# PATTERNS OF WATER TABLE DYNAMICS AND RUNOFF GENERATION IN A WATERSHED WITH PREFERENTIAL FLOW NETWORKS

by

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## Abstract

Our understanding of subsurface flow depends on assumptions of how event characteristics and spatial scale affect the relationships between subsurface water velocity, discharge, water table dynamics, and runoff response. In this thesis, three chapters explore some of these patterns for a hillslope and small watershed in coastal British Columbia. In the first chapter, tracers were applied under natural and steady state conditions to determine the relationship between lateral tracer velocities and various hillslope and event characteristics; such as hillslope subsurface flow, rainfall intensity, water table level, hillslope length, and antecedent condition. The results showed that preferential flow made up a large percentage of the subsurface flow from the gauged hillslope. Flow velocities as measured by tracers were affected by slope length and boundary conditions. The flow velocity was most closely related to the rainfall intensity, and changes in flow velocity were large compared to the changes in the water table. In the second chapter, the preferential flow features that transmitted water during steady state were investigated by staining the soil with a food dye solution and excavating the soil. These data were used to explore the link between the topographical factors (slope and contributing area), the network of preferential features and soil properties. The contributing area appeared to be an indicator of the size of the preferential features and their connectivity. In the final manuscript chapter, water table level and stream discharge measurements were used to determine if areas within a watershed with runoff dominated by preferential flow could be grouped based on the observable physical information such as slope, contributing area, distance to stream, and vegetation. Preferential flow made the water table responses dynamic and thus, distinct zones could not be identified. Models of

the water table – runoff were not able to predict the water table response for other sites with similar physical characteristics. Even though there was high variability in the results, the patterns and relationships revealed in this thesis conform to existing conceptual models of hillslope subsurface preferential flow. These patterns and relationships may be useful in developing or validating numerical models.

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# 1 Introduction

Researchers have shown that hillslopes play an important roll in controlling the hydrology of headwater catchments. As a result, hillslope hydrology has been the focus of research for nearly one hundred years (Engler, 1919). Decades of hydrological research have identified many important conceptual models of hillslope processes (see reviews by McGlynn *et al.*, 2002; Weiler *et al.*, 2005; and Beven 2006). Hursh and Brater (1941) were the first to quantify the role of subsurface flow in runoff generation and proposed that streamflow was a result of precipitation and subsurface flow. Shortly after, Hoover and Hursh (1943) showed that the stream peak discharge was influenced by topography, soil depth, and hydrological characteristics of elevation bands. Hillslope hydrology research increased during the International Hydrological Decade, providing many conceptual frameworks of hillslope processes such as; the importance of lateral preferential flow (Whipkey, 1965), saturated surface flow and the interactions with hillslope subsurface flow (Dunne and Black, 1970), the development of the saturated wedge (Weyman, 1973), and the idea of the variable source area (Cappus, 1960; Tsukamoto, 1961; Hewllet and Hibbert, 1967). Conceptual models developed to explain the rapid stream response to rainfall at Maimai, New Zealand sparked debate about the source of the subsurface water (McGlynn *et al.*, 2002). The first experiments observed concentrated seepage at the intersection of the bedrock and the soil and in pipes that was closely synchronised with streamflow. These observations suggested that the stream water was event water that by-passed the soil matrix through soil pipes (Mosley, 1979 and 1982). Subsequent experiments contradicted this conceptual idea by using natural tracers to show that stream water was isotopically closer to the water stored in the hillslope (old water) than the rainwater (new water) (Pearce *et al.* 1986; Slkash *et al.*, 1986). They suggested that the development of a saturated wedge displaced the old water from the bottom of the hillslope. McDonnell (1990) developed another conceptual model at this Maimai hillslope based on hydrometric measurements, isotope and chemical tracer analyses, and tensiometric measurements. These measurements showed the water table developed at the interface of the soil and bedrock and the water table was short-lived because the soil pipes quickly drained the soil. This conceptual model suggested that the rainfall infiltrated to the base of the soil where it mixed with the stored water and produced a water table that caused the pipe flow. Larger scale trenching experiments showed that the bedrock topography influenced subsurface flow and the age of the stored water (Brammer *et al.*, 1995; Woods and Rowe, 1996). It is now widely accepted that, in areas with shallow soils and high conductivities, water moves through the subsurface as perched groundwater and that the topography and permeability of the subsurface boundary layer largely controls the accumulation of the water. (Freer *et al.*, 2002; Hutchinson and Moore, 2000; Kim *et al.*, 2004 and 2005; McDonnell, 1990; Peters *et al.*, 1995; Sidle *et al.*, 2000; Tani, 1997; Tromp-van Meerveld and McDonnell, 2006; Tsukamoto and Ohta, 1988; Uchida *et al.*, 2002).

After nearly a hundred years of hillslope experiments, we still have few general relationships that link hillslope characteristics to the runoff processes dominating the flow. This is important for an un-gauged watershed and hillslopes where there are no hydrometric or tracer data. Recently it has been proposed that rather than focusing on the uniqueness of individual sites, we should compare and contrast different sites to determine the dominant factors controlling subsurface flow, or first-order controls (Uchida *et al.*, 2006). However, our conceptual ideas about the first-order controls still should be tested at individual sites. The first-order controls affecting subsurface flow will depend on the climate and physical characteristics such as topography and soil/bedrock characteristics. In many areas, preferential flow is a first-order control for subsurface flow generation (Uchida *et al.*, 2005). Preferential features can be distinct features in the soil or areas of higher permeability. Preferential features are created by plant roots and animals, but flowing water has a role in the modification and maintenance of the features and can enlarge smaller macropores into what is often referred to as soil pipes (Jones, 1971; Anderson and Burt, 1990). Continued subsurface erosion can develop highly connected drainage networks within a hillslope; however excavations of forested hillslope have revealed that preferential features are often short and discontinuous (less than 5m) (Noguchi *et al.*, 1999; Terajima *et al.*, 2000). These short and discontinuous features can still create fast subsurface velocities (Weiler and McDonnell, 2007), and soils with hydraulically limited water table responses. Hydraulically limited water table response refers to the condition where the water table reaches a maximum water level below the soil surface while the subsurface flow continues to increase (Sidle, 1986; Montgomery and Dietrich, 1994 and 1995; Fannin *et al.*, 2000). This has provided the basis for the conceptual idea of lateral preferential flow networks where saturated soil is presumed to provide the connection between the features (Sidle *et al.*, 2000). Preferential flow networks are dynamic and are influenced by antecedent condition and event characteristics (Hutchinson and Moore, 2000; Kim *et al.*, 2005; Tromp-van Meerveld and McDonnell, 2006). As soils with preferential networks become wetter (increased rainfall, snowmelt, and antecedent conditions), more connections in the network are initiated and the network expands, limiting the increase in the water table. In many models of soil and hillslope water the flow (Q) is assumed to be a function of the velocity (V) and the cross-sectional area (A) of the flow (Q=V*A) and that a rising water table is the mechanism that increases the cross-sectional area. However, when preferential flow dominates subsurface flow, an increase in the subsurface flow happens while the water table stays relatively constant, which requires an increase in the velocity of the water moving laterally in the saturated zone.

## 1.1 Hillslope trenching experiments

Trenching of hillslopes has been common practice for decades and is used to explore the temporal and spatial dynamics of hillslope subsurface flow. Trenching of hillslopes refers to gauging the subsurface discharge from an exposed soil cut face, which can be natural (e.g. streamside bank) or artificial (e.g. road or trench excavation). The position of the trench on the hillslope and the width of the trench can influence the water captured and the conclusions drawn from the collected data (Freer *et al.*, 1996, 2002; Tromp-van Meerveld and McDonnell, 2006). The water captured at the base of the hillslope can also be influenced by the subsurface topography (Freer *et al.*, 1996). It is also very difficult to predict or quantify the losses (or gains) of water into (from) the bedrock. The excavations associated with the creation of the trenches also can disturb the soil structure and influence the hydraulic conditions. Despite these drawbacks, trenching is still one of the most useful tools for exploring the characteristics of hillslope subsurface flow generation. These methods have provided insight into the behaviour of subsurface water including:

- the effect of subsurface topography on subsurface flow generation (Freer *et al.*, 2002; Hutchinson and Moore, 2000; Tsuboyama *et al.*, 1994),
- the dominance of pre-event water in subsurface flow (Hewlett and Hibbert, 1963; McDonnell, 1990; Sklash *et al.*, 1976),
- the effect of lateral pipes and soil horizons on subsurface water flow (Kim *et al.*, 2004; Mosley, 1979; Weyman, 1973; Whipkey, 1965), and
- the relationship between watershed zones and hillslope subsurface flow at different scales (McGlynn *et al.*, 2004).

## 1.2 Hillslope-scale applied tracer experiments

Artificially applied tracers are often used in combination with trenching to measure vertical percolation, lateral hillslope subsurface velocity and dispersion of water in soils with macropores (McGuire *et al.*, 2007; McIntosh *et al.*, 1999; Roth *et al.*, 1991; Tsuboyama *et al.*, 1994). The best tracers are isotopes of hydrogen and oxygen that make up the water molecule (Nyberg *et al.*, 1999; Rodhe *et al.*, 1996). However, due to the high cost of isotope analysis, ion tracers such as Bromide or Chloride are often used (Nyberg *et al.*, 1999). Tracer experiments are conducted under laboratory conditions and in the field under natural conditions or under artificially induced steady state conditions. Steady state and laboratory conditions are preferred because under natural conditions, the boundary conditions are constantly changing, which can make it difficult to interpret the results (McIntosh *et al.*, 1999). However, it may be difficult to relate the controlled steady state or laboratory experiments to the complex natural conditions and to larger scales generally found in the natural environment. Very few studies have used tracer experiments to determine relationships between steady state and natural flow conditions (Eriksson *et al.*, 1997).

For tracer application using mathematically defined input, such as a Dirac pulse or constant input concentration under steady state flow rates, analytical solutions of the convection-dispersion equation can be fitted to the observed breakthrough curves to calculate the solute velocities and dispersion rates (Roth and Jury, 1993). When the tracer inputs do not conform to these boundary conditions, or the experiments are conducted under natural conditions, a response function can be used to transform the input signal to the output signal (Roth and Jury, 1993).

## 1.3 Dye and straining tracer experiments

Artificial dye tracers and excavation are used to visualize and determine the flow paths exploited by the water. Most studies have focused on vertical infiltration or lateral flow over short distances (Noguchi *et al.*, 1999; Zehe and Fluhler, 2001). Some studies have combined ion tracers with the dye tracer to qualitatively and quantitatively describe both the dynamics of the flow and the distribution of flow paths active during the experiment (Ohrstrom *et al.*, 2004). Less destructive methods such as ground penetrating radar, fibre optics, and electrical conductivity have been used, but they require expensive equipment and have seen limited success (Holden, 2004; Sherlock and McDonnell, 2003).

## 1.4 Modelling preferential flow

Conceptual models of preferential flow are useful for understanding the behaviour of hillslopes in gauged watersheds. Numerical models are often used in the prediction of un-gauged basins, where concepts are extrapolated to areas with limited data. Some models have incorporated lateral preferential flow. Feah *et al.*, (1997) and Bronstert, (1999) both used a zone of higher conductivity and a kinematic wave function to simulate preferential flow. Beckers and Alila (2004) modified the distributed hydrology soil vegetation model (DHSVM) (Wigmosta *et al.*, 1994) by adding a threshold formulation to divide the water into two flow components and used Darcy's law with different flow velocities to route the subsurface water. Weiler and McDonnell (2007) presented a new model structure based on Hill-vi (Weiler and McDonnell, 2004) and a relationship derived from experimental data to represent the preferential flow (Sidle *et al.*, 1995). A good understanding of the patterns of processes is important for developing models and validating model behaviour (Seibert and McDonnell, 2002). Models represent the world through empirical relationships and/or physically based equations of mass and energy transfer. Often measurements of the parameters are not at the same scale as the model components, so during the development and calibration of models the modeller makes assumptions and simplifications to represent the natural processes.

There are two common methods of modelling hillslope and watershed processes:

1. Divide the watershed into regular elements (usually a grid) and deterministically represent the processes between each grid (e.g. Hill-vi, DHSVM). This type of model assumes that if we properly represent the processes at the small element scale the model will reproduce measurements at the scale of interest (hillslope or watershed).
2. Create groups of watershed elements or zones that are expected to have similar subsurface flow generation processes and then model each group with the same

equations that represent the conceptual processes (Seibert and McDonnell, 2002). Groups are identified using observable factors (Seibert *et al.*, 2003): a) slope, b) distance to stream, c) contributing area, d) vegetation, e) soil properties, f) topographical index, etc.

Seibert and McDonnell (2002) used a 'three-box' conceptual model to simulate runoff at Maimai, New Zealand. They used boxes to represent the hillslopes, hollows, and riparian areas and threshold-based linear functions to route water between the boxes. The hollow box used two functions; one to represent matrix flow and the other to represent flow through macropores. Preferential flow was included in the model because field observations had identified preferential flow as an important process (McDonnell, 1990). Often measurements are not available for modelling so information about the patterns and relationships between factors have to be inferred from physical characteristics and indices that are easy to calculate with readily available data. Information gathered from experimental watersheds that describe the patterns of discharge – velocity or water table – discharge are useful for determining appropriate watershed zones and the dominant processes within the zones.

## 1.5 Objectives and hypotheses

Although preferential flow features have been the focus of decades of research there is still a lack of data that can be used to develop and test the ideas of hillslope response, and there are still some unanswered questions. This thesis is in manuscript format and contains an introduction chapter, three chapters that will be submitted for publication, and a concluding chapter. The first manuscript chapter (Chapter 2) addresses the issue of subsurface water velocity in the hillslope under different rainstorms and steady state boundary conditions. Artificial tracers are applied under different steady state conditions (flow rates and slope lengths) and during different storm events to determine the distribution of flow velocities in the hillslope, and the patterns of change in boundary conditions. The second manuscript chapter (Chapter 3) tests the feasibility of extending dye tracer methods commonly used for plot scale (of the order of few meters) experiments to the hillslope scale. The objective is to determine the preferential network active under steady state conditions and to test the hypothesis that the contributing area is linked to the developments of individual preferential features, the preferential network, and soil properties. The last manuscript chapter (Chapter 4) tests the hypothesis that water table response can be classified and grouped in a watershed with complex topography where preferential flow is a first-order control on subsurface flow. The resulting patterns in the spatial variability of water table response are linked to the patterns found at the smaller hillslope scale presented in Chapters 2 and 3.

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# 2 Subsurface flow velocities in a hillslope with lateral preferential flow[1]

## 2.1 Introduction

Subsurface flow in hillslopes dominates the hydrological response and the transport of solutes and nutrients in steep, forested watersheds in humid climates. Decades of hillslope experiments have identified many dominant processes; numerous (sometimes conflicting) conceptual models about the flow features and the mechanisms that control water flow have been developed. Preferential flow has emerged to be an important factor in hillslope hydrology (Mosley, 1979). Preferential lateral flow occurs either in distinctive structures in the soil where water flows only under gravity (macropores or pipes) or in areas with a higher permeability than the surrounding soil matrix (Weiler *et al.*, 2005). Excavations have found that forested hillslopes in humid climates have relatively short (generally less than 5 m) preferential flow features (Noguchi *et al.*, 1999; Terajima *et al.*, 2000). Some steep forested hillslopes have been reported to have large preferential flow features, but it is not known how far upslope they extended (Kitahara, 1993; Roberge and Plamondon, 1987; Tsukamoto and Ohta, 1988; Uchida *et al.*, 1999).

[1] A version of this chapter is in preparation for submission for publication, Anderson, A. E., Weiler, M., Alila, Y., and Hudson, R., 2008. Subsurface flow velocities in a hillslope with lateral preferential flow, *in preparation.*

Even though individual preferential features are usually short and discontinuous, fast subsurface velocities and quick runoff responses to precipitation have been observed in many hillslopes (Hutchinson and Moore, 2000; Peters *et al.*, 1995; Tani, 1997). These fast velocities and subsurface flow responses have led to the idea of a preferential flow network, which describes a series of hydraulically connected preferential features that appear to be physically discontinuous. The exact mechanisms that cause water to move through the preferential flow pathway are not well known, but it is assumed that saturated soil provides the connection between preferential features (McDonnell, 1990; Sidle *et al.*, 2001). As water is redistributed vertically and laterally the saturated areas increase, which increases the active number of preferential features and affects the subsurface flow response of the hillslopes (Sidle *et al.*, 2000). Studies have shown that this dynamic subsurface flow response is influenced by antecedent moisture condition, precipitation intensity, precipitation amount, topography, and the physical characteristics of the preferential flow network (Sidle *et al.*, 1995; Sidle *et al.*, 2000; Tromp-van Meerveld and McDonnell, 2006a; Tsuboyama *et al.*, 1994; Uchida *et al.*, 2005).

Physically based, numerical models are often used for predicting the effects of land use changes on watershed hydrology and for testing hypotheses of watershed behaviour. Numerical models use statistical relationships and mathematical formulation of flow through soil to represent conceptual ideas about how water flows through the landscape. To properly use models, the modeller requires a good understanding of the processes and mechanisms that affect the dynamics in the system (Weiler and McDonnell, 2004). Preferential flow models have been developed for a single pipe (Tsutsumi *et al.*, 2005), for hillslopes (Faeh *et al.*, 1997; Weiler and McDonnell, 2007), and for watersheds (Beckers and Alila, 2004). The subsurface water velocity is usually the primary parameter used (directly or indirectly) to simulate subsurface flow and solute transport. Most hillslope and watershed scale models are developed using a small number of velocity measurements at a small scale (Beckers and Alila, 2004) or relationships developed for single preferential features (Weiler and McDonnell, 2007).

Artificial and natural tracers have been used to quantify hillslope response under natural and steady state conditions. The best tracers are the so-called ideal tracers, such as isotopes of Hydrogen and Oxygen, which make up part of the water molecule (Nyberg *et al.*, 1999; Tsuboyama *et al.*, 1994). However, these tracers can be expensive, so other less desirable ion tracers such as Chloride or Bromide are still commonly used (Feyen *et al.*, 1999; Nyberg *et al.*, 1999; Tsuboyama *et al.*, 1994). Depending on the experimental design, tracers are used to determine the vertical, lateral, or combined vertical and lateral velocity of subsurface water. Tracers are applied during steady state (generally sprinkling or pumping) or natural conditions. However, steady state experiments are preferred because they are simpler to analyse and interpret (Tsuboyama *et al.*, 1994).

In this chapter, results from a hillslope-scale experiment under different boundary conditions are presented. Artificial tracer (NaCl) was applied under natural and steady state lateral flow conditions to determine the effect of slope length and flow rate on the velocity and dispersion in lateral subsurface flow. The experimental hillslope was gauged at a road cut-bank from February to June 2005 to examine the behaviour of water and artificial tracers exiting from preferential flow features and the soil matrix under natural conditions. These data were used to determine average velocities that describe the transport of solute from the soil surface to the road cut during different storms. Following the experiments under natural conditions, steady state experiments were conducted to determine the lateral tracer velocities for different flow rates and different hillslope lengths (12 m and 30 m). The results were compared to conceptual models and mathematical formulation of flow through soil and preferential features. Specifically, this chapter explores the following questions:

1. Can existing mathematical formulations of subsurface flow explain the observed subsurface flow discharge-velocity relationship?
2. Are there patterns and relationships between subsurface flow velocity and discharge, precipitation characteristics, or water table depth?
3. Do the patterns and relationships found at this hillslope conform to conceptual models of preferential flow networks in hillslopes?

## 2.2 Methods

### 2.2.1 Study site

The experiments were conducted in the Russell Creek research watershed located in north-eastern Vancouver Island, British Columbia, Canada. The watershed ranges in elevation from 275 m to 1715 m above sea level (a.s.l.), which places the majority of the watershed into the rain-on-snow zone (300 – 800 m) and the snow zone (above 800 m). This area has high annual precipitation. Average precipitation at two gauges in the watershed was 2258 mm/yr at 830 m a.s.l. and 1906 mm/yr at 300 m a.s.l., with the majority of the precipitation falling in the winter months (80 % of total precipitation in

September to April). A moderately steep (30 %) hillslope at 400 m elevation that produced concentrated flow at the road cut-bank during storms was selected for the experiments. This site was chosen because it appeared similar (in terms of soil, vegetation and flow characteristics) to many other sites at Russell Creek. This site was also close to meteorological instrumentation, gauged streams and piezometers. We expected relatively easy winter access because the road was in good condition and only an intermittent snow pack was expected.

The lower 30 m of the approximately 100 m long hillslope (Figure 2.1) was the site of the experiments. The topography of this 30 m hillslope section was undulating with wet hollows and drier convex ridges as indicated by changes in herbal vegetation and soil types. Soil characteristics were observed at the road cut-banks, during piezometer installation, and during excavations. In general, the soils were 0.5 m to 2 m deep. The 30 m experimental hillslope section covered two small-scale topographical units and soil types common at Russell Creek. The centre of the lower 10 – 15 m of the hillslope (above section 2 in Figure 2.1) was typical of topographical hollows with clay and organic rich soils (Bg and Ah) less than 1 m deep. The remainder of the hillslope (above section 1 and 3, and above 15 m, Figure 2.1) was typical of convex and planer hillslopes, with podzols that had a 0 – 10 cm thick Ae layer, and an approximately 1 m deep Bf layer. Relatively impermeable till was the lower bounding layer for the entire experimental site. A 300-year-old, 200 cm diameter, 47 m tall stand of Western Hemlock (*Tsuga heterophylla*) and Amabilis Fir (*Abies amabilis*) covered the whole hillslope (stand information from inventory and observations).

### 2.2.2 Hillslope experiment set-up

In the Russell Creek watershed forest roads were mainly constructed along hillslopes, which resulted in many road cut-banks intersecting the entire soil profile and part of the till or bedrock. After months of observing stormflow exiting from hillslopes at road cut-banks and following preliminary experiments conducted in the summer of 2004, a 9 m wide hillslope section was gauged at a road cut-bank (Figure 2.1). The 9 m section was divided into three sub-sections (S1, S2, and S3), each 3 m wide. Three preferential flow features were also gauged (pipe 2A, pipe 2B and PF1 in Figure 2.2).

S1 and S3 were below convex and planar hillslopes. In both sections, the podzol soil was 1 m to 1.5 m deep with a 5 – 30 cm Ae layer above a Bf layer. Preferential flow was observed at the interface of Bf layer and the till in S1 (PF1) and large roots were connected to the interface of the till and the Bf layer (upper left corner of Figure 2.2). It was not possible to isolate all the preferential flow in S1, so a large portion of the water measured from S1 was expected to be preferential flow.

Small live roots (less than 1 cm in diameter) transmitted small amounts of water during storms in S3. S2 was below a topographical hollow, and the podzol was higher in clay content with a 30 cm Ah layer and a 30 – 50 cm Bg layer. Before installing the instruments, it was noticed most of the storm outflow from the hillslope drained as concentrated flow in S2. After the soil face was cleaned two large soils pipes (pipe 2A and pipe 2B, Figure 2.2) were discovered. Pipe 2A was 10-12 cm in diameter and was connected to high conductive features creating a preferential flow network that extended 10 m up slope (Anderson *et al.*, 2008). Pipe 2B was 5-8 cm in diameter and was less connected then pipe 2A. Both pipes were near the interface of the organic layer Ah and the Bg layer. Small gravel (2 to 5 mm) was deposited on the bottom of these pipes and old bark from decayed tree roots lined the top and sides of pipe 2B.

Water table fluctuations during storms were measured using two piezometers, each made of 2.5 cm diameter PVC pipe screened for the bottom 30 cm of the pipe. The hole was backfilled with gravel and capped with bentonite clay. Unidata Hydrostaic Water Depth and Temperature Probes (model 6542) connected to a Unidata StarLogger monitored and recorded water level depths every 5 min. Piezometer 1 was 1000 mm deep and Piezometer 2 was 950 mm deep (Figure 2.1).

Troughs excavated into the dense till layer collected the water draining from the three sections and the three preferential features (Figure 2.2) and diverted the water to 7.5 cm diameter ABS pipes sealed to the till with fast-drying concrete. The pipes directed the water into tipping buckets constructed from sheet aluminium and mounted on a level platform. Magnetic switches connected to a Campbell Scientific CR10 data logger monitored the tipping buckets and recorded the tips per minute. The tipping buckets were initially calibrated with a one litre graduated cylinder. After the experiments were complete water was pumped at specific flow rates into each tipping bucket to determine the effect of the flow rate on tipping capacity. The tipping bucket capacities ranged from

0.80 to 1.06 l $tip^{-1}$ and the flow rate did not significantly affect the tipping capacity. The instruments were shielded from rain, snow and wind by walls and a roof.

### 2.2.3 Tracer applications under natural condition

NaCl tracer was applied to the soil surface during two rain events, on March 8th and March 31st, 2005. For these two events, 10 and 20 kg of NaCl were applied, at 12 m and 30 m above the road, respectively (see locations in Figure 2.1). Self-made conductivity probes that included a thermistor, connected to Campbell Scientific CR10 data loggers measured the NaCl concentrations as electrical conductivity in the water draining into the tipping buckets. The self-made probes were similar to a Campbell Scientific conductivity probe (CS547A-L). The probes were calibrated directly to NaCl concentration (ppm) using standard solutions and a relationship between temperature and concentration was established to correct for temperature dependence. The readings from the self-made probes were periodically checked with a Laboratory conductivity probe. The background measurements, which were very low and relatively constant during storms (less than 20 μs $cm^{-1}$), were subtracted from the measurements to yield only the concentration due to the tracer.

### 2.2.4 Steady state tracer experiment

During dry conditions in July 2005, two trenches (4 m long and 30 cm wide) were excavated to the till layer at the locations where the tracer was applied to the soil surface for natural condition experiments (12 and 30 m above the road, Figure 2.1). Water from a nearby stream was diverted into the trench using a 2.5 cm diameter, 300 m long polyethylene pipe. Steady state conditions were assumed to occur when a constant outflow rate was measured with the tipping buckets at the base of the hillslope. During the day, the input pumping rates were regularly measured with a bucket and stopwatch. The experiments extended throughout the night so the tipping bucket measurements were used to determine that steady state was maintained during the experiment. Once the outflow of the hillslope had reached steady state, NaCl solution was added at a rate of 0.1 to 0.2 litres min$^{-1}$ to the trench from a 200 litre container over a period of 3 to 6 hours. The NaCl concentrations in the input trenches and the outflow were measured with the self-made conductivity probes.

Two experiments were conducted at each trench. These experiments were named 12 m high rate (12mHR), 12 m low rate (12mLR), 30 m high rate (30mHR), and 30 m low rate (30mLR). The goal was to have the high flow rate experiments mimic the highest flow rates observed during the natural storms (30.8 l min$^{-1}$ for the large Pipe 2A). However, only a maximum rate of 29.1 l min$^{-1}$ and 23.5 l min$^{-1}$was achieved for the 12mHR and 30mHR, respectively, before water overtopped the input trench as overland flow. The low pumping rates were chosen to be approximately 50 % of the maximum rates, 15.2 l min$^{-1}$ for the 12mLR and 14.0 l min$^{-1}$ for the 30mLR. All experiments lasted 22 to 24 hours.

### 2.2.5 Analysis of steady state tracer data

Artificial tracers are often applied during steady state experiments to determine the velocity and dispersion of solutes in soil columns (e.g. Chendorain and Ghodrati, 1999; Zhang *et al.*, 2006). This approach was applied to the hillslope experiments. For steady state flow rates and tracer application using mathematically defined input, such as a Dirac pulse or constant input concentration, analytical solutions of the convection-dispersion equation (CDE) can be fitted to the observed breakthrough curves to calculate the solute velocities and dispersion (Roth and Jury, 1993). When the water flow and tracer input do not conform to these boundary conditions a response function can be used to transform the input signal to the output signal (Roth and Jury, 1993). For this experiment a steady state flow rate was establish and a pulse of tracer was added to the flow. The tracer added to the input trench had to mix with the water in the trench, which changed the input, so the tracer input was no longer a well defined pulse (e.g. Figure 2.4). To compensate for the irregular input signal a convolution integral or transfer function was used to transform the input signal ($d_{in}$) to the output signal for each of the measured outputs ($d_{out}$):

$$d_{out}(t) = \int_0^\infty g(t')d_{in}(t-t')dt' \qquad [2.1]$$

where *g(t)* is the response function or the distribution of transit times (*t'*), and *t* is real time (Roth and Jury, 1993).

Many models for the response function were tested; including the gamma distribution, the log normal distribution and different forms of the convection-dispersion equation, and concentrations and mass flux for the input and outputs. Although most combinations resulted in similar results, the convection-dispersion equation produced the best results for all applications, so this model was selected:

$$p(t') = \frac{e^{-(1-t'/t'_t)^2/(4/P_e t'/t'_0)}}{\sqrt{4\pi/P_e(t'/t'_t)^3}} \qquad [2.2]$$

where $t'_t$ is average travel time through the system and *Pe* is the Peclet Number (Maloszewksi, 1994). The Peclet Number is the ratio between the diffusive and convective parts of solute transport through a flow field (*Pe* greater than 1 is a convective system and *Pe* less than 1 is a diffusive system). For the steady state experiments the transfer function can be applied using solute concentration or mass flux (mg $min^{-1}$) but the natural storm event analyses had to use mass flux, so for consistency, the mass flux was used for all the analyses.

The steady state experiments had one input and multiple outputs, so in order to apply the mass flux method the total input mass was scaled to equal the output mass for each section. The splitting of water and tracer into the outflow sections was assumed constant for the entire experiment and mass factor (*k*) was added to Equation [2.1]:

$$d_{out}(t) = \int_0^\infty \frac{g(t')}{k} d_{in}(t-t')dt' \qquad [2.3]$$

A Monte Carlo search algorithm was used to determine the parameter values for the average flow time ($t'_t$), the Peclet Number (*Pe*), and the mass factor (*k*) that produced the optimal solution for each outflow section. The optimal solution was considered to be the model with the best Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970). General Likelihood Uncertainty Estimation (GLUE) methodology was used to determine the sensitivity of the input parameters and establish a confidence bound for the models (Beven and Freer, 2001). Following the approach by Zhang *et al.* (2006) Monte Carlo simulations were used to produce 500 model outputs that had Nash-Sutcliffe efficiencies of at least 0.05 less than the optimal solution. The parameter values were plotted against the Nash-Sutcliffe efficiency for the 500 random model results to check that the parameter values were not truncated because this would affect the error bounds. The 500 models were weighted by the efficiency results and used to determine a cumulative distribution for each time interval. The percentiles for each time interval became the error bounds for the model results and the percentiles for the parameters (average flow time ($t_t'$), the Peclet Number (*Pe*), and the mass factor (*k*)) became the error bounds for the model inputs. To calculate an average hillslope velocity, the same methods were applied to the entire hillslope mass flux breakthrough curve.

### 2.2.6 Analysis of natural storm tracer data

The same transfer function and GLUE methodology was used to determine the average tracer velocity and *Peclet Number*s for the natural storm experiments. However, during the natural storms the input of tracer was not known. The NaCl tracer was applied to the soil surface and it was assumed that rainfall mobilized a mass of tracer during each storm that was proportional to the rainfall intensity. The rainfall became the input function ($d_{in}(t)$ in Equation [2.3]) and the mass factor (*k*) represented the mass mobilized by a unit rainfall (mg $mm^{-1}$). The output function ($d_{out}(t)$) was the mass flux for the entire hillslope measured at the output (mg $min^{-1}$).

The time series was divided into 12 individual events (Table 2.1), which ranged in size from 10 – 123 mm of rain. The start of an event was determined to be the start of the rainfall that obviously contributed to an outflow response from the hillslope, and the end of an event was considered to be the start of the next rainfall that produced an outflow response.

To compare the results with existing mathematical formulation of lateral subsurface flow and conceptual models of subsurface flow with preferential features, the calculated velocities were plotted against several flow and storm characteristics. The average flow rate, total rainfall, 1 hr precipitation intensity, and water table depth measurements of the two piezometers were used. The streamflow before the event was used for a measure of antecedent condition. The stream was gauged with a weir approximately 25 m from the experimental hillslope. Uneven topography and the available elevation data made it difficult to accurately determine the watershed area, however the area was less than 1 $km^2$.

### 2.2.7 Comparison to mathematical equations of flow

Relative discharge – velocity relationships for Manning's equations [2.4] and Darcy's law [2.7] (with a constant hydraulic conductivity and an exponential decline in hydraulic conductivity with depth [2.8] ) were fitted so that the results could be compared to existing mathematical formulation of subsurface flow. These relationships were plotted against the average flow rates and velocities at the site.

To developed the relative discharge – velocity relationships we calculated velocity and discharge for 1 % depth increments and then we divided the increment values by the values for the maximum depth to yield the relative values.

Manning's Equation for flow through a pipe calculates velocity (*V*):

$$V = \frac{1}{n} R^{2/3} S^{1/2} \qquad [2.4]$$

$$R = \frac{A}{P} \qquad [2.5]$$

where n is Manning's roughness, $R$ is the hydraulic radius, A the area of flow, P is the perimeter of the flow, and the slope ($S$). The discharge was then calculated using the area of flow times the velocity:

$$Q = VA \qquad [2.6]$$

Darcy's law for flow through a porous medium calculates the discharge ($Q$) as:

$$Q = -kAS \qquad [2.7]$$

where $k$ is the hydraulic conductivity that can be constant or a function of depth. We used the used an exponential decline with depth to describe the hydraulic conductivity of the soil:

$$k_z = k_0 \exp\left(-\frac{z}{b}\right) \qquad [2.8]$$

where $z$ is depth below the soil surface and $b$ is the exponential factor. The velocity is determined by dividing the discharge by the area of flow ($A$) and the effective porosity ($n_{eff}$):

$$V = \frac{Q}{A * n_{eff}} \qquad [2.9]$$

## 2.3 Results

### 2.3.1 Hillslope subsurface flow response

Twelve events between March and June 2005 were measured. The storm outflow ranged in volume from 0.5 to 100 $m^3$ (calculated as the sum of the outflow greater than the outflow rate before the start of the event) from the 9 m section of hillslope (Table 1). On average 63.3 % of the total outflow was collected from pipe 2A. Pipe 2B and PF1 produced on average 10.3 % and 10.1 % of the outflow respectively. S2 and S3 produced on average 4.8 % to 4.2 % of the outflow. S1 produced on average 9.9 % of flow. However, the outflow rate of S1 increased dramatically during some large storms (Figure 2.3), which caused an increase in the percentage of outflow in those storms. This increase could be a result of one of the following factors:

1. this section of the hillslope was connected to a larger contributing area (Tromp-van Meerveld and McDonnell, 2006b) , or
2. portions of the preferential flow network reached their capacity to transmit water to pipe 2A, resulting in water exploiting different features (Sidle *et al.*, 2000).

These ideas are discussed further after the steady state tracer results are presented in the next section.

### 2.3.2 Tracer recovery under natural condition

From the 12 m and 30 m tracer experiment, 19.8 % and 24.2 % of the applied tracer was recovered at the base of the hillslope (Table 2.2). Of the recovered tracer, almost the entire (99.1 %) NaCl tracer from the 12 m experiment was recovered in Pipe 2A and Pipe 2B (Table 2.2). In contrast, a higher percentage of tracer was recovered from the other sections of the hillslope during the 30 m experiment. The amount of tracer recovered from pipe 2A decreased from 94.7 % to 77.7 % and all other sections showed an increase (Table 2.2). The quick breakthrough of tracer observed almost immediately following the 12 m application of NaCl was not observed after the 30 m application (Figure 2.3). The difference in breakthrough was likely affected by the vertical infiltration and the lateral connectivity of the hillslope preferential network. During storms the water table at the 12 m application site was near the surface. The tracer was applied to the soil surface, and some of the 12 m tracer would quickly reach the saturated zone and would then be transported down slope. The remainder of the 12 m tracer application and the 30 m application had to infiltrate vertically before reaching the saturated zone and lateral preferential flow features. The preferential flow network between the 12 m application site was also more highly connected when compared to the 30 m application site.

### 2.3.3 Tracer recovery under steady state conditions

As expected from the experiments under natural conditions, the 12 m steady state experiments (12mHR and 12mLR) produced a concentrated response in section 2. Both experiments produced very similar responses for pipe 2A. However, more of the tracer (98.9 % versus 97.5 %, Table 2.4) and water (97.4 % versus 96.5 %, Table 2.3) was recovered from pipe 2A during the 12mLR tests. To offset the reduction in tracer and water from pipe 2A during 12mHR, pipe 2B had twice the amount of tracer recovered (1.1 % and 2.4 %, Table 2.4), and more water (3.1 % and 2.1 %, Table 2.3). S3 had less than 1 % of the tracer and water recovered for all experiments (Tables 2.3 and 2.4).

Even though most tracer was still recovered in the large pipe 2A during the 30 m tracer experiments, more tracer and water were recovered from other sections. Pipe 2A transmitted 82.9 % and 88.1 % of tracer (Table 2.4) and 84.7 % and 85.9 % of the water (Table 2.3) during 30mHR and 30mLR, respectively. Pipe 2B transmitted a higher percentage of the tracer (7.4 % and 9.1 %, Table 2.4) during the 30 m experiments than during the 12 m experiments.

The ability of the network above the 12 m trench to deliver water and solutes to pipe 2A can be seen when the 30mLR and 30mHR tracer recovery results are compared (Tables

2.3 and 2.4). Increasing the flow rate caused less tracer to be recovered from pipe 2A and pipe 2B (97.2 % vs 90.3 %, Table 2.4) and more tracer to be recovered from S1 and PF1 (9.3 % vs 2.8 %, Table 2.4). Similarly the water recovered from S2 decreased and the water recovered from S1 increased when the pumping rate was increased (Table 2.3). It was not the maximum capacity of the features in S2 (pipe 2A in particular) that limited the flow during 30mHR because the measurements for natural events of pipe 2A exceeded 30 l min$^{-1}$ (Figure 2.3) and the 12 m high rate experiment transmitted 28 l min$^{-1}$ (pipe 2A only in Table 2.3), which are both more than the 30mHR steady state input 23.5 l min$^{-1}$ (Table 2.3). This could be caused by the preferential flow network that transmits water to S2 is reaching its maximum capacity, after which additional water exploited features that routed water to S1. This might also explain the rapid change in flow rate seen in S1 during large natural events. It is possible that S1 does not connect to another part of the hillslope, but that features in the upper 18 m of the hillslope had reached their maximum capacity to deliver water to S2 and the additional water and tracer was diverted into S1.

### 2.3.4 Transfer functions results

The velocities were of interest for the experiments; however, the transfer function methods produced both velocity and *Peclet Number*s. There is a weak relationship between average flow and Peclet Number (Figure 2.5), suggesting that in general, increasing velocities do correspond with increasing *Peclet Number*s, indicating a more convective system. This positive correlation between the velocity and Peclet Number was expected because a more conductive system is expected at higher velocities.

### 2.3.5 Tracer velocities under steady state conditions

During the 12 m tests the velocities observed in pipe 2A were one to two orders of magnitude faster than the velocities measured in all other sections (Figure 2.6). This suggests that this pipe was connected to highly conductive features that had little exchange with the surrounding hillslope (soil matrix and preferential features). Excavations later confirmed that the network connecting the outflow with the input trench was highly connected and had flow with little interaction with the soil matrix (Anderson *et al.*, 2008). Reducing the pumping rate (12mHR compared to 12mLR, Figure 2.6) had no significant effect on the velocity of the tracer through pipe 2A, but the velocity through S2 was reduced. At the high flow rate the preferential features could have been close to their maximum capacity, which would create a large pressure gradient in the surrounding soil matrix and cause higher and faster flows through the soils surrounding pipe 2A (Figure 2.6, Table 2.4).

The 30mHR experiment produced mean tracer velocities that were in the order of $10^{-3}$ and $10^{-4}$ m $s^{-1}$ for all gauged features (Figure 2.6). With the exception of Pipe 2B, reducing the pumping rate from 23.5 to 14.0 l $min^{-1}$ (reduced to 59 % of the 30mHR) produced velocities that were reduced only by 15 to 25 % (Figure 2.6). Pipe 2B had no significant change in velocity when the flow rate was varied. Similar to the 12 m tests, pipe 2A had the highest velocities, but the difference between the velocity of pipe 2A and the other sections were much smaller. This suggests that the preferential flow network connecting the upper trench to the road cut-bank was similar to the conceptual model, where the soils connecting the individual preferential flow features reduce the overall velocity in the hillslope (Sidle *et al.*, 2000).

The mean velocities for the entire hillslope are dominated by flow through pipe 2A because it carries the majority of the tracer during all experiments (82.9 to 98.9 %, Table 2.4). The 30 m experiments produced a mean hillslope velocity that was over an order of magnitude lower than the 12 m experiment velocities (Figure 2.6).

### 2.3.6 Tracer velocities under natural conditions

The maximum height of the water table in piezometer 2 and the maximum 1 hr precipitation intensity have the closest relationship to the hillslope velocity (Figure 2.8, and Figure 2.10). The velocity increases with the average storm flow (Figure 2.7); however storm 8 is an outlier that had a high velocity but low average storm outflow rate. Storm 8 is a short duration high intensity event. The high intensity storm could activate the preferential features in the network causing a high velocity, but the short event duration may limit the amount of outflow generated. The velocities are also influenced by the vertical transport of the tracer; faster vertical infiltration of storm water during high intensity storms would be expected. Although there tends to be increasing velocity as the antecedent condition increases (Figure 2.9), in general the antecedent condition has little effect on the velocity, which is similar to other studies (e.g. Kienzler and Naef, 2007). The antecedent condition has poor relationship with the velocity in part because the experiments were conducted in the winter when the antecedent conditions for each event are all relatively wet compared to summer or fall conditions.

The good relationship between the response of piezometer 2 and the velocity (Figure 2.10) was not expected because the processes governing the vertical infiltration of water and the lateral velocity should be different. However, excavations revealed that peizometer 2 was close to a major preferential feature (Anderson *et al.*, 2008) and it responded during the steady state experiments. It is possible that the water table response was a result of the close proximity to the preferential features and not from vertical infiltration.

## 2.4 Discussion

Tracer studies have been used to quantify the subsurface velocity of hillslopes with preferential flow in many areas around the world. Studies that focused on subsurface flow velocities in forested and grassland environments were selected to determine how the velocities measured in these experiments fit in relation to other experiments. Measurements from studies of larges pipes in peatland were not included (e.g. Holden and Burt, 2002). The average velocities from the selected studies are summarized in Table 2.5. The results from the experiments are in the upper range of other measured subsurface velocities. An experiment conducted on the west coast of Vancouver Island in similar soil conditions as this 12 m tracer experiment (Hetherington, 1995) and an experiment in New Zealand at Maimai (Mosley, 1979) measured velocities in the order of 100 m $hr^{-1}$. Hetherington (1995) simultaneously measured velocities at another site that was similar to the upper section of this study site and found velocities the same order of magnitude as the 30 m steady state experiments. The humid climate (2000 – 5000+ mm $yr^{-1}$ of precipitation), shallow soils (often less than 1 m deep) and lush vegetation of these regions may cause highly developed preferential flow networks in areas with concentrated subsurface flow resulting in fast local subsurface velocities.

The issue of the spatial scale and representative elementary volume (Beven and Germann, 1981) of these measurements is important. In this study, faster velocities and different discharge-velocity relationships were observed for the 12 m steady state experiments than the natural storms or the 30 m experiments, which included the 12 m section. With the shorter distance (12 m) the tracer was injected directly into a highly connected preferential flow network that hydraulically connected the input trench with the outflow site. Steady state experiments over the longer distance (30 m) and during the natural condition experiments (applied to the surface) measured velocities through a less hydraulically connected system and produced much slower responses. This highlights the role that the connections between the preferential flow features have in governing the subsurface velocity. This connectivity may have been a factor in other experiments as well. Mosley (1979) and Hetherington (1995) both measured flow over a relatively short distance (3 and 4 m), which would increase the likelihood that their experiments measured a highly connected preferential network or even flow through one single preferential feature. A larger spatial scale experiment or an experiment that included the vertical percolation of a tracer might produce very different results. Similar observations have been revealed in studies of vertical macropores where length and connection of a single vertical preferential feature had a large influence on the observed vertical flow rate (e.g. Beven and Germann, 1981).

In addition to the two slope lengths and different boundary conditions, these experiments were conducted under different steady state flow rates and under different rainfall characteristics. The results showed that the rainfall intensity and the pumping rate affected the subsurface velocity. When experiments are conducted to determine the subsurface velocity of a hillslope with preferential flow features it is important to consider the boundary conditions, slope length, flow rate, and precipitation characteristics because these factors will affect the measured tracer velocities.

To put experimental results in context and validate models we need to understand the relationship between hillslope subsurface flow rates, rainfall characteristics, and antecedent conditions. The general concept of lateral preferential flow networks is that a rising water table increases the number of preferential connections in a generally disconnected network, which causes faster subsurface velocities and an increase in the area of hillslope contributing to subsurface flow (Sidle *et al.*, 2000; Tromp-van Meerveld and McDonnell, 2006b; Tsuboyama *et al.*, 1994; Uchida *et al.*, 2005). The results presented support this conceptual model of hillslope flow. The fast hillslope velocity and low average flow rate of Strom 8 could be a result of the high intensity storm causing fast vertical percolation of water that would develop a water table and connect the lateral preferential features (Figure 2.8 and Figure 2.10). The 30 m steady state boundary condition experiments also showed that the lateral hillslope preferential network has the ability to exploit new features and add to the network as active features reach their maximum capacity to transport water.

Most numerical models use a discharge – velocity relationship (directly or indirectly) to represent the behaviour of hillslopes. The discharge – velocity relationship in Figure 2.7 was used to fit models that are commonly applied to simulate lateral subsurface flow in hillslopes. Darcy's law with an exponential decline in the saturated hydraulic conductivity and Manning's equation were used. Darcy's law assumes that the flow of water is a function of the hydraulic gradient (water table slope), depth of the water table, and the transmissivity of the soil which is generally derived from a function that represents the saturated hydraulic conductivity of the soil. Many different functions can be used to approximate the hydraulic conductivity of the soil including exponential, parabolic, and linear (Ambroise *et al.*, 1996). The exponential function was chosen because it fit the data well and is commonly used (Ambroise *et al.*, 1996). Manning's equation for flow through a pipe has been used to model vertical flow through macropores and was chosen because it represents flow through a confined circular space which is similar to a highly connected preferential flow network found between the 12 m injection trench and the road cut bank (Anderson *et al.* 2008).

The two 12 m steady state experiments have almost identical flow velocities, which could be represented by a constant discharge-velocity relationship or by Manning's equation for flow through a pipe. Pipe 2A did show a maximum capacity to transmit water during storms and excavations at this site revealed a highly connected preferential network that connected the input trench and the road cut bank (Anderson *et al.*, 2008). Conceptually the flow through a confined space such as a highly connected preferential flow pathway is better represented by Manning's equation for flow through a pipe.

If the outliers such as Storm 8 are neglected, the other measurements show a power law relationship ($v = \beta Q^{\alpha}$) which can be reproduced with a very dramatic exponential decline in hydraulic conductivity (e.g. *b*=0.1, Figure 12). Such an extreme decline of hydraulic conductivity is unlikely, especially considering that the water table only changes by 20 cm (Figure 2.10). Yet, this relationship could still be considered an effective hydraulic conductivity (*Ksat*) for the hillslope. This type of relationship could be used in a distributed model and would likely produce good discharge-velocity results for the scale of interest, but may not adequately represent the water table and storage dynamics. For example, the hydraulic conductivity vs. relative depth curve in Figure 2.12 represents a soil profile with such an extreme change in hydraulic conductivity with depth that the curve for that soil cannot be trusted. The factors that control the flow in Darcy's Law (cross-sectional area of flow and water table slope) may not be the factors affecting the power law relationship in Figure 2.11. Models that represent the preferential flow network discretely with physical or empirical equations are more likely to reproduce the solute transport and water table dynamics of a hillslope.

Hillslopes that are dominated by preferential networks often do not have water tables that reach the soil surface because of the high capacity of the preferential flow network to drain the soil (Fannin *et al.*, 2000). The ability of water to exploit different preferential features was shown by the 30 m steady state experiment results, where an increase in the flow rate caused different subsurface features to compensate for the additional water and redirect water to S1 away from S2. Unlike a Darcy system where the cross-sectional saturated area of flow determines the velocity and flow rate, in a hillslope with a preferential flow network it is the number and type of the preferential features connected within the network that will change the flow characteristics. Features and material that create the preferential network are important in determining how the water table, hillslope discharge, and velocity will behave and how best to model a particular hillslope. Similar to the hydraulic conductivity of soils, the preferential features and connecting material will vary between hillslopes, and will depend on the processes that create and modify preferential features. Factors influencing the preferential network will include climate, soil, topography, contributing area, and processes (burrowing animals, insects, worms, roots, subsurface erosion, etc) that create features (Tsuboyama *et al.*, 1994). Preferential flow is a first order control of subsurface flow in many areas of the world (Uchida *et al.*, 2005). The hillslope processes in this study watershed and others with similar climate and topography are dominated by large highly connected preferential flow networks that are created and maintained by large amounts of water (greater than 2000 mm/yr) moving through shallow soils (0.5 – 2 m). These preferential flow networks are even activated during small storms, so the antecedent condition is not an important factor in activating the network. Models that reflect this dynamic hillslope behaviour are better suited for hillslopes with these efficient preferential flow networks (e.g. Weiler and McDonnell, 2007). Other hillslopes may have less developed preferential flow networks that are only activated during high antecedent conditions or under certain precipitation characteristics (Uchida *et al.*, 2005). To properly model and manage watersheds, it is important to be able to classify the type of hillslope response (Uchida *et al.*, 2005). Steep hillslopes with shallow soils, high rainfall regimes and no evidence of surface runoff are likely to have well developed preferential features and efficient preferential flow networks whose behaviour is likely similar to that of this experimental hillslope.

## 2.5 Conclusion

NaCl tracer was applied under natural and steady state boundary conditions to determine subsurface lateral velocity. The results of the tracer experiment were used to determine the relationship between slope length, steady state flow rate, piezometer response, storm characteristics, and the tracer velocity. The velocity was closely related to the 1 hr rainfall intensity. At this hillslope the antecedent condition and the total rainfall were poorly related to the subsurface flow velocity. Although this is consistent with other conceptual models of hillslope flow, our site had a very small water table response suggesting that the connectivity of the hillslope preferential flow network is important for the average flow velocity.

The importance of the representative elementary unit of the hillslope was highlighted during these experiments. The 12 m steady state experiments reported fast velocities (1 and 2 orders of magnitude higher than other measurements), which did not reflect the velocities measured at a larger scale and during natural storms. The 12 m section of hillslope had a highly conductive feature that connected the input trench to base of the hillslope, which did not represent the connectivity of the upper portion of the hillslope or the surface of the soil to the lateral flow.

With the exception of a short high intensity storm the discharge-velocity relationship could be represented by a power law relationship. Although Darcy's Law is not intended for systems with preferential flow, the data could be explained by the model when an extreme decline in hydraulic conductivity with soil depth was assumed. Darcy's Law relates flow to a function of water table slope and cross-sectional area, which appears not to be valid at this site. Models that explicitly represent the preferential flow may be a better choice for these types of hillslopes because the velocity and hydraulic conductivity of this hillslope system can change with a small increase in the water table depth and these changes do not happen close to the soil surface.

Table 2.1. Natural event total discharge and percentages of the total discharge for the 6 gauges. Total flow was calculated as the amount of flow above the flow before the start of the response to rainfall.

| Event # | Event Start Date | Total Precip mm | Total flow $m^3$ | Section 1 Matrix % | Section 1 Prefere-ntial % | Section 2 Matrix % | Section 2 Pipe A % | Section 2 Pipe B % | Section 3 Matrix % |
|---|---|---|---|---|---|---|---|---|---|
| 1 | March 7 | 14 | 16.3 | 5.0 | 9.5 | 1.2 | 66.0 | 15.2 | 3.1 |
| 2 | March 10 | 10 | 0.5 | 8.9 | 7.5 | 20.4 | 45.7 | 8.6 | 8.8 |
| 3 | March 16 | 27 | 5.8 | 7.0 | 9.8 | 5.1 | 66.8 | 4.2 | 7.0 |
| 4 | March 25 | 41 | 29.1 | 9.7 | 16.0 | 1.7 | 57.9 | 8.8 | 6.0 |
| 5 | March 30 | 87 | 98.0 | 11.3 | 10.3 | 1.5 | 61.0 | 11.0 | 4.9 |
| 6 | April 5 | 123 | 100.0 | 18.7 | 7.5 | 2.2 | 58.0 | 9.8 | 3.8 |
| 7 | April 15 | 45 | 49.6 | 11.0 | 11.8 | 1.9 | 61.7 | 9.1 | 4.5 |
| 8 | May 10 | 27 | 2.0 | 0.2 | 0.1 | 5.6 | 82.8 | 11.3 | 0.1 |
| 9 | May 14 | 15 | 0.8 | 0.0 | 0.0 | 12.1 | 72.8 | 14.8 | 0.2 |
| 10 | May 18 | 58 | 33.0 | 8.5 | 18.2 | 1.3 | 66.2 | [a] | 5.8 |
| 11 | May 21 | 92 | 81.3 | 29.2 | 8.2 | 2.5 | 56.2 | [a] | 3.9 |
| 12 | June 17 | 16 | 10.8 | 8.8 | 22.2 | 2.1 | 64.0 | [a] | 2.9 |
| | | | Average | 9.9 | 10.1 | 4.8 | 63.3 | 10.3 | 4.2 |

[a] The Pipe 2B tipping bucket was damaged during the May 18th storm and three storms were missed.

Note that the average storm outflow percentages do not sum too 100 because they are the average of the percent contribution per storm.

Table 2.2. Natural event tracer percent recoveries and the total water percent of water recovered for the 12 m and 30 m application of NaCl.

| Tracer Test | | Section1 Matrix % | Section1 Prefere-ntial % | Section2 Matrix % | Section2 Pipe A % | Section2 Pipe B % | Section3 Matrix % | Total Recovery % |
|---|---|---|---|---|---|---|---|---|
| 12 m | **Tracer** | **0.5** | **0.3** | **0.1** | **94.7** | **4.4** | **0.0** | **19.8** |
| | Water | 8.3 | 13.6 | 3.5 | 63.5 | 7.3 | 3.8 | |
| 30 m | **Tracer** | **9.1** | **3.9** | **0.6** | **77.7** | **7.3** | **1.4** | **24.2** |
| | Water | 13.6 | 12.2 | 3.0 | 61.8 | 5.6 | 3.9 | |

Table 2.3. Steady state experiment pumping rates and outflows expressed in l min-1 and as percents of the total output.

| Experiment | Total Flow Rate (l min$^{-1}$) | Section 1 Matrix (l min$^{-1}$) % | Section 1 Preferential (l min$^{-1}$) % | Section 2 Matrix (l min$^{-1}$) % | Section 2 Pipe A (l min$^{-1}$) % | Section 2 Pipe B (l min$^{-1}$) % |
|---|---|---|---|---|---|---|
| 12 m high rate | 29.10 | | | 0.12<br>0.4 % | 28.09<br>96.5 % | 0.89<br>3.1 % |
| 12 m low rate | 15.16 | | | 0.08<br>0.5 % | 14.77<br>97.4 % | 0.31<br>2.1 % |
| 30 m high rate | 23.48 | 0.63<br>2.7 % | 1.25<br>5.3 % | 0.15<br>0.6 % | 19.90<br>84.7 % | 1.55<br>6.6 % |
| 30 m low rate | 13.95 | 0.20<br>1.4 % | 0.43<br>3.1 % | 0.12<br>0.8 % | 11.98<br>85.9 % | 1.22<br>8.7 % |

Table 2.4. Steady state experiment measured tracer recoveries in grams and expressed as percents of the total mass recovered.

| Experiment | Measured output (NaCl g) | Section 1 Matrix (NaCl g) % | Section 1 Preferential (NaCl g) % | Section 2 Matrix (NaCl g) % | Section 2 Pipe A (NaCl g) % | Section 2 Pipe B (NaCl g) % |
|---|---|---|---|---|---|---|
| 12 m high rate | 461.3 | | | 0.7<br>0.2 % | 449.7<br>97.5 % | 10.9<br>2.4 % |
| 12 m low rate | 909.4 | | | 0.7<br>0.1 % | 899.1<br>98.9 % | 9.6<br>1.1 % |
| 30 m high rate | 430.7 | 13.1<br>3.0 % | 27.2<br>6.3 % | 1.6<br>0.4 % | 356.9<br>82.9 % | 31.9<br>7.4 % |
| 30 m low rate | 648.2 | 5.7<br>0.9 % | 12.2<br>1.9 % | 0.8<br>0.1 % | 570.8<br>88.0 % | 58.7<br>9.1 % |

Table 2.5. Average velocities measured during selected experiments.

| Distance (m) | Average velocity range (m hr$^{-1}$) | | Reference |
|---|---|---|---|
| | Minimum | Maximum | |
| 4 | 4.3 | 154.8 | Mosley, 1979 |
| 1 | 10.8 | | Mosley, 1982 |
| 2 | 0.4 | 0.6 | Tsuboyama *et al.*, 1994 |
| 10/13.5 | 7.8 | 24.0 | Mikovari *et al.*, 1995 |
| 35-40 | 0.4 | 0.5 | Nyberg *et al.*, 1999 |
| 35-40 | 2.4 | 2.5 | Nyberg *et al.*, 1999 |
| 3 | 4.3 | 22.7 | Hetherington, 1995 |
| 3 | 33.1 | 165.6 | Hetherington, 1995 |
| 7.7 | 2.5 | 32.4 | Weiler *et al.*, 1998 |
| 8.3 | 0.8 | 2.9 | Weiler *et al.*, 1998 |
| ? | 10.8 | 13.3 | Feyen *et al.*, 1999 |
| ? | 0.6 | 3.4 | Feyen *et al.*,1999 |
| 2 | 8.6 | 13.7 | Noguchi *et al.*, 1999 |
| 4 / 8 | 7.2 | 10.8 | Retter, 2007 |
| 30 / 12 | 2.9 | 331.2 | This study |
| 30 / 12 | 0.1 | 7.6 | This study |

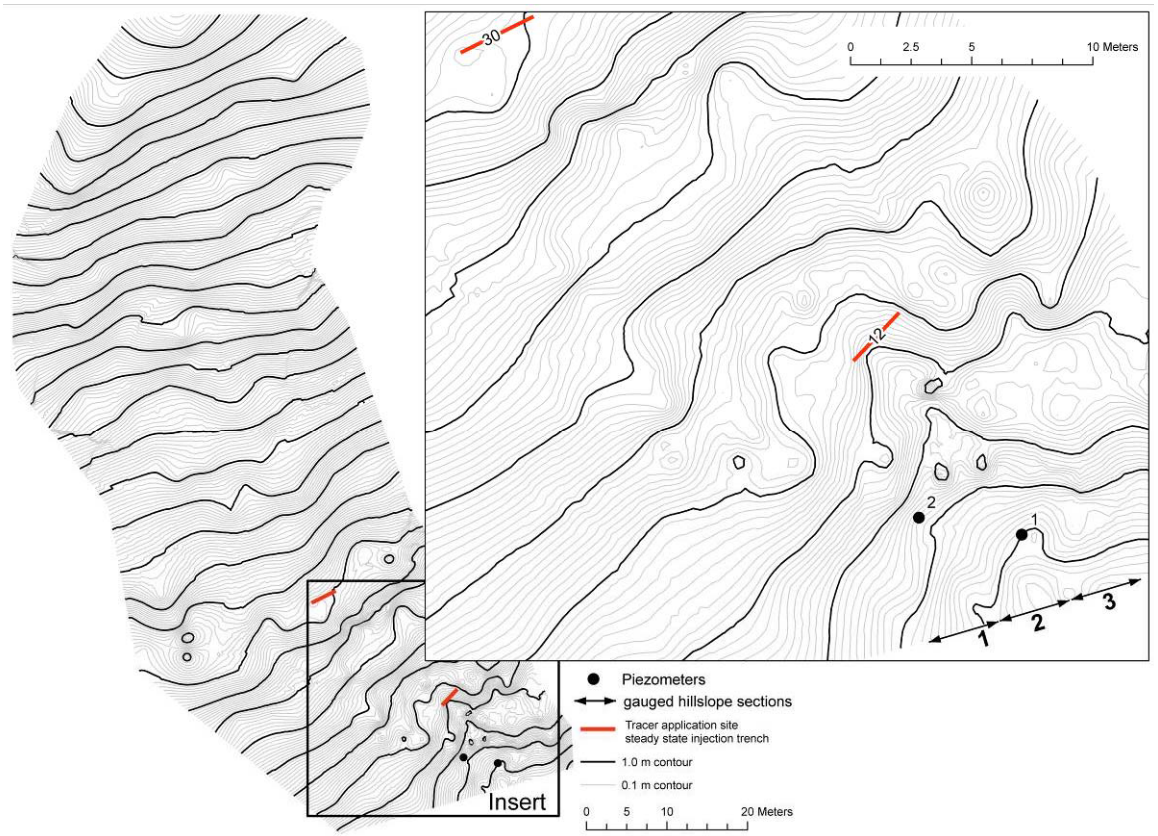


Figure 2.1. Contour map of the experimental hillslope developed from a Total Station survey showing the tracer injection sites, piezometer locations, and the gauged sections.

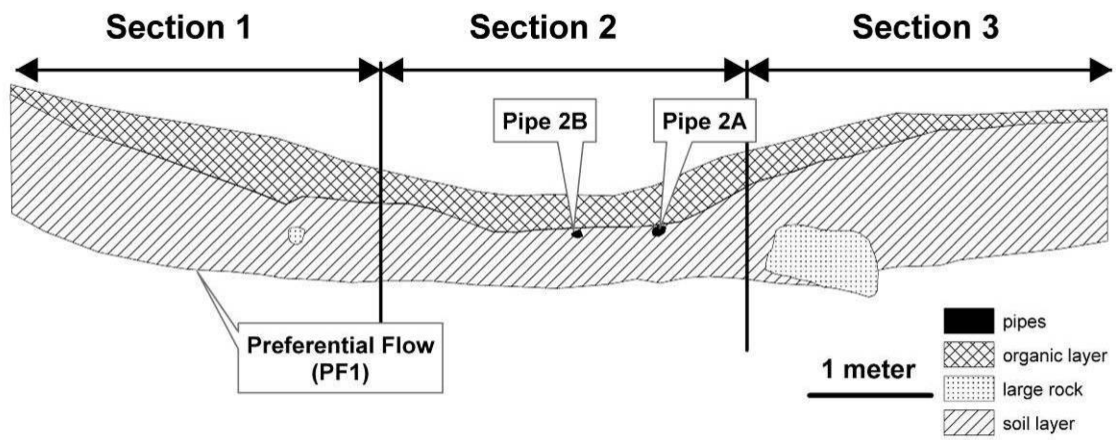


Figure 2.2 Diagram of the hillslope outflow face showing the 3 gauged sections and the 3 individually gauged features, 1) pipe 2A, 2) pipe 2B in section 2 and 3) preferential flow at the interface of the till and soil in section 1.

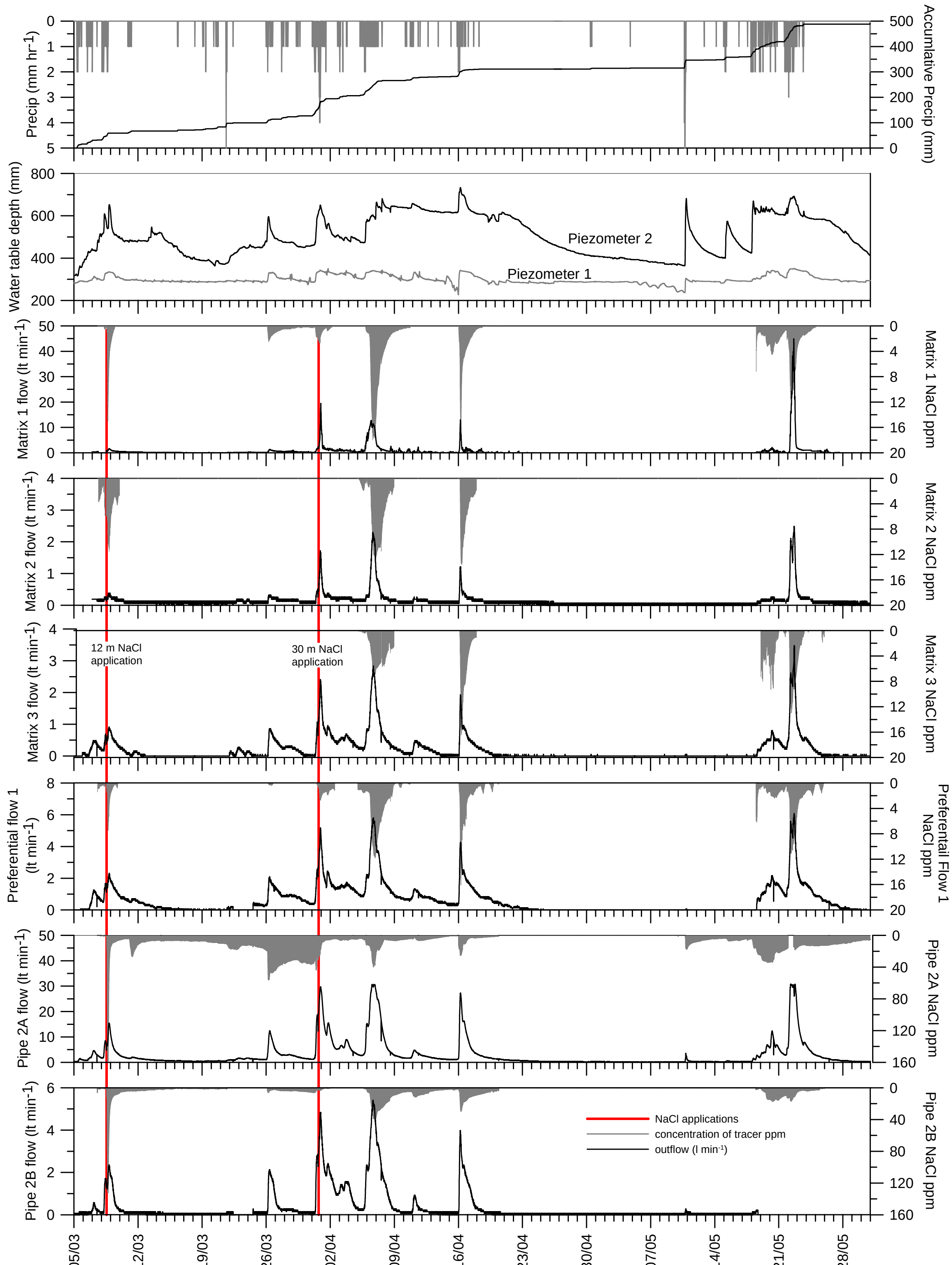


Figure 2.3. Natural event outflow and concentration of tracer for the 6 gauged sections and 2 piezometer responses.

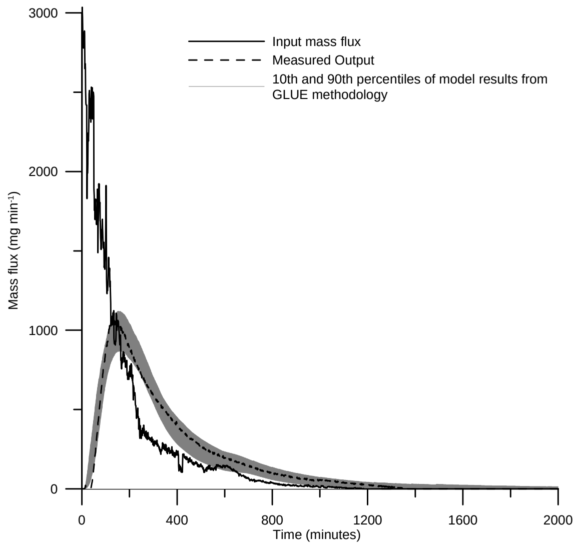


Figure 2.4. Example of the input and output signals (mg min-1) and the 10th and 90th percentiles of the 500 model results for the 30 m high rate steady state experiment

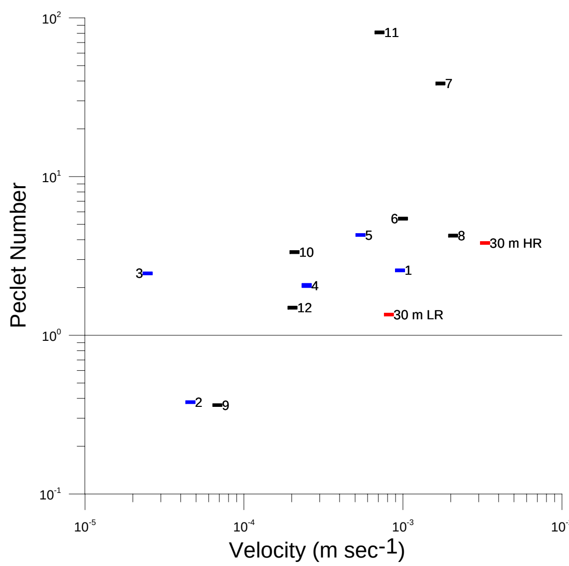


Figure 2.5 Average velocity and *Peclet Number*s from the transfer function methodology.

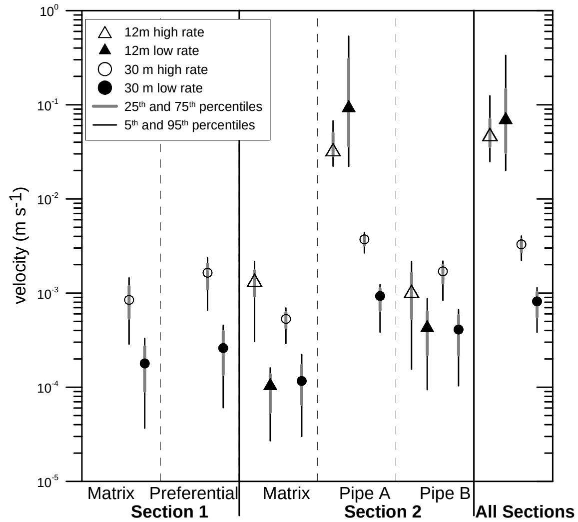


Figure 2.6. Steady state experimental results for each gauged section and the entire hillslope. Mean velocities from the advection dispersion equation and percentiles from the GLUE methodology.

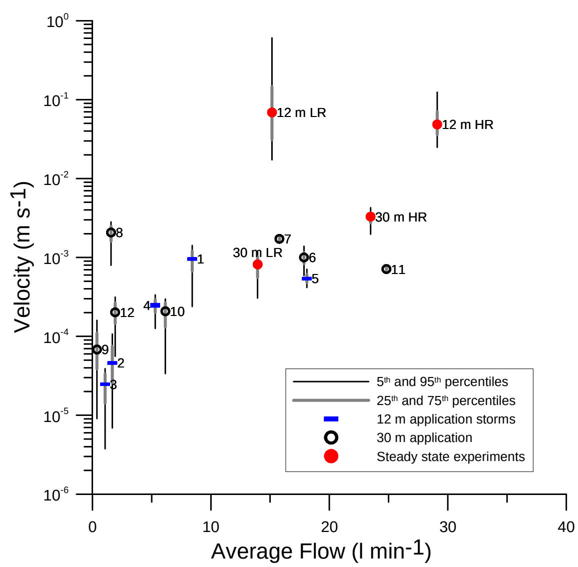


Figure 2.7. Average velocity and percentiles from the GLUE methodology for the 12 storms and the 4 steady state condition experiment versus the average flow rate for each storm.

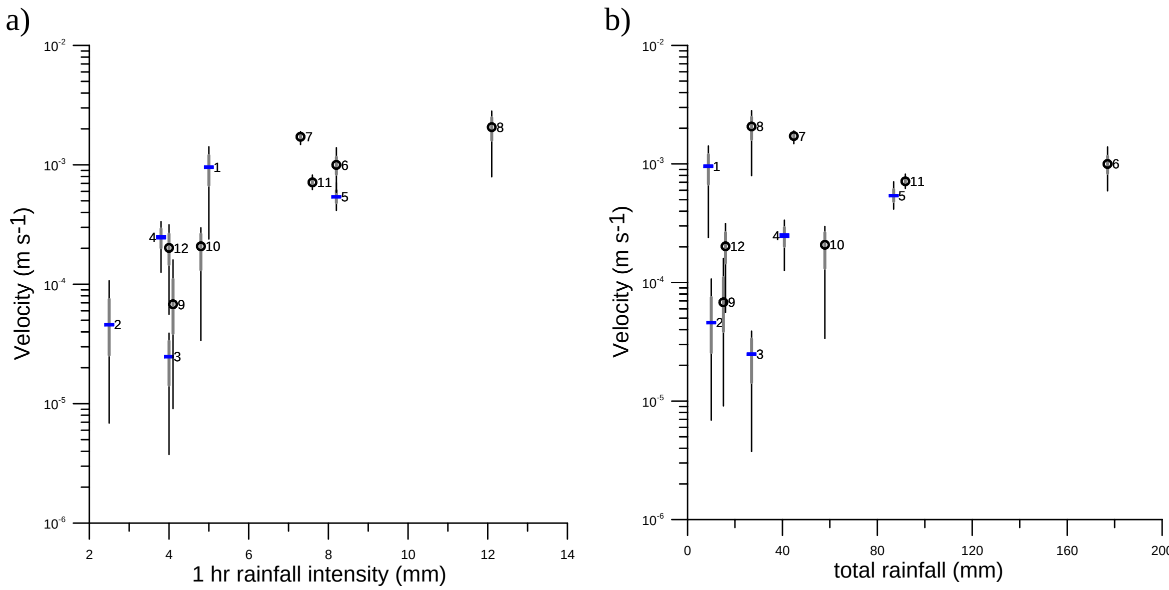


Figure 2.8. Average velocity and percentiles from the GLUE methodology for the 12 storms versus the 1 hr maximum storm intensity and the total storm rainfall.

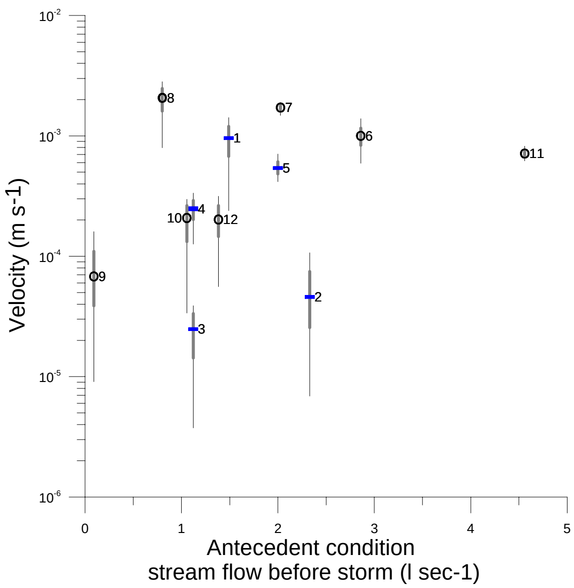


Figure 2.9. Average velocity and percentiles from the GLUE methodology for the 12 storms versus the antecedent condition (streamflow before the storm l sec-1).

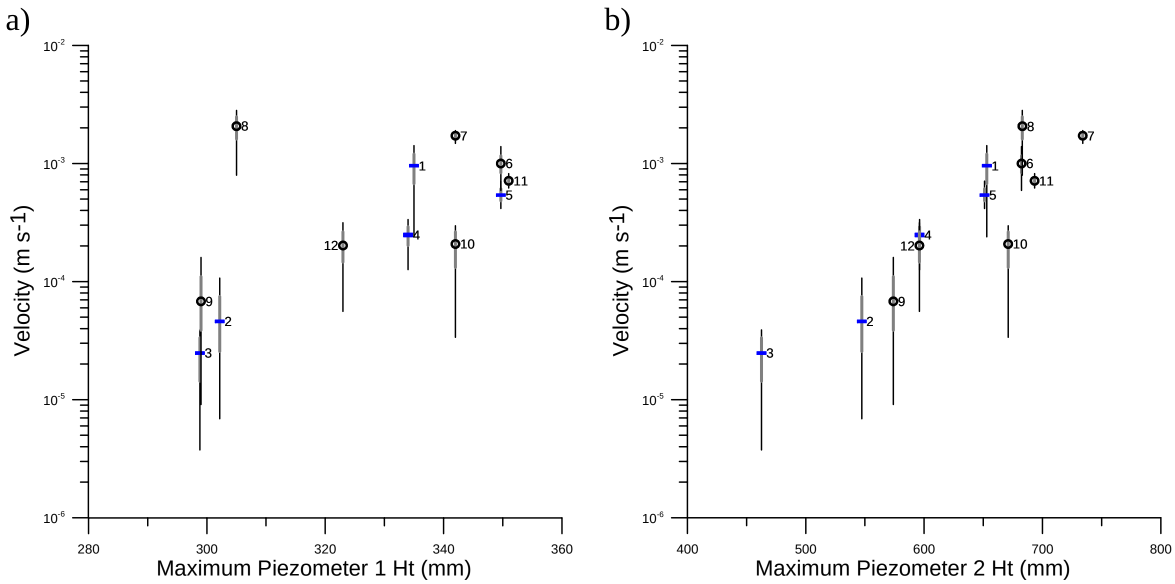


Figure 2.10. Average velocity and percentiles from the GLUE methodology for the 12 storms versus the maximum water table height for piezometer 1 and piezometer 2.

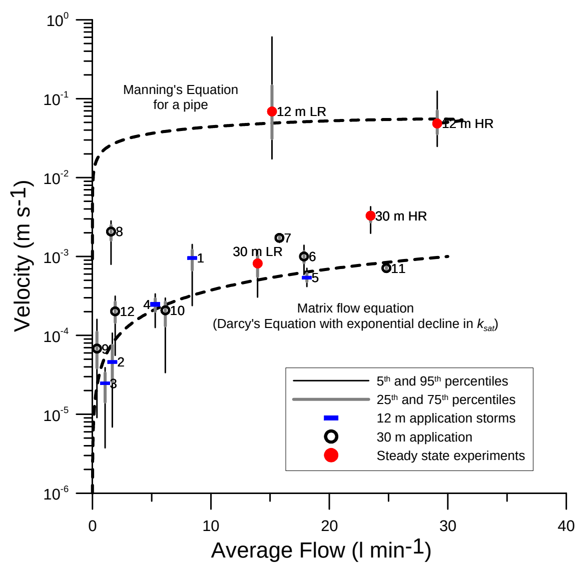


Figure 2.11. Flow rate and velocity of the mean of the convolution integral and the GLUE errors for the steady state experiments and natural condition experiments. Manning's equation for flow through a pipe (upper curve) and Darcy flow through a matrix with an exponential decline in hydraulic conductivity.

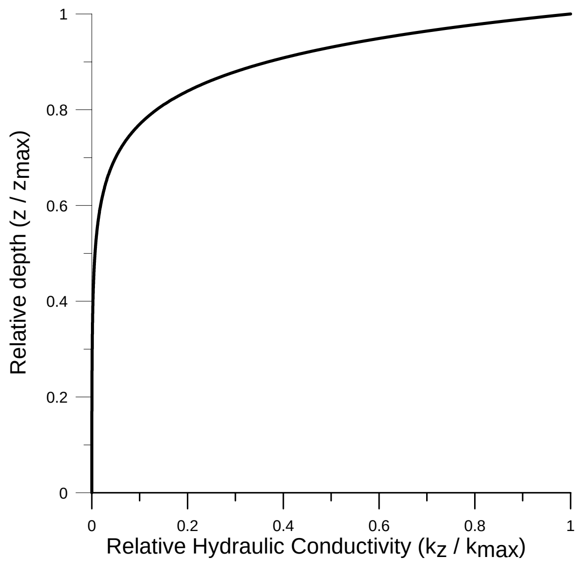


Figure 2.12. Relative depth versus relative hydraulic conductivity for the plot in Figure 2.11, exponential decay parameter (b = 0.1).

## 2.6 References


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# 3 Dye staining and excavation of a lateral preferential flow network.[2]

## 3.1 Introduction

Subsurface flow in hillslopes dominates the hydrological regime, the transport of solutes and nutrients, and can affect slope stability especially in humid climate on steep, forested watersheds (Uchida, 2004). Preferential flow has long been identified as an important factor in these environments (Mosley, 1979). However, the flow pathways that water flows through are still largely unknown. Researchers have used dyes and excavation to determine how water exploits vertical and lateral preferential flow features (e.g. Noguchi *et al.*, 1999; Weiler and Fluhler, 2004). This method involves applying dye solution or paint with sprinklers or line sources to sections of the soil under steady state conditions. The soil is excavated, photographed, and analysed to determine the flow paths (e.g. Weiler and Fluhler, 2004). These experiments have been used at the smallest scales (less than 2 meters) and often focus on the vertical movement of water during infiltration. This method is labour intensive and destroys the soil structure, but it has been proven effective. Less destructive methods such as ground penetrating radar, fibre optics, and electrical conductivity have been tested, but they require expensive equipment and have seen limited successes (e.g. Holden *et al.*, 2002; Sherlock and McDonnell, 2003).

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The few hillslope experiments that use excavation have found that hillslopes had short (generally less than 5 m) preferential flow features (Noguchi *et al.*, 1999; Terajima *et al.*, 2000). Some steep, forested hillslopes have been reported to have large preferential flow features, but it was not known how far upslope they extended (Kitahara, 1993; Roberge and Plamondon, 1987; Tsukamoto and Ohta, 1988; Uchida *et al.*, 1999). Even though preferential features are usually short and discontinuous, hillslopes produce fast tracer velocities and rapid subsurface flow responses (Hutchinson and Moore, 2000; Peters *et al.*, 1995; Tani, 1997). These fast velocities and subsurface flow responses have led to the idea of a preferential flow network, which describes a series of hydraulically connected preferential features that appear to be physically discontinuous. The exact mechanisms that allow water to exploit these preferential flow pathways are not known, but it is assumed that a saturated soil provides the connection between preferential features (McDonnell, 1990; Sidle *et al.*, 2001). As water is redistributed vertically and laterally the saturated area increases, which increases the number of active preferential features and hence increases the subsurface flow response of the hillslopes (Sidle *et al.*, 2000). This dynamic subsurface flow response behaviour has been shown to be influenced by antecedent moisture condition, precipitation intensity and precipitation amount (Sidle *et al.*, 1995; Sidle *et al.*, 2000; Tromp-van Meerveld and McDonnell, 2006a; Tsuboyama *et al.*, 1994; Uchida *et al.*, 2005).

The presence of preferential features is also an important factor in slope stability. Often preferential features are found in landslide scars near the sites where slope failures are initiated (Fannin and Jaakkola, 1999, Uchida *et al.*, 2001). Once the capacity of preferential features is exceeded it is believed that they contribute to high pore water pressures in the surrounding soils, contributing to a high landslide initiation potential (Uchida, 2004). Other studies have shown that they can also rapidly drain soils, thereby decreasing the landslide initiation potential (Fannin *et al.*, 2000; Pierson 1983). Preferential flow features are created by the actions of plant roots and burrowing animals. Once formed, subsurface erosion and deposition of material can modify preferential features, altering their capacity to transmit water. Erosion of preferential features is likely to increase their flow capacity, whereas deposition will decrease their capacity, resulting in a potential increase in local pore pressure. Modification of preferential features is affected by soil cohesion (Uchida *et al.*, 1999) and by the volume of water supplied to the features, which is related to the contributing area (Uchida, 2004, Freer *et al.*, 2002). We would expect that higher contributing areas should correspond to preferential flow networks with larger and more connected features. Most experiments have focused on the individual preferential flow features and few experiments have examined the connection to physical factors such as the contributing area. Therefore, we have very few general principals that can be used to link preferential features to physical characteristics; such as contributing area, slopes, or soil types (Uchida 2004).

In this chapter, we test the feasibility of extending the small-scale dye staining techniques to the hillslope scale (on the order of 10 to 100 m). We test the hypotheses that 1) there is a relationship between the contributing area and the extent and connectivity of preferential flow features, and 2) that there is evidence that preferential features contribute to the subsurface erosion and deposition of material. We also aim to describe lateral preferential flow features that are active during subsurface flow, their interaction with the surrounding soil matrix, and the velocities of the flow through each cross-section of the hillslope.

## 3.2 Methods

### 3.2.1 Study site

The experiment was conducted in the Russell Creek research watershed located on northeastern Vancouver Island, British Columbia, Canada. The watershed ranges in elevation from 275 m to 1715 m above sea level (a.s.l.), which places the majority of the watershed in the rain-on-snow zone (300 – 800 m) and the snow zone (above 800 m). This area has high annual precipitation. Average precipitation at two gauges in the watershed was 2258 mm/yr at 830 m a.s.l. and 1906 mm/yr at 300 m a.s.l., with the majority of the precipitation falling in the winter months (80 % of total precipitation in September to April). A moderately steep (30 %) hillslope at 400 m a.s.l. that frequently produced subsurface flow at the road cut-bank during storms was selected for this experiment. In addition, soil characteristics, vegetation, and slope morphology of this site is similar to many other sites at Russell Creek. This site was also close to meteorological instrumentation, gauged streams and piezometers and in winter, access was relatively easy because the road was in good condition and only an intermittent snow pack was expected.

The experiment was performed in the lower 30 m of the approximately 100 m long hillslope (Figure 3.1). We selected this hillslope because it had a range of contributing areas (determined by the surface topography), a range of soil surface slopes, and represented the main soil types found at Russell Creek. The topography of this area was undulating with wet hollows and drier convex ridges as indicated by changes in herbal vegetation and soil types. The centre of the lower 10 – 15 m of the hillslope (Figure 3.1) was typical of a topographical hollow with clay and organic rich soils (Bg and Ah) less than 1 m deep. The remainder of the hillslope (Figure 3.1) was typical of convex and planer hillslopes with podzols that had a 0 – 10 cm thick Ae layer, and a Bf layer approximately 1 m deep. The topography in this watershed was highly variable so it is difficult to determine the frequency, orientation, or the percentage of the watershed covered by hollows and corresponding soil types. However, in general the steeper topography (often greater than 30 %) appeared to have more areas typical of the hillslope soil types. In the steeper terrain, the hillslopes were also often directly connected to a stream or exposed gully bank without a noticeable hollow or riparian area. The area with gentler topography, often closer to the valley bottoms, had a higher percentage of area with soils and vegetation similar to the wet hollow area in the experimental hillslope. These areas were mostly topographical depressions, hollows, and riparian areas.

The parent material and lower bounding layer of the soil was compacted glacial till. A 300 year old, 200 cm diameter, 47 m tall stand Western Hemlock (*Tsuga heterophylla*) and Amabilis Fir (*Abies amabilis*) covered the whole hillslope (stand information from inventory and observations).

### 3.2.2 Experimental design

Dyes are commonly used to stain the flow paths used by water during infiltration. Various tracers have been used, including Methylene Blue (Bouma *et al.*, 1977), Acid Red 1 (Ghodrati and Jury, 1990) Brilliant Blue FCF (Flury and Fluhler, 1995; Weiler and Fluhler, 2004) and diluted white paint (Noguchi *et al.*, 1999). We used Brilliant Blue FCF even though the contrast between the dye and the dark soils found at our site was expected to be a problem. Brilliant Blue FCF was chosen because it has a relatively low toxicity, sorption, and high mobility (Flury and Fluhler, 1995). The low sorption and high mobility properties were important because the dye was required to travel 30 m through the hillslope. The sorption isotherm is also non-linear which creates a sharp boundary at the leading edge of the dye and high contrast to the soil (German-Heins and Flury, 2000). Dyes are usually applied in solution by sprinkling onto the soil; however, in order to delineate the lateral preferential features we created a steady state flow rate laterally through the hillslope similar to that used by Noguchi *et al.*, (1999) at a much larger scale. Steady state was achieved by diverting water at a rate of 23.5 l min$^{-1}$ from a nearby stream into a trench 30 m above the road cut-bank. The flow rate of 23.5 l min$^{-1}$ was chosen because it was sufficiently high to activate the preferential flow network as measured during natural storms (Anderson *et al.*, 2008). Steady state was determined with tipping buckets installed at the road cut-bank. Once steady state was achieved, a concentrated solution of Brilliant Blue dye was added to the trench to create a dye concentration of 4-5 g l$^{-1}$ in the input trench. Dye solution was added for 100 minutes, which was the approximate time required for the peak breakthrough of applied NaCl tracer (Anderson *et al.,* 2008). The input flow of water was then stopped and the hillslope was left to drain overnight (14 hrs).

Over the next 4 days, the hillslope was excavated. Even though it was extremely labour intensive, we decided to excavate the hillslope manually, rather than using machinery so that we could carefully prepare each cross-section. Using machinery could have damaged the soil because large roots, boulders, and fibrous organic horizons extended upslope and disturbing these with machines would damage the upslope soil. The roots, fallen trees, and boulders made the excavation challenging. To prepare the cross-sections, roots were cut flush with the soil face with reciprocating saws, pruning shears and axes. Boulders were moved carefully, but some boulders were too large to move and were left in place. The large fallen trees were cut into disks with a chainsaw and rolled down slope into the previously excavated sections. Sixteen cross-sections were excavated and prepared for photography. Cross-sections were approximately one metre apart in the lower 15 m of hillslope. Three additional metre-wide trenches were excavated 3 – 4 m apart in the upper part of the hillslope. Each of the cross-sections was photographed using a digital camera and surveyed with a laser Total Station resulting in 256 survey points. The entire 100 m hillslope was later surveyed with an addition 262 survey points so that contributing area could be more accurately determined.

Automated dye pattern analysis was not well suited to analyse the photographs because the dark soils made it impossible for image processing algorithms to distinguish the stained soil from the surrounding matrix (Weiler and Fluhler, 2004). In addition, the dye could not stain the large voids in the soil, and at this site, there was flow through several large soil pipes (5 – 30 cm diameter). In addition, when some cross-sections were excavated dyed water drained from the voids and stained soil that did not transmit water during the application of the tracer. To determine an accurate measure of the stained areas, the images were colour corrected, digitally rectified, and scaled so that one pixel equalled one square millimetre (Weiler and Fluhler, 2004). The mineral soil, organic soil, stones, pipes, and stained areas were then manually digitized (see example of the procedure in Figure 3.2). Detailed field notes taken during the excavation were used to ensure that all the stained areas were correctly digitized.

A Digital Elevation Model (0.5 m grid spacing) of the hillslope was derived from the 518 Total Station survey points (256 from excavated area and 262 points for the rest of the hillslope). A single directional flow algorithm (D8) was used to determine contributing areas for each cross-section based on the surface topography. The local average slope for each cross-section was determined by averaging the pixel slopes for all pixels within 0.5 m of the cross-sections.

### 3.2.3 Velocity calculations

We assumed that the total area of the stained soil for each cross-section is equal to the cross-sectional area of flow and therefore the Darcy velocity ($V$) could be calculated for each cross-section by:

$$V = \frac{Q}{A} \qquad [3.1]$$

where $Q$ was the steady state flow rate and $A$ was the cross-sectional area of the stained area including the soil pipes.

## 3.3 Results

All excavated and analyzed cross-sections shown in Figure 3.3 are in the proper x location with the y and z location exaggerated so that the flow pathways between the cross-sections could be delineated (dashed line). The pathways are not shown in cases where the distance was too large between the cross-sections, or we were unable to follow the feature during excavation. The first cross-section starts in the lower left corner of the first panel of Figure 3.3 and then the cross-sections continue on the panels to the right. The location of each cross-section can be seen in Figure 3.1. The excavations revealed flow through soil pipes, zones of highly conductive soils, porous organic soils, and through the soil matrix. The soils had many live and dead roots in the upper 30 – 50 cm, but the roots often extended down to the till layer. The till layer starts at each cross-section below the defined soil or organic layer. The specific flow processes in the three dominant soil types found at this site are described in more detail below.

### 3.3.1 Clay and organic rich soils in the topographical hollow

The first soil type was shallow (less than 1 m) with a clay-rich mineral horizon (Bg) and a generous Ah horizon of well decomposed organic material. In the experimental hillslope, these soils were located in the topographical hollow (centre portion of cross-sections 1-9, Figure 3.1), and contained a hydraulically connected set of preferential features, consisting of soil pipes and areas of fine gravel (particle size 2 – 5 mm). The dye solution moved almost exclusively through the preferential features, interacting only minimally with the surrounding soils. Most of the material on the bottom of the soil pipes (and filling the preferential features in section 4 and sections 10 – 13) consisted of fine gravel, similar to sediment found in nearby small streams. This topographical hollow had the fastest velocities (calculated with equation [3.1]), which were one and two orders of magnitude higher than those at the other cross-sections (Table 3.1). The velocity in sections with pipes (1 – 3 and 5 – 9) is underestimated. We assumed that the soil pipes were completely filled with water during the experiment, while there is evidence to suggest that the pipes were only partially filled; this was clearly seen in many larger pipes where only the lower half of the inside pipe wall was stained.

### 3.3.2 Poorly decomposed organic soils

The second type of soil had a deep (30 – 50 cm), fibrous, and poorly decomposed organic horizon, which contained many tree and herbaceous vegetation roots. This type of soil was found in cross-sections 10 – 16. Cross-sections 10 – 13 had vertical bands of dye within a relatively homogenous organic soil horizon. This was assumed to be due to flow connecting the upper cross-section (14) to the preferential pathway located below the organic horizon in cross-sections 10 – 13. On the other hand, in cross-sections 14 – 16 the dye solution was distributed horizontally, indicating that the flow of water used the organic soils preferentially due to their higher hydraulic conductivity than that of the mineral soil. This area of hillslope had relatively flat topography as indicated by the local slopes (Table 3.1) with no large preferential flow features.

### 3.3.3 Brown mineral soils on the hillslopes

The final soil type observed during the excavations was brown mineral soil (Bf, 0.3 – 1.5 m), often with a poorly decomposed dry organic horizon and a small (less than 5 cm) Ae horizon. These soils were found on the smaller hillslopes on the left of cross-sections 1 – 2 and 17 – 19. These cross-sections corresponded with the smallest contributing areas (Table 3.1). The stained area in cross-section 17 showed flow through the organic layer and through layers of coarser mineral soil that were below the organic layer. Cross-section 18 had flow through organic soil and a Bf horizon. Within the horizon of lower conductivity, a 6-cm diameter soil pipe was discovered in the lower centre of cross-section 18 (Figure 3.3). In section 19 the soil in the centre of the cross-section was very shallow because a windthrown tree had removed a large part of the mineral soil. The flow through this cross-section followed the subsurface topography and was confined to the organic and mineral soils above the till.

When cross-section 18 was excavated, the soil pipe was severed and dye solution poured out under pressure. This soil pipe was circular in cross-section, suggesting that it was initially formed by a tree root. The bottom and sides of this pipe was lined with gravely sediment of approximately 2 mm mean diameter (evidence of past erosion), and the pipe was completely filled with fine organic material. Dye solution was also around a dead root in the right-hand portion of the cross-section 18 (right upper stained area in cross-section 18). However, unlike the other pipe low in the profile, the staining was limited to the lower half of the root, which suggested that only part of the void around the root was contributing to lateral flow.

### 3.3.4 Transport of soil and organic material

We speculate that fine clay and organic material were leached and transported to the hollows where they accumulated. Evidence of buried organic material within this brown mineral soil type suggested that there was preferential transport of water and fine material to depth within the soil which accumulated in areas with preferential features (old and new). The lateral and vertical redistribution of fine organic material was also evident in cross-sections 1, 2, 17, and 18. At the road cut-bank, a low concentration of dye solution drained from the soil face (left side of the cross-section 1 and 2 in Figure 3.3). Cross-sections 1 and 2 had buried dark soil that could have been preferential features filled with accumulated organic material. Although no dye solution was found within the soil, a weak dye solution was observed exiting the soil at the road cut-bank. These dark soils were connected to the same preferential flow features that showed strong response during natural events and the steady state experiments (Anderson *et al.*, 2008). Cross-section 17 had similar redistribution of organic material into the mineral soil.

## 3.4 Discussion

### 3.4.1 Modification of preferential features

As speculated by Uchida (2004) and the first null hypotheses of this chapter, there appears to be a link between the contributing area and the distribution of preferential features. It is recognized that subsurface erosion contributes to stream sediment (Onda, 1994; Terajima *et al.*, 1997). This subsurface erosion is thought to be important for the modification and maintenance of preferential flow features (Uchida, 2004). This experiment showed the presence of highly developed preferential flow features corresponding to the largest contributing areas (greater than 1100 $m^2$). These areas also had the largest percentage of hillslope outflow during rainfall events and for steady state experiments (Anderson *et al.* 2008). Small contributing areas (less than 400 $m^2$) and relatively flat local topography (less than 15 %) coincided with areas with few preferential flow pathways. This suggests that a soil with a small contributing area might not receive flow rates large enough to modify and maintain large preferential flow features.

The headwater catchments in these areas often have hillslopes directly connected to streams. This connection between the stream and hillslope will allow the subsurface transport of sediments directly into the streams. Without an “exit” for the sediments, such as a road cut or stream bank, there will likely be an accumulation of sediment, as found in most of our excavated cross-sections. This means that the processes that maintain the preferential flow network also have the ability to fill in some features, resulting in lower capacity and flow rate. As features in the preferential network are filled in, water will be forced into other preferential features, causing the network to change over time. This subsurface erosion and deposition could affect the soil development and help contribute to the varying soil types found in this watershed. The soils with small contributing areas may contribute fine material to soils with larger contributing areas. The soil cross-sections excavated during this experiment were classified into groups in the results section, which correspond to areas receiving large amounts of water, sediments, and organic material (cross-sections 1-13) and areas losing sediments and organics (cross-sections 14-19). Preferential transport of fine material was evident within cross-sections as well. For example, there was evidence of erosion and deposition in a preferential flow feature in cross-section 18. There was fine gravely material on the bottom of the feature, indicating that it was connected to an outlet that allowed erosion of finer sediments, leaving the gravely material behind. However, the pipe was filled with fine organic material suggesting that at some point in time the outlet ceased to function and the feature began accumulating fine organic material.

### 3.4.2 Conceptual models of runoff

The general conceptual model of lateral preferential flow networks relies on a rising water table. As the water table rises, there is an increase in the connections in the preferential flow network, causing faster subsurface velocities and increasing the area of hillslope contributing to runoff (Sidle *et al.*, 2000; Tromp-van Meerveld and McDonnell, 2006b; Tsuboyama *et al.*, 1994; Uchida *et al.*, 2005). These excavations support this conceptual model. It appears that the preferential flow features were connected by matrix flow through mineral and organic soils. In some areas, this saturated flow was perched above soil with low hydraulic conductivity and spread out horizontally in the overlying layers of more conductive soils. In other areas, the flow had vertical components because the water was flowing downward to areas with higher conductivities. These observations showed that a connection may be established by a water table rising within a small localized area.

The subsurface flow in this hillslope is highly dynamic and depends on the precipitation characteristics (Anderson *et al.*, 2008). Trenched hillslopes from around the world have identified differences in subsurface flow characteristics based on the subsurface topography and the saturated zone connections of the hillslope and the trench (e.g. Hutchinson and Moore, 2000; Tani, 1997; Freer *et al.*, 2002; Tromp-van Meerveld and McDonnell, 2006a). The excavations presented here show that trenches with large contributing areas collect flow from preferential flow networks that are efficient at transferring water, due in part to a high degree of hydraulic connectivity. The soils in these areas could transport water one order of magnitude faster than other soils (Anderson *et al.*, 2008). The dye staining also revealed that there is often little interaction between water in the preferential flow feature and the surrounding soil matrix unless there was a constriction in the preferential flow network. This is important for understanding the transport and dilution of solutes and pollutants. Solutes deposited in soils with larger contributing areas (hence a well established preferential flow network) will have quicker travel times and minimal interaction with the water in the soil matrix, compared to solutes deposited in soils with smaller contributing areas, which will travel further at slower speeds and will have more interaction with water in the soil matrix (pre-event water). This may result in more dilution and retardation of the solute in soils with small contributing areas relative to those with large contributing areas.

### 3.4.3 Landslide hazard

Landslide activity and debris flows are common at Russell Creek and surrounding areas (Fannin and Wise, 2001; Nistor and Church, 2005). Areas with similar topography, climate, and soil types as this watershed are also prone to landslides. Preferential features are sometimes found near landslide initiation points (Fannin and Jaakkola, 1999; Uchida, 2004). The water table depth and the proximity to preferential features influences the pore water pressure in these types of hillslopes. Preferential features can rapidly drain the soil water, reducing the water table and the pore water pressure (Sidle, 1986; Montgomery and Dietrich, 1994 and 1995; Fannin *et al.*, 2000). However, when preferential features reach their capacity, are in-filled by subsurface deposition, or are damaged, preferential flow could increase the landslide hazard by increasing pore water pressure on the surrounding soils (Uchida *et al.*, 2001). The preferential features found in cross-section 18 exemplify this phenomenon. The soil pipe in the lower centre part of the cross-section (Figure 3.3) had water that poured out under pressure when the cross-section was excavated. Even though this pipe was completely filled with organic material, it extended up slope and held a volume of dyed water that produced a pressure head even 4 days after the steady state experiment was initiated. For the water to enter the feature, it had to displace water that was already in the pipe before dye solution was added to the input trench. Presumably, the dyed solution entered the pipe when the pore pressure was higher and water was displaced out of the feature down slope of section 18. During subsurface flow conditions, this increase in pore water pressure could increase the landslide initiation hazard. On the other hand, the subsurface flow that stained the lower half of the dead root in the right side of cross-section 18 (Figure 3.3) had completely drained and the only evidence of flow was dye on the root and surrounding soils. This means that this feature was hydraulically connected to lower slope sections and could drain even under low pore water pressures. At the flow rate used for the experiment, this feature would likely decrease the landslide initiation hazard because it would reduce the water table of the local area.

Soils with large contributing areas are often the initiation site of landslides (Uchida, 2004), which can be attributed to accumulation of subsurface water. However, it could also in part be due to the linkage between large contributing areas and highly developed and hydraulically connected preferential features. If the preferential features observed in the hollow were blocked or their capacity was reached, there is a high probability that pore water pressure would increase in the surrounding soils. If there were no other preferential features transmitting the water, the likely outcomes would be 1) discharge of water to surface runoff, or 2) if the condition are right, the initiation of a slope failure.

The relationship between the contributing area, subsurface storm water volume, and the modification and maintenance of preferential features could be used to enhance the prediction of areas with high landslide initiation hazard (e.g. Wu and Sidle, 1995). Nevertheless, we need more larger-scale excavation experiments to better develop the relationship between topographic units and preferential flow features in steep forested hillslopes.

## 3.5 Conclusion

We stained a 30 m section of hillslope with a food dye under steady state conditions and then excavated the hillslope to determine the lateral preferential flow features, the connections between the features, and velocities through each cross-section. At this site, the material that connected the preferential flow features was important for controlling the hillslope velocity, and the dye patterns suggested that saturated flow through permeable soil provided connection between the individual preferential features. Observations of erosion and deposition of fine soil and organic material within the preferential features suggested that preferential flow influenced the redistribution of the fine soil and organic material within the hillslope. Some preferential features were only partially filled with water, and others were under pressure. We tested the hypothesis that the contributing area was linked to the preferential flow network. The excavations revealed that the largest and most connected features were in the soils with the largest contributing area derived from the surface topography. The large features (up to 30 cm in diameter and meters in length) transport water and solutes while interacting minimally with the surrounding soil matrix. These findings have implications for subsurface flow generation, soil development, solute transport, and slope stability and could be used to develop better predictions of lateral preferential subsurface flow.

Table 3.1. The area of stained soil, pipe cross-sectional area, velocity of the flow through each cross-section.

| Cross-section | | Area of staining Mineral soil $cm^2$ | Organic Soil $cm^2$ | Large Pipes $cm^2$ | Darcy velocity [a] $m\ hr^{-1}$ | Local Slope % | Contributing area $m^2$ |
|---|---|---|---|---|---|---|---|
| 1 | [b] | | | 195 | 72.1 | 13.3 | 1645 |
| 2 | [b] | | | 100 | 140.9 | 20.3 | 1629 |
| 3 | [b] | | | 107 | 131.1 | 20.4 | 1604 |
| 4 | | 184 | 59 | 0 | 58.0 | 18.7 | 1591 |
| 5 | | 21 | 28 | 163 | 66.5 | 23.8 | 1591 |
| 6 | [b] | | | 223 | 63.1 | 33.7 | 1589 |
| 7 | [b] | | | 300 | 47.0 | 36.4 | 1588 |
| 8 | | 758 | 289 | 214 | 11.2 | 12.5 | 1581 |
| 9 | | 296 | 442 | 330 | 13.2 | 21.9 | 1577 |
| 10 | | 238 | 5628 | 0 | 2.4 | 40.5 | 1557 |
| 11 | | 228 | 5254 | 0 | 2.6 | 19.6 | 1197 |
| 12 | | 318 | 2205 | 0 | 5.6 | 28.4 | 1177 |
| 13 | | 1274 | 1533 | 0 | 5.0 | 16.3 | 356 |
| 14 | | 78 | 4226 | 0 | 3.3 | 8.3 | 350 |
| 15 | | 214 | 3228 | 0 | 4.1 | 11.7 | 343 |
| 16 | | 183 | 2740 | 0 | 4.8 | 15.8 | 156 |
| 17 | | 2883 | 615 | 0 | 4.0 | 19.2 | 126 |
| 18 | | 249 | 722 | 23 | 14.2 | 7.7 | 124 |
| 19 | | 390 | 1276 | 0 | 8.5 | 28.9 | 79 |

[a] Darcy velocity for the cross-sections with stained soil was as; $V=Q/A_s$, where $A_s$ is the stained area plus the area of the pipes, where applicable.
[b] Staining around pipes was not presumed to be from transmit water flow, but from water transferred from the soil pipes.

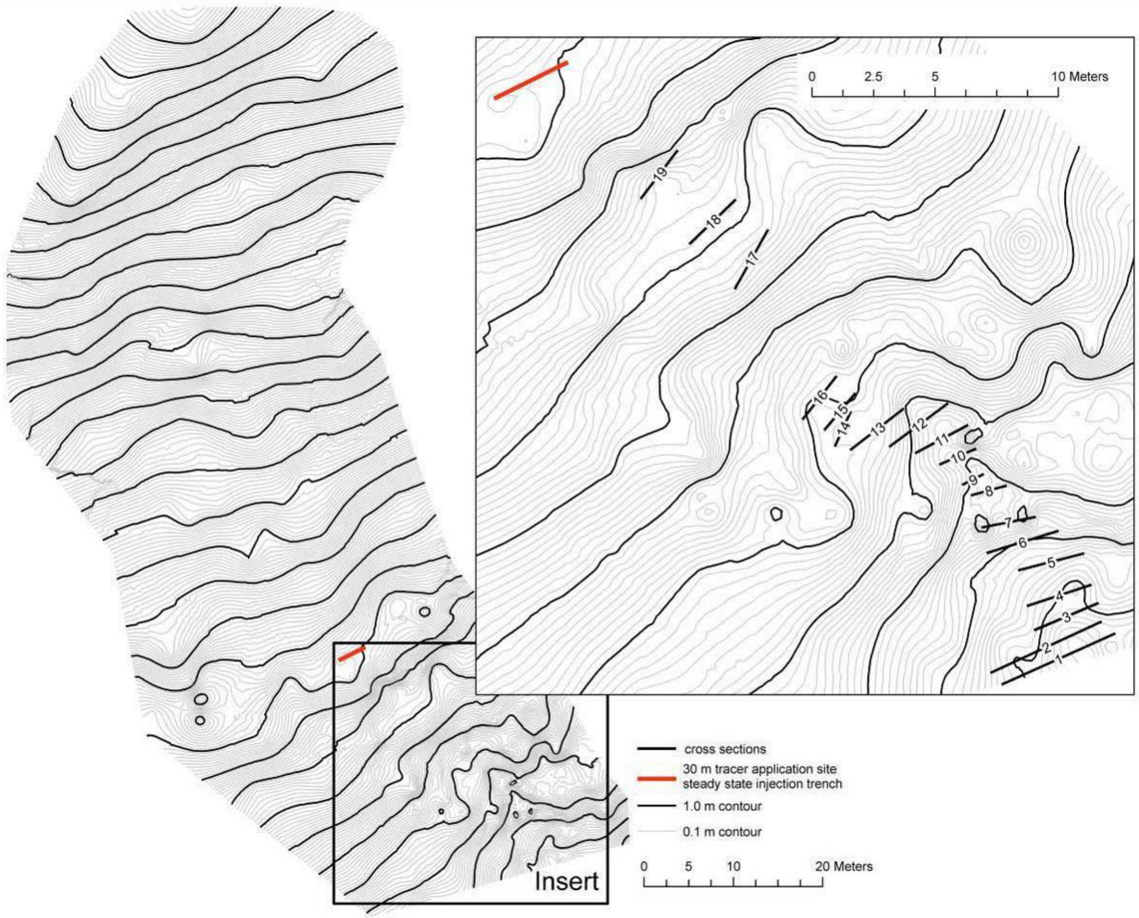


Figure 3.1 Contour map of the experimental hillslope showing the location of the dye injection and the photographed cross-sections. This map was developed using the 256 Total Station survey points for the excavated section and another 262 points for the rest of the hillslope.

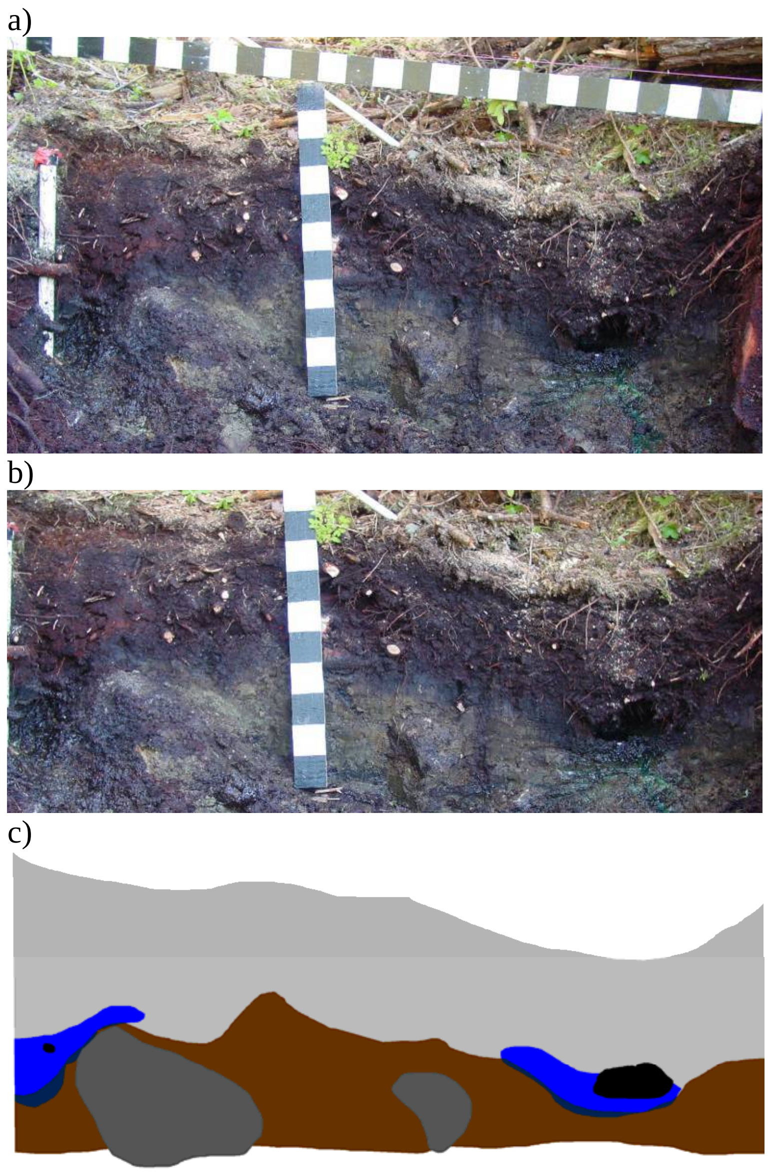


Figure 3.2. Cross-section 7, examples of a) the original photo, b) the rectified colour corrected image, and c) the digitized image shown in Figure 3.3.

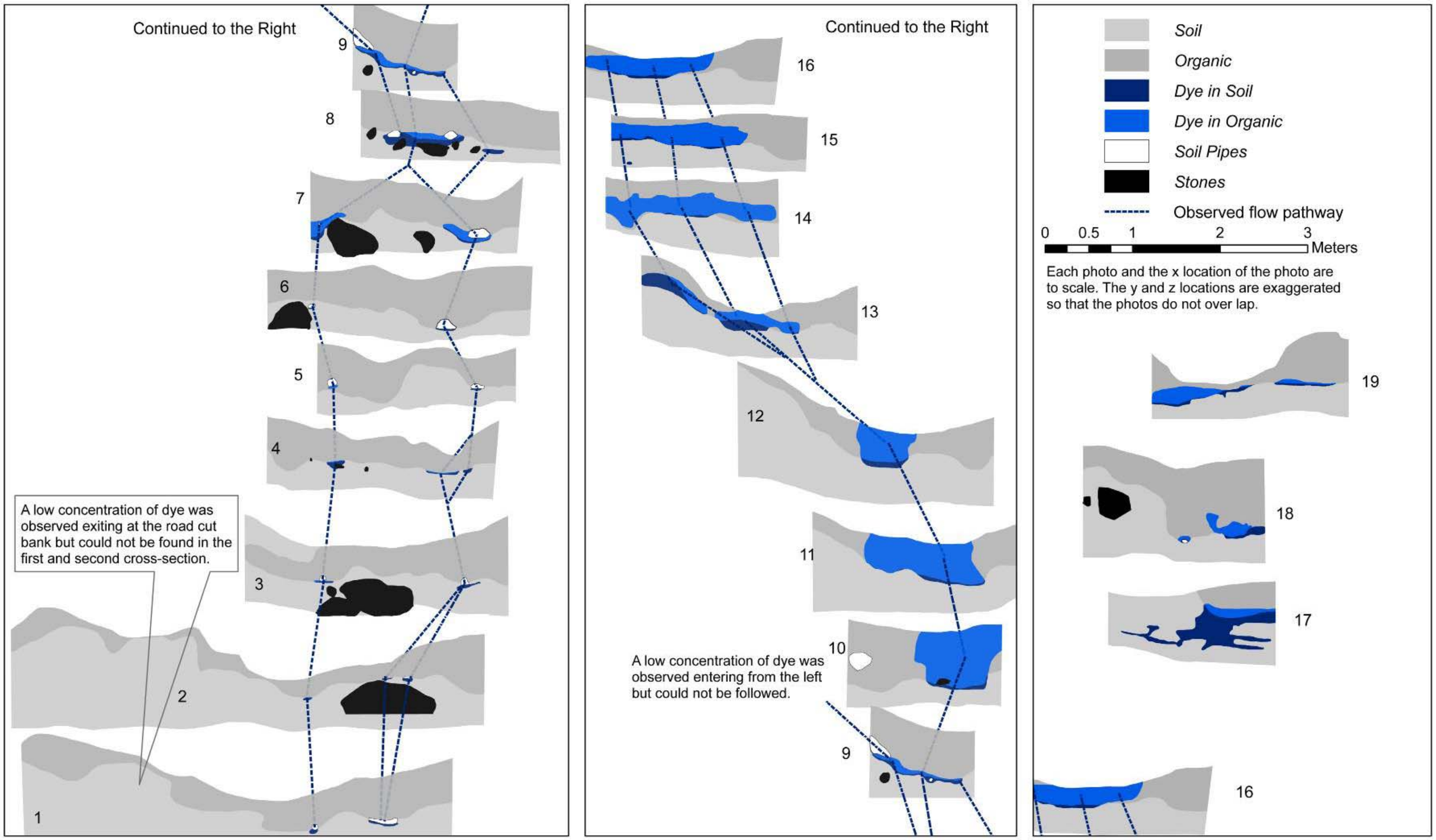


Figure 3.3. Cross-sections showing the location of the stained soil, the soil pipes, and the observed flow paths between the cross-sections. The photos and the x locations are to scale but the y and z locations have been exaggerated so that the photos do not overlap.

## 3.6 References

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# 4 Water table response in zones of a watershed with lateral preferential flow as a first order control on subsurface flow.[3]

## 4.1 Introduction

Shallow subsurface flow is a dominant process in the runoff response, solute transport, and slope stability of many hillslopes and watersheds around the world (Uchida *et al.*, 2005). Most lateral subsurface flow is generated when a saturated zone is created above a layer of lower hydraulic conductivity, often at the soil and bedrock interface. Physical factors such as the climate, slope position, soil characteristics, and surface and subsurface micro-topography will affect the water table – runoff relationship. Dynamic factors such as rainfall characteristics, antecedent conditions, and connectivity to source areas also affect the characteristics of water table response (Sidle *et al.*, 1995; Sidle *et al.*, 2000; Tromp-van Meerveld and McDonnell, 2006a; Tsuboyama *et al.*, 1994; Uchida *et al.*, 2005).

Identifying the first-order controls on the water table response is an important step in developing an understanding of how hillslopes and watersheds respond to rainfall and snowmelt. Lateral preferential flow is a first-order-control of subsurface flow and water tables in many areas (Uchida *et al.*, 2005). Lateral preferential flow creates hydraulically limited water tables, where the water table response has a capping effect due to the high

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capacity for soils to drain (Sidle, 1986; Montgomery and Dietrich, 1994 and 1995; Fannin *et al.*, 2000). Water tables become hydraulically limited when the water table rises to a level that activates the lateral preferential flow network and the apparent hydraulic conductivity of the soils dramatically increases (often a few orders of magnitude). However, for flow to occur the water table has to connect to an outflow area (Tromp-van Meerveld and McDonnell, 2006b). This conceptual process has been called the 'fill-and-spill' model because the water is required to 'fill' isolated topographical hollows before 'spilling' down slope and producing flow. This mechanism may also produce a similar capping response. There should be an initial increase in the water table as the hollows fill. Once a connection is formed between the water table and an outflow area the water table will continue to rise but at a lesser rate due to increasing subsurface flow as groundwater discharges to the stream network.

Characterizing zones and grouping areas based on the water table behaviour within a watershed is useful for understanding the internal watershed processes. The idea of watershed zones has been used in many models. The simplest models, such as the TOPMODEL (Beven and Kirkby, 1979), rely on the assumption that the entire watershed responds in unison and the response is proportional to the contributing area and the local hydraulic gradient. This steady state assumption has been tested with water table response data (e.g. Moore and Thompson, 1996; Seibert *et al.*, 2003). Seibert *et al.* (2003) used water table results for a watershed in northern Sweden to show that the steady state assumption is not valid and that the water table far from a stream responds differently than the water table close to a stream. Other conceptual models such as the variable source area model (Hewlett and Hibbert, 1967) and the 'fill-and-spill' model (Tromp-van Meerveld and McDonnell, 2006b) do not require the entire watershed to respond in unison. These models rely on the assumption that there are zones within a watershed that contribute to runoff under different event characteristics and antecedent conditions.

Modellers require information about the water table – runoff relationship within watershed zones to help develop and calibrate models. The water table – runoff response has been characterised and the effects of spatial and temporal scale have been identified for experimental watersheds by several authors (e.g. McGlynn *et al.*, 2004, Fannin *et al.*, 2000). However, only a few studies have used measurements within watershed zones to determine if the water table responses are different between zones and can be distinguished. Siebert *et al.* (2003) used the Spearman ranked correlation and the distance to the stream as potential parameters to classify water table response. They identified two zones based on the distance to the stream. Wilkinson (1996) was not able to group piezometric data based on the slope position, soil depth, and local ground slope in an area with more complex topography that was dominated by lateral preferential flow. However, Fannin *et al.* (2000) identified three types of water table behaviour based on response and recession characteristics:

1. Dry soils: the piezometers are usually dry, indicating no saturated zone prior to storms. Piezometers respond rapidly to precipitation and drain quickly. This type of water table response was typically located in upper slopes and ridges.

2. Wet soils: piezometers often have positive pore water pressure before storms and still respond quickly, but drain slowly. This behaviour typifies riparian areas with permanent groundwater discharge and clay-rich soils.
3. An intermediate type: typically located in mid-slope areas in between the first two types.

McGlynn *et al.* (2004) used water table and tracer measurements to characterise the water table – runoff response for various spatial scales within riparian and hillslope zones.

This chapter tests the hypothesis that zones within a watershed with similar water table response can be predetermined based on observable factors, such as topography, indicator vegetation, distance to stream, and contributing area. The predetermined grouping was compared to two other methods of grouping the water table behaviour after the responses are measured; 1) groups developed with a hierarchical clustering algorithm, and 2) the contributing area was used as an indicator to develop other groups. The results are also used to characterise the water table – runoff relationship within zones of our experimental watershed.

## 4.2 Methods

### 4.2.1 Study site

The experiment was conducted in the Russell Creek research watershed located on northeastern Vancouver Island, British Columbia, Canada. The watershed ranges in elevation from 275 m to 1715 m above sea level (a.s.l.), which places the majority of the watershed into the rain-on-snow zone (300 – 800 m) and the snow zone (above 800 m). This area has high annual precipitation. Average precipitation at two gauges in the watershed was 2258 mm/yr at 830 m a.s.l. and 1906 mm/yr at 300 m a.s.l., with the majority of the precipitation falling in the winter months (80 % of total precipitation in September to April). For the instrument sites, we chose an area at approximately 400 m elevation because it was expected to have only an intermittent snow pack and easy winter access. The area was previously harvested and had an approximately 10 yr old plantation of Western Hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*) and Amabilis fir (*Abies amabilis*). The topography is undulating and with moderately steep (10 – 35 %) local gradients. This site appeared similar (in terms of soil, vegetation and flow characteristics) to many other sites at Russell Creek, and was close to meteorological instrumentation and gauged streams.

### 4.2.2 Field measurements

A stratified sampling approach was used to test the hypothesis that watershed zones have distinct water table responses that can be identified and grouped based on observable characteristics available before installing the piezometers (e.g. topography, distance to stream, local slope, and indicator vegetation). In the field, these factors were used to stratify the watershed into three zones. This stratification then allowed individual piezometers to be assigned to a group such that each group was expected to have similar water table responses. Figure 4.1 shows a map of the area. The first zone contained six piezometers, it was named the “dry” zone because these sites had very small contributing areas (less than 50 $m^2$) and were on convex slope sections. The soil depth varied from 650 mm to 1100 mm deep. Dry zone soils generally consisted of brown Bf mineral soils under a 5 – 10 cm Mor humus layer. The second group was named the “wet” zone; this zone contained nine piezometers that were located in flat areas near streams and in topographical hollows. The soils in the wet zone were 600 mm to 1230 mm deep and generally consisted of a gleyed Bg mineral horizon high in clay and organic content under a 10 – 20 cm deep moder humus layer. The last zone was a transition group that was generally located on sloping hillslopes between the dry zones and the wet zones. These piezometers were named "medium" and the soil depth ranged from 600 mm to 1500 mm. The medium soil types ranged between the "wet" and the "dry" zone soil types. This classification system was used to assign *a-priori* groupings to piezometers before installation. Observations of soils at the road cut-banks and during the installation of other piezometers were used to predict the likely soil type at each site.

The piezometers were constructed from 6 cm outside diameter pipes screened at the lower 30 cm and covered with a geotextile filter cloth. The screened pipes were installed in 7.5 cm diameter holes drilled to the till layer with an auger. The holes were backfilled with 5 – 10 mm pea gravel and capped with bentonite clay. Odyssey capacitance water level probes installed in the piezometers monitored and recorded the water level every 5 minutes. V-notch weirs were installed in the four streams draining the area. The weirs were constructed from plywood and ultra-violet resistant sheet plastic. Steel strips mounted to the front of the weirs provided a sharp edge. Odyssey capacitance probes monitored and recorded the water level behind the weirs every 5 min and a stage – discharge relationship was developed from flow measurements and the equation for a v-notch. All the stream measurements were well correlated, so for these analyses only the stream with the longest continuous record was used (Figure 4.1).

It was not possible to determine the distance from every piezometer to the stream as Siebert *et al.* (2003) did because some flow paths paralleled the streams, and the road intersected other flow paths. Instead, the contributing area for piezometers was calculated from a Digital Elevation Model (DEM). Total Station survey data were available for some piezometers, and where survey data were unavailable 5 m contour information derived from 1:5000 scale air photos (Figure 4.1) was used to develop a DEM. A single-direction flow algorithm (D8) and a multiple flow direction algorithm (MD8) were used to determine a range of contributing areas for each of the piezometers. This method created uncertainty in the contributing area for some piezometers; however, the contributing area was calculated within an order of magnitude for all piezometers and within approximately 10 % for many piezometers. Field observations of the surface topography were used to verify and fine-tune the contributing area for the piezometers with high uncertainty.

### 4.2.3 Water table response – runoff relationship

One of the objectives was to characterize the behaviour of the water table response within zones of the watershed. We expected to find a relationship between the water table response and event characteristics and antecedent conditions for each zone. It is likely that the zones will have different relationships and patterns with respect to these conditions. In order to capture this variability the entire range of the water table response and stream runoff was used to determine a relationship. If the hillsope subsurface flow was dominated by lateral preferential subsurface flow the water table should be hydraulically limited (Sidle, 1986; Montgomery and Dietrich, 1994 and 1995; Fannin *et al.*, 2000). The associated capping effect of the water table response is attributed to the rapid increase in the hydraulic transmissivity of the soils when the lateral preferential flow network is activated. The water table depth – stream discharge relationships should show a non-linear relationship and there should be a rapid change from an increasing water table to a relatively constant water table as the discharge continues to increase. This inflection point would correspond to the activation of the preferential flow network or the connection of the water table with an outflow area. To quantify this behaviour a linear relationship in semi – log space was fitted to the data ($z = f\ln(Q) + b$, where $z$ is the depth to the water table and $Q$ is the stream discharge). This relationship is also a simplification of the TOPMODEL (Beven and Kirkby, 1979), which is based on the assumption of matrix flow using Darcy's Law with an exponential function representing the decline in hydraulic transmissivity [4.1]. Given the diversity of the expected water table responses this relationship is not likely to be constant for the entire watershed; however this relationship might identify patterns of response within the zones. The TOPMODEL equation expresses the local discharge as a function of the local slope ($\beta$), the depth to the water table depth ($z$), and a factor that expresses the decline of hydraulic conductivity with depth ($f$):

$$q = T\exp(-fz)\tan\beta \qquad [4.1]$$

Where, $T$ is the transmissivity of the soil:

$$T = \int_{\infty}^{0} K_i(z)dz \qquad [4.2]$$

Assuming that the hydraulic conductivity decreases exponentially with depth:

$$K_i(z) = K_{0i}\exp(-fz) \qquad [4.3]$$

Rewriting the equation to isolate the depth to the water table ($z$) gives equation [4.4]:

$$z = \frac{\ln(\frac{q}{T \tan \beta})}{-f} \qquad [4.4]$$

To simplify the model the local slope and transmissivity were considered constant for a given site and the cross-sectional flow ($q$) was proportional to streamflow ($Q$). This resulted in equation [4.5]:

$$z = f \ln(Q) + b \qquad [4.5]$$

The value of the slope ($f$) represents the change in hydraulic conductivity with depth. The intercept ($b$) represents the location of the water table when there is no discharge. In the TOPMODEL and other models that use Darcy's Law to route subsurface water (e.g. Wigmosta *et al.*, 1994) the hydraulic conductivity is often assumed to be maximum at the soil surface. In a hillslope with lateral preferential flow, the activation of the preferential flow network should coincide with a dramatic change in the hydraulic conductivity, which should cause a hydraulically limited effect. The relationship in equation [4.5] would not be expected to reach the soil surface because of the observations of preferential features showed that the features were often not near the surface of the soil (Anderson *et al.*, 2008a).

To determine if a water table was hydraulically limited, a linear regression was fitted to maximum rise in the water table for each 2 l/s increment in stream discharge above 20 l/s. The discharge of 20 l/s was determined to be past the inflection point for all the piezometers. The slope of the regression expresses the water table rise (mm) per unit change in stream discharge (l/s). If the slope of the linear regression was close to zero, the water table was hydraulically limited for the measurements on record. If the slope of the linear regression was negative, there was a disconnection between the water table and discharge (i.e. the stream responded when the water table did not respond). The linear relationship was also used to identify the water table level that corresponds with the hydraulically limited state, which should be the water table depth when the preferential flow network was activated.

### 4.2.4 Correlation of the water table response

The Spearman ranked correlation has been used to test the correlation of responses of water tables within zones, between the zones, and between water table and stream discharge (Siebert *et al.*, 2003). The Spearman ranked correlation is useful because it does not require knowledge about the shape of the relationship between the variables of interest. The Spearman ranked correlation indicates whether the variables increase together (correlation close to 1), there is no correlation (correlation close to 0) or if the variables are negatively correlated (correlation close to -1). By shifting the time series, it is possible to create a better correlation relationship and determine if the water table response preceded or lagged the stream response.

Hydrological systems with preferential flow have dynamic water table and runoff responses that are influenced by the precipitation characteristics and antecedent conditions. This variation was expected to affect the water table – runoff relationship and create different lag times and correlations values. To test this, the time series were divided into 99 events, which included both snowmelt and rainfall events. A two-step process was used to identify individual events. First, an automated computer process identified each rise in stream discharge. The lowest point before the peak discharge was identified as the start of the response. This process did not produce good results; some piezometers responded before the stream, other piezometers responded when the stream response was too small for the automated process to detect, and some events were in close succession and could be considered a single event. To compensate for these shortfalls each event identified by the automatic process was plotted and the start- and end-time was manually identified. Where possible the rainfall or snowmelt that caused the event was identified as the start of the event. The rank correlation was calculated for each storm, which allowed the offset time to be different for each storm.

### 4.2.5 Grouping of the piezometers into zones

Three methods were used to determine groups of water table response. The first was the method of predetermining groups in the field (previously explained and referred to as predetermined groups), the second method used a hierarchical clustering algorithm, and finally the water table characteristics were plotted against the contributing area. To determine the effectiveness of the first two methods, the correlation between piezometers for each event was calculated and averaged for the piezometers within each group and between groups (Siebert *et al.*, 2003). There would be good correlation for piezometers within the groups and a poor correlation for piezometers between the groups if the groups were well defined.

A hierarchical clustering algorithm was used to determine if better groups could be determined once the measurements were obtained. The average event correlation between each piezometer was used for the distance matrix (allowing the time series to be offset by up to 12 hrs). The hierarchical clustering algorithm progressively split the dataset into smaller groups with the goal of maximising the ranked correlation within the groups and minimising the ranked correlation between groups. The method produced groups with high correlation within groups and low correlation between groups. The hierarchical clustering results were used to determine three new groups.

The contributing area and correlation between the stream and piezometers was used to determine patterns and groups of piezometers. This follows the methods presented by Siebert *et al.* (2003) where the distance to stream was used to determine groups of water table responses. The correlations for the piezometers and the stream discharge were also plotted against the peak event discharge and the antecedent condition (low stream discharge before event) to determine if patterns between the event characteristics and the water table – runoff correlation could be identified.

## 4.3 Results

### 4.3.1 General description of the water table response

The piezometers and the stream were monitored from October 2004 to June 2005 and from September 2005 to June 2006. Instrument malfunctions, deep snow, and wildlife damage caused missing data for the various instruments. The piezometers were labelled with the last two digits of the serial number of the water level instrument and a prefix of "d", "m" or "w" to indicate the dry, medium and wet zones where each piezometer was located. Figure 4.2 illustrates 60 days (starting on November 11, 2004) of stream discharge and examples of five water table responses that span a range of contributing areas. Depth to water table for piezometers was normalized to the soil depth, where zero (0) is the soil surface and negative one (-1) is the soil and till interface. This time period was selected because it included large and small events and a relatively wet and dry period. The precipitation is not shown because some events included both snowmelt and rainfall.

Figure 4.2 represents a transect starting at d14 on the hilltop, m06, m11, w30, and ending with piezometer w09 in the hollow (Figure 4.1 and Table 4.1 shows the contributing areas). There was a gradient of responses, rather than distinct groups of water table response. Similar to Fannin *et al.* (2000), the water table responded with different rise and recession characteristics (Figure 4.2) and the steady state assumption may only be valid for the peak of the largest storms when the driest piezometers responded.

The piezometer with the smallest contributing area, d14, did not respond during any event shown in Figure 4.2. Piezometer m06 has the second smallest contributing area and responded to only the four largest events with a quick water table rise and recession. Piezometer m11 had a water table for the entire 60 days, responded to more storms, and had longer recession times. Piezometer m11 responded with sharp peaks during the four largest storms, when m06 responded. These sharp peaks would suggest that the water table was not hydraulically limited. The slope of regression of the maximum water table rise for discharges over 20 l/s confirm that m11 and m06 also indicate that these piezometers were not hydraulically limited (Figure 4.8). Piezometer m11 did not have sharp response peaks during the smaller storms, which suggests that the water table was hydraulically limited during the smaller storms. It may be that the storm characteristics are such that the soils were capable of draining the water inputs (vertical and lateral) only during the smaller events and during the larger events the inputs overwhelmed the capacity of the soil to drain and the sharp response was produced.

The piezometers with the largest contributing areas responded to almost every event and appeared to be hydraulically limited because the discharge continued to increase and the water table levelled off (w30 and w09 in figure 4.2). However, the slope of regression of the maximum water table rise for discharges over 20 l/s shows that w09 still had an increasing water table during the largest flows (Figure 4.8). Piezometer w30 has a poor relationship with the stream discharge which is explored later in the discussion. In general, w30 was desynchronized from the stream discharge. Piezometer w30 responded to events that did not cause a stream response; however, this response only happened during wet antecedent conditions. Prior to day 30, w30 responded frequently, but after day 30, w30 stopped responding even when there was a response in stream discharge.

### 4.3.2 Relationship of water table response to stream discharge

The water table – runoff relationship can be used to infer the dominant runoff response of specific areas. Where subsurface flow generation was dominated by preferential flow there should be hydraulically limited behaviour, which should produce a capping effect in the water table – runoff relationship (Figure 4.3). Water tables that reach the soil surface will have surface runoff which could dominate the runoff. In areas where the water table does not show hydraulically limited behaviour or reach the soil surface slower runoff processes are likely. The piezometers in Figure 4.3 are organized from the bottom left to the top right. The first piezometers dried out (had no water table) at the lowest discharge values measured during sampling period (d14 to d05). The next piezometers are the medium sites, and maintained a water table for the entire sampling period. The final piezometers could be considered the wettest piezometers.

Piezometer d14 only had a very small response to some events in Figure 4.3 and represented an extreme type of response that had the smallest contributing area (Table 4.1). In total three ridge-top piezometers were installed but there was no response to the first few large events, and two of the instruments were moved to areas where a response was expected and these piezometers were only periodically checked for the presence of water (d99 in Figure 4.1). The regression model did not produce good results for the piezometers on the bottom row of Figure 4.3 (d14 to m38). These were the driest sites and have little or no response during the recorded events. The next piezometers had quick initial responses and then an inflection point as expected in an area with a hydraulically limited water table. However, there was no pattern between the sites that showed the expected threshold behaviour and the contributing area (Figure 4.8).

The other piezometers (d05 to w01) maintained a water table for the entire measurement period. These piezometers were highly variable and some had a strong relationship to the discharge and the semi-log model (Figure 3, $r^2$ 0.60 – 0.78). However, there was a large range of parameters within a given group (predetermined groups, by the hierarchical clustering, or contributing area) so it is unlikely that this model will be able to predict the water table response of another site with similar characteristics (Figure 4.4). Piezometers w15, m43, and m32 show very little change in water table depth and wide variation for a given discharge, especially at lower discharges. Piezometers m04 and w30 had a poor relationship in the semi-log space and had a disconnected water table – runoff relationship (Figure 4.3). The water table at these sites did not always rise when the stream responded, even during large events. A similar disconnect relationship was noted by McGlynn *et al.* (2004) in riparian wells at Maimai. Similarly at this watershed, these disconnected relationships were measured at medium to wet sites and that had relatively small contributing areas (80 – 90 $m^2$) but the piezometers were located in close proximity to areas with larger contributing areas (greater than 1000 $m^2$, see m04 and w30 in Figure 4.3). We hypothesize that the disconnection between these water table responses and the discharge could be the result of two possible processes:

3. Under some event and antecedent conditions the water table could be influenced by only the smaller upslope contributing area; however, under different event and antecedent conditions the water table could be influenced by the larger 'neighbouring' contributing areas.
4. The soil conditions at similar excavated sites revealed that the soil matrix appeared to have a low permeability and that laterally moving water could be transmitted with little interaction with the surrounding soil matrix (Anderson *et al.*, 2008b). This provides the opportunity for laterally moving water to 'by-pass' the soil matrix and create a large stream discharge without a water table response. The local water table would only be influenced by infiltrating water and some locally laterally moving water.

None of the piezometers had a water table that reached the soil surface (Figure 4.3). During some large events surface water was observed within a few meters of horizontal distance from some piezometers and within 5 – 10 cm of elevation difference of some piezometers. It is likely that water was able to drain into the lower areas and the water table was not able to reach the soil surface. When the piezometers were installed it was difficult to determine the areas that would likely have overland flow because of the variable micro-topography. It was only by chance that no piezometers were located in an area of surface overland flow.

Some piezometers showed an increasing water table at the largest discharges measured. This behaviour was not expected because there is evidence of preferential flow at this site. Piezometers d33, m06, m13, m36, m11, w16, and w01 showed a rise in water table at even the highest discharges (Figures 4.3 and 4.8). This increasing flow is most clearly seen in piezometers m36 and m11. Most of the sites show an inflection point in the water table – runoff response relationship between 5 – 20 l/s.  However, there was no pattern between the maximum rise of the water table and discharge and the contributing area (Figure 4.8). For example, w01 and w02 are located approximately 10 m apart and the soil characteristics, local slope, contributing areas, and vegetation are almost indistinguishable. Piezometer w02 was hydraulically limited and w01 was not. With the exception of a slightly larger contributing area piezometers w16, w15, and w09 also have physical characteristics that are nearly indistinguishable; however w15 behaved differently from w16 and w09 (Figures 4.3 and 4.8). The clustering algorithm also grouped w09 and w16 closely but separated w15 into a different group (Figure 4.9).

### 4.3.3 Correlation of the piezometers and the stream

Examining water table responses during individual events (Figure 4.2) showed that the piezometers responded differently to events and that event size (peak discharge) and the antecedent condition might be important factors in determining the water table – stream discharge correlation. The water table – stream discharge correlation for each event were plotted against the peak stream discharge (Figure 4.6) and plotted against the antecedent condition (stream discharge before the event, Figure 4.7). Similar plots were produced for rainfall intensity and total rainfall amount; however the trends were similar to the peak discharge (Figure 4.6) so only the peak discharge is presented. The offset value used for the ranked correlation is represented by the size of the symbol in Figures 4.6 and 4.7. In general, the offset decreased as the water table – discharge correlation increased; however, it is difficult to determine if the offset was related to the antecedent condition or the peak discharge.

Piezometer d14 represented the extreme condition where the water table only seldom responds and has poor water table – stream discharge correlation regardless of the peak discharge or the antecedent condition. The next piezometers in Figure 4.6 and 4.7 (d33 to d05) represent piezometers in the transition from the extreme ridge top piezometer d14 to the intermediate type of response. These piezometers have no water table at some point during our measurements and have contributing areas of 100 $m^2$ or less. As expected the correlation between these piezometers and peak stream discharge increased as the type of piezometer progressed from the driest (d14) to medium type (d05). The ranked correlation also increases at lower peak discharges with respect to the event size (Figure 4.6). There is a strong relationship between the peak discharge and the correlation, as the peak discharge increases so does the water table – discharge correlation. Many of these piezometers responded only to the largest events, or measured a water table that was not hydraulically limited. As a result, as the event size increased so did the water table – discharge ranked correlation. The relationship between the antecedent condition and the water table – discharge ranked correlation was not as strong (for piezometers m06 to m38). The water table measured by theses piezometers had fast recessions (Figure 4.2), so there would be little effect of the antecedent condition on the next event. However, similar to the peak discharge there was an increasing relationship between the water table – discharge as the antecedent condition increased. This suggested that as piezometers progress from the driest to the medium types, antecedent condition and the event size both become more important in controlling the water table – discharge relationship.

The piezometers from m21 to w01 show the piezometers in transition from the medium to the wet sites and have the larger contributing areas (100 to greater than 1000 $m^2$). These piezometers have high water table – stream discharge correlations (greater than 0.8) and in general the ranked correlation increased as the peak discharge and antecedent condition increased (Figure 4.6). However, the correlation did not always increase as the antecedent condition increased (Figure 4.7). For example, w15, w02, w37, and w01 had poor correlation values when there were high antecedent conditions. The medium and dry sites and the stream discharge tended to have fast recessions and the wetter sites tended to have slower recessions. If the antecedent condition is high, the wet piezometer will only have a limited response, where the stream and medium piezometers will be able to respond more and thus have a higher correlation. E.g. compare w15 and m11 for a change from 10 to 40 l/s (Figure 4.3).

### 4.3.4 Grouping piezometers and grouping into zones

To determine the effectiveness of the predetermined groups the average of the event ranked correlations between each piezometer within and between the groups were calculated (Table 4.2). If the grouping was good, there would be high correlation for piezometers within a group and there would be low correlation for piezometers between groups. In general, results show that the predetermined groups are not distinct; in fact, the dry piezometers are better correlated to the medium and wet piezometers than within the group.

The hierarchical cluster analysis algorithm was used to create new groups with the water table information (Figure 4.9). Piezometer m38 was not included in the analysis because this piezometer had a short time series that created missing values in the distance matrix. The cluster tree results were used to create three groups (Figure 4.9). The first group could be considered the new dry group and contained piezometers d33 to d14. The second group was the new wet group and contained piezometers w16 to w37. The final group was the new medium group and contained piezometers m04 to w15. Piezometer m36 was separated early in the process. The new groups were analyzed with m36 and m38 in the medium and dry groups which made little difference to the final results so they were added to the dry group because of the characteristics of the response (Figure 4.3). These three new groups showed marginal improvement over the predetermined groups (Table 4.2); however, the algorithm produced the desired outcome and the within group correlation was higher than the between group correlation. Assuming that these groups were the best possible grouping given the water table measurements, the predetermined grouping was respectable.

The last method we used to determine groups was to plot the ranked correlation, and regression coefficients against the contributing area (Figures 4.4, 4.5 and 4.8). The correlation for the entire time series and average of the correlation for each storm (Figure 4.5) showed that the correlation did increase with the contributing area. Also, the piezometers with the smallest contributing area showed the most improvement when the correlation was calculated for each event. The hierarchical clustering algorithm 'dry sites' stand out from the other piezometers in most of the plots. However, the hierarchical clustering algorithm did not always classify the piezometers with large contributing areas as 'wet sites'. For example, the clustering algorithm classified the piezometers with the largest contributing area, w15 and w05 as 'medium sites'. The predetermined groups did capture the wet sites as sites with large contributing areas, however the contributing area, as determine in the field, was used to define the predetermined groups. In general, the predetermined groups capture the extremes, (e.g. driest piezometers have the smallest contributing area and wettest piezometers with the largest contributing area) however the intermediate water table responses were difficult to determine.

Our grouping methods did conflict, however the predetermined groups could be improved once the water table response was measured. Some of the medium and dry piezometers (predetermined groups) with contributing area of less than 100 $m^2$ were very difficult to classify as a dry or medium piezometers (e.g. d05, d18, m36, d33, m13, and m06). After the response was measured it was clearer how to group the piezometers. The same problem was found when the piezometers near the medium/wet classification were assigned to a group.

## 4.4 Discussion

### 4.4.1 Hydraulically limited water table response

Peak water table response information has been used to determine hydraulically limited sites and infer the presence of preferential flow networks. Once a preferential flow network is connected down slope and active the capacity of the soils to drain increases substantially causing the water table to stop rising in relation to the runoff. Soil excavations near this site (Anderson *et al.*, 2008a) showed that the development of the preferential flow network and the soil characteristics were related to the contributing area. Piezometers with large contributing areas had large well developed preferential flow features that were well connected and could laterally transmit water without interaction with the surrounding soil matrix. Soils with smaller contributing areas had less developed preferential flow networks. This pattern would be expected to be present in Figure 4.8. The piezometers with the smallest contributing areas should not be hydraulically limited because there would be flow through smaller preferential features that are not well connected. These piezometers would only respond during some of the largest storms and likely would only contribute saturated water down slope for a short time. The piezometers in the middle of the contributing area spectrum (100s $m^2$) would start to show the hydraulically limited behaviour. The piezometers with the largest contributing areas (1000s $m^2$) would have complex and possibly desynchronized water table – runoff relationships because of highly connected preferential flow features that may only be hydraulically linked to the soil matrix under certain conditions. Although most piezometers show an inflection in the water table – runoff relationship, there was no discernable trend between the contributing area or the predetermined groups and the hydraulically limited behaviour (Figure 4.8). The highly variable soil characteristics, subsurface topography, and the preferential flow networks make the water table – runoff relationship complex.

The concept of fill-and-spill also will create complex water table – runoff relationships (Tromp-van Meerveld and McDonnell, 2006b). Similar behaviour was observed at this experimental watershed, where the preferential flow pathways appeared to become overwhelmed and the water was diverted (spilled) to another part of the outflow of a gauged trench (Anderson *et al.*, 2008a). These processes are likely to cause the capping affect noticed in the water table – discharge relationship as the water connects down slope and drains rather than increasing in depth. However, the down slope receiving areas of this water may behave differently once the upslope areas connect. We observed a dynamic behaviour that may be a result of this effect. Figure 4.2 shows that m11 had sharp response peaks during large events when the upslope areas have water tables (m06). When the upslope areas were not active there were smaller response peaks that appeared to be behave differently and might be hydraulically limited.

### 4.4.2 Grouping the water table responses

Grouping piezometer responses has worked at other sites (Siebert *et al.*, 2003); however predetermining groups in the field, using the Spearman ranked correlation between piezometers, or the contributing area did not define distinct zones of water table response at this site. The piezometers with extreme dry or wet conditions could be identified; however it was not possible to use physical indicators to determine the dynamics of the response for the intermediate piezometers. Even though some piezometers had good relationships with discharge (Figure 4.3) it was still not possible to determine physically based patterns of response that would enable model parameters to be transferred to other sites (e.g. Figures 4.4, 4.5, and 4.8). This was expected because studies at this experimental watershed, and around the world have shown that complex soil characteristics, surface and subsurface topography, and preferential flow networks make the runoff and water table response highly variable (Anderson *et al.*, 2008b; Freer *et al.*, 1997 and 2002; Hutchinson and Moore, 2000; Kim *et al.*, 2005; McDonnell, 1990; Peters *et al.*, 1995; Sidle *et al.*, 2000; Tani, 1997; Tromp-van Meerveld and McDonnell, 2006a; Tsukamoto and Ohta, 1988; Uchida *et al.*, 2002). These factors also make the water table response different for sites that are within a few meters of each other, and the variable soil depths and topography make it difficult to determine the subsurface topography which will influence factors such as contributing area and distance to stream of individual piezometers. Two piezometers located within a few meters of each other in an area of similar site characteristic can have very different contributing areas (as defined by the preferential flow network and the subsurface topography) and one site could receive large amounts of upslope subsurface flow and the other area would not have any contributions from upslope.

This information is still useful for determining the range of characteristics for a zone within a watershed (McGlynn *et al.*, 2004). Classification and simplification of internal watershed processes are often required for watershed management and modelling purposes (Siebert and McDonnell, 2002). This type of internal watershed process information presented here will help modellers determine if models are producing the good results for the right reasons. These characteristics of watersheds are often referred to as “soft data” and are descriptors of the behaviours and patterns within a watershed rather than hard imperial measurements (Siebert and McDonnell, 2002). At this site, there was a gradient of responses rather than distinct groups of response types. Even though the responses were complex, the contributing area still reflected this response gradient.

One response type was observed in the driest areas, where approximately 50 % of piezometers were hydraulically limited, and there were fast response and recession characteristics. These piezometers required a minimum event size (stream discharge) before a response was observed and the number of responses increased as the contributing area increased. Within this zone the piezometers with the smallest contributing areas generally had the poorest correlation with the stream discharge regardless of the event size or antecedent condition (Figures 4.6 and 4.7). As the contributing area increased so did the water table response – stream discharge ranked correlation.

The other response type was found in the wettest zones, generally with the largest contributing areas. These piezometers responded to most storms and had slow recession characteristics. Within the wet group a gradient of response types were observed. This variation in type of responses was reflected in the water table – stream discharge ranked correlations. The first type of response had a small amount of variation for a given stream discharge (e.g. w09). The second type of response had relatively large variation for a given discharge and the variation decreased with stream discharge (e.g. w15). The final group was not synchronized with the stream response and the stream responded without an increase in the water table (e.g. m04).

## 4.5 Conclusion

A stratified sampling methodology was used to determine if site physical characteristics could identify the water table response within a zone of a watershed. This field method of predetermining groups was tested against a hierarchical clustering algorithm to determine if better groups could be made once the water table responses were determined. The clustering algorithm produced marginal improvements over the method of predetermining groups in the field. The water table response characteristics were also plotted against the contributing area to determine patterns in the model parameters. There were weak relationships between the contributing area and the correlation of the water table and stream responses. In general, the extreme dry and wet types of water table response could be identified, however the intermediate types were difficult to determine. There was also no clear pattern to the presence of hydraulically limited water tables, although the medium piezometers did show more responses that continued to increase with increasing discharge. The lack of apparent groups, poor relationship to contributing area (topography), and high variability of response between piezometers that appeared similar could be a result of preferential flow, variable soil depths, and the complex micro-topography. The topography and observable factors could be used to identify extreme types of responses; however the variability within these watersheds made it very difficult to predict the water table response from relationships between depth to water table and stream discharge.

The single most problematic issue in applying any area-based method in coastal watersheds is the difficulty in determining watershed areas, yet area-based methods are perhaps the most common. An example of this is the use of proportional areas to synthesize a streamflow record for an un-gauged site based on nearby gauge records. This problem increases in importance as we go towards smaller scales. We have generally assumed that this problem is due primarily to the near-planar terrain and the relatively high drainage density, leading to large uncertainties when using topographic maps to estimate watershed areas. Results of this work now show that the distribution of preferential flow features in a hillside acts as a wild card because it greatly magnifies the variability of the subsurface flow response within watershed boundaries.

This all contributes to the idea of a representative elemental volume (REV), which might be quite large in the case of hillslopes in coastal watersheds, in order to make sense of how these hillslopes contribute to streamflow, and how forestry activities might alter flow characteristics. It probably means that while it is important to recognize the importance of preferential flow, it is not necessary to worry about specifically quantifying it at smaller scales. Rather, we need to come to understanding of what proportion of the subsurface flow from a hillslope is delivered by preferential flow paths and at what rate.

Table 4.1. Soil depth and contributing area for each of the piezometers. The topography and indicator vegetation were used to determine the groups. The prefix of the piezometer identifies the group "d" – dry, 'm' – medium, 'w' – wet.

| Piezometer name | Soil depth (mm) | Contributing Area ($m^2$) |
|---|---|---|
| D05 | 650 | 35 |
| D14 | 660 | 6 |
| D18 | 1100 | 30 |
| D33 | 680 | 20 |
| M04 | 950 | 85 |
| M06 | 1500 | 25 |
| M08 | 990 | 300 |
| M11 | 1400 | 50 |
| M13 | 1000 | 40 |
| M17 | 650 | 50 |
| M21 | 1260 | 250 |
| M32 | 500 | 200 |
| M36 | 650 | 30 |
| M38 | 930 | 80 |
| M43 | 700 | 200 |
| W01 | 900 | 500 |
| W02 | 800 | 480 |
| W05 | 1000 | 1650 |
| W09 | 850 | 1800 |
| W15 | 1230 | 1500 |
| W16 | 600 | 1220 |
| W30 | 950 | 90 |
| W37 | 750 | 450 |

Table 4.2. Average best correlation of each storm between and within groups 1) the groups predetermined in the field ("dry" "medium" and "wet"), and 2) the groups determined from the hierarchical clustering algorithm with the average best correlation between piezometers as the distance matrix (Bold text).

| | DRY | MEDIUM | WET | STREAM |
|---|---|---|---|---|
| DRY | 0.646 [a]<br>**0.663** [b] | 0.697<br>**0.650** | 0.701<br>**0.651** | 0.729<br>**0.667** |
| MEDIUM | | 0.736<br>**0.844** | 0.761<br>**0.807** | 0.804<br>**0.861** |
| WET | | | 0.793<br>**0.822** | 0.846<br>**0.865** |

[a] Groups predetermined in the field, and
[b] Groups identified using the clustering algorithm (Figure 9).

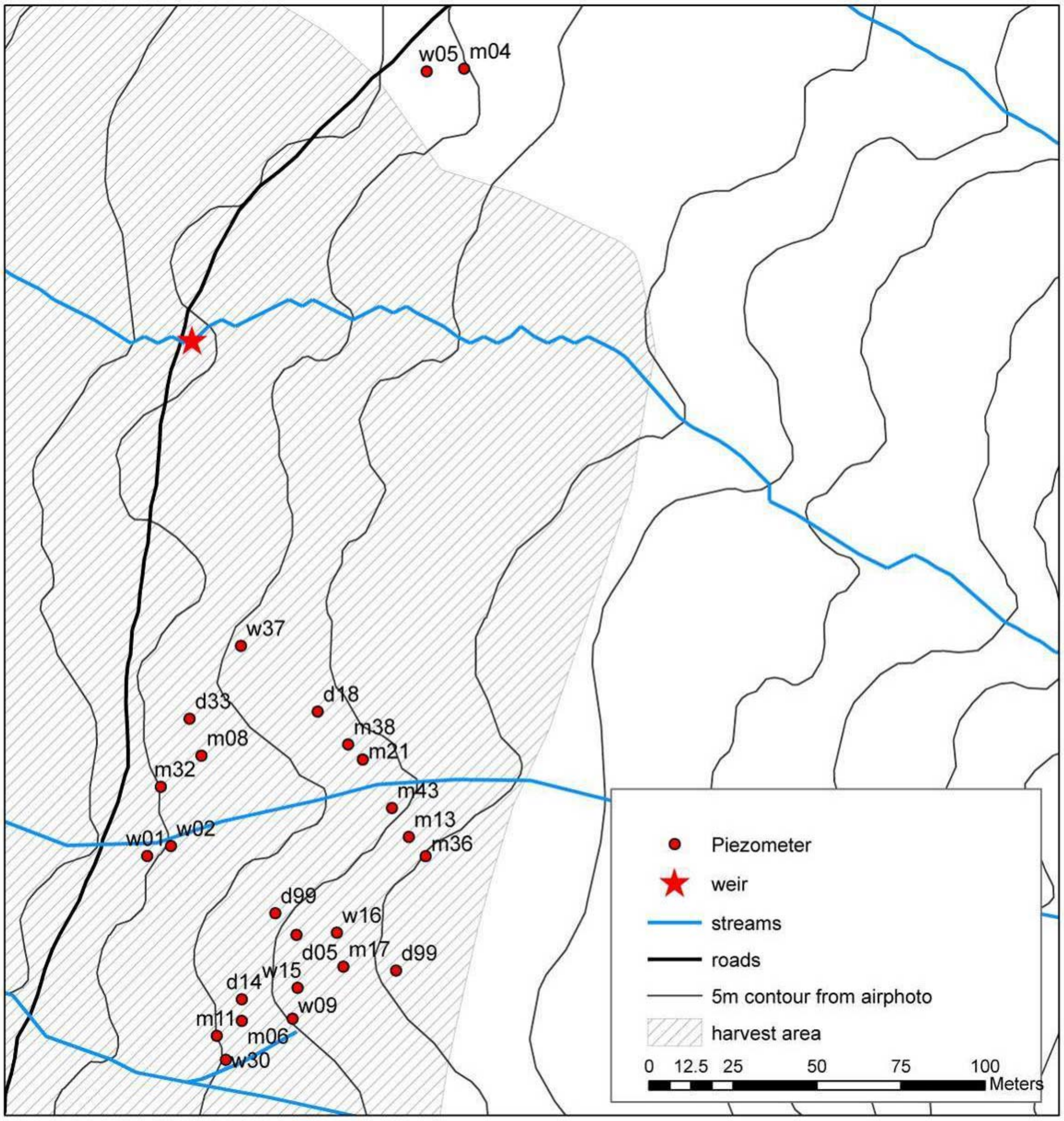


Figure 4.1. Map of the piezometer locations and stream gauging site. The predetermined groups are identified by the prefix of the piezometer d, m, and w represent the dry, medium, and wet groups, respectively. 'd99' indicates piezometers with no response and the instruments were moved.

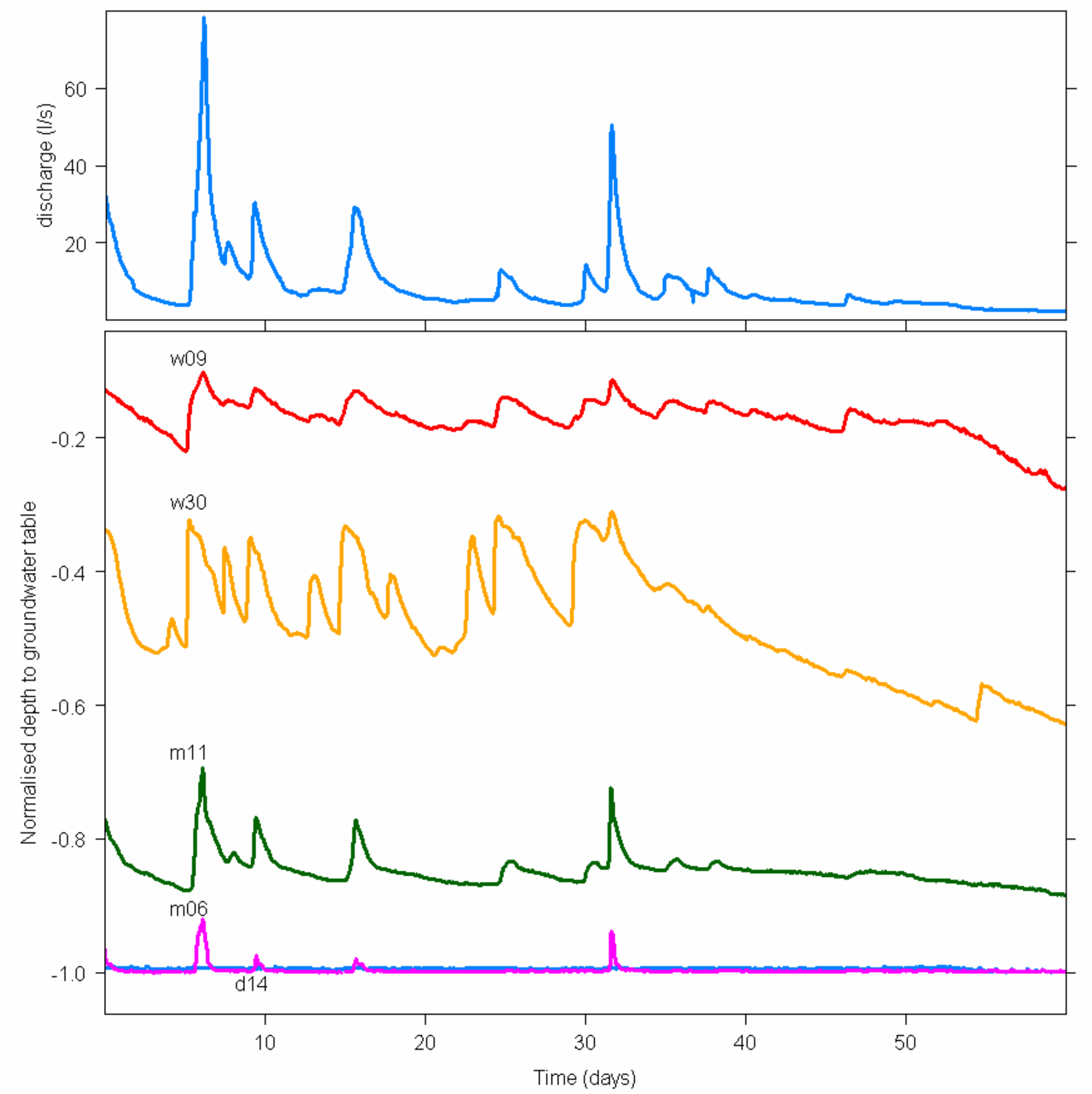


Figure 4.2. Stream discharge and the water table response for 5 piezometers with increasing contributing area for a 60 day period.

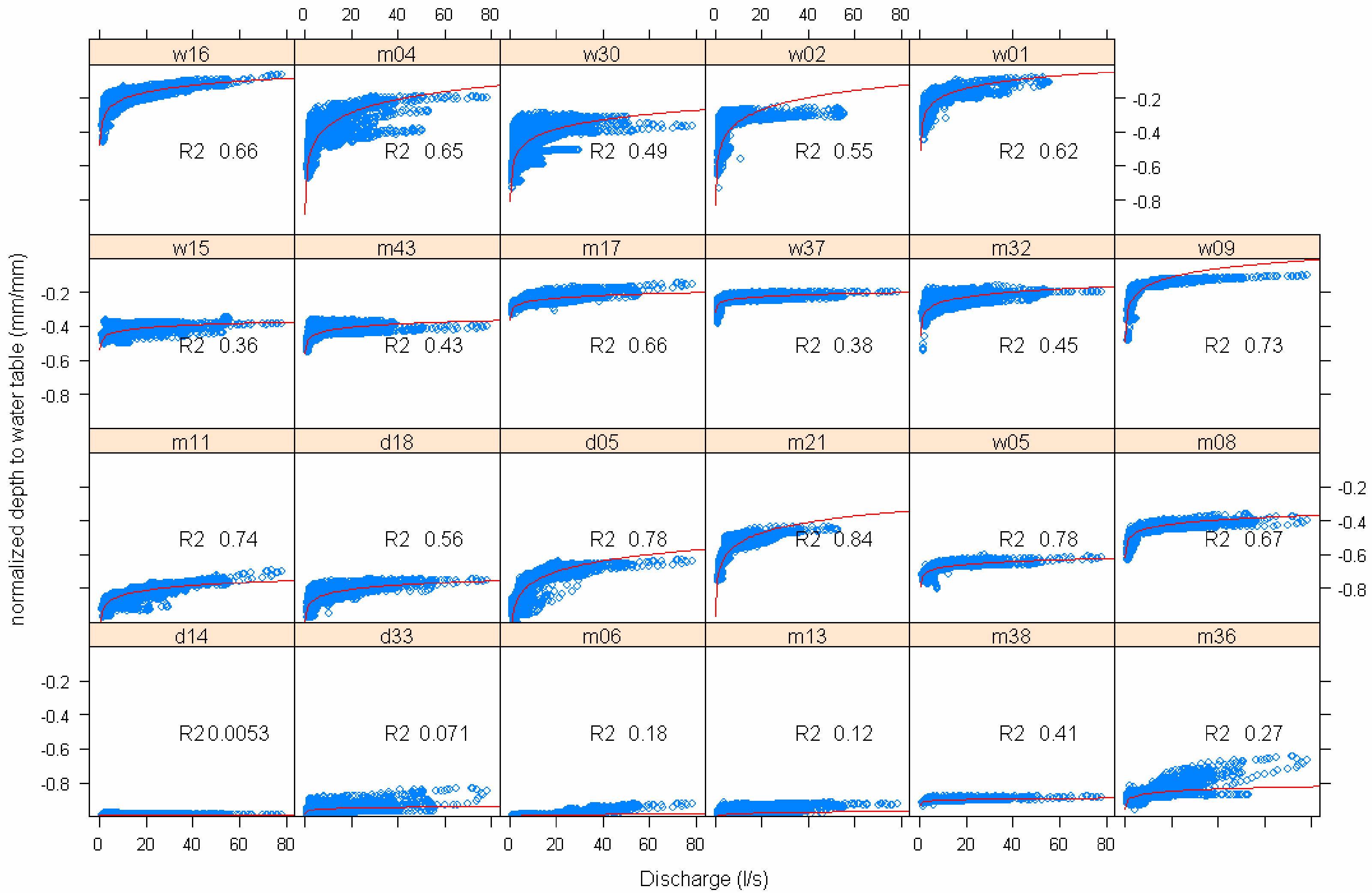


Figure 4.3. The normalized depth to the water table, (z), mm/mm (depth to water/depth of piezometer) versus the stream discharge (Q) l/s. The red line is the regression $z = f * \ln(Q) + b$ and the $r^2$ are shown (calculated in semi-log space).

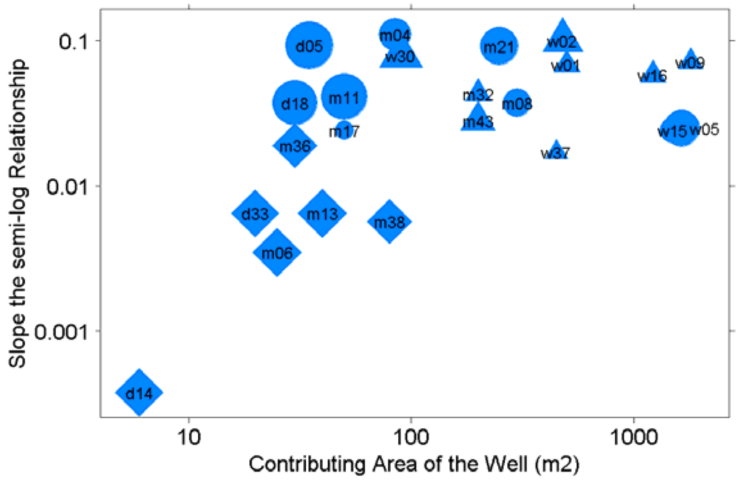


Figure 4.4. The regression coefficients for $z = f * \ln(Q) + b$ (calculated in semi-log space). The size of the symbol identifies relative depth of the water table at zero discharge (d14 and m06 are examples of the maximum (-1) and w37 is minimum (-0.28)). The symbols correspond to the groups identified by the clustering algorithm. Note that m38 was not used in the clustering process because there were too many missing values, for the purposes of this figure m38 is grouped with the new 'dry' class.

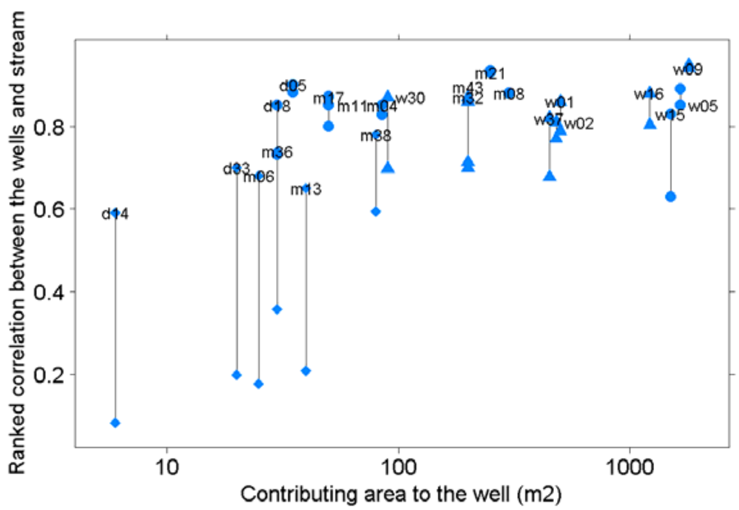


Figure 4.5. The best ranked correlation between the piezometers and the stream versus the contributing area 1) the entire time series, and 2) the average of the best ranked correlation values for each event. The symbols correspond to the groups identified by the clustering algorithm. Note that m38 was not used in the clustering process because there were too many missing values, for the purposes of this figure m38 is grouped with the new 'dry' class.

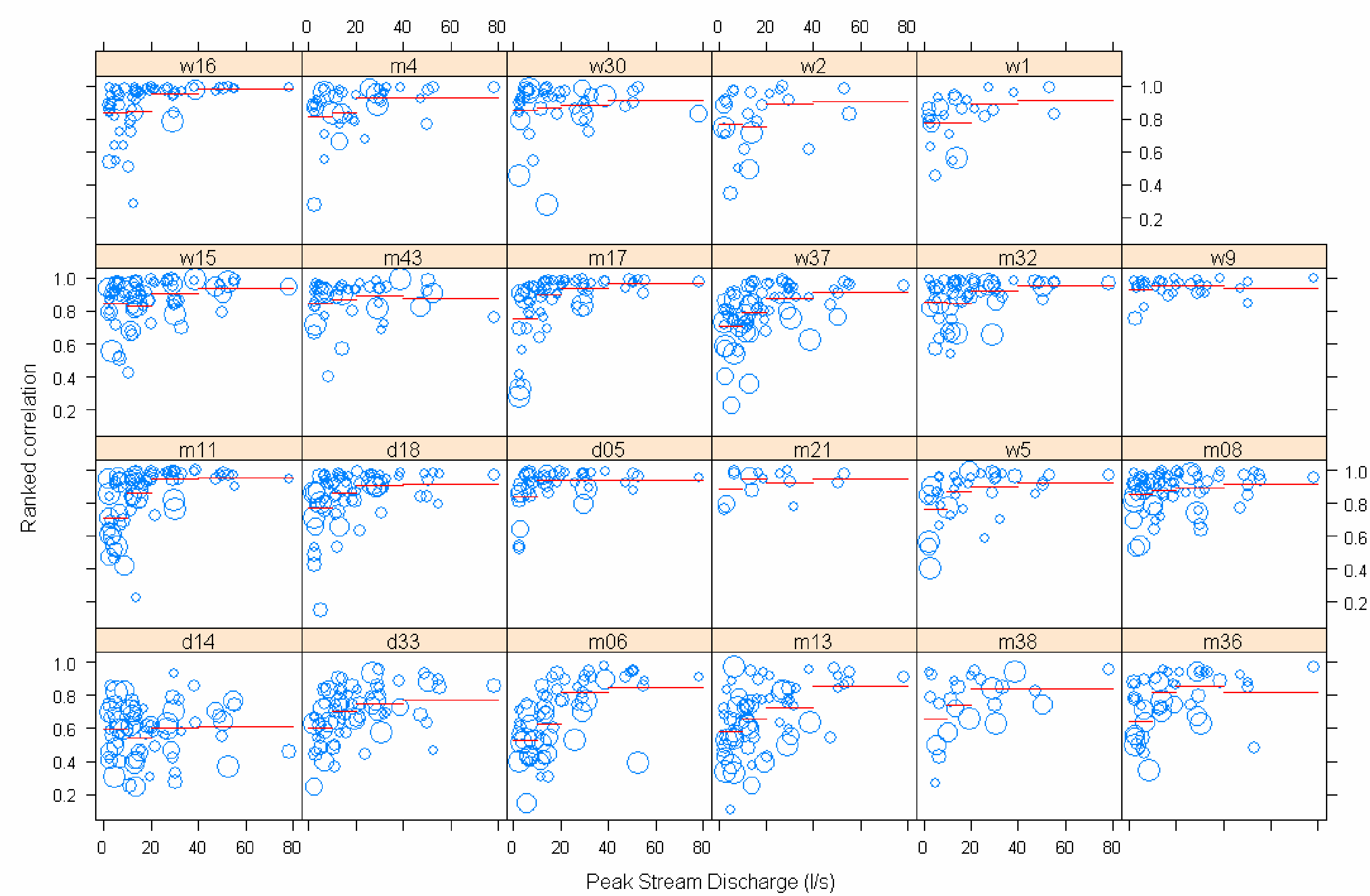


Figure 4.6. Best ranked correlation between the stream and water table response plotted against the peak streamflow for each storm. The size of the symbol reflects the time offset between the stream and the water table response. The red lines are the average ranked correlation for each increment in peak discharge (0-10, 10-20, 20-40, >40 l/sec).

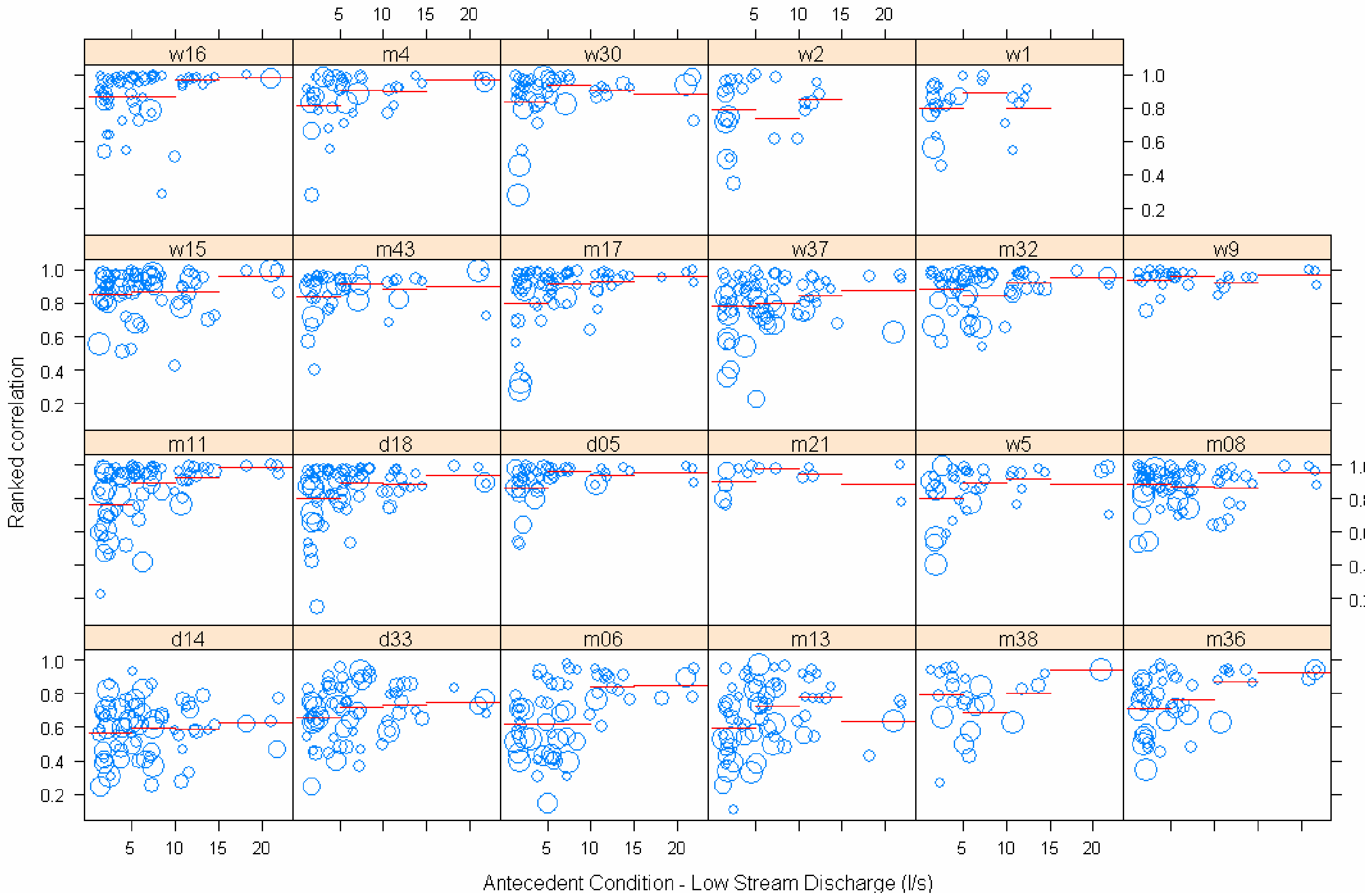


Figure 4.7. Best ranked correlation between the stream and water table response plotted against the antecedent condition, the lowest streamflow before each event. The size of the symbol reflects the time offset between the stream and the water table response. The red lines are the average ranked correlation for each increment in low discharge (0-5, 5-10, 10-20, >20 l/sec).

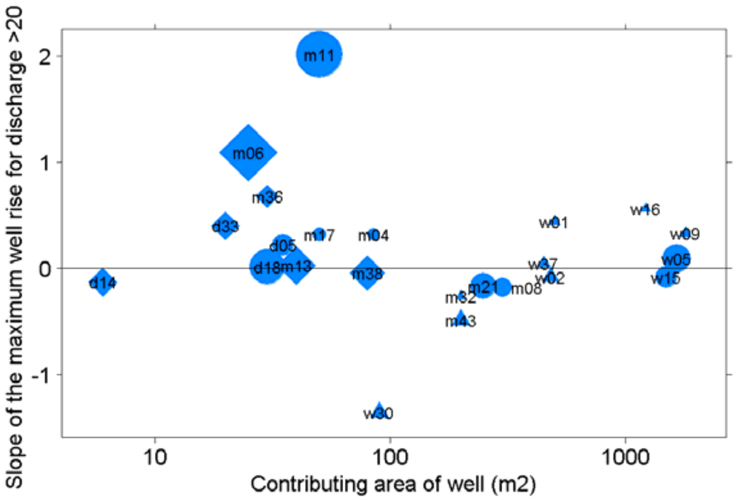


Figure 4.8. The linear regression coefficients for the maximum water table depth for the discharge greater than 20 l/s. The slope units are mm of water table rise per litre/sec of stream discharge (mm per l $sec^{-1}$). The size of the symbol identifies the maximum depth of the water table at zero discharge. The smallest is m32 at -80 mm and the largest is m06 at -1460 mm The symbols correspond to the groups identified by the clustering algorithm. Note that m38 was not used in the clustering process because there were too many missing values, for the purposes of this figure m38 is grouped with the new 'dry' class.

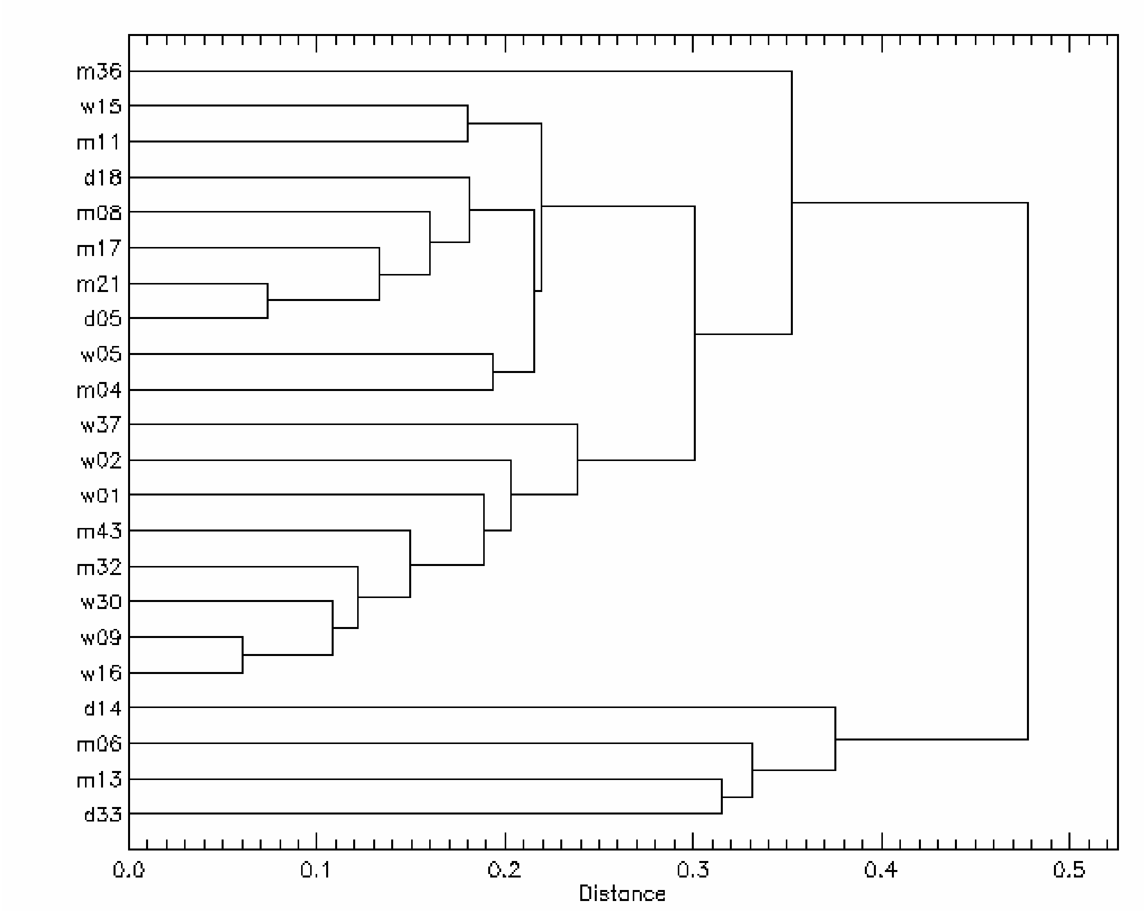


Figure 4.9. Tree diagram of the clustering algorithm with the average best event correlation between piezometers as the distance matrix.

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# 5 Conclusion

The International Association of Hydrological Sciences (IAHS) has identified 2003–2012 as the IAHS Decade on Predictions in Ungauged Basins (PUB). To facilitate this goal, researchers are encouraged to move away from model calibration and towards the understanding of the processes that govern watershed hydrology. The need to understand the patterns at the hillslope scale is important, however testing the patterns and conceptual models is important to validate the concepts. This thesis produced mixed conclusions; many conceptual ideas and hypotheses were supported by the data; however, the fact that subsurface preferential flow dominated the runoff generation at this site made it difficult to define general and transferable trends for water table data.

Few experiments have combined steady state, natural condition measurements, and excavations at one site. In Chapter 2, subsurface velocity was measured during natural storms and under steady state conditions to compare methods and explore the effect of slope length on the average subsurface velocity. These experiments highlighted the need to consider the representative elementary volume (Beven and Germann, 1981) when analysing experimental results. The results also suggested that the rainfall intensity was the factor that best explained the subsurface velocity. Dye tracers have been used to identify the preferential features active in vertical percolation and for lateral flow over a distance of a few metres. In Chapter 3, we tested the feasibility to extend these methods to the hillslope scale. The objective was to determine if there was a relationship between observable physical factors and the preferential flow features. We observed that contributing area might be a factor that controls the modification of preferential features. However, in Chapter 4 we were not able to identify a clear trend between the contributing area and an indicator of hydraulically limited water table response, which should correspond with well-developed preferential networks. We were also not able to group water table responses into watershed zones using physical site factors. This variation in the water table response and the lack of defined patterns were expected because the hillslope scale data presented in Chapters 2 and 3 suggested that the subsurface flow was dominated by the rainfall intensity and that water could be transmitted through preferential features with little interaction with the surrounding soil matrix.

Hewlett *et al.* (1977) and Hewlett and Doss (1982) used streamflow and climate to demonstrate that the hourly rainfall intensity was a poor indicator of peak flow rates in most forested watersheds. Since then, hydrologic model development and application has shifted away from simple rainfall based models (e.g., the Rational Method) to more complex conceptual models that account for effective contributing area, topography, antecedent condition and other factors. However, at Russell Creek, we found that the patterns between water table and site characteristics were not well defined, but there was a strong relationship between subsurface velocity and the rainfall intensity. This suggests that at the hillslope-scale, the dominant control on subsurface flow was the activation of preferential features by rainfall, while antecedent conditions and the physical factors used to describe the watershed zones were less important. We found that the velocity – rainfall intensity relationship appeared to reach a maximum value (asymptote) quickly. This would suggest that the preferential network was activated with a relatively small amount of rainfall and with minimal water storage. At this site the annual rainfall is high (2000 mm/yr), soils are shallow (0.5 – 1.5 m) and derived from morainal veneers, and the lower bounding layer is relatively impervious glacial till. The forested environment and the high rainfall may also play a role in the development and maintenance of large well-connected preferential features, and the wet climate may maintain soil moisture content close to field capacity for most of the year.

We put forward the possibility that this subsurface flow generation mechanism has similarities to other runoff mechanisms that are strongly influenced by rainfall intensity, such as infiltration overland flow and saturated surface overland flow. The mechanisms are different (i.e. limited infiltration versus the initiation of preferential flow networks); however the conceptual ideas and effects of rainfall intensity dominated responses may be applicable to areas with preferential flow. Currently, rainfall intensity dominated response is usually assumed to occur only on small areas of saturated soil, road surfaces, compacted fields, and other surfaces with low infiltration (Hewlett *et al.*, 1977; Jackson *et al.*, 2005). However, preferential flow could be the dominant subsurface flow process over a large proportion of the watershed, and it is conceivable that the runoff response of many coastal watersheds of the size of Russell Creek is driven almost entirely by rainfall intensity characteristics. Water table data presented here showed that for convex and planar hillslopes there is a threshold event size that must be exceeded before a water table can develop. Presumably, the water table would be the feature that provided down slope water via preferential flow and matrix flow. Although excavations suggested that soils in similar areas (small contribution areas) had small preferential features and relatively unconnected preferential networks, the measured subsurface flow velocities suggested rainfall intensity was the most important factor. If the rainfall intensity is the mechanism that activates the preferential flow network and causes the subsurface flow, it is conceivable that once the preferential flow networks in the convex and planar areas are active, runoff that can be modelled by rainfall intensity may be present on a large portion of the watershed.

The forested watersheds of coastal British Columbia are managed for timber. The idea that rainfall intensity controls preferential flow in these types of watersheds is likely to affect not only our understanding of how antecedent conditions and event characteristics influence runoff generation in these types of watersheds, but also our understanding of the effects of harvesting and roads on the flow regime. Harvesting reduces canopy interception and evapotranspiration. In a rain-dominated climate, this is thought to increase the frequency of smaller streamflow peaks because of the reduced interception capacity of the vegetation and the reduced storage in the wetter soils. However, if the rainfall intensity activates the runoff generation and there is low pre-harvest storage capacity of the soil and low interception capacity of the forest canopy because of the year-round wet conditions, the effect of harvesting on the frequent streamflow peaks may be less than previously thought. Roads are thought to extract slow moving subsurface flow and convert it to faster surface flow in the ditches, resulting in a change of runoff generation mechanism and thus affecting the timing and magnitude of the streamflow peak. However, if subsurface velocities are fast and dominated by rainfall intensity there may be less of a difference between an undisturbed hillslope and a hillslope with roads compared to a watershed with slower runoff generation mechanisms.

## 5.1 Limitations and future research opportunities

Hillslopes are important parts of headwater catchments; however, as the scale increases the relationship between the hillslope processes and the watershed response is less important (Uchida *et al.*, 2005). Although this area could be considered representative of many areas in the Russell Creek experimental watershed, there are other areas with different physical characteristics that are likely to have different first-order controls on the water table and runoff response. Comparing the responses presented in this thesis to areas where there would be different first-order controls dominating the runoff generation process (such as with deeper/shallower soils, more permeable bedrock/till, different topography, or different climate) will help us understand the processes that dominate a wider range of sites. This is important for understanding the runoff dynamics of larger scale watersheds and watersheds with different characteristics. Determining the runoff processes and patterns at larger scales was one of the initial objectives of this work. This study was designed in a nested fashion, starting with the gauged hillslope, then to gauged road ditch flow (larger aggregated hillslope scale), to the small gauged watershed (less than 1 $km^2$ presented here), to a 2 $km^2$ watershed, to a 4 – 5 $km^2$ watershed, and finally to the Russell Creek experimental watershed at 30 $km^2$. The elevations ranged from approximately 350 m to over 1500 m for the 4 – 5 $km^2$ watershed. The precipitation, soil types, bedrock/till interface and topography were highly variable. However, time constraints, access problems, and bad weather interfered with data collection, so it was decided to focus the efforts on the one location.

We conducted other experiments that attempted to determine the effect of scale on the runoff process, but they also failed for various reasons. Samples were collected in a nested fashion for an End Member Mixing Analyses (Burns *et al.*, 2001). However, no conclusive results were obtained because the ion concentrations in the streams were too low and there was not enough variation between samples collected from the suspected end members. In another experiment, artificial tracers were applied to the soil surface at two locations while conducting the hillslope scale natural condition tracer experiments presented in Chapter 2. This first application was intended to measure the subsurface velocity in a hillslope above a stream with no riparian zone. The second application was similar in terms of slope, contributing area, and distance to stream, but with a well-developed riparian zone between the hillslope and the stream. This experiment failed because the stream diluted the applied ion tracer concentrations to below the detection level. Florescent tracers were applied later, but the weather did not cooperate and no storm events were recorded.

Another area for future work includes developing and/or testing existing models. Often data are collected to test specific hypotheses and the potential modelling uses are not considered. Modellers then opportunistically use the existing data to develop and calibrate models to test other hypotheses (Seibert and McDonnell, 2002). However, the data for this study were collected to suite various modelling frameworks. The next step would be to test the overall conceptual frameworks of runoff generation using existing or new models in conjunction with the data presented in this thesis. Modelling is an important component of hillslope and watershed hydrology and there are formalised methods for testing and comparing the models (e.g. Clarke, 2008).

## 5.2 References


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