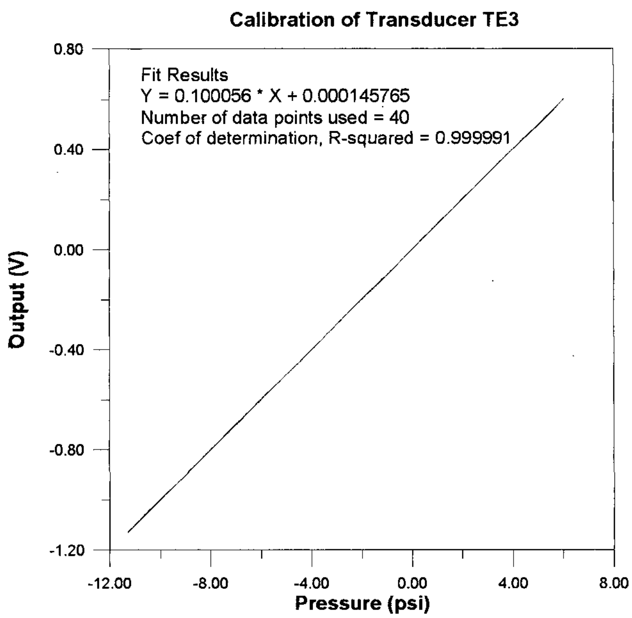
CALIBRATION CURVES

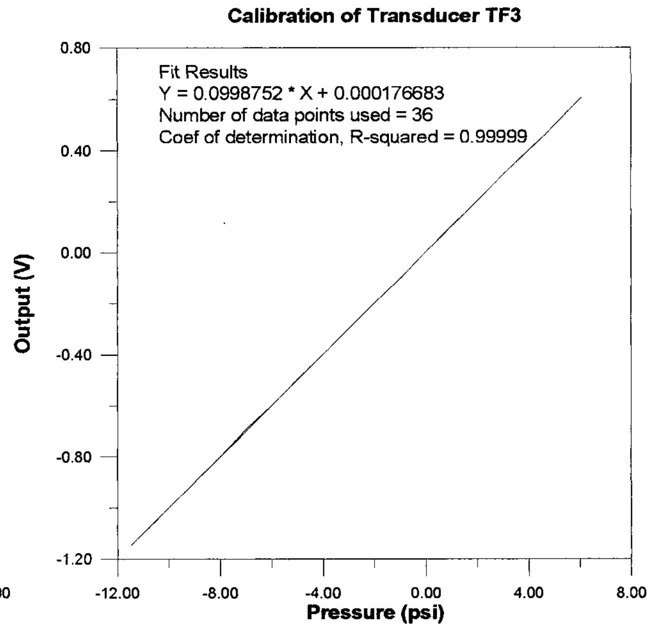

Calibration of Transducer TA1
Fit Results
Y = 0.0998375 * X + 0.000303118
Number of data points used = 36
Coef of determination, R-squared = 0.999989
Output (V)
Pressure (psi)
0.80
0.40
0.00
-0.40
-0.80
-1.20
-12.00
-8.00
-4.00
0.00
4.00
8.00

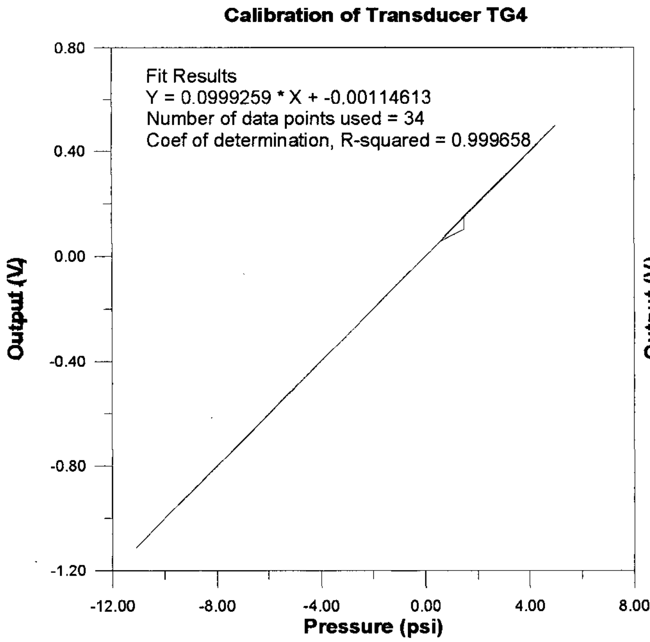

Calibration of Transducer TB2
Fit Results
Y = 0.100432 * X + 0.000956955
Number of data points used = 35
Coef of determination, R-squared = 0.999988
Output (V)
Pressure (psi)
0.80
0.40
0.00
-0.40
-0.80
-1.20
-12.00
-8.00
-4.00
0.00
4.00
8.00

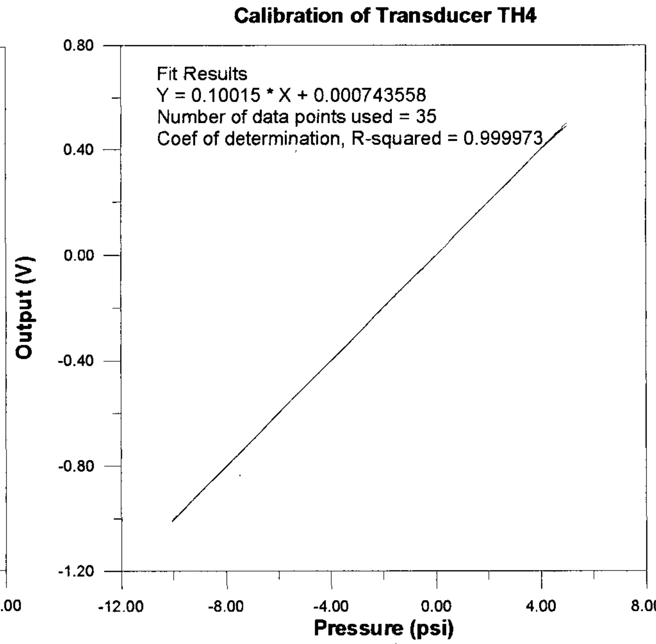

Calibration of Transducer TC3
Fit Results
Y = 0.0999271 * X + 0.000745362
Number of data points used = 39
Coef of determination, R-squared = 0.999991
Output (V)
Pressure (psi)
0.80
0.40
0.00
-0.40
-0.80
-1.20
-12.00
-8.00
-4.00
0.00
4.00
8.00

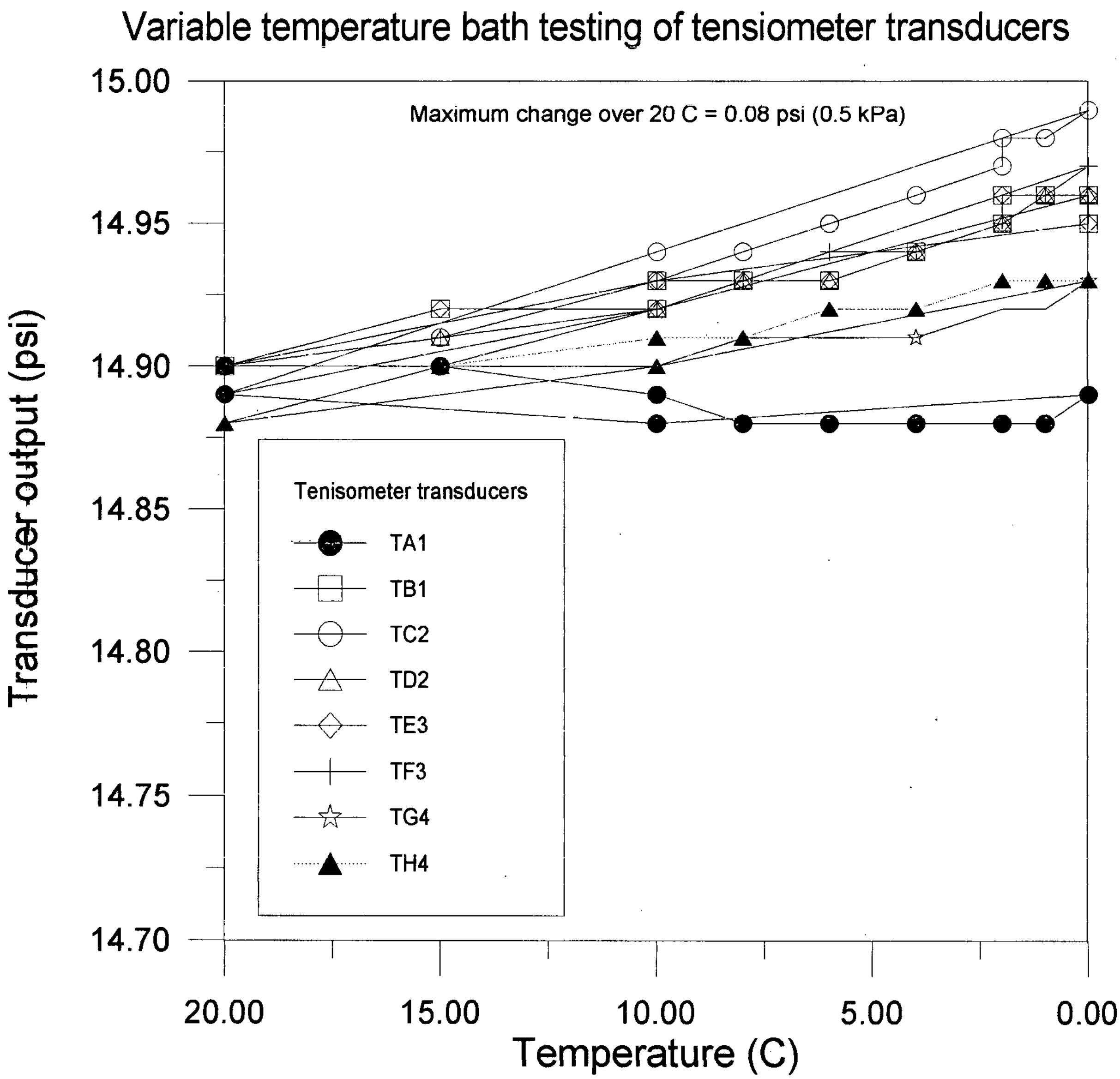

Calibration of Transducer TD3
Fit Results
Y = 0.0999271 * X + 0.000745362
Number of data points used = 39
Coef of determination, R-squared = 0.999991
Output (V)
Pressure (psi)
0.80
0.40
0.00
-0.40
-0.80
-1.20
-12.00
-8.00
-4.00
0.00
4.00
8.00


Calibration of Transducer TE3
Fit Results
Y = 0.100056 * X + 0.000145765
Number of data points used = 40
Coef of determination, R-squared = 0.999991
Output (V)
Pressure (psi)
0.80
0.40
0.00
-0.40
-0.80
-1.20
-12.00
-8.00
-4.00
0.00
4.00
8.00


Calibration of Transducer TF3
Fit Results
Y = 0.0998752 * X + 0.000176683
Number of data points used = 36
Coef of determination, R-squared = 0.99999
Output (V)
Pressure (psi)
0.80
0.40
0.00
-0.40
-0.80
-1.20
-12.00
-8.00
-4.00
0.00
4.00
8.00

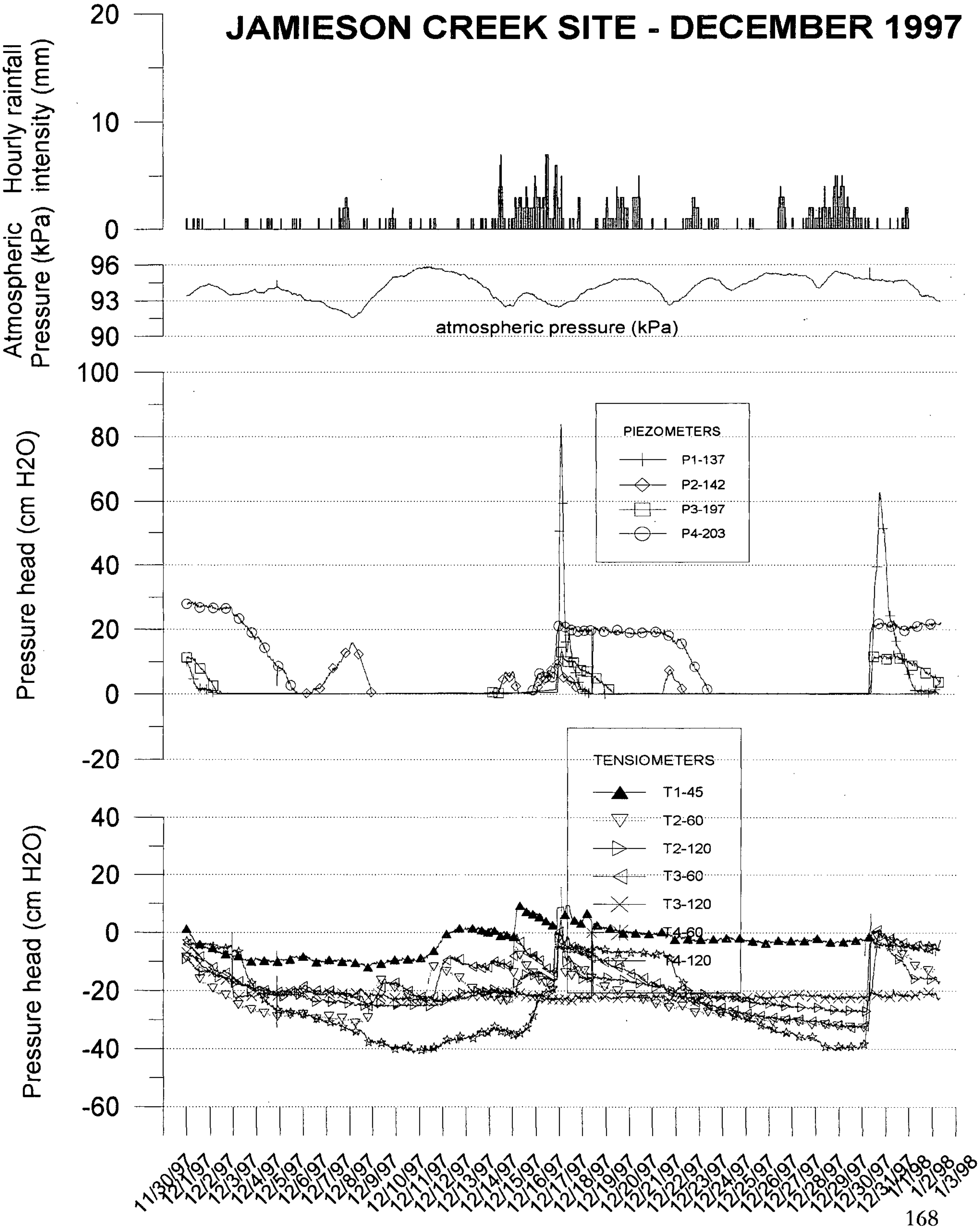

Calibration of Transducer TG4
Fit Results
Y = 0.0999259 * X + -0.00114613
Number of data points used = 34
Coef of determination, R-squared = 0.999658
Output (V)
Pressure (psi)
0.80
0.40
0.00
-0.40
-0.80
-1.20
-12.00
-8.00
-4.00
0.00
4.00
8.00


Calibration of Transducer TH4
Fit Results
Y = 0.10015 * X + 0.000743558
Number of data points used = 35
Coef of determination, R-squared = 0.999973
Output (V)
Pressure (psi)
0.80
0.40
0.00
-0.40
-0.80
-1.20
-12.00
-8.00
-4.00
0.00
4.00
8.00


Variable temperature bath testing of tensiometer transducers
Maximum change over 20 C = 0.08 psi (0.5 kPa)
Transducer output (psi)
15.00
14.95
14.90
14.85
14.80
14.75
14.70
20.00
15.00
10.00
5.00
0.00
Temperature (C)
Tenisometer transducers
TA1
TB1
TC2
TD2
TE3
TF3
TG4
TH4

APPENDIX II

JAMIESON SITE DATA



JAMIESON CREEK SITE - DECEMBER 1997
Hourly rainfall intensity (mm)
Atmospheric Pressure (kPa)
atmospheric pressure (kPa)
Pressure head (cm H2O)
PIEZOMETERS
P1-137
P2-142
P3-197
P4-203
Pressure head (cm H2O)
TENSIOMETERS
T1-45
T2-60
T2-120
T3-60
T3-120
T4-60
T4-120
11/30/97
12/1/97
12/2/97
12/3/97
12/4/97
12/5/97
12/6/97
12/7/97
12/8/97
12/9/97
12/10/97
12/11/97
12/12/97
12/13/97
12/14/97
12/15/97
12/16/97
12/17/97
12/18/97
12/19/97
12/20/97
12/21/97
12/22/97
12/23/97
12/24/97
12/25/97
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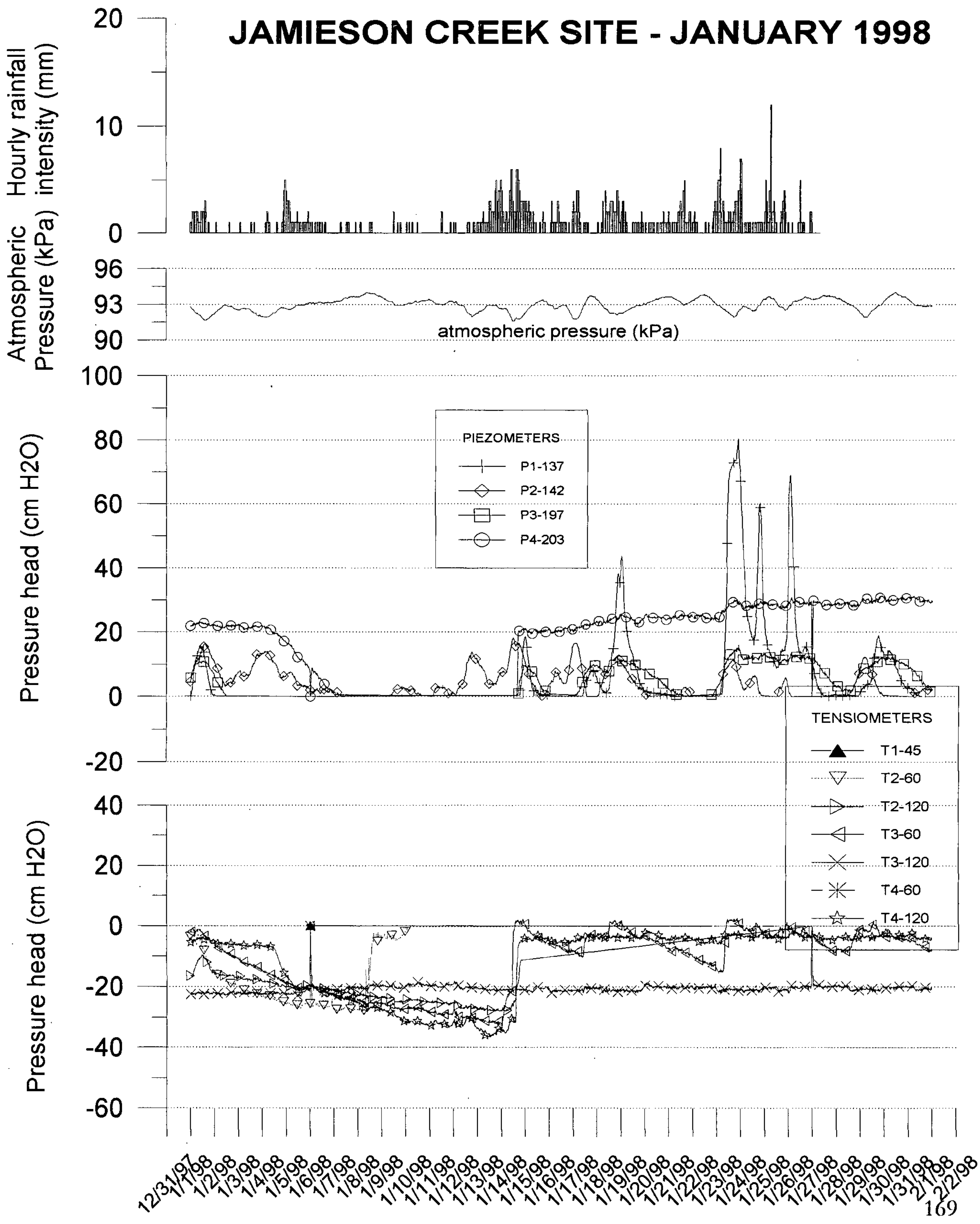
1/2/98
1/3/98


JAMIESON CREEK SITE - JANUARY 1998
Hourly rainfall intensity (mm)
Atmospheric Pressure (kPa)
atmospheric pressure (kPa)
Pressure head (cm H2O)
PIEZOMETERS
P1-137
P2-142
P3-197
P4-203
TENSIOMETERS
T1-45
T2-60
T2-120
T3-60
T3-120
T4-60
T4-120
Pressure head (cm H2O)
12/31/97
1/1/98
1/2/98
1/3/98
1/4/98
1/5/98
1/6/98
1/7/98
1/8/98
1/9/98
1/10/98
1/11/98
1/12/98
1/13/98
1/14/98
1/15/98
1/16/98
1/17/98
1/18/98
1/19/98
1/20/98
1/21/98
1/22/98
1/23/98
1/24/98
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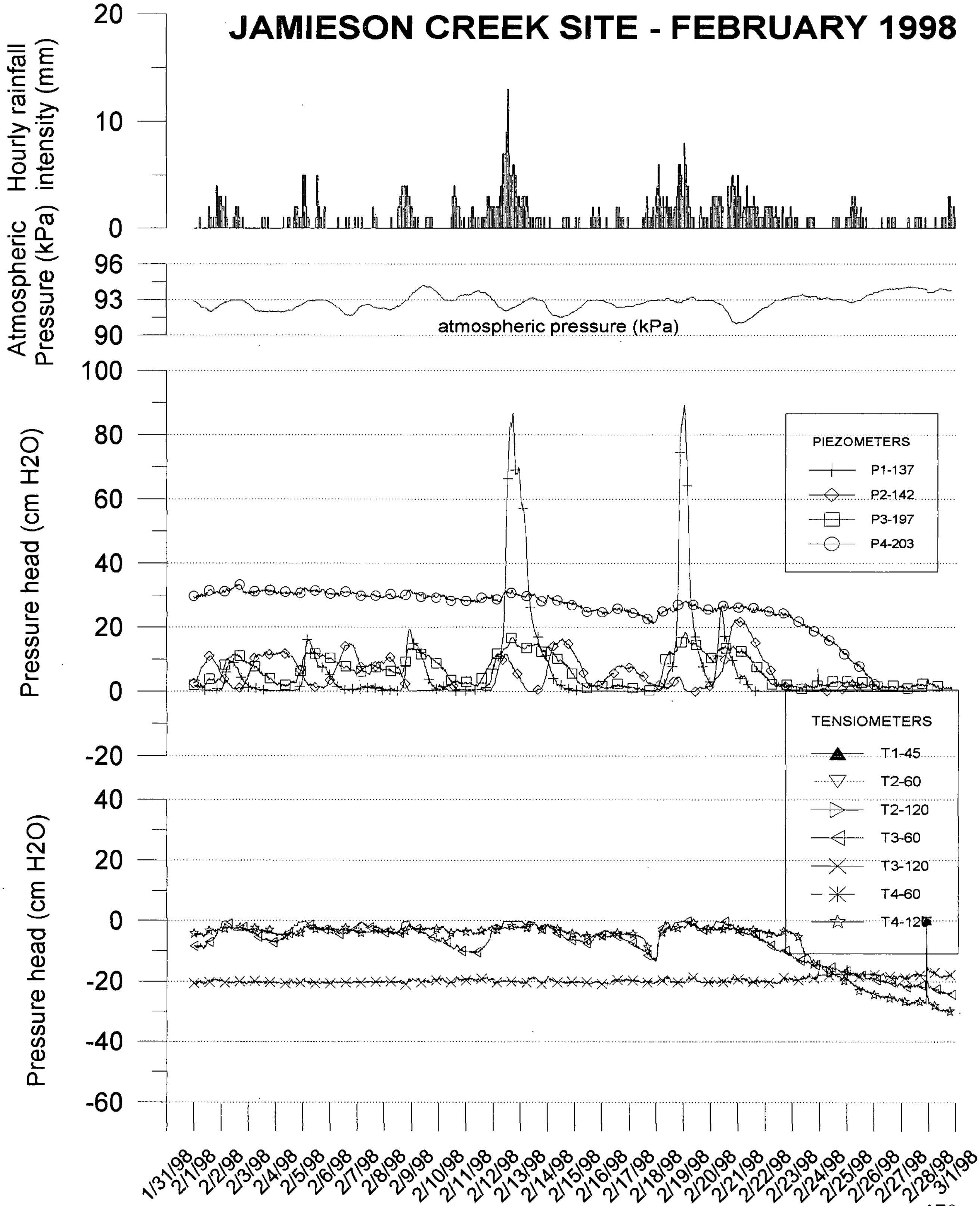
2/1/98
2/2/98


JAMIESON CREEK SITE - FEBRUARY 1998
Hourly rainfall intensity (mm)
Atmospheric Pressure (kPa)
atmospheric pressure (kPa)
Pressure head (cm H2O)
PIEZOMETERS
P1-137
P2-142
P3-197
P4-203
TENSIOMETERS
T1-45
T2-60
T2-120
T3-60
T3-120
T4-60
T4-120
Pressure head (cm H2O)
1/31/98
2/1/98
2/2/98
2/3/98
2/4/98
2/5/98
2/6/98
2/7/98
2/8/98
2/9/98
2/10/98
2/11/98
2/12/98
2/13/98
2/14/98
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2/20/98
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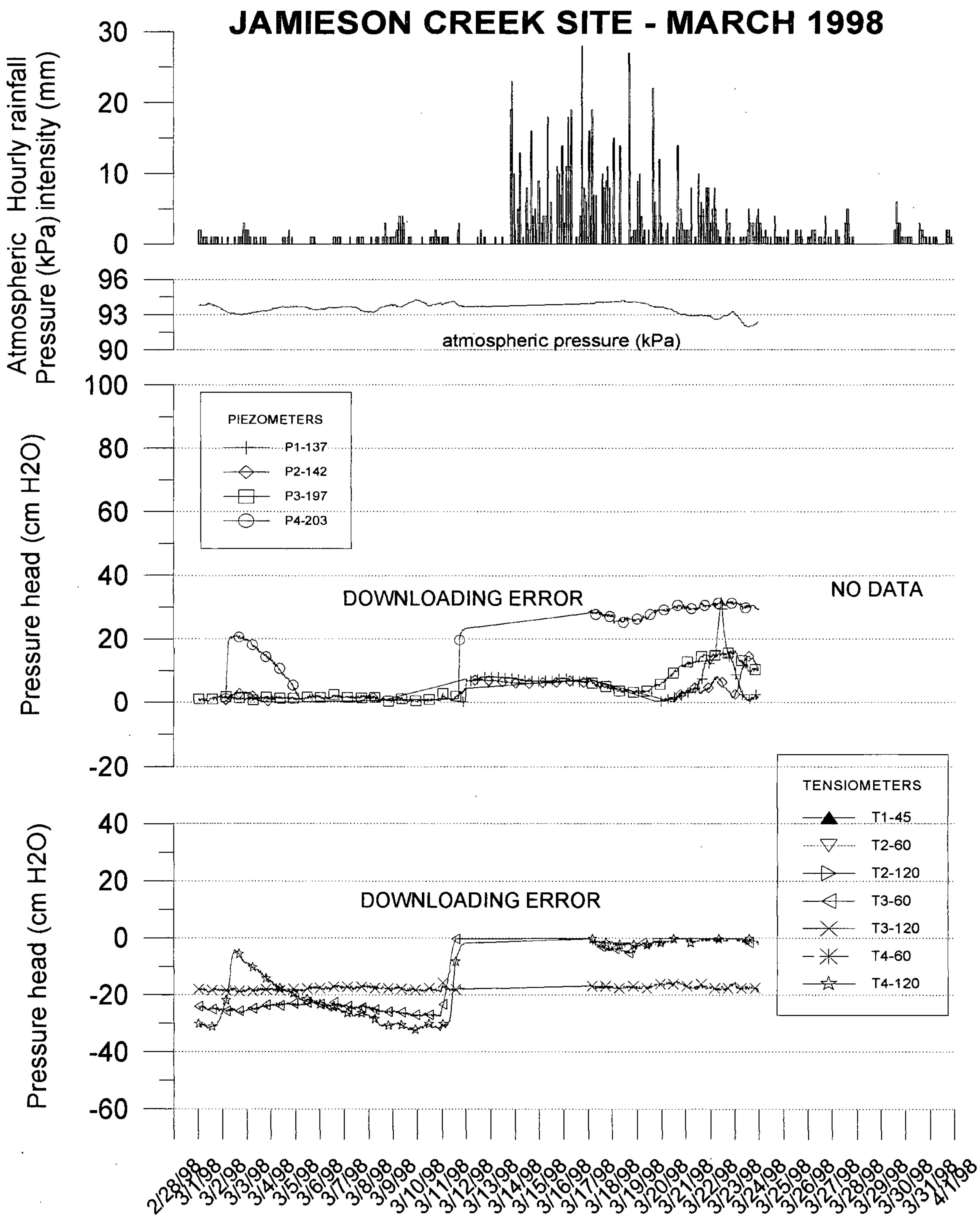
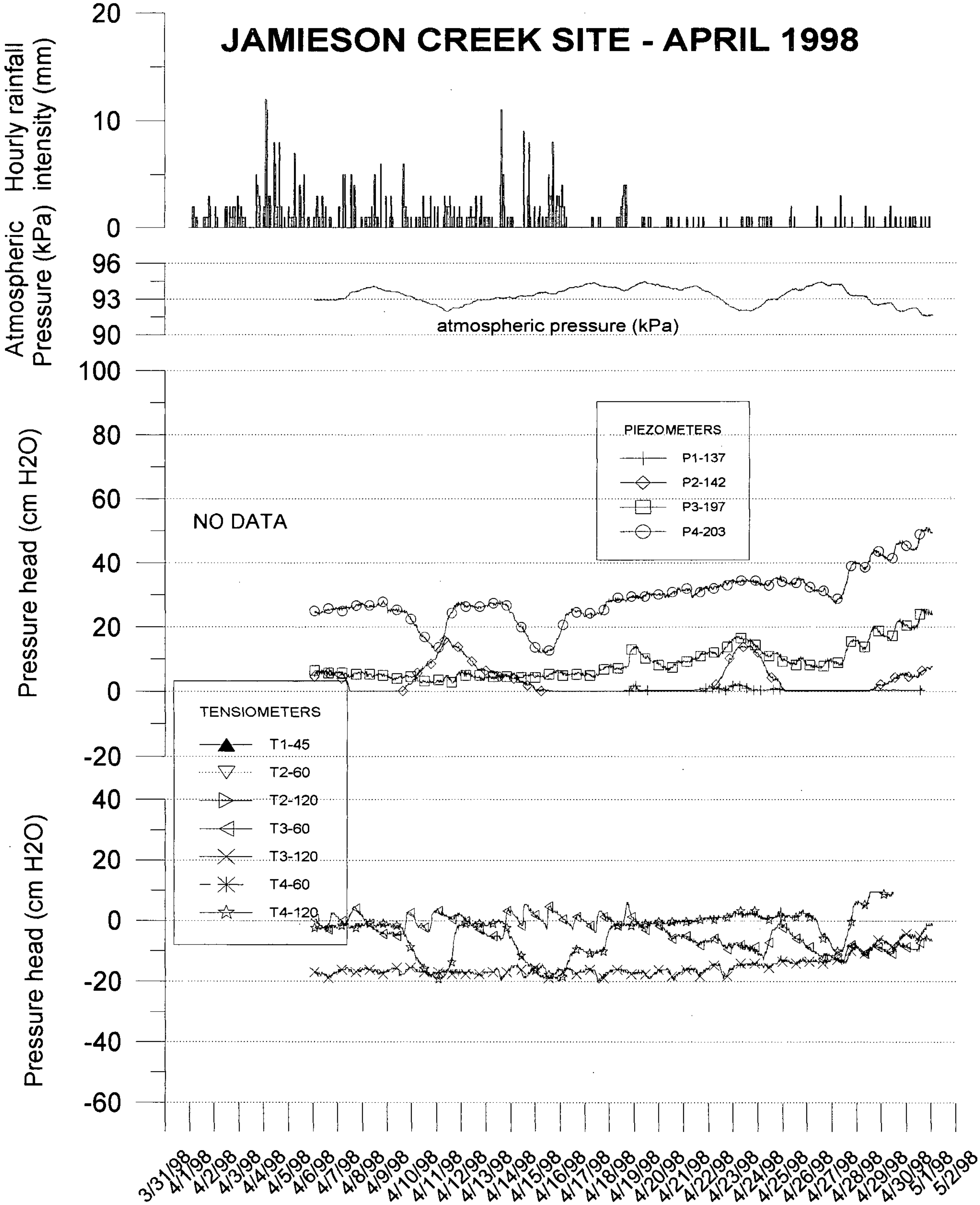
2/28/98
3/1/98



JAMIESON CREEK SITE - MARCH 1998
Atmospheric Pressure (kPa)
Hourly rainfall intensity (mm)
atmospheric pressure (kPa)
Pressure head (cm H2O)
PIEZOMETERS
P1-137
P2-142
P3-197
P4-203
DOWNLOADING ERROR
NO DATA
TENSIOMETERS
T1-45
T2-60
T2-120
T3-60
T3-120
T4-60
T4-120
DOWNLOADING ERROR


JAMIESON CREEK SITE - APRIL 1998
Hourly rainfall intensity (mm)
20
10
0
Atmospheric Pressure (kPa)
96
93
90
atmospheric pressure (kPa)
Pressure head (cm H2O)
100
80
60
40
20
0
-20
NO DATA
PIEZOMETERS
P1-137
P2-142
P3-197
P4-203
TENSIOMETERS
T1-45
T2-60
T2-120
T3-60
T3-120
T4-60
T4-120
Pressure head (cm H2O)
40
20
0
-20
-40
-60
3/31/98
4/1/98
4/2/98
4/3/98
4/4/98
4/5/98
4/6/98
4/7/98
4/8/98
4/9/98
4/10/98
4/11/98
4/12/98
4/13/98
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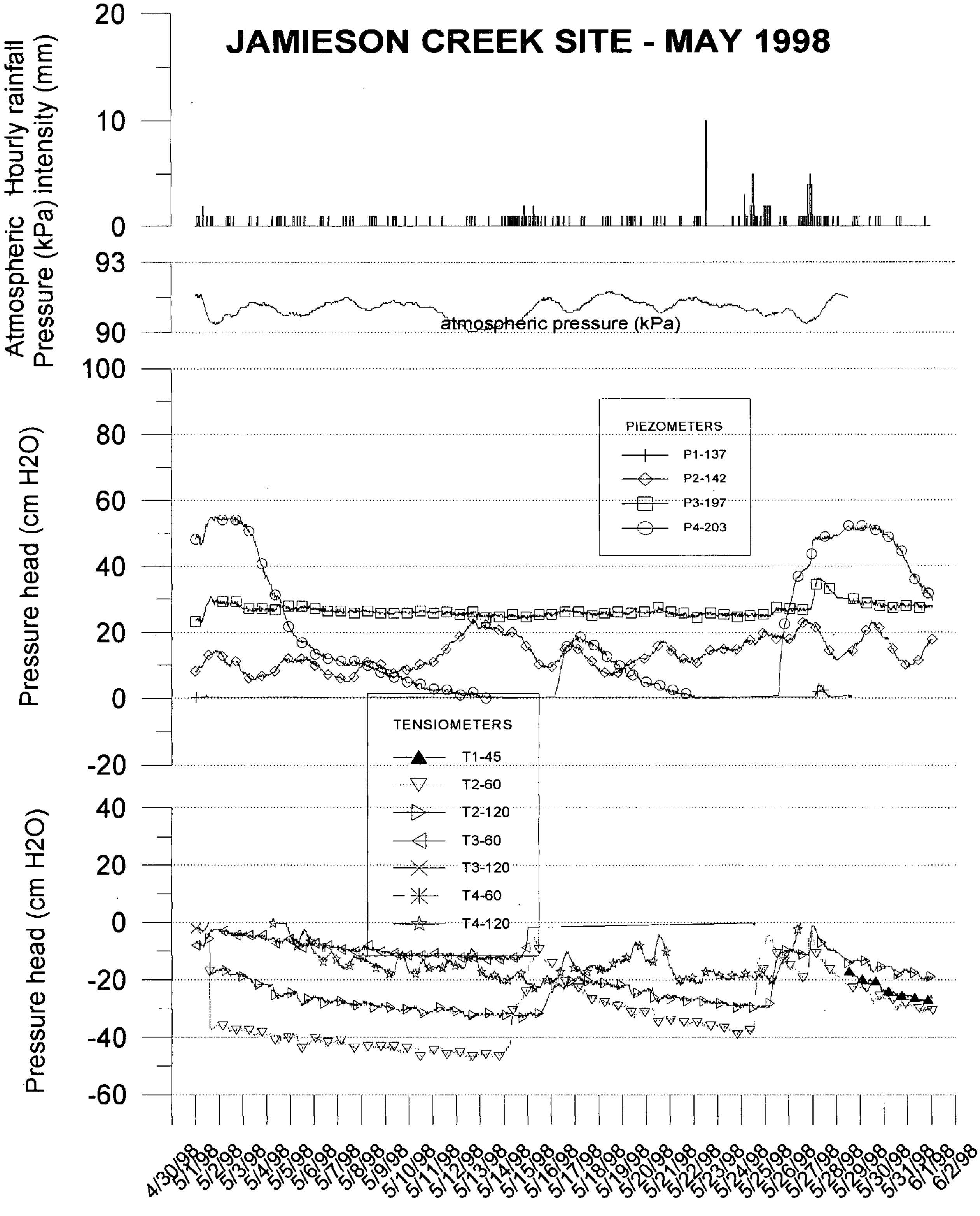
5/1/98
5/2/98



JAMIESON CREEK SITE - MAY 1998
Hourly rainfall intensity (mm)
Atmospheric Pressure (kPa)
atmospheric pressure (kPa)
Pressure head (cm H2O)
PIEZOMETERS
P1-137
P2-142
P3-197
P4-203
TENSIOMETERS
T1-45
T2-60
T2-120
T3-60
T3-120
T4-60
T4-120
Pressure head (cm H2O)
20
10
0
93
90
100
80
60
40
20
0
-20
40
20
0
-20
-40
-60
4/30/98
5/1/98
5/2/98
5/3/98
5/4/98
5/5/98
5/6/98
5/7/98
5/8/98
5/9/98
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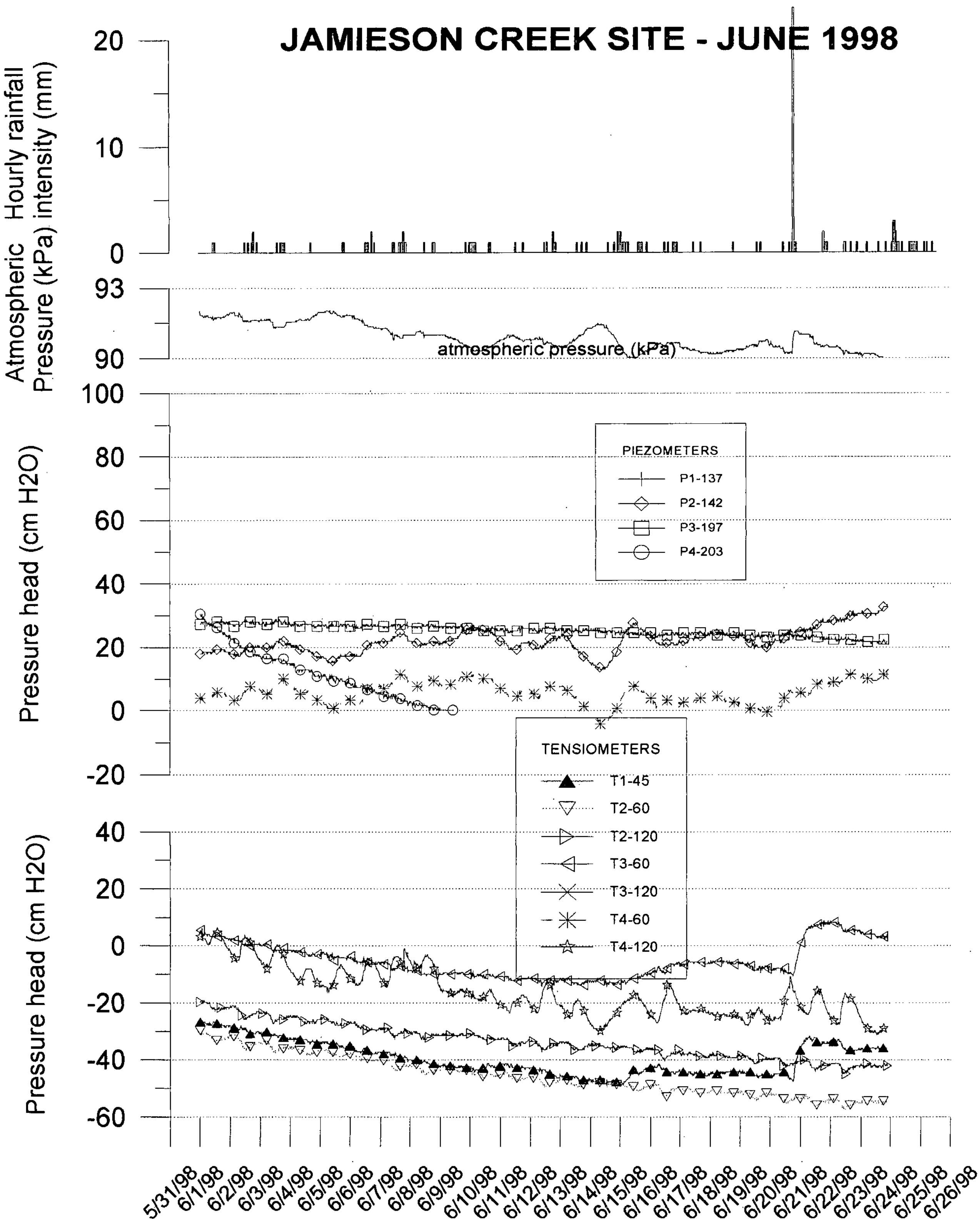
6/1/98
6/2/98



JAMIESON CREEK SITE - JUNE 1998
Hourly rainfall intensity (mm)
20
10
0
Atmospheric Pressure (kPa)
93
90
atmospheric pressure (kPa)
Pressure head (cm H2O)
100
80
60
40
20
0
-20
PIEZOMETERS
P1-137
P2-142
P3-197
P4-203
TENSIOMETERS
T1-45
T2-60
T2-120
T3-60
T3-120
T4-60
T4-120
Pressure head (cm H2O)
40
20
0
-20
-40
-60
5/31/98
6/1/98
6/2/98
6/3/98
6/4/98
6/5/98
6/6/98
6/7/98
6/8/98
6/9/98
6/10/98
6/11/98
6/12/98
6/13/98
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6/18/98
6/19/98
6/20/98
6/21/98
6/22/98
6/23/98
6/24/98
6/25/98
6/26/98